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- nanoICT Position Paper: Carbon Nanotubes
- European Research Roadmap for Nanoelectronics
- Nanoscience & Nanotechnology Companies in Spain

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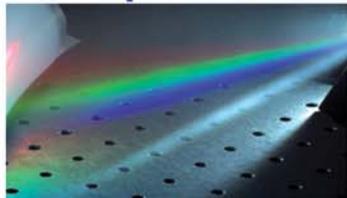
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Dear Readers,

This E-nano Newsletter special double issue contains the updated version of the nanoICT position paper on Carbon Nanotubes (CNTs) summarising state-of-the-art research in this field as well as a description of the possible electrical, electronic and photonic applications of carbon nanotubes, the types of CNTs employed and the organisations or groups that are most proficient at fabricating them.

In the second paper, the Nanoelectronics European Research Roadmap is addressed focusing on the main European Programmes supporting the short, medium and long-term research activities.

This issue also contains a catalogue (insert), compiled by the Phantoms Foundation providing a general overview of the Nanoscience and Nanotechnology companies in Spain and in particular the importance of this market research, product development, etc.

We would like to thank all the authors who contributed to this issue as well as the European Commission for the financial support (project nanoICT No. 216165).

Dr. Antonio Correia
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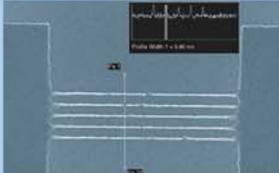
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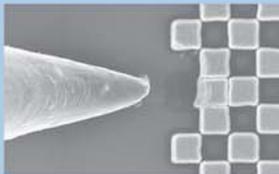
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Carbon Nanotubes (Position Paper version 2)

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Key Words

Growth

Carbon nanotubes, multiwall, singlewall, nanofibres (all the words in a and the subtopics), cap structure, catalysts, adhesion, mechanism, modelling.

Post-growth Modification

Doping, & functionalization, dispersion and separation, purification, annealing, cap opening/closing, graphitization.

Properties/characterization

Defects, electron transport, phonons, thermal properties/conductivity, wetting, stiction, friction, mechanical, chemical properties, optical, toxicity, structural properties, contacts.

Electronic Applications

Field emission (X-ray), Microwave, FEDs, Ionization, Electron microscopy, interconnects, vias, diodes, thin-film

transistors, thin-film electrodes, network transistors, single CNT transistors, thermal management, memory.

Optical applications

Absorbers, microlenses in LCs, optical antennae, lighting.

Electromechanical applications

NEMS (resonators), sensors, nanofluidics, bio-medical.

Energy applications

Fuel cells, supercapacitors, batteries, solar cells.

Blue sky

Spintronics, quantum computing, SET, ballistic transport.

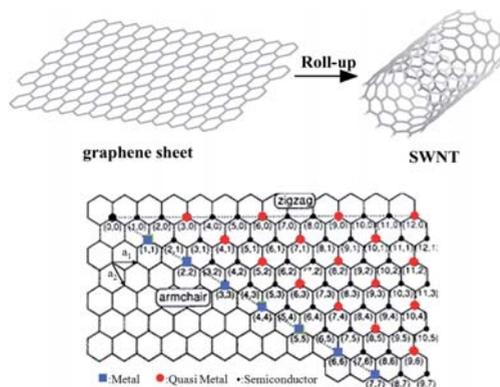


Fig 1. (top) A graphene sheet rolled up to obtain a single-walled CNT. (bottom) The map shows the different single-walled CNT configurations possible. Were the graphene sheet to roll up in such a way that the atom at (0,0) would also be the atom at (6,6), then the CNT would be metallic. Likewise, if the CNT rolled up so that the atom at (0,0) was also the atom at (6,5), the CNT would be semi-conducting. The small circles denote semiconducting CNTs, the large circles denote quasi-metallic CNTs, the squares denote metallic CNTs.

1. Introduction

There has been extensive research into the properties, synthesis and possible applications of carbon nanotubes (CNTs) since they came to prominence following the Iijima paper [1] of 1991. Carbon nanotubes are composed of sp^2 covalently-bonded carbon in which graphene walls are rolled up cylindrically to form tubes. The ends can either be bonded to a secondary surface, not necessarily made of carbon, they can be capped by a hemisphere of sp^2 carbon, with a fullerene-like structure [2], or the CNT can be open with the ends passivated (by hydrogen). In terms of electrical

properties, single-walled CNTs can be either semiconducting or metallic and this depends upon the way in which they roll up, as illustrated in Fig. 1 (page 5).

Multi-walled CNTs are non-semiconducting (i.e. semi-metallic like graphite) in nature. Their diameters range from 2 to 500 nm, and their lengths range from 50 nm to a few mm. Multi-walled CNTs contain several concentric, coaxial graphene cylinders with interlayer spacings of ~ 0.34 nm [3]. This is slightly larger than the single crystal graphite spacing which is 0.335 nm. Studies have shown that the inter-shell spacing can actually range from 0.34 to 0.39 nm, where the inter-shell spacing decreases with increasing CNT diameter with a pronounced effect in smaller diameter CNTs (such as those smaller than 15 nm) as a result of the high curvature in the graphene sheet [4],[5]. As each cylinder has a different radius, it is impossible to line the carbon atoms up within the sheets as they do in crystalline graphite. Therefore, multi-walled CNTs tend to exhibit properties of turbostratic graphite in which the layers are uncorrelated. For instance, in highly crystallized multi-walled CNTs, it has been shown that if contacted externally, electric current is generally conducted through only the outermost shell [6], though Fujitsu have been able to contact the inner walls to measure CNTs with resistances 0.7 k Ω per multi-walled CNT [7].

This position paper summarizes state-of-the-art research in CNTs. It should be noted, however, that what is regarded as state-of-the-art is dependent upon the nature of the desired end-structure. The optimum properties listed in section 7 cannot be incorporated into one CNT. Therefore, a selection of the properties listed is chosen for a specific desired end-application, which is controlled by the growth method, described first. Subsequently, there follows a description of the possible electrical, electronic and photonic applications of carbon nanotubes (excluding bulk material composite applications), the types of CNTs employed and the organizations or groups that are most proficient at fabricating them.

2. Growth

CNTs can be grown by three main techniques, chemical vapour deposition (CVD), arc discharge and laser ablation. The latter two techniques developed out of fullerene research and involve the condensation of carbon atoms generated by the evaporation of solid

carbon. The CVD method is by far the most widely employed method at present, both for bulk growth (for use in composites for example) or for growth onto surfaces (for use in electronics). This is despite the fact that the CNTs produced by this method are not the best; laser ablation remains the best method for producing reference SWNT samples of high structural and electrical quality, but CNTs produced by this method are often coated by a large amount of amorphous carbon.

Common to all growth methods and of key importance to CNT growth is the use of a nano-particle catalyst. The understanding of the role of the catalyst and a detailed CNT growth mechanism is still incomplete. This hinders the refinement of current growth techniques, in particular with regard to growth selectivity and efficiency.

Here, the progress in catalytic CVD of CNTs is reviewed, which is widely used because it offers high production yield and an ease of scale-up for both bulk production and localized growth on surfaces. The CVD review is split into two parts:

1. Fundamental understanding of the growth process,
2. State-of-the-art growth results.

2.1 The catalytic CVD process

CNT growth occurs as a result of the exposure of catalyst nano-particles to a gaseous carbon feedstock at elevated temperatures. CNTs are selectively seeded by the catalyst (Fig. 2) [8]. This can give control over the position at which CNTs form by patterning the catalyst onto a substrate – vertical arrays being a prominent example [9].

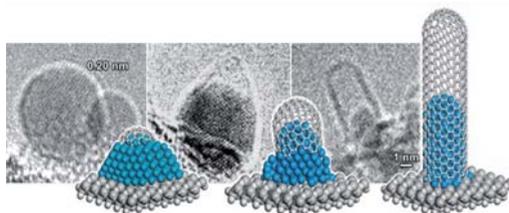
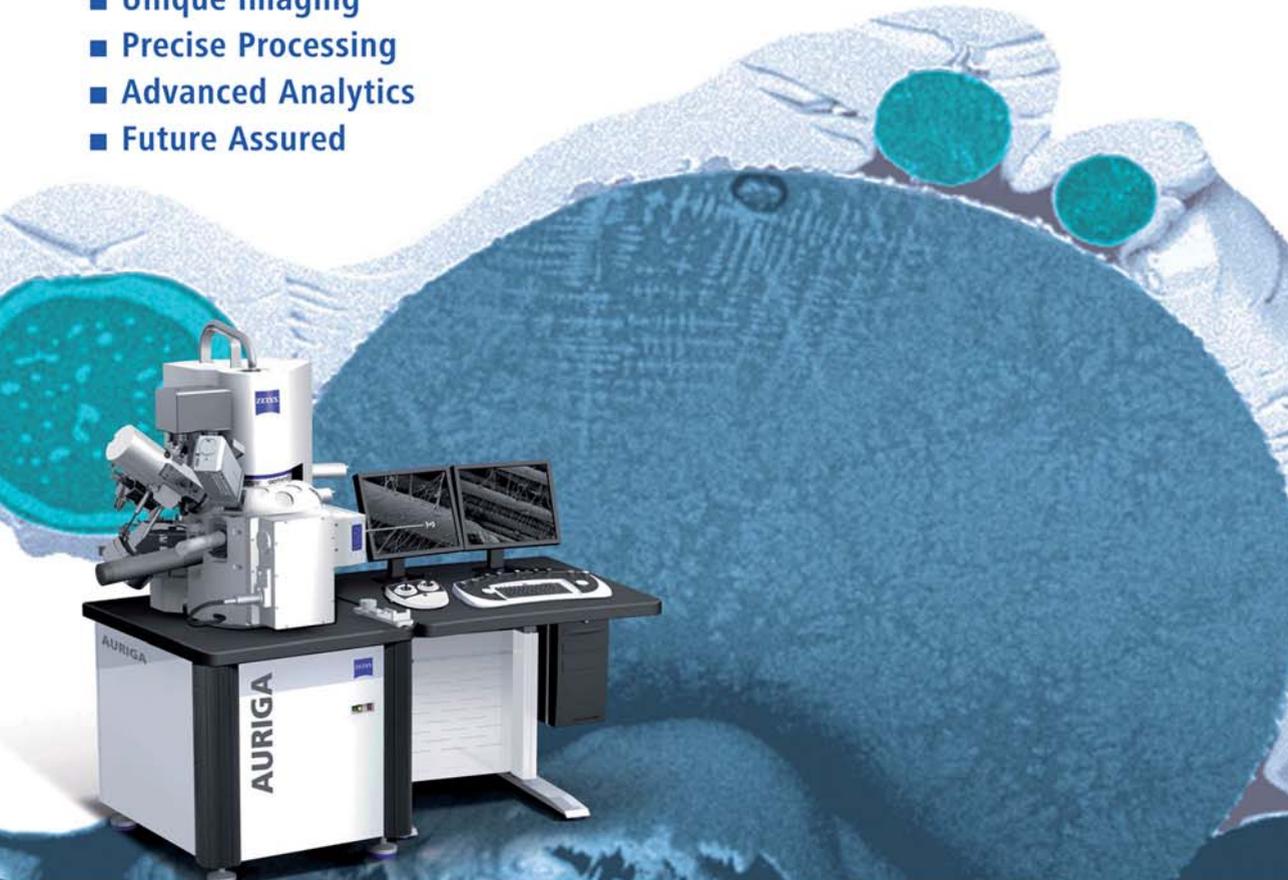


Fig. 2: Environmental-TEM image sequence of Ni-catalyzed SWNT root growth recorded in 8×10^{-3} mbar C_2H_2 at $615^\circ C$ and schematic ball-and-stick model [8].

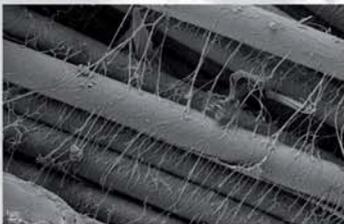
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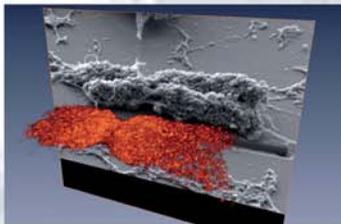
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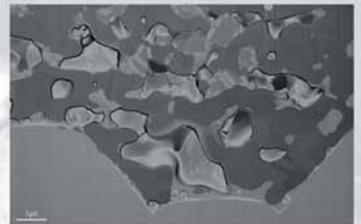
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Chamber SE image of an uncoated fibre adhesive (used in modern shipbuilding). Taken with local charge compensation at 5 kV.



3D reconstruction of chromosomes based on real-time movie. Taken with in-lens SE detector at 2 kV. Courtesy of Prof. G. Wannier, Munich, Germany.



Cross section through the front contact of a Si wafer-based solar cell. Taken with in-lens SE detector at 2 kV. Courtesy of Dr. F. Machaleit, erisol Solar Energy AG, Erfurt, Germany.

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In bulk CVD, a catalyst is injected into a hot furnace with the feedstock and the nanotubes are recovered at the base. This is realised with either a fluidised bed [10], or direct injection with fast growth.

More relevant to electronics, however, is the surface-based growth of CNTs which has many aspects in common with classical heterogeneous catalysis. There are three basic stages to the growth process:

1. A catalyst is deposited/patterned on the desired surface,
2. It is transformed into a series of nano-particles and/or its active phase is stabilised by some pre-treatment, and
3. It is exposed to the growth atmosphere.

There are numerous deposition methods for the catalyst, ranging from methods based on wet chemistry in atmosphere to physical vapour deposition in vacuum (Fig. 3).

CNT growth is essentially based on the self-organisation of carbon; control over the carbon structure requires careful tuning of the growth parameters. A significant challenge is the large parameter space to optimise which includes:

- The size and material of the catalyst,
- The nature of the support (or surface),
- The constituents of the carbon feedstock,
- The quantity and type of diluents /etchants used,
- The temperature of the annealing and subsequent growth process
- The pressure of the reactor.

A CNT growth recipe is a suitable combination of these parameters.

The catalysts used to gain the highest CNT yield are most commonly the 3d transition metals Fe, Co and Ni on the oxides SiO_2 or Al_2O_3 . The feedstock is commonly diluted C_2H_2 , C_2H_4 or CH_4 , depending on the temperature range. For high temperature CVD ($>800^\circ\text{C}$) methane is often used, whereas for low temperature growth ($<750^\circ\text{C}$) CVD recipes are often based on ethylene or the more reactive acetylene [11]. The carbon activity can thereby be regulated by diluting the feedstock. Of key importance is to avoid/minimise pyrolysis of the carbon precursor, to prevent the formation of a deleterious amorphous

carbon film over the substrate and nanotubes, and for this reason diluents/etchants are added, which can be hydrogen, argon, water vapour or ammonia (at low temperatures).

The CNT growth process involves the dissociation of the carbon precursor on the catalyst particle surface, transport of carbon atoms through or over the particle, and precipitation of the carbon as a growing tube. All the carbon in the nanotube is incorporated via the catalyst particle [12]. In contrast to arc-discharge or laser-ablation, each catalyst particle typically forms only one nanotube with CVD. Therefore, the catalyst particle size controls the CNT diameter [8],[13],[14]. Catalyst nanoparticles, or rather their atoms, have a high surface mobility, hence a key challenge for elevated CVD temperatures is to stabilize a narrow particle size distribution. This catalyst coarsening can be minimised by a suitable choice of support and deposition conditions. A wider catalyst size distribution and larger particle size leads to a loss of control of the nanotube diameter and ultimately a loss of catalytic activity.

Important to CNT growth, however, are not only support interactions and gas-induced catalyst dynamics but also the restructuring of the catalyst due to the presence of the growing nanostructure. A SWNT nucleates by lift-off of a carbon cap (Fig. 2) [8]. Cap stabilization and nanotube growth involve the dynamic reshaping of the catalyst nanocrystal itself. For a carbon nanofibre (CNF), the graphene layer stacking is determined by the successive elongation and contraction of the catalyst nanoparticle [8],[15]. Generally, CNTs grow by either root or tip growth from the catalyst particle, depending upon whether the catalyst remains attached to the support or rides at the tip of the growing nanostructure.

In the laser or arc methods, the catalyst particles are liquid, at least during the initial stage. In many high temperature bulk growth methods, the catalyst is also liquid. But in surface-bound CVD the catalyst can be either liquid or solid. There is no necessity for catalyst liquefaction, as in-situ growth experiments at lower temperatures have shown that for Fe and Ni, the active state of the catalyst is that of a crystalline metallic nanoparticle [8],[16]. Solid catalysts are expected to allow for more controlled growth, especially with regard to potential chiral selectivity.

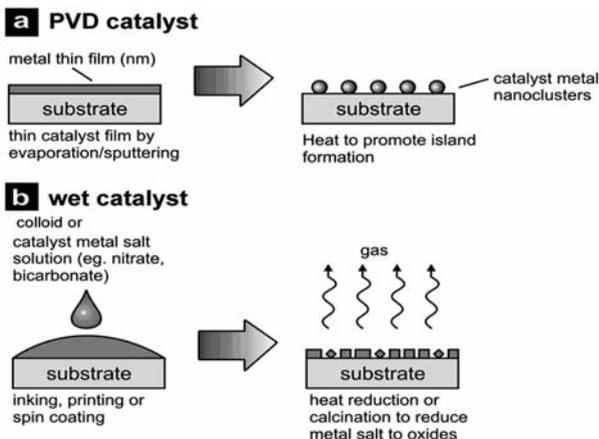


Fig 3. Catalyst preparation by (a) PVD and (b) wet chemistry [17][18][19].

In-situ experiments have shown that the active state of the most efficient catalysts Fe, Co and Ni is the metallic rather than the oxide state [16]. Thus a key part of the

catalyst pre-treatment is to reduce the catalyst to its metallic state prior to or during carbon feedgas exposure.

A catalyst prepared by PVD is transformed into its active state as a nano-particle by a pre-treatment [16] as shown in figure 3. Catalyst can also be deposited from solution, but this tends to lead to less control over CNT dimensions. This causes the de-wetting of the catalyst thin film into a series of separated nano-particles to reduce their total surface and interface energies. For Fe, this is aided by the reduction process, where the reduction in molecular volume from oxide to metal also creates nano-particles. The diameter of the resulting nano-particles is directly proportional to the initial film thickness h . Assuming volume conservation and a contact angle of 90° , this means the particle diameter D , is given by

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$$D \sim 6h \quad \text{Equation 2.1.1}$$

With a density, N , of

$$N \sim 1/60h^2 \quad \text{Equation 2.1.2}$$

Processing conditions can affect the CNT type and diameter distribution [8],[14]. For some years, certain catalysts such as CoMoCAT or some plasma enhanced growth have produced preferential semiconducting SWNTs, although the process was unknown. Recently the preferential growth of metallic SWNTs was reported by modifying the catalyst annealing atmosphere [20]. Nano-particle restructuring is driven by a minimization of the surface free energy of the system and support interactions and adsorbate-induced effects are well known from heterogeneous catalysis to affect this process. In particular for Al_2O_3 supported Fe, it has been shown that support interactions restrict the catalyst surface mobility, leading to a much narrower catalyst particle size distribution [21]. Moreover, these support interactions give a higher CNT density and a vertical nanotube alignment due to proximity effects, i.e. these support interactions trigger CNT forest growth. This is summarized in figure 4.

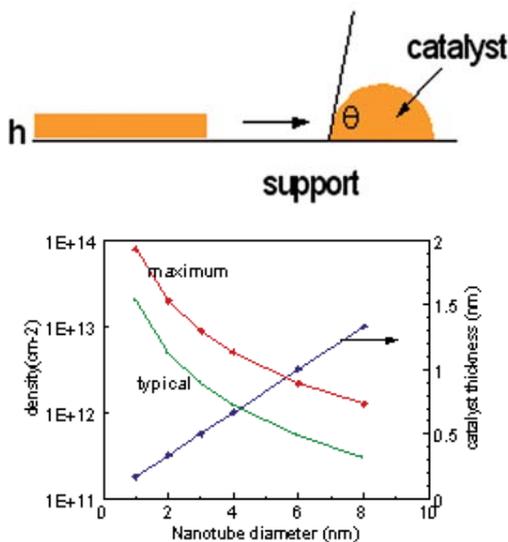


Fig 4. Above, the dewetting on the catalyst depends on surface interactions between the catalyst and support. Below, a general comparison of typical CNT growth densities with nanotube diameter (reflecting eqs 2.1.1 and 2.1.2).

The question as to what makes a good CNT catalyst has not been answered in sufficient detail. Fundamentally, CNT CVD growth requires a nano-particulate catalyst. An interesting comparison is graphene CVD, whereby planar catalyst films with a large grain size are required. However, the actual CVD exposure is often chosen to be very similar to SWNT growth. Ni and Fe films catalysing graphene CVD were shown to be metallic and showed no signature of carbide formation. CNT growth is not exclusive to Ni, Fe and Co, but has been reported, albeit often at lower yield and/or at higher temperatures, for a range of metals (such as Au, Pt, Ag, Pd, Cu, Re, Sn, Ta) and semiconductors (Si, Ge).

“Catalyst-free” SWNT formation has been reported on the Si face of hexagonal silicon carbide (6H-SiC) at temperatures above 1500°C [22] and “catalyst free” growth of arrays of multiwall carbon nanostructures has been reported on cylindrical pores of porous anodic aluminum oxide at 900°C [23]. More recently, metal-catalyst-free CVD of SWNTs has been reported on roughened Al_2O_3 and SiO_2 at 900°C [24][25][26] and SWNT nucleation has been observed from diamond nanoparticles at 850°C [27]. The CNT growth mechanism for these “metal-catalyst-free” CVD processes is largely unknown and currently very speculative. In particular, the physical and the chemical state of the catalyst during growth are often unknown and what is stated is only the state before/after growth.

Recent in-situ XPS measurements showed that nano-particulate zirconia during CNT nucleation at moderate temperatures (~750°C) does not reduce to metallic zirconium or zirconium carbide, i.e., the nano-particulate oxide is the active phase. This indicates that CNT formation can be mediated solely by a surface reaction, i.e., bulk C permeability is not a necessity for a CNT catalyst [28].

There are numerous methods by which nano-particulate catalysts can be prepared (fig. 5). Physical vapour deposition (PVD; evaporation, sputtering), aerosol based techniques, colloids, (electro-)plating and wet chemistry (salts) are among various methods used to prepare catalyst for CNT CVD. Each preparation method requires a different CVD pre-treatment to form well defined catalyst clusters with a narrow size distribution. Furthermore, the catalyst preparation is linked to available patterning techniques. For PVD catalysts, photo- or e-beam lithography offer most

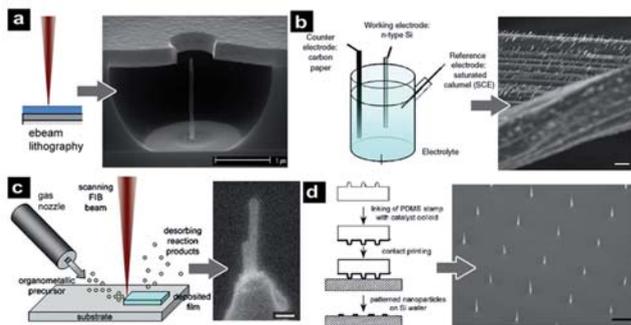


Fig 5. Catalyst patterning techniques: (a) e-beam lithography, (b) electroplating, (c) FIB, (d) contact printing [9].

control, whereas laser interferometry and nanosphere lithography are among alternative patterning techniques which can be used to pattern small feature sizes at a lower cost over large areas. Nanocontact printing and micro-fluidic techniques are often used with catalyst colloids.

