# CARBON NANOTUBES AS ELECTRON SOURCES

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Carbon nanotubes (CNTs) are a unique form of carbon filament/fiber in which the graphene walls roll up to form tubes. They can exhibit either metallic-like or semiconductor-like properties. With the graphene walls parallel to the filament axis, nanotubes (single wall metallic-type or multi-wall) exhibit high electrical conductivity at room temperature. This high electrical conductivity allied to their remarkable thermal stability has made CNTs one of the most intensely studied material systems for field emission ( F.E.) applications. F.E. is the emission of electrons from a solid under an intense electric field. The simplest way to create such a field is by field enhancement at the tip of a sharp object. Si or W tips were initially used, made by anisotropic etching or deposition. However a key advantage over these is that CNTs have a low turn on field which is associated with their high aspect ratio 'whisker-like' shape which provides the optimum geometrical field enhancement.. CNTs have the added advantage over Si or W tips in that their strong, covalent bonding means they are physically inert to sputtering, chemically inert to poisoning, and can carry a huge current density of $10^9$ A/cm$^2$ before electromigration. In addition, when driven to high currents, their resistivity decreases, so that they do not tend to suffer from electric-field-induced sharpening, which causes instabilities in metal tip field emitters. CNTs also have better FE performance than other forms of carbon such as diamond and diamond-like carbon.
For some FE applications today, nanotubes are first mass produced by arc-discharge as this is presently the most cost-effective production technique. The arc discharge nanotubes are purified and mixed with an epoxy/binder, and then screen-printed or applied at emitter locations. For other field emission applications however it is necessary to have either gated structures where the emission is controlled via the gate or aligned arrays of CNTs where the tubes have been spaced optimally to reduce field screening effects in order to increase the emitted current density.

In this paper we will describe the growth of multiwall CNTs and their application in a range of field emission based systems. These will include the use of FE from CNTs in electron guns for next generation scanning electron microscopes (SEMs) and transmission electron microscopes (TEMs). In a low voltage SEM, the largest market, the lateral resolution is limited by chromatic aberration, and an electron source with a small energy spread is needed. Present day microscopes use Schottky emitters of doped Si or metal FE tips. For this application a single MWNT FE source is needed and is found to have a factor of 30 higher brightness than existing electron sources and a small energy width of 0.25 eV. MWNTs are preferred to SWNTs because of their greater mechanical stiffness. The significant performance advantage of CNT electron sources should see them implemented in this high-value niche where cost is not critical.

The second use of CNTs, which will be described here, is as FE cathodes in high power microwave amplifiers. In this instance arrays of MWCNTs are required in order to produce the high current densities necessary. They have to be aligned and spaced approximately twice their height apart in order to prevent field screening from adjacent CNTs. The major advantage CNTs have in this instance is that they can be directly modulated at the required GHz frequencies. This is in marked contrast to conventional thermionic emitters where a re-entrant cavity is need to modulate the d.c. beam produced by the emitters. The use of CNTs here significantly reduces the amplifier size leading to significant cost savings. For CNTs for use as the electron emitters for miniature x-ray sources similar aligned arrays are required. Here an electron beam from the CNT cathode is accelerated to strike a metal target to create X-rays. A small, high-brightness device with a pulsed electron beam allows real-time imaging.

Their application as the electron emitter in Field Emission Displays will also be described. This has been investigated by several groups and most recently Samsung have announced a large area 38” pre-prototype FED based television based on the screen-printing of the emitter material. For such large areas (and also for backlight units) thick film screen printing methods can be used to produce the emitters but for smaller higher resolution displays CVD processes are required to produce well aligned arrays of CNTs. In such a high resolution FED the emitted current from a sub-pixel has to be highly directed so as to minimise inter pixel ‘cross talk’ and maximize colour definition. Gated arrays of CNTs are required for this application and must be produced on standard glass back-planes via PECVD at ~ 500C. Applications of high resolution displays include avionic displays, back-seat passenger videos and in-car displays.

Finally the use of CNTs in parallel e-beam lithography will also be briefly discussed where an array of parallel electron beamsis utilized instead of the normal single beam. For such micro-electron sources a “triode” type arrangement with an additional integrated extraction gate electrode is needed. By integrating the gate, the gate-to-emitter distance can be substantially reduced and hence the voltage required for controlling electron emission is also reduced to few tens of volts. This reduces the power, complexity, and cost of the gate drive/modulation circuitry.

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