2.2 State-of the art CNT growth results

The growth of CNTs depends on the desired application. For instance, certain field emission applications require spaced arrays of CNTs. It is preferable that the CNTs remain fixed and vertical. Consequently, MWNTs are the best choice in this situation. The best controlled growth of spaced arrays of MWNTs is as defined in 2001 using PECVD [29]. There have also been recent developments to scale down the diameter and height of the CNTs, in order to increase the emission current density.

Other applications such as vias, interconnects, heat spreaders, super-capacitors or adhesive surfaces require densely packed aligned nanotube arrays. This area was revolutionized by the so-called super-growth method of Hata et al [30]. This uses a Fe catalyst on Al_2O_3 support, and thermal CVD at $700^\circ C$, in hydrogen-diluted ethylene gas. A small proportion (400 ppm) of water vapour is added to the growth gas. The water is shown by EELS to act as a mild etchant for amorphous carbon which ultimately starts to cover the catalyst and terminate growth. This led to an era where mm to cm high forests could be grown by many groups world-wide. The nanotube density is controlled by the catalyst film thickness, as previously described.

A significant disadvantage of the arc method and some bulk CVD processes is that the product contains 10% of the catalyst and other graphitic material which must be removed by purification. The purification using acid washing can then add a factor of 10 to the total cost. Consequently, the super-growth method, which produces high aspect ratio CNTs has a nanotube to catalyst ratio of 10^5 , which gives a very high purity. Therefore, super-growth is the only surface-bound method of producing high-purity bulk nanotubes. This is critical for some applications such as supercapacitors in which metal impurities have a significant effect.

A key criterion for growth is to lower the temperature. This is important for a number of electronic applications such as interconnects where the temperature should not exceed $400^\circ C$, limited by the fact that it is a “back-end” process.

The first method used to reduce the growth temperature was to use PECVD which is widely used to lower processing temperatures during growth [31]. PECVD in nanotube growth was assumed to dissociate the carbon pre-cursor gas and allow the growth reaction to occur at lower temperatures. However, it is now realized that the key role of the plasma is to convert the catalyst into an active nano-particulate, metallic form at a lower temperature. Therefore, so long as growth uses acetylene, it can proceed at quite low temperatures.

Two other low temperature activation methods have been used. First, Corrias et al [32] and also AIXTRON [33] use pre-heating or plasma pre-dissociation. A second method used by S.R.P. Silva et al in Surrey is to use non-thermal light irradiation to heat the substrate surface.

Growth on metals is required for applications such as interconnects. However, metallic supports often show interactions with the gas atmosphere and catalyst, i.e. oxide, carbide and alloy formation is likely. Hence, CNT CVD directly on a metal support requires careful calibration and often gives poor growth. The way around this is to use metals with small Al content which then

preferentially oxidizes into an ultra-thin layer of Al_2O_3 , or to use metallic compounds such as CoSi_2 or TiN .

The quality of grown carbon nanotubes is subjective, since their quality depends on the structure required. Quality screening is a challenge on its own and the detailed characterisation of as-grown CNT samples remains time-consuming and relies on a combination of direct imaging methods (such as SEM, AFM, TEM, STM) and indirect methods (such as Raman, PL, optical absorption, TGA, XPS, XRD). Some applications require high purity and crystallinity; others require tight dimensional control, whilst others might require high packing densities and/or alignment. Consequently, the state of the art depends on the type of structure and application required.

2.2.1 Single-walled growth

2.2.1.1 State of the art for bulk single-walled growth

The highest purity CNTs nucleate from catalysts in a fluidized bed and are currently sold by Thomas Swan [34]. The process produces high-quality CNTs, inexpensively in large quantities. Windle's [35] group grow CNTs in a continuous flow furnace. The nanotubes are created rapidly by injecting ethanol and ferrocene into a furnace at 1200°C . An aerogel then starts to stick to the cooler wall in the furnace to form fibres. A spindle then winds the aerogel fibres into a thread, at several centimetres per second. The result is an

extremely fine, black thread consisting of aligned CNTs [36]. Nanocyl also produce purified single-walled nanotubes [37].

2.2.1.2 Horizontally aligned single-walled CNTs

Horizontally-aligned SWNTs have been grown on epitaxial surfaces such as sapphire and quartz with varying densities. The growing CNTs follow the crystal planes with a great degree of alignment. The process is standard CVD but the substrate needs to be annealed for surface reconstruction before growth. Among the best, Tsuji's group have grown on sapphire [38] and the Rogers group [39], who have grown on quartz (figure 6). The density is some way ($\times 10$) below that achieved in vertically aligned forests.

Horizontal alignment can also be achieved by electrical fields, gas flow, or liquid post-treatment. Hata and co-workers dipped a vertical aligned forest in alcohol to get alignment in plane samples by capillary forces when he pulls up the substrate from the liquid [40].

2.2.1.3 Challenges for SWNTs

A key challenge for SWNTs still concerns control of chirality during growth. For applications such as transistors, all grown CNTs need to be semiconducting (and preferably of identical chirality and diameter) whilst for interconnects, all CNTs need to be metallic. Control of diameter is related to this issue.

The second challenge is nanotube density. For interconnects, a high density (of $\sim 10^{13}$ tubes/ cm^3) is needed if it is to replace copper. This is now looking possible.

The yield of SWNTs grown with templates is very low and must be solved if it is to be seriously considered as a method for growing SWNTs. Also, for SWNT growth to be combined with CMOS, the temperature needs to be reduced to $\sim 400^\circ\text{C}$.

To a certain extent the chirality problem has been overcome by using devices based on random network of

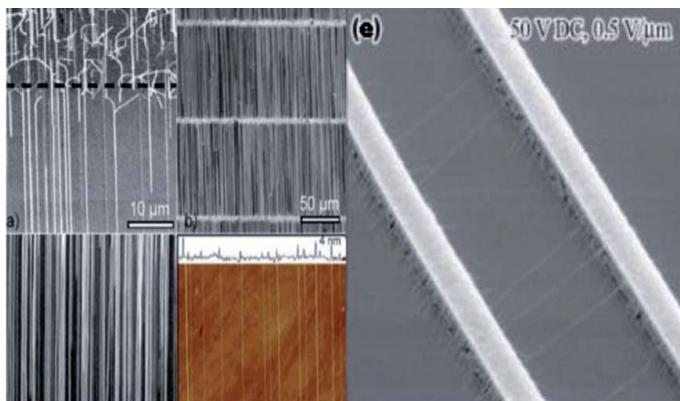


Fig 6. (a-d) CNTs grown along quartz crystal planes by the Rogers group [39]. (e) Horizontally aligned CNTs grown by Dai's group using field to align the CNTs [13].

nanotubes instead. This approach was first brought to light by Snow and co-workers in 2003 [41] although it was patented by Nanomix in June 2002 [42].

2.2.2 Multi-walled CNTs

Though Endo started the injection process, for bulk growth, the best CNTs are again grown by Thomas Swan (as a result of rigorous qualification by Raman and TEM) and Windle's group in Cambridge, though Hyperion [43] are the leading suppliers of nanofibres using a similar process to Thomas Swan. So-called Endo-fibres 150 nm in diameter can also be purchased from Showa Denko. Bayer produce narrower "Baytubes" 5-20 nm in

and Arkema [45] and Bayer [44] have made significant contributions to up scaling CVD. Recently, AIXTRON [46] and Oxford Instruments [47] have begun to provide large area PECVD capability. The leading universities in Europe include Cambridge Univ, Dresden and EPFL. Growth of MWNTs on large wafers (200mm) is now routinely done at various locations for microelectronics applications (see for example, images of CNTs grown in various CVD reactors at CEA-Grenoble in figure 7). The aerosol-assisted CCVD process allowing the production of carpets of aligned nanotubes is produced at CEA-Saclay in the group of Martine Mayne (and can also be seen in figure 7).

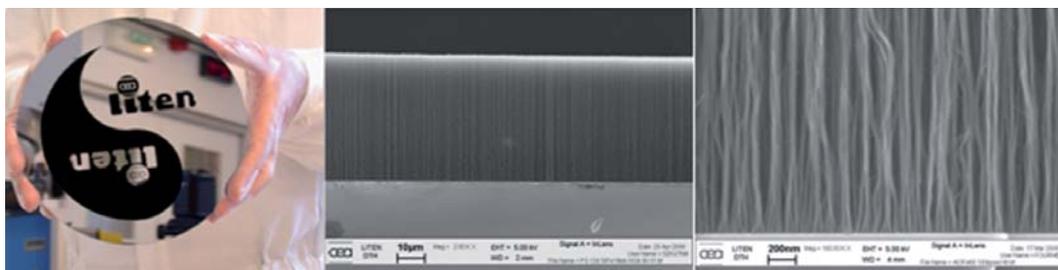


Fig 7. Dense forest of Small diameter MWCNT from left to right: a) Patterned layer on a 200mm layer b) 50µm high forest on conductive layer of TiN c) close view of the material with individual CNT making bundles of 60nm of diameter (courtesy of CEA-LITEN)

diameter [44], but these are impure. However, they are suitable for many uses because the metal is encapsulated in the tube ends and not exposed.

2.2.2.1 Challenges for multi-walled CNTs

Some of the challenges for MWNT growth are identical to that of SWNT growth. Growth temperature needs to be reduced if CNTs are to be employed in CMOS. Raman spectra of MWNTs grown by CVD/PECVD at low temperatures show them to be highly defective. Post-annealing processes can increase graphitization, but these are typically at temperatures much higher than circuitry can withstand. There is also the question of contact resistance that is often quite high and variable. This needs to be addressed with still further improvements on dimensional control.

European Position: Europe led the way with research in arc deposition but commercialisation was limited. More recently Nanocyl [37], Thomas Swan [34],

3. Post growth modification

If no particular attention is paid to it, CVD generally produces CNTs with numerous defects. Such defects are favoured:

- (i) when low temperatures are being used for the growth;
- (ii) when dopants such as nitrogen or boron are inserted;
- (iii) when the growth process is allowed to continue while the process is being ended (namely, when the power is shutdown and the substrate allowed to cool whilst still in the presence of a carbon source often resulting in the deposition of amorphous carbon around the CNT).

Many defects can be removed either by hydrogen or ammonia plasma, or by a rapid thermal annealing process which also increases the graphitization, conductivity and contact of the CNT [48]. Hence, careful monitoring of CVD parameters can lead to defect free carbon nanotubes [49]. Single defects can

HV sources

Senoidal HV source (HV-7030)



10 kV bipolar voltage source (HV-7010)



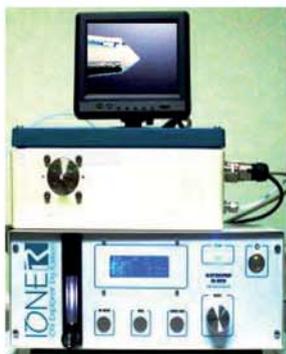
Unipolar 20kV source (HV-7020)

- 0.1V resolution
- Max current 0.3mA
- Ripple: 0.001% pp
- Programmable
- Optional USB/RS485/Zig-bee output
- Applications: mass spectrometry, electron and ion beams, SEM



- Delivers a pure senoidal voltage
- Freq range 50kHz-1MHz
- Amplitude up to 300Vpp
- Auxiliar DC output up to 50V

Electrospray source (ES-3020)



- Fluid-electrodynamic device that generates an electrically charged nanoparticles or ions from a dispersion or solution.
- Can be operated downwards, upwards or horizontally
 - Easy maintenance
 - Separate control module (pressure, voltage and sheath gas flowrate) and spraying head for greater versatility.
 - Taylor's cone can be monitored thanks to a video camera installed in the spraying chamber. Capture of images and video is also possible.
 - Applications: nanoparticle generation, mass spectrometry, thin films

Corona charger (CC-8020)



- Device for charging aerosols and particles based on corona effect.
- No radioactive source, no cumbersome paperwork.
- Especially effective for ultrafine particles.
- Bipolar
- Includes high DC voltage source
- Current measurement

Electrometers



EL-5010, an all-purpose electrometer:

- Range: +/- 9999.9 fA, Resolution: 0.1 fA
- Noise: < 1 fA (RMS)
- A/D effective resolution: 21 bits
- Selectable digital filter
- Selectable amplifier gain
- Remote control interface: USB, RS485
- Labview control software
- Electronic offset correction
- CE-marked

EL-5020, compact electrometer (16 x 6 x 3 cm), battery-powered (8 working hours) and communicated through wireless protocol Zig-Bee, especially conceived for the measurement of ultra-low current at high voltages. It is PC-controlled, with an option of a console for manual interface.

EL-5030, electrometer for the measurement of ultra-low currents generated by ionized gases and electrically charged aerosols. It includes, besides the electronics for the measurement of the current, a Faraday cup with a HEPA filter inside for the collection of nanoparticles and a flowmeter for the calculation of the concentration of particles or ions.



even be created, monitored and can serve as the point for a single functionalization [50][51].

Various techniques have been employed to purify CNTs grown by arc discharge and laser ablation. This is because the best samples are only 70% pure (using laser ablation), with the remainder made up of amorphous carbon, fullerenes, and catalyst particles surrounded by shells of chemically resilient turbostratic carbon (TSG). CNTs are first dispersed by sonication [52]. The gas-phase method developed at the NASA Glenn Research Center to purify gram-scale quantities of single-wall CNTs uses a modification of a gas-phase purification technique reported by Smalley and others [53], by combining high-temperature oxidations and repeated extractions with nitric and hydrochloric acid. This procedure significantly reduces the amount of impurities such as residual catalyst, and non-nanotube forms of carbon within the CNTs, increasing their stability significantly. Once the CNTs are separated, the use of a centrifuge enables the isolation of certain chiralities of SWNTs, particularly (6,5) and (7,5) as shown by Hersam's group at North Western University [54]. This method seems to be the way forward for scalable chirality separation.

European Position: The US lead the way in novel techniques based on density differentiation but in Europe, Krupke, Knappes and co-workers at Karlsruhe pioneered the dielectrophoresis method. Regarding industrial production, a trend is observed in which CNTs are produced and included in a polymer matrix in the same process line hence reducing the risk of exposure to airborne nanotubes.

4. Doping

Conventional doping by substitution of external impurity atoms in a semiconductor is unsuited to CNTs, since the presence of an external atom modifies the properties resulting from ideal symmetry in the CNT. Theoretically, substitutional doping by nitrogen (n-type) and boron (p-type) has been widely examined [55],[56],[57],[58],[59],[60]. Adsorption of gases such as H₂, O₂, H₂O, NH₃, NO₂ have been reported [61],[62],[63],[64]. More appropriate doping strategies which conserve the mean free path of the charge carriers involve physisorption of alkali metal atoms [65],[66],[67],[68],[69],[70],[71],[72],[73] [74],[75],[76],

[77],[78],[79],[80]. Alkali-metal atoms located outside or inside the tube act as donor impurities [81],[82] while halogen atoms, molecules, or chains act as acceptors [65],[73],[83],[84]. Fullerenes or metallo-fullerenes, encapsulated inside CNTs, allow good structural stability and have been used to tune the band gap and/or Fermi level of the host tube [85],[86],[87],[88].

"Doping" by physisorption of molecules, lies at the heart of a growing field of chemical sensors, but their stability and selectivity issues must be very carefully addressed.

European Position: In Europe Maurizio Prato's group in Trieste are the most successful in this area.

5. Oxidation/Functionalization/tip opening

CNTs can be oxidized by various means including treatment in acids, ozone and plasma oxidation [89]. Reflux in nitric acid not only purifies the nanotubes but at the same time introduces a variety of oxygen groups [90] at the open ends and sidewalls, which strongly facilitates the separation of nanotube bundles into individual tubes and enhances their dispersibility. The tips of CNTs are more reactive than their sidewalls and reflux in HNO₃ has proven to open the nanotubes tips and introduce carboxylic groups at the open ends. In particular, sonication under harsh conditions, in a mixture of concentrated nitric and sulphuric acid effectively cuts the single walled nanotubes into small fragments and gives rise to the formation of small length (100 to 300 nm) open pipes. The oxidatively introduced carboxyl groups represent useful sites for further modifications, as they enable the covalent coupling of molecules through the creation of amide and ester bonds. It has also been shown that CNTs react with ozone [91].

The growth of VACNTs is important for many potential technological applications such as field emission cathodes, vertical interconnects, and biosensors. Both thermal chemical vapour deposition (TCVD) and microwave plasma enhanced chemical vapour deposition (MPECVD) have shown promising results on producing well-aligned CNT arrays. In thermal CVD the grown nanotubes are very closely packed, the growth rate is very high and topology is highly defective compared to that of MPECVD grown CNTs. Various plasma sources have been successfully used to clean,

and open nanotube tips [92]. Low energy, high flux plasma such as ECR plasma is a suitable technique for efficient cleaning, tip opening and produces less damage.

Open-capped CNTs, unless functionalized, can be unstable structures because of dangling bonds. Cap closing of open-capped structures often occurs during field emission. De Jonge et al. [93] demonstrated this happens for currents as low as 80 nA per tube.

Several treatment methods such as chemical, electrochemical, polymer wrapping, and plasma treatment have been applied to functionalize the CNT surface for specific applications including, catalysis, bio/gas sensors, composites, drug delivery, field emission and cell scaffolds [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104]. Among these, plasma-treatment has the advantages of retaining the structural integrity of the nanotube, is environmentally friendly and it provides the possibility of scaling up for commercial use. Also, reactions are much slower than other chemical modification methods and can also provide a wide range of functional groups depending on the plasma parameters. Papakonstantinou's group has shown that plasma functionalisation can preserve the vertical alignment of CNT arrays.

Generally, the main approaches to functionalisation can be grouped into two categories:

- (a) the covalent attachment of chemical groups through reactions with the π -conjugated skeleton of the CNT;
- (b) the non-covalent adsorption or wrapping of various functional molecules

The covalent functionalization of SWCNTs is not limited to the chemistry of carboxylic acid. More elaborate methods have been developed to attach organic moieties directly onto the nanotube sidewalls. These include:

- (a) photoinduced addition of azide compounds; Reports of fluorination [106],[107] chlorination [108], atomic hydrogen [109]; aryl groups [110], nitrenes, carbenes, and radicals [111]; COOH [112],[113], NH₂ [114] N-alkylidene amino groups [115]; alkyl groups [116] and aniline [117] amine and amide [118] have been reported.
- (b) Bingel reactions;

Grafting of biomolecules such as bovine serum albumine [119], [120], [121] or horse spleen ferritin [122], poly-Llysine, a polymer that promotes cell adhesion [123], [124], Streptavidin [125] and biotin at the carboxylic sites of oxidized nanotubes [126] and polymers [127], [128],[129], [130], [131], [132] have been reported.

(c) cycloadditions [133].

European Position: Haddon and co-workers in the US were early leaders and Carroll and co-workers in Wake Forrest University applied functionalisation to devices. In UK Papakonstantinou et al at the University of Ulster have demonstrated a variety of plasma based routes as an alternative to chemical functionalisation. In Europe Hirsch in Erlangen has made major contributions and Coleman and co-workers at TCD have furthered our knowledge in this area.

7. Properties/characterization

The physical properties of carbon nanotubes depend on a number of variables. These include, if the tube is multi-walled or single-walled, the diameter of the tube and if we have a bundle or a rope, or just an individual tube. The chirality of the tube is also important for single walled nanotubes. Table 1 summarises the experimental findings of several different properties of carbon nanotubes, highlighting differences between different types of tube.

Table 1: Summary of main properties of CNTs

MECHANICAL PROPERTIES

Young's modulus of multi-walled CNTs	-0.8-1.3 Tpa [134],[135]
Young's modulus of single-walled CNTs	~1-1.3 TPa [136],[137]
Tensile strength of single-walled nanotube ropes	> 45 GPa [138]
Tensile strength of multi-walled nanotube ropes	1.72GPa [139]
Stiction	~10 ⁻⁷ N on 5 μ m latex beads [140]
Hydrophobicity of MWNT forest	26°[141] -161°[142] contact angle

THERMAL PROPERTIES AT ROOM TEMPERATURE

Thermal conductivity of single-walled CNTs	1750-5800 WmK [143]
Thermal conductivity of multi-walled CNTs	>3000 WmK [144]

ELECTRICAL PROPERTIES

Typical resistivity of single- and multi-walled CNTs	10 ⁻⁸ - 10 ⁻⁶ Ω m [145]
Typical maximum current density	>10 ⁸ A cm ⁻² [146]
Quantized conductance, theoretical/measured	(6.5 k Ω) ⁻¹ / (12.9 k Ω) ⁻¹ per channel

ELECTRONIC PROPERTIES

Single-walled CNT band gap	
Whose n=m, armchair	0 eV (metallic)
Whose n-m is divisible by 3	<0.1eV (quasi metallic) [146]
Whose n-m is non-divisible by 3	0.4-2eV(semiconducting) [148],[149]
Multi-walled CNT band gap	~0 eV (non-semiconducting)



8. Electronic Applications

Various applications for CNTs in the ICT field have been touted but in the near term only a few of these seem feasible: their use as a thermal interface material has gained the most interest in the last two years, as has their application to transparent conductors. Work on interconnects and vias continues whereas field emission has remained somewhat static. There follows a list of applications which, in the authors' opinions, orders the interest attracted by industry in terms of investment.

8.1 Thermal management

There is an increasing need to replace indium for thermal interfaces in eg: CPUs, graphic processors and (automotive) power transistors, as price and scarcity increase. Various companies and universities (such as Ajayan's group [150]) are working in this area but very little has been published.

As a thermal interface material for high brightness LED's, CNTs have been shown to outperform silver epoxy and other metal systems [151]. Fujitsu has also evaluated 15 micron tall CNT thermal bumps, bonded at 6 kg/cm² between a GaN high performance amplifier and an AlN substrate, to have a thermal conductivity of 1400 W/mK [152]. It is believed that the key advantage of CNTs is their compliance, which eliminates the problems of thermal mismatch between surfaces as well as ensuring a good contact.

By annealing the catalyst in different atmospheres of Ar/He/water, the catalyst shape can be controlled, leading to the preferential growth of up to 91% metallic SWNTs [153].

Current problems in using CNTs are insufficient packing density and problems with graphitisation leading to a reduction in conductivity.

European Position: Ajayan is the most notable contributor to this research together with the contributions from Fujitsu above. Intel Europe are also known to be working in this area. Very little work has been published by them and other workers from the EU.

8.2 Transparent conductors/contacts.

As the use of ITO becomes ubiquitous and indium becomes more scarce and thence more expensive there is an ongoing search for alternative transparent conducting contact materials. Initiated at Nanomix [154], various groups worldwide including those of Rinzler, Roth, Chhowalla and Grüner have worked to replace indium tin oxide (ITO) in e.g. LCDs, touch screens, and photovoltaic devices. Nantero Inc. (Boston), Eikos Inc. of Franklin, Massachusetts and Unidym Inc. (recently bought by Arrowhead) of Silicon Valley, California are also developing IP and transparent, electrically conductive films of carbon nanotubes [155].

CNT films are substantially more mechanically robust than ITO films, potentially making them ideal for use in displays for computers, cell phones, PDAs and ATMs as well as in other plastic electronic applications. At SID2008, the University of Stuttgart and Applied Nanotech presented the world's first 4-inch QVGA colour LCD display using CNT as the transparent conductive film. The CNTs were deposited by spray coating [156].

There is still a need to increase conductivity whilst maintaining a sufficiently high (~95%) transparency and for some applications, roughness is a problem. Recent developments have addressed these issues. First, the separation of metallic single walled nanotubes from semiconducting ones using scalable density gradient centrifugation has improved transparency and conductance [157]. Second, the National Renewable Energy Laboratory in the US reported ultra-smooth transparent and conducting SWNT thin film electrodes for organic solar cells which yielded efficiency values of > 3.5%, the highest thus far for SWNT electrodes [158]. Despite this progress, the sheet resistance of SWNT networks has remained at ~100 Ω/sq (about an order of magnitude higher than ITO) at a transparency of 85%. Also, most recently it has been pointed out by Fanchini et al. [159] that CNT/Polymer films are anisotropic and suffer from birefringent effects which may cause problems in some of its most useful

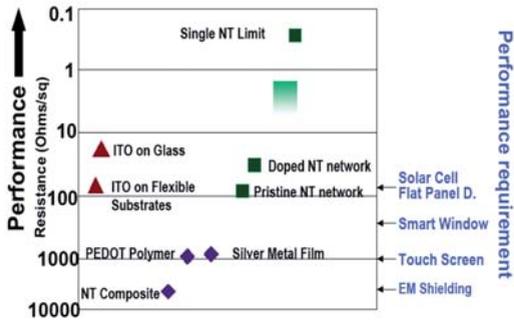


Fig 8. Comparison between the various transparent Conducting Materials [166].

potential application areas such as in Liquid Crystal Displays. Gruner summarizes the work in this area well (figure 8).

Recent studies have also demonstrated that SWCNT thin films can be used as conducting, transparent electrodes for hole collection in OPV devices with efficiencies between 1% and 2.5% confirming that they are comparable to devices fabricated using ITO [160], [161]. Note, however, that graphene based films are very quickly gaining momentum as transparent conductive electrodes and may very likely overtake the performance of CNTs in this area [162].

Chemically derived graphene obtained from reduction of graphene oxide is attractive because it is synthesized from graphite, a ubiquitous and inexpensive mineral. The state-of-the-art reduced graphene oxide films have yielded sheet resistances of $\sim 1 \text{ k}\Omega/\text{sq}$ at 85% transparency [163]. However, chemical vapour deposition (CVD) of graphene on copper and transfer onto desirable substrates have

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yielded sheet resistance values of 10–30 Ω /sq at transparency values > 85% [164]. Workers at SKKU have developed a process for synthesizing large-area graphene films for use in touch screens [165]. Sony are also working in this area.

These latest results suggest that CVD graphene can meet or surpass the properties of ITO. The main limitation of CVD graphene at present is that it can only be grown on copper and subsequently transferred. A general limitation of graphene is how to scale up the process to produce a uniform film over a large area, which is why CNT networks are the leaders in the area at present.

European Position: US dominate this area through the work of Eikos Inc, Nanomix Inc., Grüner and co-workers and Rinzler's group in Florida. Chhowalla at Imperial College, London has now carried on this work and Roth in Stuttgart leads the way in Europe.

8.3 Supercapacitors and batteries

8.3.1 Supercapacitors

Research efforts in the field are directed towards combinations of materials with high dielectric constant (for higher capacitance values) and high breakdown strengths (for the ability to sustain higher voltages). Alternatively, the effective surface area can be enhanced by using nanomaterials. Jang et al. [167] demonstrated such a device by using an ordered array of CNTs and coating them with a dielectric and another conductor (figure 9), demonstrating a 5x increase in capacitance per cm^2 . These structures open new possibilities for ultrahigh integration density devices such as random access memory and other nano-electric devices.

Energy-storing electrochemical double-layer capacitors (EDLCs) or supercapacitors have electrical parameters between ordinary capacitors and batteries; they are used primarily as power sources or reserves. However, unlike batteries, electrodes in EDLCs, typically made of carbon, do not undergo any chemical reactions as in batteries; they store the charge electrostatically using reversible adsorption of ions of the electrolyte onto active materials that are electrochemically stable [168].

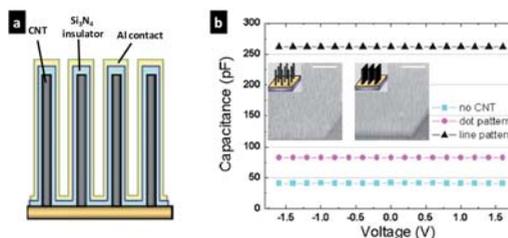


Fig 9. Enhancement of a capacitor performance by enhancing its surface area by using an ordered CNT backplane (a) Device structure (b) Comparison of capacitance of flat and CNT enhanced structures. Inset shows SEM images of the respective CNT arrays. Reprinted with permission from (Jang et al). Copyright 2005, American Institute of Physics.

CNTs are a natural candidate material for electrodes in supercapacitors. Experimental devices replace the activated carbon with CNTs. The surface area of carbon CNTs is not much greater than that of activated carbon, therefore energy densities are not much improved. However they are mechanically arranged in a much more regular fashion, allowing a lower internal resistance of the device and hence higher power densities.

In the last few years, many examples have appeared in literature where different forms of CNTs have been used in a multitude of ways to produce supercapacitor devices (see figure 10, page 20). Thin films of SWNTs can be deposited from solution, sprayed or inkjet printed on any substrate with relative ease [169], [170]. Due to their conductive nature, these films can substitute both the carbon electrode and the aluminium current collector, allowing for better charge storage/device weight ratios. CNTs can also be grown in an orderly fashion, as aligned forests for direct electron transport, higher packing density and direct contact with electrodes. Capacitors from forests of both SWNTs [171] and MWNTs [172] show promising behaviour, and the ever increasing control achievable during growth allows for much fine tuning of devices.

In more simple cases, CNTs are mixed into a low conductivity but very high surface area activated carbon electrode. Due to their high conductivity and aspect ratio, the resulting composite results in an appreciably lower internal resistance [173]. A similar capacitive effect results also from the very fast redox reactions that occur at the surface of some materials, known as pseudocapacitance. CNT forests are used as templates

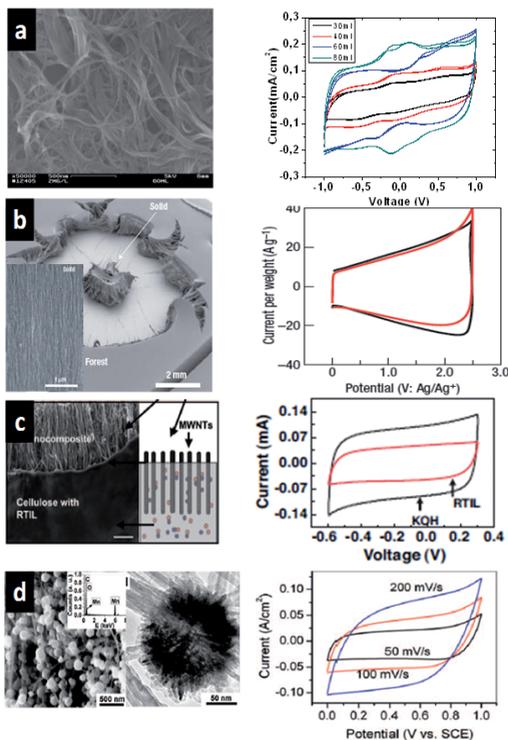


Fig 10. Various carbon nanotube architectures which have been employed for supercapacitors. Left column shows the SEM image while the right column shows the resulting cyclic voltammetry performance. (a) SWCNT random thin film (b) Ordered aligned array of SWCNTs, which have been compressed with liquid. Inset shows profile view. Reprinted by permission from Macmillan Publishers Ltd: Nature Materials [v], copyright (2006) (c) An array of freestanding pre-grown MWCNTs embedded in a cellulose matrix, resulting in a paper-like electrode [176]. Copyright (copyright year) National Academy of Sciences, U.S.A. (d) An array of MWCNTs used as a scaffold to hold low conductivity but high capacitance MnO_2 . Reprinted with permission from [177]. Copyright 2008 American Chemical Society.

on which to deposit high pseudocapacitance materials (e.g. oxides [174] or polymers [175]). Whether the use of CNTs will be possible at a reasonable cost is yet to be determined.

European Position: Main progress in this field is carried in the US (Ajayan group) and Japan. The leaders in Europe are Beguin et al. [178] who have used multi-walled CNTs mixed with polymers to create capacitance values of 100-330 F/g. Europe also has a strong industrial input in this area with companies such as Maxwell (formerly Montena, Switzerland).

8.3.2 Batteries

The conductive properties and the high surface-to-volume ratio make carbon nanotubes potentially useful as anode materials [179] or as additives [180] in lithium-ion battery systems. The CNTs give mechanical enhancement to the electrodes, holding the graphite matrix together. They also increase the conductivity and durability of the battery, as well as increasing the area that can react with the electrolyte. Sony produces the best CNT-enhanced lithium-ion batteries.

The use of CNTs as scaffolds for other materials has made the search for new electroactive materials wider than ever because requirements for such materials are now much relaxed. Low electronic conductivity, a low diffusion coefficient for lithium, and poor structural stability can all be compensated to some extent by CNTs.

Recently, a so-called paper battery has been developed, where CNT arrays bound with cellulose are used as electrodes. The technology is cheap, the batteries are flexible and no harmful chemicals are required [181]. Mass production of this technology is still some distance away and the process is currently manual and laborious. Cost of CNT production remains high and commercialisation is strongly dependent on this.

Overall, there are several potential advantages and disadvantages associated with the development of CNT based electrodes for lithium batteries.

Advantages include:

- (i) better accommodation of the strain of lithium insertion/removal, improving cycle life;
- (ii) higher electrode/electrolyte contact area leading to higher charge/discharge rates;
- (iii) short path lengths for electronic transport (permitting operation with low electronic conductivity or at higher power); and
- (iv) short path lengths for Li^+ transport (permitting operation with low Li^+ conductivity or higher power).

Disadvantages include:

- (i) an increase in undesirable electrode/electrolyte reactions due to high surface area, leading to self-discharge, poor cycling and calendar life;
- (ii) inferior packing of particles leading to lower volumetric



energy densities unless special compaction methods are developed; and

(iii) potentially more complex synthesis.

Toward further integration and large scale production, CNT-based negative electrodes for lithium micro-batteries are being developed by a consortium led by CEA-LITEN, ST Microelectronics and Schneider [182].

European Position: Although much of the innovation has been carried out in the US and the Far East, in Europe there are various groups notably in Germany contributing in this area.

8.4 Interconnects/vias

In order to achieve the current densities/conductivity needed for applications in vias, dense arrays of CNTs are required. Very dense arrays of nanotubes have been grown by chemical vapour deposition (CVD) by various groups, following Fan et al. [183]. They are called forests, mats or vertically-aligned nanotube arrays. They are usually multi-walled and grown from Ni, Co or Fe catalysts. It has been suggested that a nanotube density of at least 10^{13} cm^{-2} is needed in order to produce the required conductivity but recently Fujitsu have indicated that $5 \times 10^{12} \text{ cm}^{-2}$ would be acceptable [184]. However growing such dense arrays in vias of high aspect ratio is not so straightforward. Numerous groups worldwide are trying to optimise the process including CEA but Fujitsu [185] (see figure 11) have reported the most significant advances and have recently reported that they have achieved a density of $9 \times 10^{11} \text{ cm}^{-2}$. They have also reported a resistivity of $379 \mu\Omega\text{cm}$ for a $2 \mu\text{m}$ diameter via. A Microwave CVD method was employed to produce CNTs at temperatures compatible with CMOS. However, much improvement is still required before these become a practical proposition.

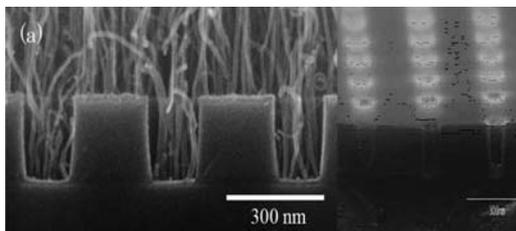


Fig 11. Left, CNT vias grown in pores etched into silicon. Right, CNTs grown in pores in silicon [186].

Problems include choice of catalyst, catalyst deposition, depositing top contacts, increasing the packing density and reducing the overall resistivity. The growth also needs optimization for back-end processing and must be carried out at low enough temperatures so as not to damage CMOS. If SWNTs are to be employed, the packing density of metallic tubes must be high enough to justify replacing metal interconnects. For MWNTs, for a sufficient current density, internal walls must also contribute to conduction. Neither has as yet been achieved.

European Position: Infineon identified vias as a possible early application of CNTs in electronics, Intel in the US evaluated spun-on CNTs for contacts but more recently Fujitsu, Japan lead the way. In Europe, the TECHNOTUBES project which includes many partners from throughout Europe is focussing on this application amongst others.

8.5 Sensors

8.5.1 Electronic Sensors

The use of CNTs for sensing is one of their most interesting electronic applications. Both SWCNTs and MWCNTs, functionalised and unfunctionalised, have been investigated as single nanotube and network devices. A vast number of prototypes and device strategies have been demonstrated for gas [187], electrochemical and biological sensors [188], and so far field-effect based sensors have detected NO_2 concentrations in the ppb range [189]. Ultrathin films of SWNTs appear to be the most viable basis for an electrical sensor in terms of scaleability, and can be fabricated through a number of different techniques including dielectrophoresis [190], direct CVD growth [191] and solution-based transfer [192], for instance embedded in a polymer coating [193]. The review by N. Sinha et al. [187] from 2006 covers carbon nanotube sensors generally, while the recent reviews by Goldoni et al [187] and Jacobs et al [188] overviews carbon nanotube gas sensors and electrochemical sensors, respectively.

However, there are still many other problems to overcome in bringing this technology to market; high volume/quality manufacturing, the intrinsic variability of SWNT, functionalisation and cleaning/recycling. While

very high sensitivity has been achieved, the results in terms of selectivity are often less convincing, as the inert carbon nanotubes are difficult to functionalise effectively.

As the energy bandgap, carrier mobility and also the chemical reactivity depend on the diameter and chirality, the variability must either be averaged out by a network architecture or by sorting by chirality, which can be done by ultracentrifuging; network TFT transistors with an on/off switching ratio above 10^4 have been demonstrated [195], [196]. Reproducibility of the CNT growth, processing as well as variable behaviour once integrated into a sensor can result in poor selectivity and sensitivity. Resetting electronic nanotube sensors is another issue; methods such as annealing or using a gate voltage in a TFT architecture have been used [197].

In some devices, defects play a key role, in others, the source/drain metal-nanotube contact is key. Also, the nanotube-nanotube junction or even the amorphous carbon remaining on the nanotube can play a part in the detection scheme. [198] Indeed, there are many possible sensing mechanisms, hence a fundamental understanding of them is required to enable good optimisation and reproducibility of the sensors. However, this research area is very active, so further progress is expected.

The US company Nanomix Inc was the first to put an electronic device that integrated carbon nanotubes on a silicon platform (in May 2005 they produced a hydrogen sensor) on the market [199]. Since then, Nanomix has taken out various other sensing patents e.g. for carbon dioxide, nitrous oxide, glucose, DNA detection etc. [200]. The next product to become available should be a breath analyzer detecting NO as a marker of asthma. More recently workers in Cambridge and Warwick University in collaboration with ETRI, South Korea have integrated CNTs onto SOI substrates to produce smart gas sensors (see figure 12) [201]. The CNTs have been locally grown on microheaters allowing back end deposition at $T \sim 700^\circ\text{C}$ without significantly affecting the surrounding CMOS.

Other groups have been using a multi-functionalized network of sensors combined with a principal component analysis in order to enable pattern recognition approach (artificial nose) [202]. Such an approach could enable early diagnosis of various

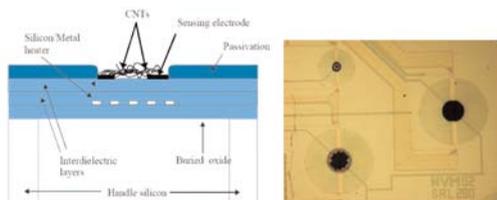


Fig.12: Left, structural cross-sectional layout of the sensing area of the chip. Right, microscopic images of carbon nanotubes grown locally on ultrathin membranes incorporating a tungsten heater [201].

pathology from the detection of biomarkers in the breath.

Due to cost of R&D, commercialization of such sensors are however very costly. For example Nanomix has already raised more than \$34 million and they have yet to deliver a significant, high volume product to the market although they are currently seeking FDA approval for their NO sensor, mentioned above, to be used in the monitoring of asthma (Figure 13). Progress in these areas continues to be made globally.



Fig. 13: Preproduct picture of Nanomix's NO sensor (with authorisation from YL Chang, Nanomix).

European Position: Many companies and research institutions in Europe are carrying out work in this area, with THALES, Dekker (Delft), being the most notable.

8.5.2 CNTs in Biotechnology and Medical Device Research.

Nanomedicine, or the application of nanotechnology to achieve breakthroughs in healthcare, exploits the improved and often novel physical, chemical and biological properties of materials at the nanometer scale. Nanomedicine has the potential to enable early detection and prevention, and to essentially improve

diagnosis treatment and follow-up of diseases. This section addresses the overall roadmaps associated with nanomedicine and in particular identifies the role of CNTs. Technologically, most CNT applications in biotech are in biosensing, lab-on-a-chip, drug screening and drug delivery. The key issues associated with CNTs related to nanomedicine closely resemble those mentioned in the previous section and are mainly related to the following issues:

- Some of the main challenges are linked to industrialisation. There is no conventional manufacturing method that creates low cost CNTs. Desirable properties are robustness, reproducibility, uniformity and purity.
- Reproducible production relating to surface defects; surface chemistry, size (height and diameter; morphology; type etc.
- The ability to functionalise the surface with appropriate chemistries.
- The ability to produce arrays; periodicity; catalyst free- or tailored catalyst grown from self-assembly.
- To produce low cost routes to manufacture in the case of disposable or competitive devices.
- The ability to integrate into microfluidic systems; CMOS circuitry or flexible substrate systems.

In the next ten years, the development of biosensors and importantly, nanotechnology, will allow the design and fabrication of miniaturised clinical laboratory analysers to a degree where it is possible to analyse several laboratory measurements at the bedside with as little as 3 μ L of whole blood. The use of quantum dots; self-assembly; multifunctional nanoparticles, nano-templates and nano-scale fabrication including nanoimprinting will have a major impact on the design and development of much improved highly sensitive and rapid diagnostics; thus allowing accurate drug delivery integration. Nanoenabled high throughput analysis will also reduce the time it takes to bring a new drug delivery platform to market.

CNTs have also been shown to favour neuronal growth and reduce glial scar formation (gliosis). CNT-based electrodes have therefore been proposed for use in implants to enable long term treatment of Alzheimer disease using deep brain stimulation [203].

A clear set of studies is required to resolve all the issue

of biocompatibility and nanotoxicity associated with the use, manufacture and purchase of CNTs in all forms. Recent reviews point out that fullerenes have potentially useful properties, and that several of the reports on toxicity have used unrealistic conditions and doses [204]. Nevertheless, the possible toxicity remains the single largest barrier in terms of practical use of nanotubes for drug delivery or cancer therapy; the nanotubes do not break down in the body, and are able to kill cells if not effectively passivated. Since the carbon nanotubes will ultimately last longer than any passivation, and have been shown to aggregate in the lungs and brains of animals, it is questionable whether or not carbon nanotube-based medicine will be used in clinical tests in the near future. Furthermore, other very effective, nontoxic systems are available for drug delivery, such as protein-coded liposomes [205].

European Position: The area of carbon nanotube based sensors is very broad and diverse due to the many different physical quantities, applications and environmental conditions for such devices. In terms of gas and biological sensing, a substantial number of groups are pursuing high sensitivity gas or biological molecular sensing, better functionalisation/specificity as well as scaleable fabrication methods, in US as well as in Europe. While the research activities are spread all over Europe, a few commercial players are active. Cambridge CMOS Sensors are developing sensor platforms based on carbon nanotubes. There are strong activities in many universities including ETH Zurich and Cambridge University but it is not possible to identify single leading groups. In terms of nanotubes used inside humans, it is not likely that this will be possible on a short or even long term due to the unresolved toxicity issues.

8.6 Field emission

Because of their high-current-carrying capability, chemical inertness, physical strength and high aspect ratio, CNTs can be applied to many technologies requiring field emission. Immediately after the growth, CNTs contain impurities such as amorphous carbon, catalyst, residual growth gases as well as varying degrees of structural defects dependent on the growth parameters. The defects and impurities should be removed or passivated for optimum field emission properties. Treatments such as plasma, IR and UV lasers and oxidative annealing can be used to clean the tips of the CNTs.

Researchers have reported low threshold field (field required to emit electrons at a level of $1 \mu\text{A}/\text{cm}^2$) for various types of CNTs. However there is a debate about the long term emission stability of CNTs. Open tips, aligned CNTs and aligned CNTs embedded in PMMA matrix have shown significant improvement in emission stability as compared to the as-grown CNT samples. Nanotubes can be used for single electron beam devices (such as field-emission scanning/transmission electron microscopy) or multiple beam devices (like flat panel displays, or as light sources). The major field emission applications are listed below.

8.6.1 Field Emission Displays

Motorola in the early/mid 1990's investigated the use of carbon based materials for Field Emission Displays including the use of diamond, DLC and CNTs [206],[207]. More recently they have reported a CNT based Field Emission HDTV [208]. Over the last 10 years or so various companies including Philips, TECO Nanotech, ISE Electronics and especially Samsung (SAIT) [209] have worked on the use of CNTs for TV applications. SAIT successfully produced demos of full colour 39" diagonal TVs and this technology was transferred to Samsung SDI for production in the late 2000s. However, no displays based on their technology have reached the market.

Other work on Field Emission displays based on SEDs (Surface-conduction Electron-emitter Displays) also took place in the late 2000's. Formerly a collaboration between Toshiba and Canon, the displays utilise emission from carbon but not CNTs [210], but these are yet to appear commercially. Most recently, Sony have announced a major investment in FEDs based on a Spindt process. Teco Nanotech Co Ltd (a small company based in Taiwan) also market three basic CNT-based FEDs, the largest being an 8.9" diagonal [211].



Fig.13: Two stages of development of CNT FED at CEA. On the left: monochrome display with $350\mu\text{m}$ pixels, on the right: color video display with $600\mu\text{m}$ pixels. On these display the non uniformity from pixel to pixel is 5% while it is 3% with LCD displays and 2% for CRT (courtesy of CEA-LITEN).

CEA of France continue to fund research in this area, with typical displays produced shown in figure 13.

8.6.2 Microwave Generators

High power/frequency amplifiers for higher bandwidth, more channels and microwave links are increasingly using the 30 GHz and above frequency range. Attempts have been made to replace the thermionic cathode in a travelling wave tube (TWT) with a Spindt tip cathode delivering the dc electron beam. However, the most effective way to reduce the size of a TWT is via direct modulation of the e-beam, for example, in a triode configuration using CNTs as the electron source.

Thales, in collaboration with Cambridge University Engineering Department, have successfully demonstrated a Class D (i.e. pulse mode/on-off) operation of a carbon nanotube array cathode at 1.5 GHz, with an average current density of $1.3 \text{ A}/\text{cm}^2$ and peak current density of $12 \text{ A}/\text{cm}^2$; these are compatible with travelling wave tube amplifier requirements ($>1 \text{ A}/\text{cm}^2$) [212]. Recently, they have also achieved 32 GHz direct modulation of a carbon nanotube array cathode under Class A (i.e. sine wave) operation, with over 90% modulation depth [213]. Other advantages that carbon nanotube cathodes offer

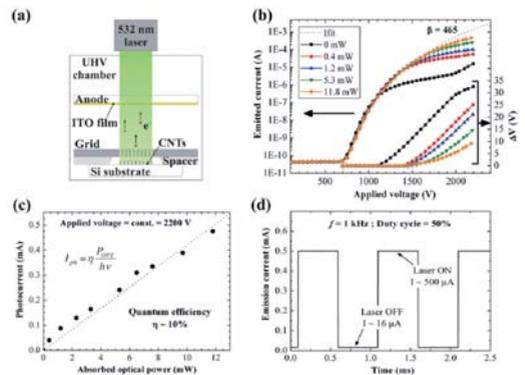


Fig.14: (a) Schematics of the experimental setup with the cathode-grid assembly (spacer thickness = $100 \mu\text{m}$), the transparent and conductive anode, and the 532 nm laser. (b) Top, left axis: emitted current as a function of the applied voltage and absorbed optical powers. Bottom, right axis: voltage drop ΔV as a function of the applied voltage and absorbed optical powers. The dotted curve $\beta = 465$ is the Fowler-Nordheim fit for the case where the p-i-n photodiode exhibits no voltage drop. (c) Photocurrent as a function of the absorbed optical power for a 2200 V cathode-grid applied voltage. The associated quantum efficiency calculated from the slope is $\sim 10\%$. (d) Example of optical modulation of the emission current from MWCNTs by pulsing the laser source at low frequency (1 kHz) [215].



include no heating requirement and the ability to turn on or off instantly (for efficient operation). Xintek have also been working on CNT-based microwave amplifiers for the US Air Force [214]. The main problem at present is the limited modulation bandwidth associated with such devices. However, Hudanski et al [215] reported the use of photocathodes (shown in figure 14), which combine semiconducting silicon p-i-n photodiodes with MWCNT field emitters, which exhibited high quantum efficiency (~10%), significant current density (0.2 A cm^{-2}) which can be operated continuously or be optically modulated.

8.6.3 X-ray Instruments

Oxford Instruments have worked together with NASA on CNT-based X-ray sources that employ field emission as the electron source, rather than thermionic emission, which has much lower power efficiency [216]. Their application is targeted towards low-power use for a space mission to Mars (though high power would be more preferable), once again because of their low weight and fast response time. Oxford Instruments have also developed and sold hand-held low power X-ray imagers which can be applied to medicine and for diagnostics in circuit boards [217]. Zhou and co-workers at Xintek (see figure 15) have developed a fast response, sharp-focus X-ray tube with quick pulsation [218]. MoXtek have also produced similar devices [219].

Challenges for these devices are in achieving high power with stability and reproducibility.

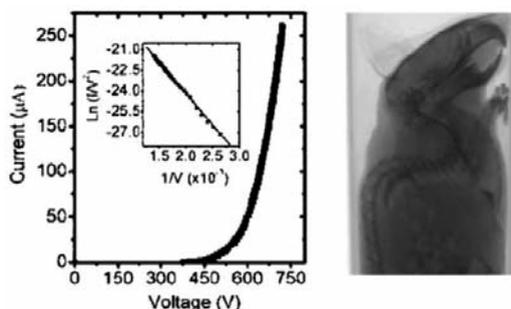


Fig.15: Left, the X-ray tube current versus the gate voltage measured with the anode voltage fixed at 40 kV. It follows the classic Fowler–Nordheim relation. The distance between the cathode and the gate is 150 μm . Right, X-ray image of a normal mouse carcass (25 g) obtained using a CNT source-based imaging system.

8.6.4 Backlighting

Although their use in full colour FE-based TVs is still problematical, the use of CNTs as electron emitters in FE-based backlight units for AMLCDs is still under investigation by various companies worldwide. Major players in the TFT-LCD display industry, such as Samsung, Corning and LG Electronics (LGE), are keen to develop carbon-nanotube (CNT) backlight modules, with Taiwan-based backlight-module makers also interested in following suit [220]. In Korea Iljin also have several years of experience in this area [221].

In theory, CNT backlight modules have a lower temperature, consume less power and are less expensive to produce than traditional backlight modules. It is a good candidate to eventually replace CCFL (cold cathode fluorescent lamp) backlighting but has strong competition from LEDs, which could be much cheaper to produce and are already in the market place.

The challenges are again to improve the lifetime of the emitters and to reduce cost to be competitive with other technologies.

8.6.5 Electron microscopy

Recent research has investigated whether the carbon nanotube can act as an improved electron source for microscopy and how it compares to the other electron sources available today. Various groups from FEI, Cambridge University, EMPA, El-Mul etc have researched the optimum way to produce CNTs for use in microscopy. The CNTs act as a cold cathode source and the standard manufacturing procedure is to add a single CNT to the tip of a standard tungsten emitter. Growth, rather than attachment is felt to be a better process [222]. Mann et al. [223] used PECVD and describe how such a procedure is scalable with the ability to grow a single CNT on each W tip (shown in figure 16, see page 26). El Mul has developed a silicon-based CNT microcathode in which the CNT is grown in an etched pore [224].

The emission characteristics of the CNT have been found to be extremely promising with the key parameters of the process understood. Progress still needs to be made to optimise reproducibility.



Fig.16: Left, electron micrograph of a single CNT grown on a tungsten tip. Note that the growth is aligned with the tungsten axis. Centre, a tungsten tip mounted in a suppressor module. Right, a CNT grown on a tungsten already mounted in the suppressor in situ.

8.6.6 Ionization for Propulsion and Detection

8.6.6.1 Electric Propulsion

Replacing hollow and filament cathodes with field emission (FE) cathodes could significantly improve the scalability, power, and performance of some meso- and microscale Electric Propulsion (EP) systems. There is considerable interest now in microscale spacecraft to support robotic exploration of the solar system and characterize the near-Earth environment. The challenge is to arrive at a working, miniature electric propulsion system which can operate at much lower power levels than conventional electric propulsion hardware, and meets the unique mass, power, and size requirements of a microscale spacecraft.

Busek Company, Inc. (Natick, MA), has developed field emission cathodes (FECs) based on carbon nanotubes. The non-thermionic devices have onset voltages about an order of magnitude lower than devices that rely on diamond or diamond-like carbon films.

Worcester Polytechnic Institute (WPI) includes the programmes headed by Professors Blandino and Gatsonis. Blandino's research is largely focused on the study of colloid thrusters for small satellite propulsion, and in the development of novel, earth-orbiting spacecraft formations [226]. The Gatsonis' activity also includes modelling of plasma micropropulsion [227].

Groups from the Rutherford Appleton Laboratory [228] and Brunel University [229] are studying the field emission performance of macroscopically gated multi-walled carbon nanotubes for a spacecraft neutralizer.

8.6.6.2 Gauges/Sensors

The Physical Metrology Division, Korea Research Institute of Standards and Science are using the field emission effect from a carbon nanotube to characterize a new type of technology for detecting low pressures. The fabricated low pressure sensor is of a triode type, consisting of a cathode (carbon nanotubes field emitter arrays), a grid and a collector. Due to the excellent field emission characteristics of CNTs, it is possible to make a cost effective cold cathode type ionization gauge. For an effective CNT cathode for both the sensor and gauge the researchers used the screen-printing method and also controlled the collector and the grid potentials in order to obtain a high ionization current. They found that the ratio of the ionization current to the CNT cathode current changes according to the pressure in the chamber [230].

8.6.6.3 Miniaturised gas ionization sensors using carbon nanotubes

Ajayan et al. from the Rensselaer Polytechnic Institute have developed ionization sensors by fingerprinting the ionization characteristics of distinct gases [231]. They report the fabrication and successful testing of ionization microsensors featuring the electrical breakdown of a range of gases and gas mixtures at carbon nanotube tips. The sharp tips of the nanotubes generate very high electric fields at relatively low voltages, lowering breakdown voltages several-fold in comparison to traditional electrodes, and thereby enabling compact, battery-powered and safe operation of such sensors.

The sensors show good sensitivity and selectivity, and are unaffected by extraneous factors such as temperature, humidity, and gas flow. As such, the devices offer several practical advantages over previously reported nanotube sensor systems. The simple, low-cost, sensors described here could be deployed for a variety of applications, such as environmental monitoring, sensing in chemical processing plants, and gas detection for counter-terrorism.

McLaughlin and Maguire [232] at the University of Ulster report the use of CNTs in order to decrease the turn-on voltage associated with microplasmas and the enhancement of emission spectra associated with gas types. In particular the device focuses on mixed gas types such as breath analysis and environmental monitoring. The ability of low cost CNT structured electrodes is key to

improving performances related to higher sensitivity and specificity of gases such as NO_x. Catalyst free growth techniques have been reported using thermal CVD routes and the study is also looking at the optimum CNT spacing and height required for short time ionisation or FE applications to gas sensors.

The main driver at present is to improve the efficiency which currently lies at around 1%.

European Position: From a display viewpoint Europe were very much forerunners but then Samsung provided the more recent display drive. As regards work on sources for electron microscopy in Europe De Jonge and co-workers did some excellent work on characterisation of single emitters as did Groning on arrays of emitters. Thales in collaboration with several universities has continued European interest in the design of high frequency CNT based sources. For X-ray sources Oxford Instruments led the way and more recently Xintek in the US and Philips in Europe has expanded the work. In backlighting as in Displays the Far East leads the way. The leaders in the FE based propulsion area are in the US where the Jet Propulsion Laboratory Pasadena, Busek Co., Inc. and the Worcester Polytechnic Institute (WPI) lead the way. In Europe the main groups are from the Rutherford Appleton Laboratory, Brunel University, the University of Cambridge, the University of Groningen, and the University of Ulster. However, with the exception of display technology, the field emission market size is comparatively low when compared with the other ICT applications described above.

8.7 NEMS switches, resonators and sensors

Jang et al [233] demonstrated novel non volatile and volatile memory devices based on vertically aligned MWCNTs (see figure 17). Nanoelectromechanical switches with vertically and horizontally [234] aligned carbon nanotubes have been demonstrated. However, Nantero are the market leaders in this area and have created multiple prototype devices, including an array of ten billion suspended nanotube junctions on a single silicon wafer [235]. Nantero's design for NRAM™ involves the use of suspended nanotube junctions as memory bits, with the "up" position representing bit zero and the "down" position representing bit one. Bits are switched between states through the application of electrical fields.

In theory the NRAM chip would replace two kinds of memory. While cell phones, for example, use both flash chips and SRAM or DRAM chips, NRAM would perform both functions. However the memory market is oversupplied and they frequently have to be sold at a loss, making it difficult for any new technology to break in. In addition, several other major companies are developing their own non-volatile memory technologies with PRAM perhaps the leading contender at present.

PRAM, FRAM, MRAM and RRAM are all dominated by highly competitive, large companies. With Nantero's relatively small size and long development time, market penetration is a big issue.

CNT-NEMS have been suggested for high frequency mechanical resonators and switches, where the low mass and high stiffness can lead to GHz switching speeds and resonance frequency. High frequency resonators are targeting RF electronics [234] and high-sensitivity mass sensing [236]. Here the advantages provided by the outstanding material properties of CNT are possibly outweighed by the numerous technological and manufacturing challenges including controlled growth, durability of switches and scaled up production with a sufficient repeatability and yield [237].

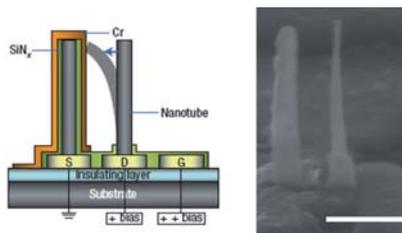


Fig. 17: Left, a schematic diagram showing a cross-section of a switch fabricated by Jang et al.. Both contacts and catalyst were deposited with e-beam lithography. Right, an electron micrograph showing the grown CNTs acting as a switch.

A significant effort has also been focused on CNT for piezoresistive applications, the advantage being a much larger gauge factor as compared to for instance silicon. While high-performance, high yield CNT based strain gauges have been realised with wafer-level on-chip synthesis [238], the gauge factor's dependence on chirality remains a very significant challenge in terms of commercialisation.

CNTs as high aspect ratio and supersharp tips for Atomic Force Microscope remain a possibility; the high stiffness and yield strength of MWNT allows more slender tips to be used for probing deep trenches and sidewalls [239], SWNT nanotubes present unparalleled sharpness and wear resistance [240], and bundles of SWNT show enhanced surface potential imaging [241]. CNT-HARP tips are either manufactured by growth [242] or direct manipulation [239],[240]. Recently, DTU, the University of Cambridge and Oldenburg University demonstrated multiple assemblies of MWNT on AFM probes [243] using a microgripper-based approach to automated robotic assembly [244]. A comprehensive overview is given by Wilson and Macpherson [240].

European Position: Nantero are the world leaders but in Europe, one can cite the partners of the NanoRF [245] European project as well as ETH, TU Denmark. A collaboration between Cambridge Univ. Engineering, Samsung and Thales is also ongoing.

8.8 Saturable Absorbers

The band gap of semiconducting CNTs depends on their diameter and chirality, i.e. the twist angle along the tube axis [246]. Thus, by tuning the nanotube diameter it is easy to provide optical absorption over a broad spectral range [247]. Single-walled CNTs exhibit strong saturable absorption nonlinearities, i.e. they become transparent under sufficiently intense light and can be used for various photonic applications e.g in switches, routers and to regenerate optical signals, or form ultra-short laser pulses [248],[249],[250]. It is possible to achieve strong saturable absorption with CNTs over a very broad spectral range (between 900 and 3000 nm [251]). CNTs also have sub-picosecond relaxation times and are thus ideal for ultrafast photonics [252],[253]. CNT saturable absorbers can be produced by cheap wet chemistry and can be easily integrated into polymer photonic systems. This makes a CNT-based saturable absorber very attractive when compared to existing technology, which utilises multiple quantum wells (MQW) semiconductor saturable absorbers and requires costly and complicated molecular beam epitaxial growth of multiple quantum wells plus a post-growth ion implantation to reduce relaxation times [254]. Additionally, MQW saturable absorbers can operate only between 800 and 2000 nm - a much narrower absorption bandwidth than that available using CNTs.

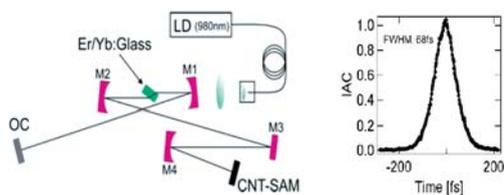


Fig.18: Left, Experimental setup of the Er/Yb:glass laser. OC: output coupler; M1-M4: standard Bragg-mirrors; CNT-SAM: Saturable absorber mirror based on carbon nanotubes; LD: pigtailed laser diode for pumping the Er/Yb:glass (QX/Er, Kigre Inc., 4.8 mm path-length). Right, background-free autocorrelation. The solid line is a sech² fit with a corresponding FWHM pulse-duration of 68 fs [255].

The major laser systems mode-locked by CNT saturable absorbers demonstrated so far (see figure 18) include fibre lasers, waveguide lasers and solid-state lasers, generating sub-ps pulses in a spectral range between 1070 and 1600 nm [255]. The shortest pulse of about 68 fs was achieved with a solid state Er³⁺-glass laser by using a CNT-polyimide composite [256]. Additionally, amplified spontaneous emission noise suppression has been demonstrated with CNT-based saturable absorbers, showing great promise for this technology for multi-channel, all-optical signal regeneration in fibre telecom systems [257].

Challenges include justifying the research to industry due to the limited market potential.

European Position: There are 5 major research groups working on CNT saturable absorber applications around the world: Sakakibara at the National Institute for Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, Maruyama and Yamashita at Tokyo University & Set in the Alnair Labs and Yoshida at Tohoku University. In Europe Dr. E. Obratzsova at the Institute for General Physics, Moscow, and Cambridge University Engineering Department are the major players.

8.9 Fuel Cells

Carbon nanotubes can be used to replace the porous carbon in electrode-bipolar plates in proton exchange membrane fuel cells, which are usually made of metal or graphite/carbon black. The CNTs increase the conductivity and surface area of the electrodes which means that the amount of platinum catalyst required can be reduced [258]. The state of the art in this area is the mixing of CNTs and platinum catalyst particles reported by Sun et al of Taiwan [259].

Whilst CNTs reduce the amount of platinum required, it is only a small percentage, which means that the cost of the fuel cell remains high. Also, CNTs are comparable in price to gold, meaning the saving is minimal.

Nevertheless, vertically aligned MWCNTs can be used as highly efficient fuel cell electrode material. Aligned CNTs electrode have a host of advantages in the Polymer Electrolyte Membrane fuel cells (PEMFC) and Direct Methanol fuel cells (DMFC), such as higher electrical conductivity, large surface area, possible higher gas permeability and higher hydrophobic surfaces facilitating faster removal of water from the electrodes. In general, Pt, Pt/Ru nanoparticles are dispersed in CNTs to obtain platinum/CNT-based electrocatalysts [260]. However the large-scale market application of fuel cells will be difficult to realize if the expensive Pt-based electrocatalysts for oxygen reduction reactions (ORRs) cannot be replaced by other efficient, low-cost, and stable electrodes. Recent results from Gong et al. [261] have shown that N doped arrays of MWCNTs (acting as a metal-free electrode), can provide superb catalytic activity for Oxygen Reduction Reaction (ORR).

European Position: The leaders in this area are the Taiwanese groups. The European leaders are linked to S. Roth (Max Planck Institute, Stuttgart).

8.10 Solar panels

CNTs have been utilised in solar cells in a number of ways. Primarily they are used to enhance charge collection. Kymakis et al [262] dispersed CNTs in the photoactive layer of organic solar cells to replace C₆₀ and benefit from the 1D structure. However, the power efficiency of the devices remains low at 0.04% suggesting incomplete exciton dissociation at low CNT concentrations. At higher concentrations, the CNTs short-circuit the device. More recently, a polymer photovoltaic device from C₆₀-modified SWCNTs and P3HT has been fabricated [263]. P3HT, a conjugated polymer was added resulting in a power conversion efficiency of 0.57% under simulated solar irradiation (95mWcm⁻²). An improved short circuit current density was attributed to the addition of SWCNTs to the composite causing faster electron transport via the network of SWCNTs. Hybrid CNT-polymer devices however have shown so far only moderate performance.

CNTs have also been used as a high surface area charge collecting scaffold for nanoparticles in several types of cells. Photoconversion efficiencies of 1.5% and 1.3% have been achieved with SWCNTs deposited in combination with light harvesting CdS quantum dots and porphyrins, respectively [264]. Other varieties of semiconductor particles including CdSe and CdTe can induce charge-transfer processes under visible light irradiation when attached to CNTs [265]. In dye-sensitized solar cells (DSSC), titanium dioxide coated onto CNTs shows enhanced electron transport and increases the photoconversion efficiency [266].

Much work has been done to use SWCNT thin films in PV as transparent conductive coatings to replace ITO which has both a limited supply and a limited tolerance to flexibility. Conductivity to transparency ratios are fast approaching that of ITO. Barriers to commercialisation are now more related to problems with the adhesion of the CNT film to the substrate.

Novel antennae effects, as well as improved charge collection and optical enhancement can be obtained in cells in which CNT growth is patterned. Zhou et al. [267] recently demonstrated enhancement in amorphous silicon solar cells deposited onto a patterned array of CNTs with spacing of the order of visible light wavelengths.

European Position: Although much of the work in this area has been driven by Japan and the USA (with Unidym Inc. which announced in February 2010 a joint venture to market printable CNT electronics in Korea), significant input on both the incorporation of the CNTs as part of the active layer and in transparent contact materials has been made across the European community. Commercial ventures are in place in both the USA and Finland to commercialise CNT thin films.

8.11 Antennae

Ren' group at Boston College has demonstrated the use of a single multi-walled CNT to act as an optical antenna, whose response is fully consistent with conventional radio antenna theory [268]. The antenna has a cylindrically symmetric radiation pattern and is characterized by a multi-lobe pattern, which is most pronounced in the specular direction. Possible applications for optical antennae include optical switching, power conversion and light transmission.

One particular application is the “rectenna”, which is the light analogue of the crystal radio in which an antenna is attached to an ultrafast diode. This could lead to a new class of light demodulators for optoelectronic circuits, or to a new generation of highly efficient solar cells.

The growth of microwave applications, such as mobile phones, remote sensing and global navigation satellite systems, etc, requires the development of materials with a large tunability and very low loss in the microwave frequency range (from GHz to sub-THz). This is particularly important, as the intrinsic loss of the existing tunable dielectrics based on ferroelectric ceramics increases significantly when the frequency in use is above a few GHz. Liquid crystals (LCs) have attracted much attention in recent years because of their low loss at microwave frequencies. However, although the dielectric anisotropy/tenability of LCs is comparatively higher than other low loss materials, it is desirable to further increase its value. This is particularly important for antennae and phase arrays for beam steering in the applications such as automobile forward looking radar and satellite up-links. At Cambridge, preliminary work shows that mixing CNTs of suitable sizes with LCs can significantly enhance dielectric anisotropy (see Fig. 19). Further measurement confirms similar trend at much higher frequency ranges.

European Position: Early stages of research in the Department of Engineering at Cambridge University, in collaboration with Technische Universität Darmstadt, Queen Mary College, London, ALPS Electric, Japan, Dow Corning, USA, and Nokia, Finland/UK.

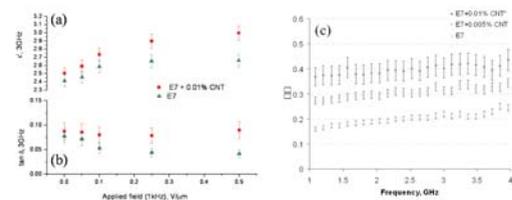


Fig 19. Studies of pure and CNT loaded E7 using capacitor method, switching with electric field: (a) 3GHz, sweeping from ϵ_{\perp} to ϵ_{\parallel} ; (b) 3GHz, sweeping from $\tan\delta_{\perp}$ to $\tan\delta_{\parallel}$; (c) $\Delta\epsilon$ in 1-4GHz range, switching with $0.5V/\mu\text{m}$.

8.12 Lighting

There is ongoing work on the use of CNTs for low energy lighting applications. The use of CNTs as electron

emitters to stimulate phosphors has been reported by various groups and the replacement of metallic filaments with carbon CNTs/Fibres has been investigated by groups mostly in China. Carbon nanotube bulbs made from CNT strands and films have been fabricated and their luminescent properties, including the lighting efficiency, voltage-current relation and thermal stability have been investigated. The results show that a CNT bulb has a comparable spectrum of visible light to a tungsten bulb and its average efficiency is 40% higher than that of a tungsten filament at the same temperature (1400—2300K) [269]. The nanotube filaments show both resistance and thermal stability over a large temperature region. No obvious damage was found on a nanotube bulb held at 2300 K for more than 24 hours in vacuum, but the cost needs to be significantly reduced and the lifetime significantly increased for this to be considered seriously as an option.

European Position: Most effort is located in the Far East but Bonnard et al at EPFL have also contributed in this area.

8.13 Nanofluidics

The interest in taking advantage of the unique properties of carbon CNTs in nanofluidic devices has increased tremendously over the last couple of years. The CNTs can either be used directly as a nanofluidic channel in order to achieve extremely small and smooth pores with enhanced flow properties [270] or be embedded into existing fluidic channels to take advantage of their hydrophobic sorbent properties and high surface-to-volume ratio for improving chemical separation systems [271], [272].

By integrating vertically aligned CNTs into silicon nitride [273] and polymer membranes [274],[275] respectively, it has been possible to study the flow of liquids and gases through the core of carbon nanotubes. The flow rates were enhanced by several orders of magnitude, compared to what would be expected from continuum hydrodynamic theory [266]. The reason for this is believed to be due to the hydrophobic nature of the inner carbon nanotube sidewall, together with the high smoothness, which results in a weak interaction with the water molecules, thereby enabling nearly frictionless flow through the core of the tubes. This effect resembles transport through transmembrane protein



pores, such as aquaporins, where water molecules line up in a single file with very little interaction with the sidewall.

This application of CNTs is envisioned to result in novel ultrafiltration and size-based exclusion separation devices, since the pore sizes approach the size of ion channels in cells [266]. The CNT membranes are, however, fabricated by CVD and this application suffers from the lack of large scale cost-effective CNT deposition equipment.

In the last couple of years CNTs have also been investigated as a sorbent material for improving both the resolution and sensitivity of chemical separations [271], [272]. This has been done by incorporating the nanotubes in the stationary phase of mainly gas chromatography columns to take advantage of their high surface-to-volume ratio and better thermal and mechanical stability compared to organic phases, which make them ideal for especially temperature programmed separations [271],[272],[276]. The carbon nanotubes, in the form of powder, are hard to pack directly in columns due to their tendency for aggregation and hence channel blockage [271],[272],[277] so the CNTs have typically either been incorporated in a monolithic column [278] immobilized on the inner channel wall [279] or deposited on the surface of beads that subsequently were packed [280].

A major complication of these methods, apart from the fact that they are manual and very labour-intensive, is that they rely on the necessity of forming uniform CNT suspensions, which is difficult, since CNTs are insoluble in aqueous solutions and most organic solvents [271]. It is therefore typically required to either dynamically or covalently modify the CNTs to avoid aggregation [272]. These problems can be overcome by direct growth of the CNTs on a surface, in e.g. microfluidic channels [281],[282],[283], so they are anchored to the channel wall and therefore unable to form aggregates. This also allows a much higher CNT concentration without clogging the fluidic devices. Growing of CNTs in microfluidic systems has the additional benefit that lithography can be used for the pattern definition, which should make it possible to make much more uniform and therefore more efficient columns [284].

A major limitation of this application is also the lack of low cost CNT deposition equipment, since it is necessary to use vertically aligned CNTs that are attached to the

surface to avoid aggregation and to benefit from the high uniformity of the nanostructures.

European Position: Montena Components of Switzerland are in competition with Maxwell Technologies in this area. DTU is also very active in the field.

8.14 Liquid crystal microlenses

Liquid crystals (LCs) are potentially a very exciting technology for creating a real-time holographic three dimensional (3D) display system. For the reproduction of a full 3D image, a fully complex hologram is the ultimate solution, but it is very difficult to display using current technology such as Liquid Crystal (LC) over silicon (LCOS), as shown by the simple image in Figure 20(c) projected using a binary phase only LCOS device.

A purely phase only hologram (or kinoform) is the best for building 3D displays, however there are limits due to the way in which a liquid crystal can be used to modulate a phase only hologram. A traditional pixel has a top and bottom planar electrode creating a uniform electric field. The device pixel as shown in Figure 20(a) has a CNT in the centre which creates a non-uniform electric field profile [285]. This changes the way in which the LC switches and responds to the field.

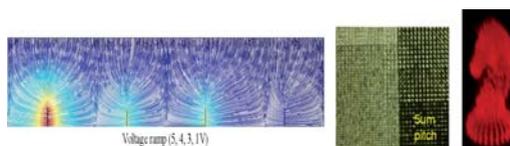


Fig 20. (a) A nanotube electrodes in a liquid crystal cell with an external fields applied. (b) Individual LC electrodes (top left are 1 μm pitch), (c) 3D projected hologram image.

Applications such as 3D holography require large densities of very fine pixels [286]. Current LCOS devices are limited to pixels pitches of around 5 μm before alignment and fringing fields become a problem. Figure 20(b) shows a CNT electrode device fabricated at Cambridge with a pixel pitch of 1 μm. Due to the non-uniform field profile, the LC material clearly switches as single pixels. The device as shown only switches as a single array of electrodes and to make a hologram we need them to be individually addressed, hence we need an active backplane such as that found in LCOS to grow them upon [287].

European Position: The Engineering Department in Cambridge as far as we know, are the only group in Europe working in this area.

6000 S/m and a subthreshold swing of ~ 70 mV/decade respectively [295]. Table 2 summarizes the work in this area.

8.15 Transistors

Table 2: A summary of the optimum properties obtained from single electron transistors

8.15.1 Individual CNT-Based Transistors

Arguably this has been the electronic application on which most research has focused. Martel et al. and Tans et al. first reported a bottom gate individual single walled carbon nanotube field effect transistor (SWNT-FETs) with an on/off ratio of $\sim 10^5$ and a mobility of $20 \text{ cm}^2/\text{Vs}$ in 1998 [288], [289]. Afterwards, Durkop et al. claimed a mobility for bottom-gate SWNT-FET of $>10^5 \text{ cm}^2/\text{Vs}$ with a subthreshold swing ~ 100 mV/decade [290]. This mobility is still the highest reported for bottom gate CNT-FETs thus far. Meanwhile, top gate SWNT-FETs were also attracting attention since such a structure can be readily used for logic circuits. In 2002, Wind et al. first demonstrated a top gate SWNT-FET with an on/off ratio of $\sim 10^6$, a transconductance of 2300 S/m and a subthreshold swing of 130 mV/decade [291]. Rosenblatt et al. and Minot et al. [293] using NaCl and KCl solutions as the top gate in SWNT-FETs showed a mobility of $1500 \text{ cm}^2/\text{Vs}$, a subthreshold swing of $\sim 80 \text{ mV/decade}$ and an on/off ratio of 10^5 . Yang et al. [294] showed a very high transconductance of 1000 S/m in a top gate device (shown in figure 21, together with a bottom gate device). Javey et al. also demonstrated high performance SWNT-FETs using high-k dielectric ZrO_2 as the top gate insulator. Devices exhibited a mobility of $3,000 \text{ cm}^2/\text{Vs}$, a transconductance of

First author	Contact	Architecture	Mobility / cm^2/Vs	On-off ratio	Conductance S/m	Sub-threshold slope / mV/dec
Martel [288] Tans [289]	Au	Bottom gate (SiO ₂ /Si)	20	10^5	0.0017	-----
Durkop [290]	Cr/Au	Bottom gate (SiO ₂ /Si)	$>10^5$	-----	1.4	100
Wind [291]	Ti	Top gate (SiO ₂ /Al or Ti)	2300	10^6	3.25	130
Rosenblatt [292] Minot [293]	Au	NaCl and KCl solution top gate (Ag/AgCl probe)	1500	10^5	20	80
MH Yang [294]	Pd	Top gate Al	-----	10^5	1000	67-70
Javey [295]	Mo	ZrO ₂ top gate (Metal Ti/Au)	3000	10^4	6	70

Several groups have also investigated vertical CNT-FETs (wrap-around gate). Choi et al. reported the first vertical MWNT-FET with a best conductance of 50 mS in 2003 [296] but this only works at low temperatures. Maschmann et al. demonstrate a vertical SWNT-FET in 2006 [297]. Their devices exhibited a good ohmic SWNT-metal contact, but the gate effect is not as efficient as either the top gate or bottom gate SWNT-FETs. SWNT-FETs always exhibit p-type operation when contacted ohmically, but n-type SWNT-FETs are also needed for fabrication of logic circuits. Derycke et al. claimed both annealing (removal of oxygen) and doping (e.g. potassium) can convert a p-type SWNT-FET into a n-type and a logic inverter was demonstrated [298],[299]. Javey et al. and Chen et al. reported that using different metal electrodes (e.g. Al) they could also obtain n-type SWNT-FETs with a ring oscillator also fabricated [300],[301].

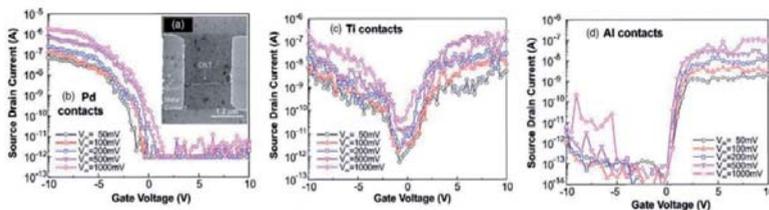


Fig. 21: Typical SWNT-FET transistor characteristics made at the University of Cambridge with different contacts. Left, Pd makes an ohmic contact which results in p-type conduction. Centre, Ti contacts result in strong ambipolar behaviour. Right, Al makes a Schottky contact which results in n-type conduction but with a strong leakage current.

Challenges for the future include controlling the chirality and diameter, improving the yield of working devices, improving the reproducibility of the contact, ensuring all CNTs are semiconducting, improving the uniformity of the devices, controlling their positioning, and developing a process that can be scaled up to mass-production.



European Position: The state-of-the-art transistors (dependent on characteristics) are those produced by the groups of Avouris at IBM and in Europe, Bourgoin at CEA, Saclay, Ecole Polytechnique and Dekker at Delft University of Technology.

8.15.2 Network CNTs

In order to overcome the various problems with individual CNT transistors, numerous groups have concentrated on the production of transistors manufactured from CNT networks or even CNT/Polymer mixtures.

In 2002, the first report (a patent) for transistors based on random networks of nanotubes and their use in chemical sensors was produced by Nanomix Inc., [302] followed in 2003 by the disclosure of their integration onto a 100 mm Si wafer. [303] The first public disclosure was made in 2003 by Snow et al. [304] who demonstrated a SWNT thin film transistor with a mobility of $>10 \text{ cm}^2/\text{Vs}$ and a subthreshold swing of $250\text{mV}/\text{decade}$ with an on/off ratio of 10. In 2007, Kang et al. grew highly dense, perfectly aligned SWNT arrays on a quartz substrate which were then transferred to a flexible plastic substrate (PET). The SWNT-FETs were fabricated on the PET substrate and exhibited a mobility of $1000 \text{ cm}^2/\text{Vs}$ and a transconductance of 3000 S/m [305]. The Rogers group has exhibited state-of-the-art network transistors

for on/off ratio and mobility (see figure 22). The group in Grenoble have also investigated this and have made a small chip incorporating 75 such transistors.

The interest in the networks comes from the fact that if the average nanotube length is small compared to the distance between source and drain and more than one tube is needed to make the connection, the probability of having an electrical path made only of metallic tubes is $\sim(1/3)^n$ where n is the number of tubes needed to make the junction. Secondly, the on/off ratio increases since, even if two tubes are metallic, their contact is not metallic. [306] Finally, even a single defect is enough to open a bandgap in a metallic tube, turning it into a semiconductor. [307] This means that controlling the number of defects is an important challenge to overcome.

The first transparent CNT based transistor made on a flexible substrate was achieved by transferring a CNT random network from a silicon substrate onto a polyimide polymer [308].

8.15.3 High frequency nanotube transistors

The high carrier mobility of CNTs makes them potential candidates for high frequency transistors. It was shown in 2004 that optimized carbon nanotube field effect transistors (CNTFETs) would have cut-off frequencies f_T above those of FETs built from any other semiconductor [309]. For aggressively scaled devices working in the ballistic regime, the intrinsic f_T could reach the THz range. These first projections were confirmed by detailed calculations from several groups worldwide [310], [311].

From an experimental point of view, measuring the high frequency performances of CNTFETs is very challenging. Indeed CNTs, when considered individually, have very high impedance ($R_{ON} > 6.5 \text{ k}\Omega$) whilst conventional high frequency equipment is adapted for the 50Ω measurement range. In addition, due to the small size of the CNT, parasitic contributions from the device structure tend to dominate the intrinsic contribution of the CNT.

To circumvent these problems, several groups proposed the use of mixing techniques and obtained *indirect* indications of the high frequency operation of CNTFETs.

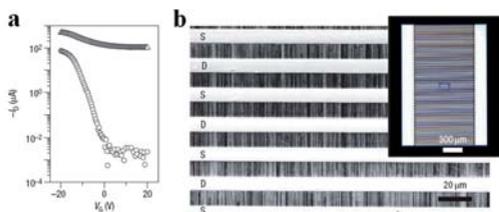


Fig. 22: (a) Transfer curves from a transistor that uses aligned arrays of SWNTs transferred from a quartz growth substrate to a doped silicon substrate with a bilayer dielectric of epoxy (150 nm)/ SiO_2 (100 nm). The data correspond to measurements on the device before (open triangles) and after (open circles) an electrical breakdown process that eliminates metallic transport pathways from source to drain. This process improves the on/off ratio by a factor of more than 10,000. (b) Optical (inset) and SEM images of a transistor that uses interdigitated source and drain electrodes, in a bottom gate configuration with a gate dielectric of HfO_2 (10 nm) on a substrate and gate of Si. The width and length of the channel are 93 nm and 10 μm , respectively. The box indicated by the dashed blue lines in the optical image inset delineates the region shown in the SEM image [39]. Figure reproduced with permission from the American Chemical Society.

For example, IBM reached 580 MHz in 2004 [312], then Cornell University and Northrop Grumman Corporation respectively reached 50 GHz [313] and 23 GHz [314]. Direct measurements of the HF operation of a single nanotube CNTFETs are scarce. The most convincing result was obtained at ENS Paris in 2008 [315]. From direct measurements of g_m and C_g up to 1.6 GHz, they obtained f_T 50 GHz for a 300 nm long channel. A convenient and powerful way of directly measuring the full S-parameters matrix of CNT based devices (which is a critical requirement from a circuit design point of view), consists in studying multiple nanotubes in parallel, thus reducing both the device impedance and the relative impact of parasitics. This strategy was used by different groups [316], [317], [318] [319], [320], [321], [322] to demonstrate f_T above 10 GHz. In particular, the collaboration of two French groups from IEMN and CEA achieved an intrinsic f_T of 30 GHz in 2007 and 80 GHz in 2009. Interestingly, the latter result was only made possible through the use of a high quality nanotube source from Northwestern University containing 99% semiconducting nanotubes. The important results from the Rogers's group also originate from recent progress at the material level (CVD growth of aligned CNTs in their case).

European Position: Rogers in the USA produces the state of the art thin Film transistors and in Europe, apart from some preliminary work in Universities little seems to be happening.

8.15.4 High frequency flexible electronics

Even if they can reach high operating frequencies, the use of CNTFETs in conventional integrated circuits remains unlikely in the near future. Indeed, the potential gains in performances when compared with conventional semiconductors do not compensate for the immense efforts required at the material level to solve the issues of selective placement and nanotube variability. Conversely, when carbon nanotubes are compared with organic materials in the field of flexible electronics, the potential gains in performances are huge. Indeed, the low carrier mobility in organics (typically in the 10^{-3} - 10 cm²/Vs range) prevents their use at very high frequencies. Flexible electronics with CNTs has been studied since but only very recently at high frequency. The first results are already very promising with operating frequencies in or close to the GHz range [316],

[323], [324]. Most importantly, CNT-based network transistors can be made compatible with printing technologies [324].

European Position: This is a small research field and most of the activity is located in the USA (Univ. Illinois, Stanford, IBM). Main academic players in Europe are CEA and IEM & Delft University. From an industrial point of view one can cite Brewer Science (for the ink formulation and deposition process) as well as Northrop Grumman for circuitry developments.

8.16 Hydrogen storage

CNTs have been suggested as potential candidates for hydrogen storage. However, the reported hydrogen uptake varies significantly from group to group, with the mechanism not clearly understood. Current methods involve compressing the CNTs into pellets which are then subjected to hydrogen at high pressure. The target set by the US Department of Energy is 6% by weight hydrogen by 2010. Whilst most groups have found hydrogen uptake to be in the 1-2% region [325], amongst the highest reported are Gundish et al. [326] at 3.7% and Dai's group [327] at 5.1%. It should be noted that Hirschler and Roth found most reported values to be false [328], for example due to Ti take up during sonication.

From a more fundamental point of view, the average adsorption energy of hydrogen on CNTs is not significantly different from its value on amorphous carbon. It is mainly the surface area which plays a crucial role; e.g. 5.8% was achieved a long time ago on super-high surface area activated carbon, a significantly cheaper material when compared to CNTs. [329] Also, because the bond of hydrogen with silicon is weaker than that of carbon, it is much easier to get hydrogen out again.

European Position: Over the last 10 or so years there have been numerous groups worldwide working in this area; especially in the USA, Japan and China. Europe too has made a significant investment, notably through groups in Germany, France, Greece (theoretical work) and the UK but still the DoE 6% target remains elusive. It is generally accepted that absorptions of about 1% are practical [330]. Other

Catalogue of Nanoscience & Nanotechnology Companies in Spain

This catalogue, compiled by the Phantoms Foundation (coordinator of the Spanish Nanotechnology action plan funded by ICEX), provides a general overview of the Nanoscience and Nanotechnology companies in Spain and in particular the importance of this market research, product development, etc.

Note: only those contacted companies which provided their details are listed.

Edited and Coordinated by



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N&N Companies in Spain



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e-mail	antoniojose.sanchez.rojo@acciona.es
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Main Research Areas	Nanocoatings • Nanocomposites
Created in	1997
No. of employees in R&D	152
% Nanoscience and Nanotechnology (R&D)	9,8
No. of Patents	6 National and 2 European



ACTIVERY BIOTECH S. L.

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Main Research Areas	Drug Delivery • Nanomedicine
Created in	2003
No. of employees in R&D	5
% Nanoscience and Nanotechnology (R&D)	50
No. of Patents	6



AGROINDUSTRIAL KIMITEC

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Main Research Areas	NanoBio • Nanochemistry
Created in	2010
No. of employees in R&D	15
% Nanoscience and Nanotechnology (R&D)	2



AIRBUS OPERATIONS S. L.

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Main Research Areas	Nanocomposites • Nanotubes
Created in	2000
No. of employees in R&D	≈3000
% Nanoscience and Nanotechnology (R&D)	< 5

N&N Companies in Spain



ARAGONESA DE COMPONENTES PASIVOS S. A.

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Main Research Areas	Nanomaterials • Nanoparticles
Created in	1988
No. of employees in R&D	2
% Nanoscience and Nanotechnology (R&D)	3
No. of Patents	1

APPLIED RESEARCH USING OMIC SCIENCES S.L.



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Main Research Areas	NanoBio
Created in	2005
No. of employees in R&D	5
% Nanoscience and Nanotechnology (R&D)	15



ASOCIACIÓN DE LA INDUSTRIA NAVARRA

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Main Research Areas	Energy • Manufacturing • Nanocoatings • Nanomaterials Nanophotonics • Nanotubes
Created in	1963
No. of employees in R&D	125
% Nanoscience and Nanotechnology (R&D)	10



ATOS ORIGIN

Address	C/ Albarracín, 25 - Madrid (Spain)
WEB site	www.atosorigin.eu
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Main Research Areas	Modelling/Simulation/Software • Nanomedicine Nanoparticles • Project Management
Created in	1987
No. of employees in R&D	300
% Nanoscience and Nanotechnology (R&D)	3

N&N Companies in Spain



AVANZARÉ INNOVACIÓN TECNOLÓGICA S. L.

Address	C/ Antonio de Nebrija, 8 -26006 Logroño (Spain)
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Main Research Areas	Graphene • Nanocomposites • Nanomaterials • Nanoparticles Nanosensors
Created in	2005
No. of employees in R&D	24
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	12

BIOKER RESEARCH S. L.



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Main Research Areas	NanoBio • Nanomaterials • Nanoparticles
Created in	2005
No. of employees in R&D	2
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	3

EL ARTE DE REFRIGERAR



TERMOELECTRICIDAD

CIDETE INGENIEROS S. L.

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Main Research Areas	Nanoelectronic/Molecular Electronic • Nanomaterials Nanosensors
Created in	2001
No. of employees in R&D	4
% Nanoscience and Nanotechnology (R&D)	60



DATAPIXEL S. L.

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Main Research Areas	Manufacturing • Modelling/Simulation/Software Nanometrology • Nanosensors
Created in	1999
No. of employees in R&D	7
% Nanoscience and Nanotechnology (R&D)	20
No. of Patents	1

N&N Companies in Spain

DOLMAR INNOVA S. L.



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Main Research Areas	NanoBio • Nanoparticles • Nanosensors
Created in	1992
No. of employees in R&D	8
% Nanoscience and Nanotechnology (R&D)	15 - 20

DROPSSENS S. L.



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Created in	2006
No. of employees in R&D	3
% Nanoscience and Nanotechnology (R&D)	40



DYNASOL ELASTOMEROS

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Main Research Areas	Nanocomposites • Nanomaterials
Created in	1999
No. of employees in R&D	> 150



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Main Research Areas	Drug delivery • Nanomedicine
Created in	2007
No. of employees in R&D	7
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	1

N&N Companies in Spain

FUNDACIÓN PHANTOMS



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No. of employees in I+D	8
% Nanoscience and Nanotechnology (R&D)	100

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Main Research Areas	Graphene • Nanochemistry • Nanomaterials
Created in	2010
No. of employees in R&D	3
% Nanoscience and Nanotechnology (R&D)	75

N&N Companies in Spain



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No. of employees in R&D	11
No. of Patents	4



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Created in	2003
No. of employees in R&D	16
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	50

N&N Companies in Spain



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Main Research Areas	Nanoelectronic/Molecular Electronic • Nanomaterials
Created in	2006
No. of employees in R&D	8
% Nanoscience and Nanotechnology (R&D)	90
No. of Patents	4

INTERQUÍMICA

InTER química

Instituto de Tecnologías Químicas Emergentes de la Rioja

Address	San Francisco, 11 - 26370 Navarrete (La Rioja)
WEB site	www.interquimica.org
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Main Research Areas	Graphene • NanoBio • Nanoclays • Nanocomposites Nanomaterials • Nanomedicine • Nanoparticles • Nanosensors
Created in	2005
No. of employees in R&D	14
% Nanoscience and Nanotechnology (R&D)	90



LABORATORIOS ALPHASIP

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Main Research Areas	Nanomedicine • Nanotubes • Nanowires
Created in	2009
No. of employees in R&D	6
% Nanoscience and Nanotechnology (R&D)	90
No. of Patents	120



LABORATORIOS ARGENOL S. L.

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e-mail	lab-argenol@laboratorios-argenol.com
Phone	+34 976 336 266
Main Research Areas	NanoBio • Nanoparticles
Created in	2005
No. of employees in R&D	3
% Nanoscience and Nanotechnology (R&D)	50
No. of Patents	1

N&N Companies in Spain



LAIMAT SOLUCIONES CIENTÍFICO TÉCNICOS

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e-mail	mfvalmayor@laimat.com
Phone	+34 958 750 951
Main Research Areas	Drug delivery • Encapsulation • Microsensors • Nanomedicine
Created in	2006
No. of employees in R&D	6
% Nanoscience and Nanotechnology (R&D)	80



MECWINS S. L.

Address	C/ Santiago Grisolia, 2 - 28760 Tres Cantos - Madrid (Spain)
WEB site	www.mecwins.com
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e-mail	oahumada@mecwins.com
Phone	+34 918 049 064
Main Research Areas	NanoBio • Nanosensors
Created in	2008
No. of employees in R&D	6
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	3



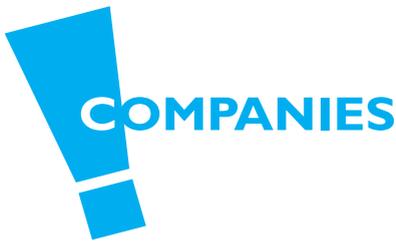
NANOBIOMATTERS INDUSTRIES S. L.

Address	Parque Tecnológico. Louis Pasteur, 11, Nave 5-6 46980 Paterna - Valencia (Spain)
WEB site	www.nanobiomatters.com
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Main Research Areas	NanoBio • Nanoclay • Nanocoating • Nanofabrication Nanocomposites
Created in	2004
No. of employees in R&D	20
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	10

NANOGAP SUBNMPOWDERS

NANOGAP SUB-NM-POWDER S. A.

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e-mail	info@nanogap.es
Phone	+34 981 523 897
Main Research Areas	Nanomaterials • Nanomedicine
Created in	2006
No. of employees in R&D	7
% Nanoscience and Nanotechnology (R&D)	35
No. of Patents	6



COMPANIES

	Carbon nanofibres	Drug delivery	Encapsulation	Energy	Graphene	Manufacturing	Microsensors	Microwires/Nanowires	Modelling/Simulation/Software	NanoBio
ACCIONA INFRAESTRUCTURA										
ACTIVERY BIOTECH S. L.		—								
AGROINDUSTRIAL KIMITEC										—
AIRBUS OPERATIONS S. L.										
ARAGONESA DE COMPONENTES PASIVOS S. A.										
APPLIED RESEARCH USING OMIC SCIENCES S.L.										—
ASOCIACIÓN DE LA INDUSTRIA NAVARRA				—		—				
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CIDETE INGENIEROS S. L.										
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DOLMAR INNOVA S. L.										—
DROPSENS S. L.										—
DYNASOL ELASTOMEROS										—
ENDOR NANOTECHNOLOGIES		—								
FUNDACIÓN PHANTOMS										
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LAIMAT SOLUCIONES CIENTÍFICO TÉCNICAS		—	—				—			
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NANOBIOMATTERS INDUSTRIES S. L.										—
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NANOINMUNOTECH S. L.										
NANOINNOVA TECHNOLOGIES S. L.					—					
NANORIOJA S. L.					—					
NANOTEC ELECTRÓNICA S. L.										
NANOTECNOLOGÍA SPAIN S. L.										
NANOTEX (SOLUTEX GROUP)		—				—				—
NANOZAR S. L.										
NEOKER S. L.										
NLAB DRUG DELIVERY		—	—							—
OPERÓN S. A.										—
RAMEN S. A.										
REPSOL YPF (DIRECCIÓN DE TECNOLOGÍA)				—						—
SENSIA S. L.										
SGENIA S. L.				—					—	
SINATEC S. L.										
TAMAG IBÉRICA S. L.							—	—		
TECN. NAVARRA DE NANOPRODUCTOS S. L. (TECNAN)										
THRELLUP NANOTECHNOLOGY									—	—
TOLSA S. A.										
TORRECID S. A.										
TRIMEK S. A.						—				
UNIMETRIK S. A.						—				
YFLOW SISTEMAS Y DESARROLLOS S. L.			—							
ZF BIOLABS										—
TOTAL	1	6	3	3	5	5	2	2	4	15

N&N Companies in Spain



NANOIMMUNOTECH S. L.

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Main Research Areas	Nanomedicine • Nanotoxicology
Created in	2010
No. of employees in R&D	1
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	7



NANOINNOVA TECHNOLOGIES S. L.

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Main Research Areas	Graphene • Nanosensors • Nanotubes
Created in	2010
No. of employees in R&D	2
% Nanoscience and Nanotechnology (R&D)	100



NANORIOJA S. L.

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Main Research Areas	Graphene • Nanocomposites • Nanomaterials
Created in	2008
No. of employees in R&D	3
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	1



NANOTEC ELECTRÓNICA S. L.

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Main Research Areas	SPM
Created in	1998
No. of employees in R&D	18
% Nanoscience and Nanotechnology (R&D)	45

N&N Companies in Spain



NANOTECNOLOGÍA SPAIN S. L.

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Main Research Areas	Nanocomposites
Created in	2004
No. of employees in R&D	8
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	1

NANOTEX (SOLUTEX GROUP)



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Main Research Areas	Drug delivery • Manufacturing • NanoBio • Nanochemistry Nanofabrication • Nanomagnetism/Spintronics • Nanomaterials Nanomedicine • Nanoparticles
Created in	2004
No. of employees in R&D	100
No. of Patents	6

Nanozar sl
CARBON NANOTUBE RESEARCH

NANOZAR S. L.

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Main Research Areas	Nanocoatings • Nanocomposites • Nanotubes
Created in	2005
No. of employees in R&D	2
% Nanoscience and Nanotechnology (R&D)	100



Neoker, S.L.

NEOKER S. L.

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Main Research Areas	Nanocomposites • Nanomaterials
Created in	2008
No. of employees in R&D	8
% Nanoscience and Nanotechnology (R&D)	80
No. of Patents	4

N&N Companies in Spain



NLAB DRUG DELIVERY

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Main Research Areas	Drug delivery • Encapsulation • Nanomaterials • Nanomedicine
Created in	2010
No. of employees in R&D	4 (2011)
% Nanoscience and Nanotechnology (R&D)	80
No. of Patents	4



OPERÓN S. A.

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Main Research Areas	NanoBio • Nanoparticles
Created in	1996
No. of employees in R&D	8
% Nanoscience and Nanotechnology (R&D)	35
No. of Patents	1



RAMEN S. A.

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Phone	+34 914 044 575
Main Research Areas	Nanoparticles
Created in	1958
No. of employees in R&D	34
% Nanoscience and Nanotechnology (R&D)	30
No. of Patents	5



REPSOL

REPSOL YPF (DIRECCIÓN DE TECNOLOGÍA)

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Main Research Areas	Energy • NanoBio • Nanocomposites • Nanomaterials
Created in	2000
No. of employees in R&D	11
% Nanoscience and Nanotechnology (R&D)	< 10
No. of Patents	2

N&N Companies in Spain



SENSIA S. L.

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e-mail	ilarroulet@seimcc.com
Phone	+34 918 049 622
Main Research Areas	Nanosensors
Created in	2004
No. of employees in R&D	1
% Nanoscience and Nanotechnology (R&D)	35



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Main Research Areas	Energy • Modelling/Simulation/Software • Nanosensors
Created in	2003
No. of employees in R&D	4
% Nanoscience and Nanotechnology (R&D)	10



SINATEC S. L.

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Main Research Areas	Nanocomposites • Nanomaterials • Nanotubes
Created in	2007
No. of employees in R&D	7
% Nanoscience and Nanotechnology (R&D)	60



TAMAG IBERICA S. L.

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Phone	+34 619 163 930
Main Research Areas	Microsensors • Microwires
Created in	2000
No. of employees in R&D	1
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	2

N&N Companies in Spain

TECNOLOGÍA NAVARRA DE NANOPRODUCTOS S. L. (TECNAN)



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Phone	+34 948 640 318
Main Research Areas	Nanocoatings • Nanomaterials • Nanoparticles
Created in	2008
No. of employees in R&D	3
% Nanoscience and Nanotechnology (R&D)	35

THREELLOP NANOTECHNOLOGY



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Main Research Areas	NanoBio • Modelling/Simulation/Software
Created in	2007
No. of employees in R&D	4
% Nanoscience and Nanotechnology (R&D)	100
No. of Patents	20

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Phone	+34 913 606 900
Main Research Areas	Nanoclays • Nanocomposites • Nanomaterials • Nanoparticles
Created in	1957 (Nanoscience and Nanotechnology: 2002)
No. of employees in R&D	7
% Nanoscience and Nanotechnology (R&D)	30
No. of Patents	1



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Phone	+34 964 630 900
Main Research Areas	Nanocoatings • Nanomaterials • Nanoparticles
Created in	1963
No. of employees in R&D	9
No. of Patents	4

N&N Companies in Spain



TRIMEK S. A.

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Phone	+34 945 430 718
Main Research Areas	Manufacturing • Nanometrology
Created in	1993
No. of employees in R&D	11
% Nanoscience and Nanotechnology (R&D)	10

UNIMETRIK S. A.



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WEB site	www.unimetrik.es
Contact person	Borja de la Maza
e-mail	bmaza@unimetrik.es
Phone	+34 945 465 800
Main Research Areas	Manufacturing • Nanometrology • Nanosensors • SPM
Created in	1997
No. of employees in R&D	10
% Nanoscience and Nanotechnology (R&D)	20
No. of Patents	2



YFLOW SISTEMAS Y DESARROLLOS S. L.

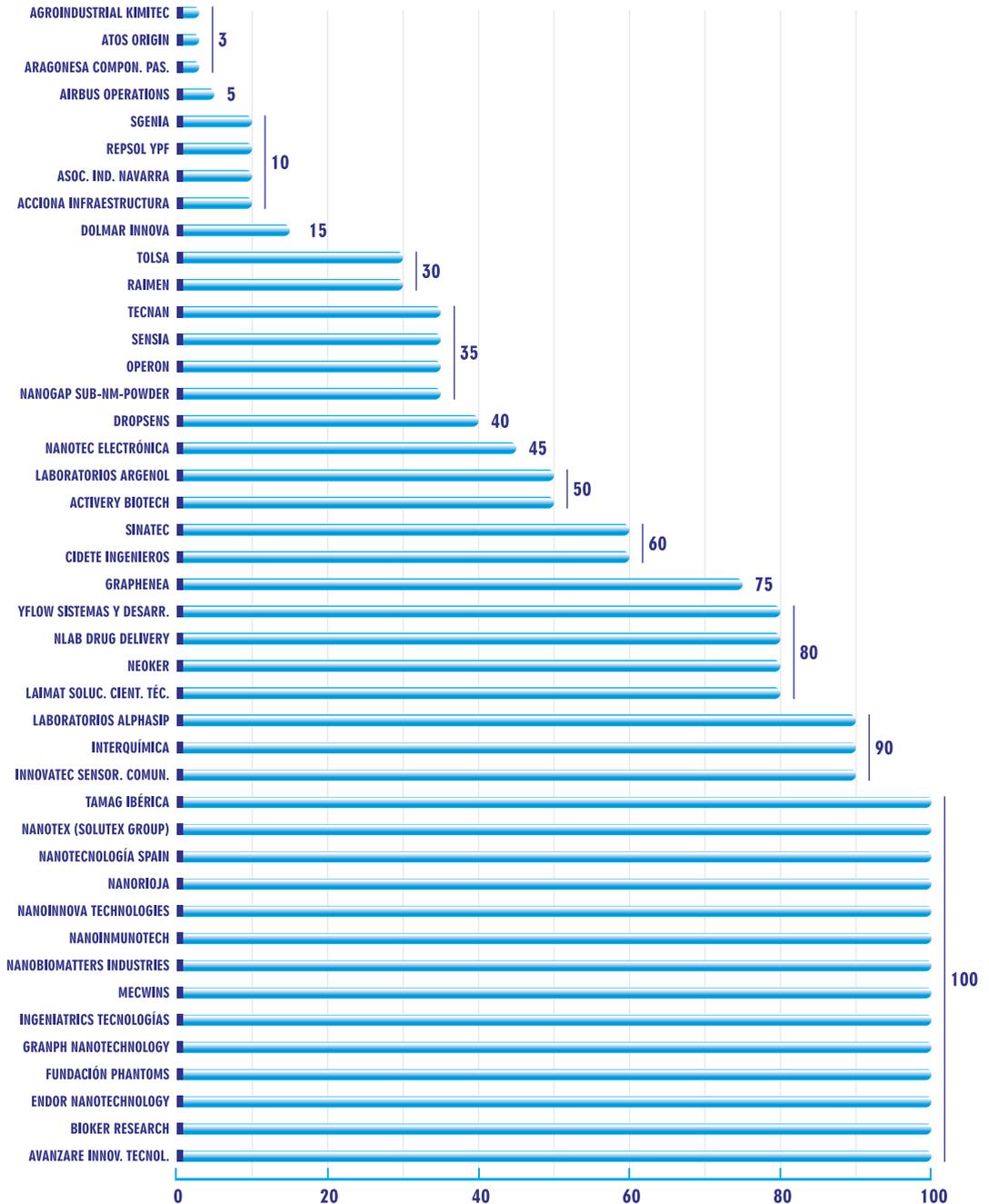
Address	C/ Marie Curie, 4. Parque Tecnológico de Andalucía 29590 Málaga (Spain)
WEB site	www.yflow.com
Contact person	David Galán
e-mail	contact@yflow.com
Phone	+34 952 020 370
Main Research Areas	Encapsulation • Nanocoatings • Nanocomposites • Nanoparticles
Created in	2001
No. of employees in R&D	6
% Nanoscience and Nanotechnology (R&D)	80
No. of Patents	6



ZF BIOLABS

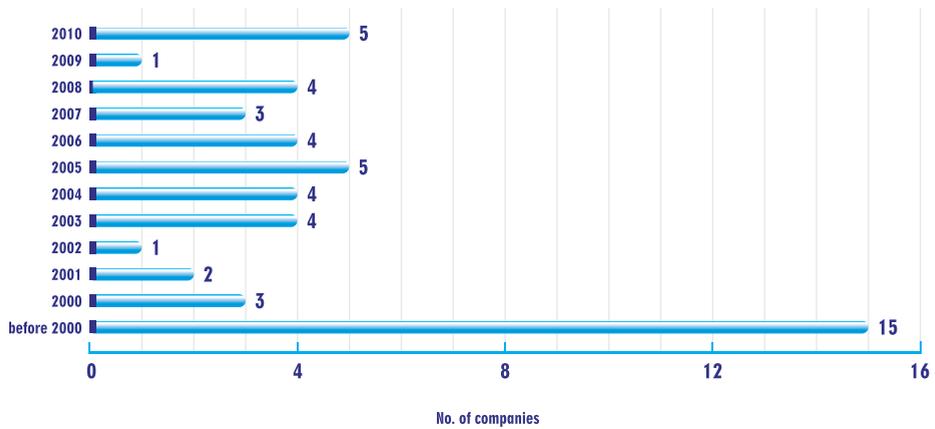
Address	Ronda de Valdecarrizo, 41B - 28760 Tres Cantos - Madrid (Spain)
WEB site	www.zfbiolabs.com
Contact person	Erika Sela
e-mail	esela@zfbiolabs.com
Phone	+34 918 049 020
Main Research Areas	NanoBio • Nanotoxicology
Created in	2003
No. of employees in R&D	5
% Nanoscience and Nanotechnology (R&D)	10

% Activity in Nanoscience and Nanotechnology in R&D

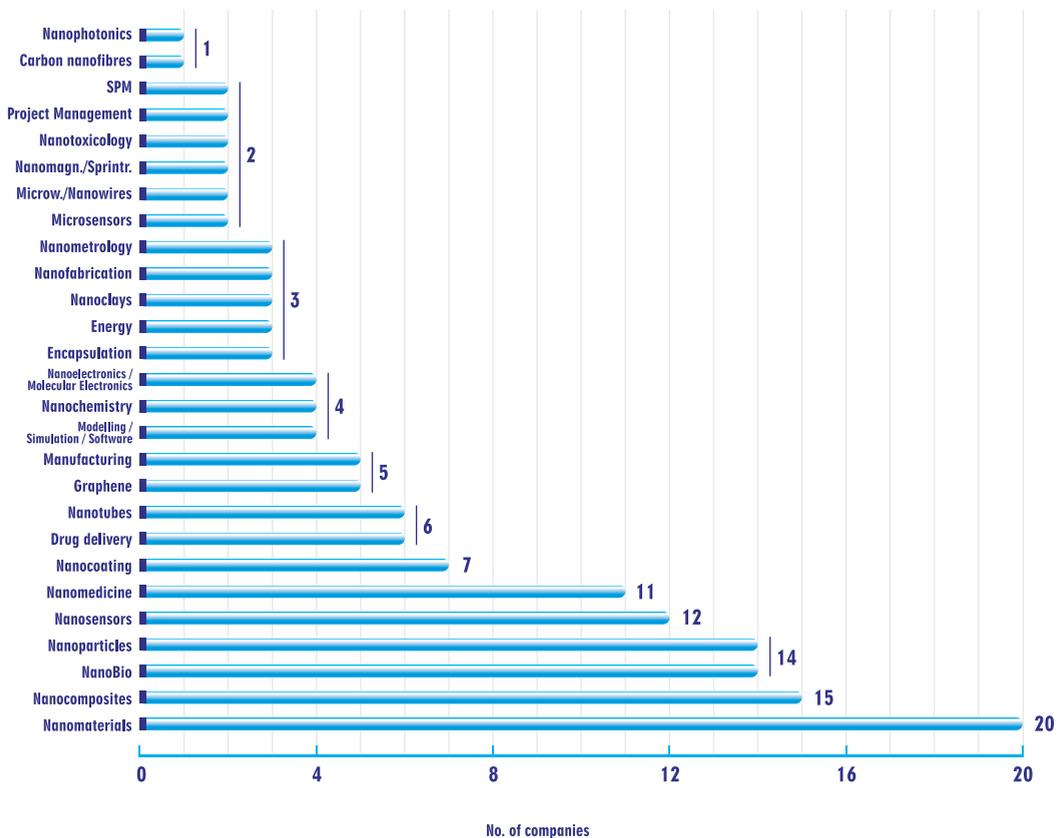


% Activity in N&N

Created in vs No. of Companies



Distribution of Research Topics vs No. of Companies





Implementing the European Commission Code of Conduct for Responsible Nanotechnologies

Partners

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Phantoms Foundation (Spain)
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Department of Science and Technology, (Rep. of South Africa)
Delft University of Technology (The Netherlands)
Centro Atómico Bariloche (Argentina)

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www.nanocode.eu

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knowledge

expertise

excellence

Phantoms Foundation

nanoscience & nanotechnology

innovation

$H_2SO_4 + 2Na + 2O$

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technologies involving other compounds such as carbohydrates are expected to be used instead.

8.17 Quantum computing

8.17.1 Spintronics

Spin transport has been demonstrated over lengths of hundreds of nanometers in CNTs [331], and the limit may be much longer. The Kondo effect has been demonstrated [332], and Fano resonances have been found [333]. Spin blockade has been demonstrated in double dot structures [334],[335]. With the development of aberration corrected transmission electron microscopy at low voltage (80 kV), which minimises knock-on damage, it has become possible to image the actual piece of active material in a device [336], as shown in figure 23.

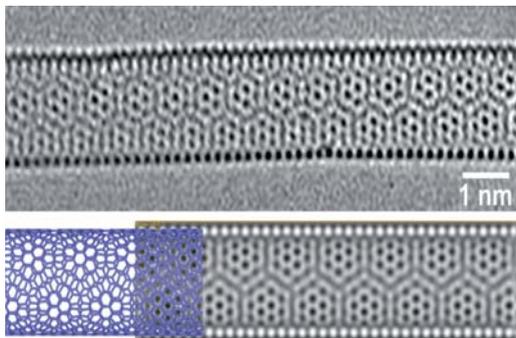


Fig. 23: A 20,3 chirality SWNT, observed in transmission electron microscopy (aberration-corrected JEOL 2200MCO operating at 80 kV, image courtesy of Dr Jamie Warner). Below the micrograph is an atomic model to the left and an image simulation to the right, with a small overlap also shown.

Problems to overcome include the production of uniform, defect-free SWNTs, free from paramagnetic impurities, with a single chiral index, and fabrication of reproducible devices with uniform contacts.

European Position: Hitachi Cambridge Laboratory, and the Cavendish Laboratory Mark Buitelaar, in collaboration with Andrew Briggs at Oxford are the leaders in the field; Others include Delft (Leo Kouwenhoven) and the Niels Bohr Institute, Copenhagen.

8.17.2 Quantum computing

Arrays of qubits have been created in the form of endohedral fullerenes in SWNTs, to make so-called peapods [337]. These structures have been modelled [338] and imaged [339]. The interactions between the spins have been characterized by electron paramagnetic resonance, showing transitions from exchange narrowing to spin-spin dephasing [340]. Theoretical architectures have been developed for global control of qubits [341], [342]. The spin properties of $N@C_{60}$ (or atomic hydrogen inside a C_{60}) have been shown to make it one of the strongest candidates for condensed matter quantum computing [343], [344]. $Y@C_{82}$ can also be used and typical relaxation and coherence times are shown in figure 24. Quantum memories have been demonstrated, in which information in the electron spin is transferred to the nuclear spin, and subsequently retrieved, with gate operation times of order 10 ns and storage times in excess of 50 ms. The theoretical limit for such memories is limited by twice the electron spin flip time [345], and since this can exceed one second the prospects are excellent. Entangled spins offer further

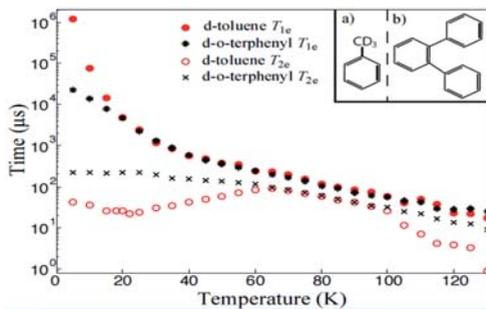


Fig. 24: $Y@C_{82}$ relaxation and coherence times as a function of temperature in deuterated toluene (circle red, T_1 closed, T_2 open) and deuterated o-terphenyl (symbol black, T_1 star, T_2 cross) [347]. Insert: Structural representation of a) d-toluene and b) o-terphenyl.

possibilities for other quantum technologies, such as metrology and sensors [346].

Problems to overcome include the development of the technology for single spin read out in CNTs and the demonstration of entanglement using peapods.

European Position: Oxford leads the world in peapods for quantum computing, in collaboration with Princeton (Steve Lyon), Nottingham (Andrei Khlobystov), Cambridge (Charles Smith), EPFL (Laszlo

Forro) and Peking (Lianmao Peng). There is also activity in Berlin (Wolfgang Harneit), at L. Néel Institute in Grenoble and at CEMES-CNRS in Toulouse [348].

8.17.3 CNT Single Electron Transistors

Single electron transistors (SETs) use the ‘Coulomb blockade’ effect to control charge at the one-electron level, on a nanoscale conducting ‘island’ isolated by tunnel barriers from source and drain electrodes. In these devices, the total island capacitance C is small enough such that the single-electron charging energy $E_c = e^2/2C \gg k_B T$ at the measurement temperature T . A very low current ‘Coulomb blockade’ region exists around zero bias voltage in the I_{ds} - V_{ds} characteristics, where the charging energy prevents current flow. As the applied bias overcomes integer multiples of E_c , electrons are added one by one to the island. In a SET, an additional gate electrode is used to add/remove electrons from the island. The I_{ds} - V_{gs} characteristics show periodic single-electron conductance oscillations, where each oscillation corresponds to the addition of an electron. If $C \sim 10^{-18}$ F or smaller, single-electron effects can occur at room temperature, raising the possibility of single-electron memory and logic applications. For islands small enough such that the quantum confinement energy is also significant, the device forms a quantum dot (QD), sometimes referred to as an artificial atom. A combination of quantum confinement and single-electron charging effects are then observed. If the island in a SET is formed by a section of a SWCNT, then electrons are confined in the axial as well as the circumference direction.

SET operation at cryogenic temperatures, with conductance oscillations in the CNT I_{ds} - V_{gs} characteristics, was demonstrated in the late 1990s in a single SWCNT [349] and in ropes of SWCNTs [350]. More recently, SET operation at room temperature has been demonstrated in a number of works [351], [352], [353], [354]. Here, islands as small as ~ 10 nm [352] have been defined along single SWCNTs [351], in MWNTs [353], and in CNT bundles [352] using nicks or kinks defined by AFM, or by chemical modification. The addition energy in these devices may be as large as ~ 120 meV [351]. QDs may also be defined along a nanotube by variations in the doping type [355], [356]. In investigations of the physics of electron transport through QDs, coupled QD behaviour at low temperature, controlled by multiple gates, has been observed in a number of works [357],

[358], [359], [360]. Single-electron memory operation, with charge storage on an Au nanoparticle and sensing using a CNT FET, has now been demonstrated [361]. In recent work, QDs have been induced along a SWCNT wrapped with single-stranded DNA [362]. Furthermore, a nanoscale resonator has recently been demonstrated using a suspended CNT, where a single electron added to the CNT can be detected in a shift in the resonant frequency [363].

European Position: Considerable progress has been made in CNT based single-electron systems, in the USA, Japan and Europe. In particular, Europe is very strong in fundamental physics investigations in these systems, with a number of novel device demonstrations. Early work on room-temperature CNT SETs has also occurred in Europe.

9. Conclusions

CNTs have many unique and indeed useful properties for applications in the ICT area. Research into CNTs at the university level will continue for at least the next several years especially into quantum effects and associated behaviour, as well-characterized, high-quality SWCNTs become more available. Although CNTs are still being touted for various industrial applications, much more investment is necessary for them to reach commercial viability. The USA and Japan lead in this development but Europe has made significant impact in many areas despite the fact that investment in Europe is but a fraction of that in the other major high-tech industrial zones. Consequently, partnership between higher education and industry could form the basis of research in this enormous and diverse area for many years to come so that at least some of the many applications of CNTs can be realised.

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European Research Roadmap for Nanoelectronics

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The Nanoelectronics European Research Roadmap is addressed focusing on the main European Programmes supporting the short, medium and long-term research activities (CATRENE, ENIAC JTI/JU, Framework Programme). The main challenges we are facing in the field of Nanoelectronic technology are summarized in the More Moore (ultimate CMOS), More than Moore (adding functionalities to CMOS) and Beyond-CMOS domains. The main objectives and some highlights of the Sinano Institute, an European association created for the coordination of the efforts of the Academic Community in the field of Nanoelectronics, and of the Nanosil and Nanofunction Networks of Excellence, devoted to the convergence of More Moore and Beyond-CMOS on one hand and of advanced More than Moore and Beyond-CMOS research activities on the other hand, are also outlined.

1. European Nanoelectronics landscape

Micro-Nanoelectronics has been defined as one of the 5 Key Enabling Technologies (KET) for strengthening the knowledge economy and a sustainable growth in the strategic plan of the European Union (5 KETs: Micro-Nanoelectronics, Nanotechnology, Photonics, Biotechnology, Advanced materials). Nanoelectronics research activities in the EU are devoted to remain at the forefront of state of the art innovation in the further miniaturization and integration of nanoelectronic devices while dramatically increasing their functionalities.

Several Programmes, funded by the European Commission and the Members States, are supporting Nanoelectronics in the EU. CATRENE (EUREKA) [1] and ENIAC Joint Technology Initiatives [2] projects are devoted to technology driven and application driven short/medium term researches, respectively, and FP7 projects [3] focus on long-term research. In the framework of ENIAC/CATRENE, 5 applications oriented and 3 technology oriented domains have been defined: Automotive and Transport; Communication; Energy Efficiency; Health and Ageing Society; Safety and

Security; Design Technologies; Semiconductor Process and Integration; and Equipment, Materials and Manufacturing.

The projects in the field of nanoelectronics technology, which is the focus of this paper, are thus funded by CATRENE, ENIAC and FP programmes. In this respect, the international roadmap proposes a minimum device size starting from 45nm in 2010 to about 9nm in 2024 (More Moore domain). The required performance improvements for the end of the roadmap for high performance, low and ultra low power applications will lead to a substantial enlargement of the number of new materials (thin and ultra-thin strain channels, high and very high k dielectrics, metallic source-drain, etc.), technologies (EUV, etc.) and device architectures (Ultra-Thin films, Multi-gates, Multi-channels, etc.).

Complexity will also derive from diversity, with an increasing number of functions integrated on CMOS platforms as envisaged in the “More than Moore” approach. To learn how to combine CMOS with sensors, actuators, MEMS, NEMS, RF components, biochips, high voltage, imaging devices, photonics on Si, energy harvesting and demonstrate their innovative benefits requires enhancing multidisciplinary experiments by a large research community.

Heterogeneous integration will also be needed in some domains in order to obtain more functions/mm³. Special interests are in the fields of 3D integration, interconnection, assembly & packaging.

Beyond-CMOS nanostructures (Nanowires, Tunnel FETs, Graphene devices, etc.) will also allow to push the limits of Si integration down to nanometric dimension and to develop new functionalities for the future Nanosystems.

In these research areas, there is a strong need to support and develop state-of-the-art Research Infrastructures (RI) open to a large research community to overcome these formidable multidisciplinary challenges for new generations of Nanoelectronic ICs. The proposed strategy in the EC is the development of a 3 levels infrastructure: i) Network of flexible RI, driven by the Academic Community, for the study of basic properties, test and validation of very innovative materials and devices for long term nanoelectronics applications; ii) Pre-industrial RI, driven by the Institutes/Integration Centres, for

medium term applications with technology implementation and performance assessment on R&D equipments; iii) Industrial RI, driven by the Manufacturing Centres, for short term applications with technology exploitation as functional product, process optimization, yield, and product reliability.

The Sinano Institute and the Nanosil/Nanofunction Networks of Excellence, which are presented below, have been launched these last years for the coordination of the European Academic Community and for the study of the convergence of the More Moore, More than Moore and Beyond CMOS domains, respectively. These European consortiums are mainly performing long term nanoelectronics research using flexible research infrastructures (level I) of the previous structuring in strong interaction with industrial and pre-industrial partners.

2. The Sinano Institute

The Sinano Institute [4], launched in 2008 as a European Academic and Scientific Association for Nanoelectronics, gathers 18 laboratories from 10 European countries, representing the main partners from the Academic Community in this field. It has been created after the FP6 Sinano Network of Excellence, which has represented an unprecedented collaboration in Europe in the field of Nanoelectronics. It is an open entity gathering the most important flexible research infrastructures available in Europe for long term Nanoelectronics research.

The Sinano Institute has especially been created to:

- establish a durable EU Network of researchers from the European Academic Community to form a distributed Centre of Excellence in the Nanoelectronics field.
- carry out a role of representation and coordination of the associated Organizations.
- explore the science and technology aspects for n+4 technology nodes and beyond using joint flexible technology, characterization and modeling platforms in order to identify the most promising topics for future ICT.
- achieve activities centred on More Moore, Beyond CMOS and More than Moore fields – in this respect the SINANO Institute is particularly focusing on the convergence of More Moore and Beyond-CMOS, on one

hand, and the merging of More than Moore and Beyond-CMOS, on the other hand, for developing innovative nanoscale structures that can improve performance and/or enable new functionalities in future terascale ICs and Nanosystems.

- perform training activities, University curricula, Workshops to develop high competence levels in Europe.
- participate in roadmap definition.
- play an important role in European structuring and programs, and strengthen the overall efficiency of the European research in Nanoelectronics.

The Sinano Institute has launched in 2008 and 2010 two FP7 Networks of Excellence which are described below.

3. NANOSIL European Network of Excellence

The FP7 Nanosil Network of Excellence (Grant agreement n°216171), entitled “Silicon-based nanostructures and nanodevices for long-term nanoelectronics applications” [5] has been launched in January 2008 for three years.

It gathers 28 Partners from 11 European countries. The main objectives of this NoE are to push the limits of Si integration down to nanometric dimension. The Nanosil partners are thus working on n+4 technology node and beyond for:

- studying and validating new concepts, novel materials and technologies, innovative device architectures using joint flexible platforms.
- identifying the most promising topics for future information and communication technologies and updating roadmaps.
- overcoming the number of research challenges of ultimate CMOS and beyond-CMOS nanodevices in order to speed up technological innovation for the Nanoelectronics of the next 2-3 decades leading to the possible integration of Si-based innovative CMOS and emerging non-CMOS devices on one Si chip, which is a strategic issue for the next IC generations.

Other important objectives are the following:

* Perform training and dissemination activities, organize Conferences and Workshops in order to develop high competence levels in Europe;

* Strengthen interaction between the Academic/Scientific Community and the European Industry;

* Establish close links with other European (STREPs, etc.) and National projects in order to enhance the overall efficiency of the European research in Nanoelectronics;

* Act as a cluster of projects, existing at the beginning or new ones to be proposed, providing they are sufficiently forward-looking;

* Prepare the path for future industrial applications in the field of communications, computing, consumer electronics, health, environment.

integrated on CMOS platforms in order to overcome some possible CMOS limitations.

In figure 2 we present a possible architecture together with some new materials which could be needed at the end of the nanoelectronics roadmap.

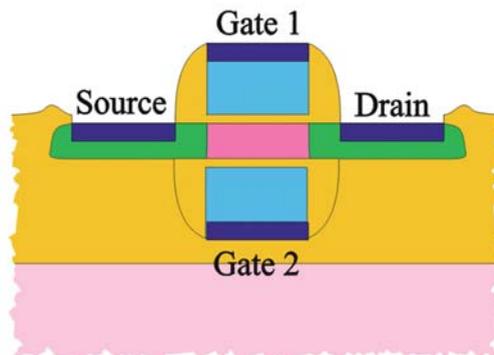


Fig. 2. Double-gate (or multi-gate) Silicon-On-Insulator MOS transistor with ultra-thin strained semiconductors channel, high k /metal gate stacks, silicide/Schottky source/drain.

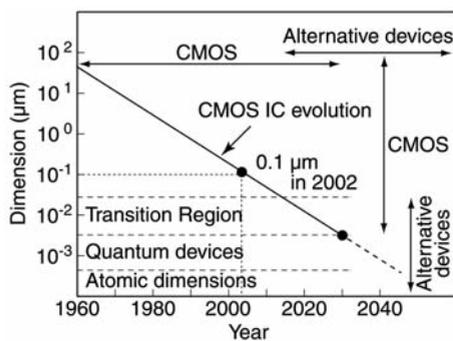


Fig 1. IC evolution in the past and next decades.

Figure 1 shows the IC evolution following Moore's law since the 60's and the perspectives for the next 30 years.

In the sub-20nm gate length range, alternative CMOS devices using new architectures and integrating innovative materials (ultra-thin Si, Ge or III-V films on insulator, double-gate, FinFET or Gate-All-Around structures, multi-channels MOSFETs, etc.) will be necessary in order to get the needed performance planned by the ITRS roadmap for high performance, low and ultra-low power applications. In the sub-10nm range, Beyond-CMOS nanodevices (Nanowires realized by top-down or bottom-up processes, Carbon electronics, Tunnel FETs, etc.) will certainly be used and

In the Nanosil NoE, we are working on the following research projects for the study and validation of innovative materials and nanodevice architectures for future CMOS (More Moore) and Beyond-CMOS components:

i) More Moore:

- Appraisal of new channel materials for end of CMOS era with improved transport parameters –carrier mobility and velocity, in order to boost the driving current I_{on} and the performance of CMOS ICs (sSOI, sSiGeOI and sGeOI, various channel orientations, etc.).

- Routes to realization of Schottky barrier contacts for end of CMOS era for reducing the source-drain access resistance and improving I_{on} (covering a wide spectrum of silicide materials and dopants for the realization of dopant-segregated metallic junction; integration of such junctions on strained and unstrained layers on insulator in n/pMOS).

- Identification and appraisal of gate stack materials/combinations for post 22nm/HfSiO era with

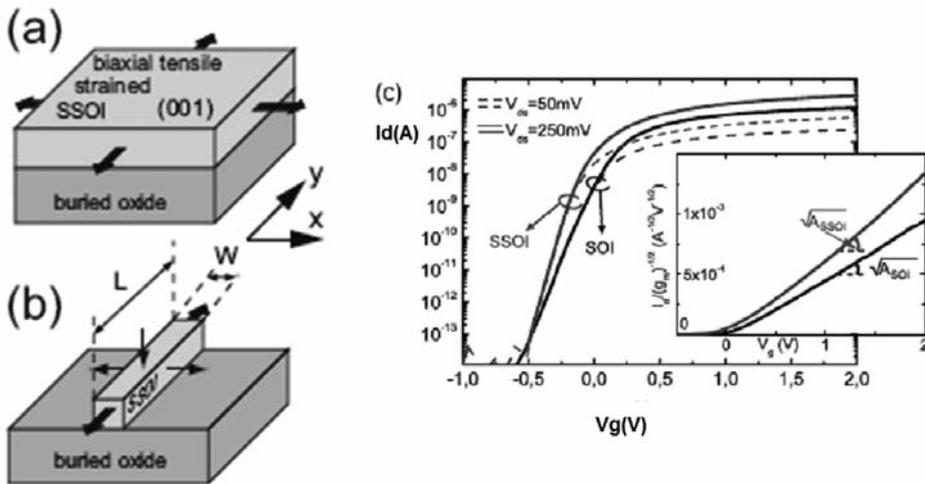


Fig. 3. 50nm sSOI with 1GPa biaxial tensile stress is used as starting material, (b) Uniaxial tensile strain obtained by lateral strain relaxation of patterned structures, (c) Transfer $I_d(V_g)$ characteristics of 2 Nanowire FET, one fabricated on SOI and one on uniaxial sSOI ($t_{ox}=5\text{nm}$, $L_g=3\mu\text{m}$). The inset shows the $I_d/g_m^{1/2}$ plot for the devices, its slope being related to carrier mobility.

chemical stability and low trap density in order to limit the tunnel leakage current I_{off} through the gate for end of CMOS era (with a product “permittivity. energy band offset” $\Rightarrow k \cdot \Delta E > 70$).

ii) Beyond CMOS:

- Evaluation of the prospects of 1D nanowires for the post CMOS era (with strain, low Schottky barrier contacts, high k /metal gate stacks, parallel nanowires, junctionless nanowires, etc.).

- Investigation of the prospects for carbon structures - especially graphene, and their technological potential.

- Assessment of the performance of new nanoelectronic switches: Impact ionisation (IMOS), tunnelling FET, NEM-FET, ferroelectric gate in order to determine if they can form the basis of new MOS device functionality with very low subthreshold swing, extremely low V_{dd} operation, acceptable I_{on}/I_{off} ratio with small off-currents and ultimately small standby power.

- Investigation of routes for producing high densities ($>10^{12}\text{cm}^{-2}$) of nanodevices (nanowires, nanodots) by templated self-assembly, and assessment of their technological potential and CMOS compatibility.

Other important research activities in the NoE are dealing with the development of new modelling approaches and characterization techniques:

* Development and comparison of semi-classical (Deterministic and Monte Carlo techniques) and full-quantum transport treatment (NEGF, Wigner-Boltzmann approach).

* Validation of new physically based and compact models for thin-body, multi-gate MOSFETs, Nanowires, etc.

* Understanding of mobility and interface effects, driving and off-state currents, variability in nanoMOSFETs and innovative device architectures by combining modelling and characterization efforts.

Finally, the support and development of the flexible research infrastructures (Joint Processing Platform, Joint Characterization and Modelling Platform) also constitutes an important goal of the joint activities.

Some highlights of the recent results obtained in the framework of Nanosil are shown below.

Fig. 3 exemplifies the possible increase of the drain current in the case of uniaxially strained nanowire

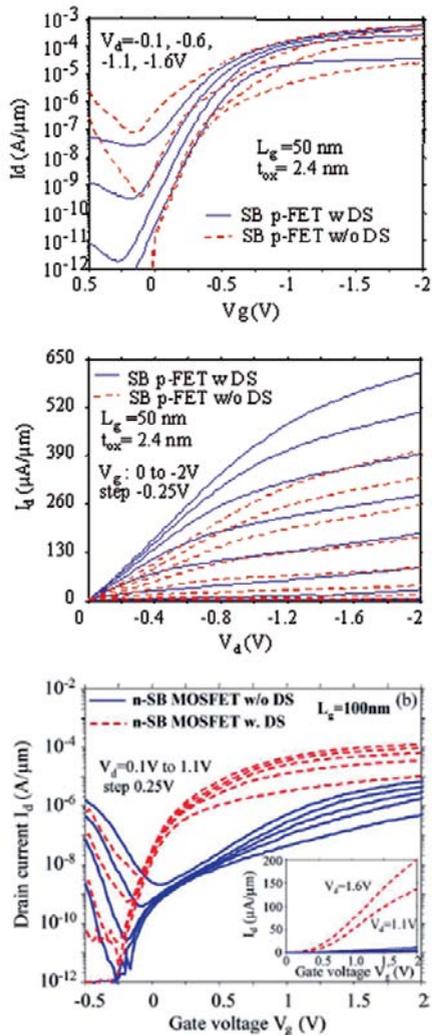


Fig. 4. $I_d(V_g)$ and $I_d(V_d)$ characteristics for Schottky barrier source-drain N- and P-channel MOSFETs with (DS) and without (w/o DS) dopant segregation (DS P-channel: PtSi, BF2; DS N-channel: YbSi, As).

devices, an enhancement of a factor of 2.5 of I_d due to the increase in electron mobility is obtained compared with unstrained nanowires (cross-section of NW $40 \times 40 \text{ nm}^2$) [6].

In Figure 4 are plotted the transfer and output characteristics of Schottky source-drain devices for N- and P-channel MOSFETs. In both cases, the use of

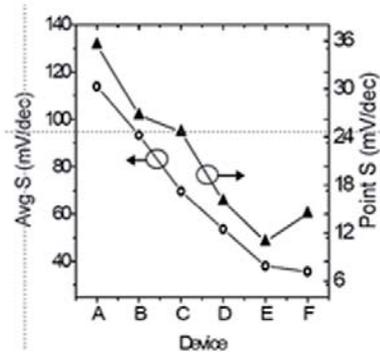
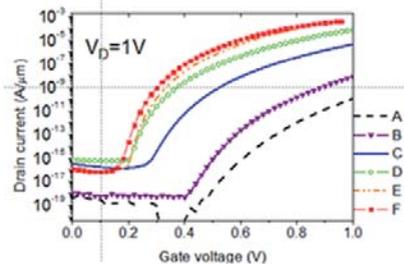
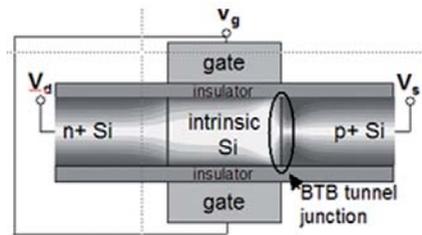


Fig. 5. Numerical simulation of Tunnel FETs realized with various architectures: A) Single gate SOI, $L_g=100 \text{ nm}$, 3 nm SiO_2 , B) with additional stress of 4 GPa at source junction, C) with high k gate dielectrics, D) with a double gate structure, E) oxide aligned to intrinsic region, F) for $L_g=30 \text{ nm}$. $I_d(V_g)$, average subthreshold slope and minimum point slope are shown.

dopant segregation (DS) at the channel/source-drain interface induces a substantial increase of the driving current [7,8].

Figure 5 shows the performance of Tunnel FET devices with various architectures. These transistors are very interesting for reducing the off-state current for very low power applications. One of the major challenge is

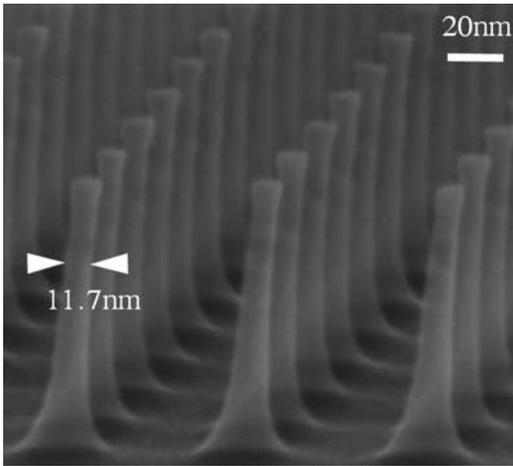


Fig. 6. Fabrication of ultra-dense Si Nanowire Networks by top-down approach for vertical device with massively parallel NWs (10^{15} nm diameter).

the possibility to obtain high drain current. The substantial improvement of the electrical properties of TFETs is demonstrated below using short channel double-gate SOI structures with strained at the source junction and high-k gate dielectrics [9, 10].

In order to get a high driving current, a 3D integration of Nanowires will be needed. This parallel integration is exemplified in Fig. 6. Vertical 3D nanowire structures with very thin wire diameter (in the 10 nm range) and a very high density ($n=4 \times 10^{10} \text{ cm}^{-2}$) is demonstrated [11]. Possible applications of these 3D NW are in the field of ultimate integration of nanoMOSFETs, photovoltaics (improvement of light absorption), nanosensors or RF devices.

The development of novel nanofunctionalities is the purpose of the new FP7 Nanofunction NoE (2010-2013).

4. Nanofunction European Network of Excellence

The FP7 Nanofunction Network of Excellence (Grant agreement n° 257375), entitled “Beyond CMOS Nanodevices for Adding Functionalities to CMOS” [12] has been launched in September 2010 for three years. It gathers 15 Partners from 10 European countries.

In addition to the integration and spreading of excellence

activities, four main scientific and technological objectives have been defined in the Nanofunction NoE:

i) Nanosensing with Si based nanowires:

- Exploring the use of Si-based nanowires for various nanosensors with improved performance (sensitivity, resolution, selectivity and response time).
- Nanowire and nanowire-FET fabrication.
- Multifunctional detection using nanowires.
- Demonstration of sensor arrays with Si based nanowires as sensing element.
- Convergence of nanowires with microelectronics substrate.

ii) Exploration of new materials, devices and technologies for Energy Harvesting:

- New materials and devices for mechanical energy harvesting.
- New materials and devices for thermoelectric energy harvesting.
- New materials and device architecture for nanostructured solar cells Storage (micro/nano-batteries), power conversion and management in energy harvesting systems.

iii) Nanocoolers:

- Development of Si-based very low Temperature coolers in order to obtain a local cooling of some devices or just the electrons in the devices using Si-based processing.
- Investigation of phonon transport at low temperature and in reduced dimensionality.
- Study of alternative nanostructures for thermal isolation (porous Si, nanowires, etc.).
- Integration of cooled detectors and read-out electronics.

iv) Exploration of new materials, devices and technologies for RF applications:

- Exploration of the potential of nanowires and other nanostructured materials (porous Si) as:
 - * Substrate materials for reducing RF losses for on-chip CMOS RF passives.
 - * Materials for RF interconnects and nano-antennas.



In Figure 7 are plotted an example the use of Nanowires for thermoelectric applications. The thermal conductivity of Si Nanowires is shown as a function of diameter and incorporating nanoscale roughness. A very small thermal conductivity is demonstrated emphasizing the extremely small phonon mean free path [13].

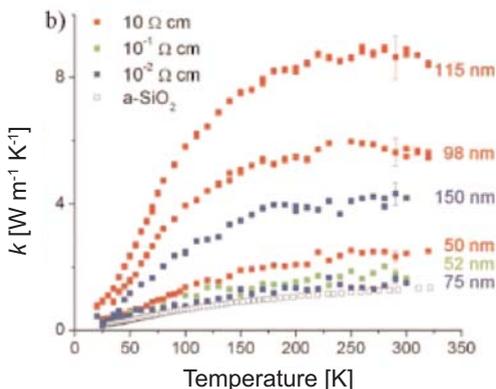


Fig. 7. Thermal conductivity of Si NW vs Diameter incorporating nanoscale roughness showing very low thermal conductivity and extremely short phonon mean free path [13].

Conclusions:

A summary of the Nanoelectronics European Research Roadmap has been presented with the main European Programmes supporting the short, medium and long-term research activities. The main challenges we are facing in the field of Nanoelectronic technology have been summarized in the More Moore, advanced More than Moore and Beyond-CMOS domains. The main objectives and some highlights of the Sinano Institute, an European association created for the coordination of the efforts of the Academic Community in the field of Nanoelectronics, and of the Nanosil and Nanofunction Networks of Excellence, devoted to the convergence of More Moore and Beyond-CMOS on one hand and of More than Moore and Beyond-CMOS research activities on the other hand, have been outlined.

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Report nanoICT Graphene and Nanotubes Session - TNT2010



Two sessions “Nanotubes & Graphene” have been sponsored by the nanoICT Coordinated Action in collaboration with GDRI (France). These sessions have presented recent advances on the electronic and transport properties of carbon nanotubes and graphene-based materials, as well as related devices and perspectives. The sessions have been chaired by Prof. S. Roche from the Catalan Institut of Nanotechnology and CIN2. One important fact has been the participation of **Prof. Andre Geim** from the University of Manchester in UK, who was awarded the 2010 Physics Nobel prize for the discovery of Graphene just a few weeks after his participation to TNT. Prof. Geim has given an outstanding lecture about “*Graphene: Status and Prospects*” in which he has first introduced the field to the large audience of TNT, and he then addressed the most challenging current research directions, including the growth strategies, the use of their exceptional physical properties such as giant mobilities or optical properties. New features of graphene such as the creation of considerable pseudo-magnetic fields as large as 300 Tesla have been shown to be triggered by strain fields. Prof. Geim has also explained the great excitement concerning the merging between chemistry and nanoelectronics, as well as perspectives for high-frequency devices or ultrafast photodetectors.

In addition to this spectacular lecture, the scientific program of these two sessions have been of high level, including presentations from Germany, France, Japan, Korea, with speakers ranging from Universities to industries such as THALES. Two talks have focused on the growth processes of carbon nanotubes and graphene, including the development of new ceramic catalysts (**Mark H. Rummeli** from IFW Dresden, Germany) or the use of advanced HRTEM to understand (and further control) the crystal growth on the nano-scale: in-situ

probes for graphene, nanotube and -wire CVD (**Stephan Hofmann** from University of Cambridge, UK). Prof. Mauricio Terrones (Carlos III Univ of Madrid, Spain & Exotic Nanocarbon Research Center, Shinshu Univ, Japan) has then presented the challenges and opportunities in using defect engineering to produce new types of nanotubes and graphene based applications and devices, whereas **Adelina Ilie** (University of Bath, United Kingdom) has explained the mechanism of symmetry breaking and on-tube modulated surface potentials in hybrids of Single-Walled Carbon Nanotubes with encapsulated inorganic nanostructures.

The potential of graphene for thermoelectrics applications has been then discussed theoretically by **Haldun Sevincli** (Dresden University of Technology, Germany), who has also proposed the use of defect engineering to enhance the thermoelectric figure of merit in disordered carbon systems, by strongly suppressing thermal conduction, while maintaining good electrical properties. Additionally, **Koji Ishibashi** (RIKEN, Japan) has proposed several options to design Carbon nanotubes and graphenes as building blocks of nanodevices, based on electron-electron interactions.

New applications have been reviewed by **Marion Cranney** (Institut de Sciences des Materiaux de Mulhouse, France) on the design of superlattices of resonators on monolayer graphene created by intercalated gold nanoclusters, or concerning optical properties by **Matthew Cole** (University of Cambridge, UK) on horizontally aligned carbon nanotube networks. The route toward the production of highly conductive, flexible & controllably transparent electrodes, field emitters and infra-red sensors for the design of Fast and wavelength selective photoresponse from QD/CNT hybrid has been presented by **Chang-Soo Han** (Korea Institute of Machinery & Materials/Nano-Mechanics, Korea).

Finally the use of graphene in near future applications has been discussed by **Jong-Hyun Ahn** (Sungkyunkwan University, Korea) who has presented his work on high-performance, flexible graphene field effect transistors on Plastic substrates. This work supported by the Korean industry SAMSUNG

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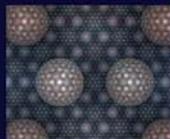
clearly evidences the great potential of graphene for replacing ITO in all transparent electrodes applications.

One also underlines the very interesting talk by **Paolo Bondavalli** (Thales Research and Technology, France) who has discussed the mass production of Gas Sensor based on carbon nanotubes based-FETs fabricated using an original dynamic air-brush technique for SWCNTs deposition. Again, industries (here THALES) shows interest in this new material (graphene) giving its wide spectrum of potential applications that range from high-frequency devices, to nanosensors or spintronics devices.

During these sessions about 100 persons were attending the talks, and the sessions were receiving large interest with questions and debate.

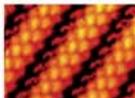
One concludes by pinpointing the importance of nanoICT support, which through its contribution to the working groups on carbon nanotubes and graphene, allows to enhance the visibility of European research excellence. The participation of the 2010 Physics Nobel prize (Prof. A.K. Geim from Manchester) was also a genuine success of this session. It profiles the high level of TNT2010 sessions on carbon nanotubes and graphene, and the relevance of nanoICT in supporting these networking as well as outreach and dissemination activities.


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RESEARCH PROGRAMMES

Molecular Nanoscience

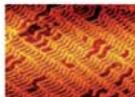


Organic nanotubes



Self-organized donor and acceptor molecules

Scanning probe microscopies and surfaces



Array of PCBM molecules on Au(111)



Monolayer of graphene / Ru(0001) periodically rippled

Nanomagnetism



Magnetic dots



Magnetic nanoparticles inside lamellar cells

Nanobiosystems: biomachines and manipulation of macromolecules



AFM image of a two dimensional crystal of the bacteriophage F29 connector

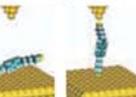


Diagram of the study of a molecular motor operating on DNA

Nanoelectronics and superconductivity

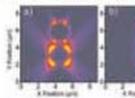


Single molecule conductivity

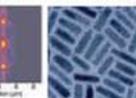


C60 nanoparticles

Semiconducting nanostructures and nanophotonics



Resonance for a photonic molecule



C60 nanoparticles

Nanofabrication and advanced instrumentation



Molecular smile assembled with the STM tip



STM microscope

IMDEA-Nanociencia is a private Foundation created by joint initiative of the Comunidad de Madrid and the Ministry of Education of the Government of Spain in February 2007 to manage a new research Institute in Nanoscience and Nanotechnology (IMDEA-Nanociencia). The Institute is located at the campus of the Universidad Autónoma de Madrid in Cantoblanco.

The Institute aims at performing research of excellence in selected areas and offers attractive opportunities to develop a career in science at various levels from Ph.D. students to senior staff positions.

The Madrid Institute for advanced studies in Nanoscience also develops an important program of technology transfer and creation of spin-offs companies.

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[Nanociencia y Nanotecnología: lo pequeño es diferente
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Phonons and Fluctuations Meeting, Paris, 8-9 November, 2010

Organised by S. Volz (CNRS), J. Ahopelto (VTT) and C. Sotomayor Torres (ICN).

Background

The field of nanophononics and thermal management is becoming very active and this has been recognised also by the European Commission which has allocated resources to advance the research in this field in Europe. There are already projects that tackle these issues, for example NANOPACK, TAIPOX, NANOPOWER, GREEN-Si and SINAPS, among others. In the large FET-Flagship initiative several of the proposed projects concentrate on energy related issues. In the US the Semiconductor Research Council has included phonon engineering and a related topic of out of equilibrium operation among the top five research needs in the near future for extended CMOS and Beyond CMOS devices.

In France there is an active network on nanophononics led by Prof. Volz, consisting of several laboratories. The Coordination Action nanolCT established a Working Group Nanophononics, led by Prof. Ahopelto, in the spring 2010 in order to bring together the groups aiming to understand and control the behaviour of phonons in solids, at interfaces, in composites and at molecular level. The Paris meeting was a joint effort between these two networks targeting to create a collaboration forum for teams active in the field.

Program and Highlights

The program (attached in the end) included two parts, first part consisted of greetings from the Commission, short reports on two important recent meetings and an update regarding the Flagship initiative status, and the second part concentrated on scientific issues related to nanophononics. Ralph Stübner from the European Commission gave a talk on possibilities for future projects in the field of nanoelectronics, related energy issues and nanophononics in Future Emerging Technologies part of the FP7 ICT priority. The focus in the international meetings reported (EU-NSF Workshop on Nanotechnology and International Workshop on the Future of Information Processing Technologies) was on energy issues in CMOS based nanoelectronics and Beyond CMOS approaches. For example, in the next edition of the ITRS Roadmap there will be a Chapter on benchmarking of a variety of non-CMOS devices based on power-delay properties.

The very interesting second part of the meeting covered topics ranging from statistical physics to phonon transport to energy harvesting. Massimiliano Esposito (University of Brussels) explained the very basics of stochastic thermodynamics in small devices and the efficiency to extract power from fluctuating systems. Adrian Bachtold (ICN) talked about nanomechanical oscillations and Bernard Perrin (Institut des NanoSciences de Paris) described the experimental work on ultrafast energy relaxation in solids by pump and probe techniques.

Phonon and heat transport in nanostructures and across interfaces was discussed in several talks. Olivier Bourgeois (Néel Institute, CNRS) talked about thermal conductance of silicon nanowires at low temperatures. He showed that the thermal conductance can be drastically decreased by adding meanders into the wires to hinder the transmission of ballistic phonons. Sebastian Volz (UPR, CNRS) discussed theoretically thermal resistances and phonon relaxation times, and showed theoretical and experimental results on near-field radiative heat transfer at nanoscale. He also showed that fluctuations can be used to move particles in microfluidic systems. Philippe Ben-Abdallah (University of Nantes) gave a talk on near-field coupling by surface polaritons and the potential to enhance tunnelling by applying metamaterials. Javier Goicochea (IBM) justified in his talk the research on thermal management by addressing the heat dissipation in transistors, microprocessors and by data centers. He has modelled heat conduction and dissipation using molecular dynamics calculations at solid-solid, solid-fluid and fluid-nanoparticle interfaces. The message was that thermal design is becoming very important for architectures and devices. Wolfgang Rosenstiel from University of Tübingen tackled the consequences of scaling both at transistor and at architecture level, showing that power management is one of the most important problems to be solved for ICs.

Energy harvesting was addressed by Luca Gammaitoni (University of Perugia), who talked about noise driven ICT and stressed the importance of understanding non-equilibrium phenomena and by Natalio Mingo (LITEN, CEA), who talked about nanophononics for thermoelectricity. Here nanoparticle embedded materials have a great promise for high ZT because of highly reduced thermal conductivity.

In addition to the talks, a poster session with about 20 posters was included in the meeting. A get

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together event was arranged in the Monday evening, 8th of November.

Participants

More than 50 scientists attended the meeting with the majority coming from academia and research institutes. The number of attendees is very high taking into account the a little short notice for the meeting. This again reflects the interest of and importance for the research community in Europe.

Follow-up

The target of this meeting was to gather the groups and individuals working in the field of nanophononics, fluctuations and thermal management at nanoscale together and initiate the formation of a coherent research community active on nanophononics and related issues. The activity in this field is currently increasing in Europe. The biennial school "Son et Lumière" was arranged for the third time in Cargèse this year, a NiPS summer school on "Energy Harvesting at micro and nanoscale" was arranged in August in Umbria, the ICREA Workshop on Phonon Engineering was held in May and NiPS Workshop on Noise in dynamical systems at the micro and nanoscale was held in August. The activity in the nanophononics research is increasing fast and it would be beneficial to establish a broader forum for discussions and to avoid fragmentation. One possibility worth to consider is to establish a Coordination Action on nanophononics as follow-up to the WG Nanophononics. This would support the recently established Coordination Action ZEROPOWER on energy harvesting, led by Prof. Gammaitoni, by addressing the fundamental issues more widely. One of the near future

tasks is to compile a Position Paper on Nanophononics. The plans also include arrangement of second Phonons and Fluctuations meeting to be held in 2011, either late in the spring or early in the fall to further amalgamate the research on nanophononics in Europe.

Phonons and Fluctuations meeting 9th November 2010

Venue:

Langevin Amphitheater
Ecole Supérieure de Physique et de Chimie
Industrielle de Paris - 15 rue Vauquelin
75005 Paris - FRANCE

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AIM: To bring the phonon and fluctuations communities together seeking convergence of partners of different projects, networks, conference series, such as NANOICT, the CNRS-network, NANO-TEC, NANOFUNCTION, NANOPOWER, ZEROPOWER, the school series Son et Lumiere, etc, in order to address topics of general concern, discuss the research trends and applications of, for example, thermal management on the nano scale, low energy ICT, nanophononics, the role of noise in ICT research and emerging design issues in future ICT. The workshop will have a combined character of touching base on the state of the art and vision in these fields

Organisers:

Sebastian Volz, Jouni Ahopelto and Cliva M. Sotomayor Torres

Email: volz@em2c.ecp.fr

Support:



NANOSCALE/THERMAL



NANOPOWER



ZEROPOWER

Monday 8th November 2010

20.00 Get together and Joint dinner Details & place to be announced

Tuesday 9th November 2010

09.00 Welcome and Introduction Jouni Ahopelto (VTT), Sebastian Volz (ECP) and Clivia Sotomayor Torres (Catalan Insti. of Nanotech.)

09.05 Research developments and trends:

- Future Emerging Technologies in Work Program 2011-2012 Proactive Initiatives
 - Report on the EU-NSF workshop on Nanotechnology: a 10-year perspective, section on Nanoelectronics
 - Emerging design Issues
 - The nanoICT Nanophononics Working group/ Report on the Int Workshop on the Future of Information Processing Technologies (focus: Green electronics)
 - Update on the Flagship Beyond the ICT Limits
- Ralf Stuebner (European Commission)
 - Clivia Sotomayor Torres (Catalan Insti. of Nanotech.)
 - Wolfgang Rosenstiel (U Tuebingen)
 - Jouni Ahopelto (VTT)
 - Clivia Sotomayor Torres (Catalan Insti. of Nanotech.)

09.30 Noise driven ICT Luca Gammaitoni (NIPS Laboratory, U Perugia)

09.50 Nanomechanical oscillations Adrian Bachtold (ICN)

10.10 Trends in statistical physics on fluctuations research Massimiliano Esposito

10.30 Coffee break & poster viewing

11.10 Ultrafast energy and momentum transfer Bernard Perrin (U P et M Curie)

11.30 Towards an underst. of thermal energy across interfaces Javier Goicochea (IBM Zurich)

11.50 Design for future low power and high reliability circuits Wolfgang Rosenstiel (U Tuebingen)

12.10 Discussion

12.30 Sandwich Lunch

13.30 Near field radiation based on phonon polaritons Philippe Benabdallah (U Nantes)

13.50 Nanophononics for thermoelectricity Natalio Mingo (CEA)

14.10 Low temperatures phonon transport in nanowires Olivier Bourgeois (Néel Institute)

14.30 Fluctuations and thermal interface resistance Adrian Bachtold (ICN)

14.50 Discussion

15.20 Poster viewing and discussions

16.00 End

INL - CREATING VALUE AT NANOSCALE



Over the next months, the International Iberian Nanotechnology Laboratory (INL) will start installing various scientific equipment which shall enhance and expedite the studies of the scientific community working in the region

INL Building in Braga, Portugal

Over the next months, the International Iberian Nanotechnology Laboratory (INL) will start installing central scientific equipment reinforcing the infrastructure that will become available for the scientific community working in the region.

The new research facility, located in Braga (North of Portugal) occupies more than 47,000 square meters, with 20,000 of them exclusively dedicated to science. The Laboratory launched in 2005 by Spain and Portugal is set to be a global centre of excellence in applied nanotechnology research attracting the world's best scientists and engineers.

The first equipment to be installed comprises cleanroom processing equipment (E-beam and laser lithography tools, a mask aligner, resist and developer tracks, three multitarget physical vapour deposition tools, a chemical vapour deposition system, reactive ion etch and ion mill tools). These tools are single wafer tools with capability of handling up to 200mm diameter wafers. In a second phase, planned for the end of 2010 and beginning 2011, characterization equipment including a CD SEM, a ultra high resolution SEM, a dual FIB, a 200kV analytical TEM, a X-ray Photoelectron Spectroscopy (XPS) system, two Scanning Probe Microscopy systems, and two X-ray systems for thin film and nanoparticle analysis will be installed. A set of NMR tools for solids (600MHz) and

liquids (450 kHz) is under consideration. In a third phase, a set of corrected atomic microscopes is being considered. The atomic imaging tools will be installed in the high accuracy labs at the basement of INL. This set of central labs is completed by a central biochemistry laboratory, a packaging laboratory, a magnetometry laboratory, and an electrical characterization laboratory.

The INL is an international institution created to foster interdisciplinary research in nanotechnology and nanoscience. As a private, non profit organisation, the Laboratory will provide a state-of-the-art research environment and favour an interdisciplinary effort in addressing major challenges in nanomedicine, nanotechnology applied to environmental & food control, nanoelectronics and, nanomachines and molecular manipulation at nanoscale.

Last February INL and the Comissão de Coordenação e Desenvolvimento Regional Norte signed the contract that allows INL to benefit from an additional 17M€ assistance, under the Portuguese North Regional Operational Program "ON.2 - O Novo Norte", also financed by the European Union through the European Regional Development Fund (ERDF).

INL aims to become a vital part of Europe's scientific area setting an example in new types of research collaboration between EU Member States. Its facilities will be open to

future members from European and non-European states, and foster international co-operation with other regions like North America, Latin America, Asia.

The construction of the INL is also co-financed by 30M€ from the ERDF (European Regional Development Fund), within the Cross-border Cooperation Programme Spain Portugal. The INL project falls under Priority 1 of the Programme Cooperation and joint management for the improvement of competitiveness and the promotion of employment.

The INL challenge is not only to assure research excellence, but also to shift its output into economic and social development. INL aims to be at the cutting edge of Public-Private Partnership (PPP's) models and Technology Transfer activities facilitating and accelerating innovative technology transfer from basic research to industry, working closely with industrial partners in the INL research areas to develop new diagnostics, drugs, machines, devices and therapies.

After this project's completion, Portugal and Spain will benefit from a competitive technological infrastructure, increasing the international competitiveness of Iberian and regional businesses, universities and technological centers. The local environment for spin-offs and technological centres will be greatly improved.

International Summer School Son et Lumière: phononics and photonics at nanoscale. (31st august-11th september 2010, IESC Cargese, France)

<http://sonetlumiere2010.univ-lemans.fr/>

Organizing committee:

- Pascal Ruello, Professor Laboratoire de Physique de l'Etat Condensé UMR 6087 CNRS-Université du Maine, France.
- Adnen Mlayah, Professor Centre d'Elaboration des Matériaux et Etudes Structurales CEMES UMR CNRS- Université Paul Sabatier, Toulouse, France.
- Clivia M Sotomayor-Torres, Professor Catalan Institute of Nanotechnology and ICREA, Barcelone, Spain.
- Antony Kent, Professor School of Physics and Astronomy, University of Nottingham, United Kingdom.
- E. Ferré, Délégation Bretagne - Pays de la Loire CNRS, France.

Scientific committee:

- J. Dijkhuis, Pays-Bas
- B. Jusserand, France
- B. Perrin, France
- A. Ivanov, Scotland
- T. Dekorsy, Germany
- V. Gusev, France
- F. Vallée, France
- H. Maris, USA
- A. Fainstein, Argentina
- O. Wright, Japan

Summary of the topics and the evaluation of the school:

The Son et Lumière (SEL) School is a School of physics dealing with nanophononics and nanophotonics. Nanophononics and nanophotonics are promising fields which aims at understanding and controlling the properties of phonon, photon and their interactions in nanostructures. Since the spatial confinement deeply modifies the properties of electron, phonon and photon, new phonon-photon and phonon-phonon interactions schemes require to be clarified and elucidated. The coherent control and tailoring of high frequency phonon (GHz-THz) and photon spectrums should pave the way of innovative functionalities in the family of acousto-optic, opto-acoustic devices, acoustic nanocavities, phononic-photonic based acousto-optic modulators, etc.

This active field of research is currently accelerated thanks to new developments in experimental methods and advanced setup. The control of coherent phonon in nanostructured material is for example well achieved by the use of femtosecond laser sources. New insight in nanophononics is currently brought by the recent development of ultrafast X-ray pulse beamlines allowing time-resolved studies of phonons dynamics at the atomic scale. New powerful THz sources should provide in a near future new routes for coupling directly light with vibronic state of the matter. Nevertheless, improvements are still necessary to increase sensitivity of probing the phonon in matter and to enhance efficiency of photon-phonon, electron-phonon coupling efficiencies for realistic manipulation of phonon in nanostructures. All these exciting potentialities become possible because of the subnanometric precision of nanostructures fabrication achieved by the most advanced nanotechnologies. Desired superlattices, nanocavities or phononic-photonic crystals with well controlled elastic and refractive index can now be processed.

The **aim of this school** was to put together different scientific communities working on acoustic excitations in solids, mainly from the optical and the acoustical point of view, communities which usually attend separate conferences and often do not share a common language.

The 3rd edition of the International Summer School Son et Lumière : phononics and photonics at nanoscale has put **together 60 attendees** among them 16 international lecturers and 4 organizers. On the total, there were 25 french people and 35 foreign people. Among the other 40 attendees, 28 were PhD student. This large proportion of students attendance confirm once again the relevance of this international school among a very competitive research area.

According to the evaluation done after the school, more than 90% of the attendees are favourable for the future edition which will be held in 2012. The results of the evaluation indicate also that the high level and high quality of the lectures were greatly appreciated even if it has been noted that some of them were too technical. We will then pay more attention next time to plan more basic lectures as introduction in the first week of the school. It has been also noted that more time should be offered to student to present their research. During this school more than 30 posters were presented during two half days. This posters session time could then be extended again for the next edition of the SEL School.

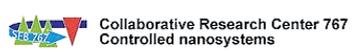


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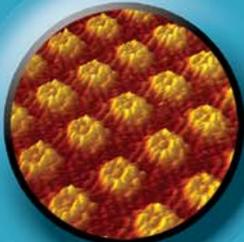
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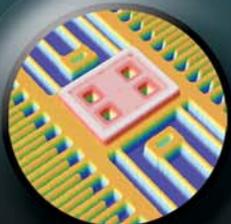
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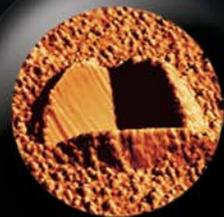
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