ELECTRON SOURCES BASED ON CARBON NANOTUBES – APPLICATION TO MICROWAVE AMPLIFIERS

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Vertically aligned multiwall carbon nanotubes/nanofibers (CNs) are particularly studied as field emission electron sources for microwave devices because they are able to emit large electron currents. Whisker like in shape and high in aspect ratio, CNs present the best shape for field emission. Due to their strong covalent bonding, they are much less sensitive to electromigration than metallic tips and are able to carry high current densities. They are also unique in that they can field emit very stable currents (I_{FE}) even if the I_{FE} induced self heating increases their temperature up to 2000 K [1].

Whether an individual CN can be operated at currents of 10 µA [2], most of field emission applications require significantly higher currents (10-100 mA) so that cathodes including a large number of CNs are required. According to Gröening [3], the ideal cathode is an ordered array of individual, vertically aligned emitters spaced by approximately twice their height in order to minimise field screening. To optimise CN cold cathode performances, we have grown, by dc plasma enhanced chemical vapour deposition at 700 °C, arrays of vertically aligned CNs with a 5 µm height, a 50 nm diameter and a 10 µm spacing (CN density of 10^6 cm^{-2}) [Figure 1].

Field emission measurements on individual CNs have been performed with a high resolution scanning anode field emission microscope [Figure 2]. I-V characteristic of as-grown CNs [Figure 3] shows a saturation for currents above 1 µA and the maximum emission current is in the range 1-10 µA. This saturation is attributed to a voltage drop that may appear along the CN or at the CN/substrate interface. After growth, we have performed a rapid thermal anneal at 850°C to improve both their crystalline quality and their electrical contact to the substrate. By this way, we have been able to suppress any saturation [Figure 4] and to extract 100 µA per single emitter [4]. By applying this post-treatment to a 0.5 x 0.5 mm^2 array of CNs, we have been able to extract 3 mA corresponding to a high current density of 1.2 $A.cm^{-2}$.

To improve emission current density, we have studied the effect of CN density on maximum emission current. For this purpose, we have grown 0.5 x 0.5 mm^2 arrays of vertically aligned CNs with a 1.5 µm height, a 15 nm diameter and a 3 µm spacing. The CN density is 10^7 cm^{-2}. CNs exhibit almost the same aspect ratio but the CN density is increased by a factor of 10. From such an array, we have measured an emission current of 10 mA corresponding to a current density of 4 $A.cm^{-2}$ [5].

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An array of uniform individual CNs spaced at twice their height apart to give maximum electrostatic efficiency, has delivered a peak current density of 12 A/cm^2 when operated at 1.5 GHz in a microwave diode [Figure 5] [6].

This new type of high frequency cold cathode could be a breakthrough in cathode technology for high frequency (above 30 GHz) microwave amplifiers. To anticipate their performances, we will present first results on carbon nanotube cathodes operated in a 32 GHz microwave triode [Figure 6].

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References:

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[3] O. Gröening, *et al*, J. Vac. Sci. Technol. B **18**, 665 (2000).
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[5] W. I. Milne, E. Minoux, et al., J. Vac. Sci. Technol. B **24**, 345 (2006)
[6] K. B. K. Teo, E. Minoux, *et al.*, Nature **437**, 968 (2005).

Figures:

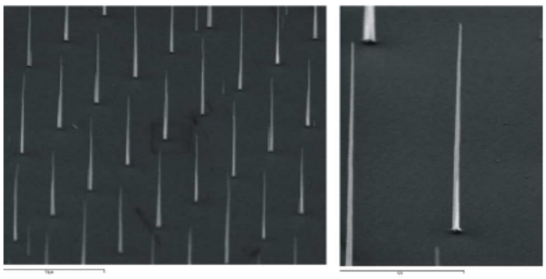

Figure 1: Highly ordered and uniform array of individual, vertically oriented CNs with a 5 µm height, a 50 nm diameter, and a 10 µm spacing (CN density of 10^6 cm^{-2}). Tilted view 45°.

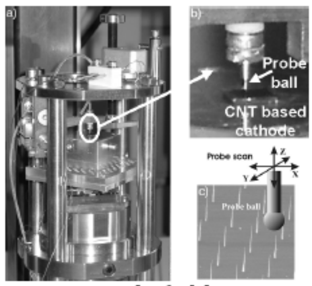

Figure 2: Scanning anode field emission microscope.
(a) Sample holder
(b) Pt/Ir anode tip
(c) Schematic of the SAFEM

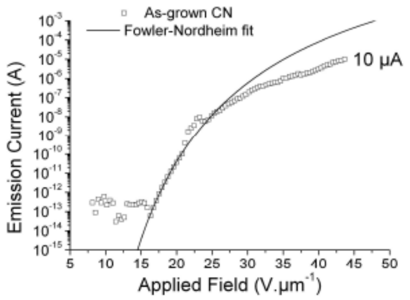

Figure 3: Individual measurements performed on a as-grown CN.

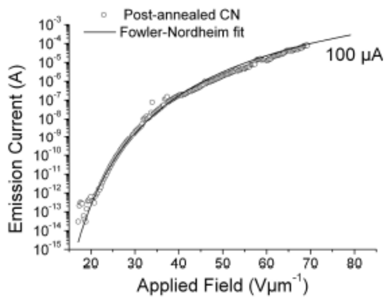

Figure 4: Individual measurements performed on a post-annealed CN, 100 µA max. per CN.

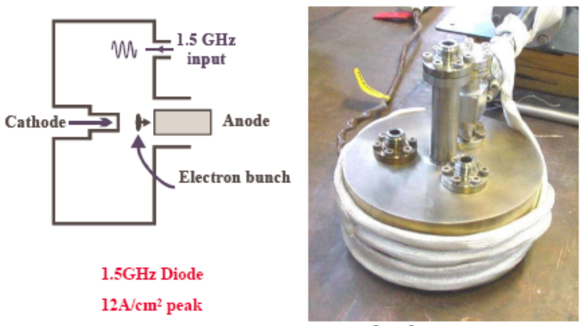

Figure 5: 1.5 GHz diode.

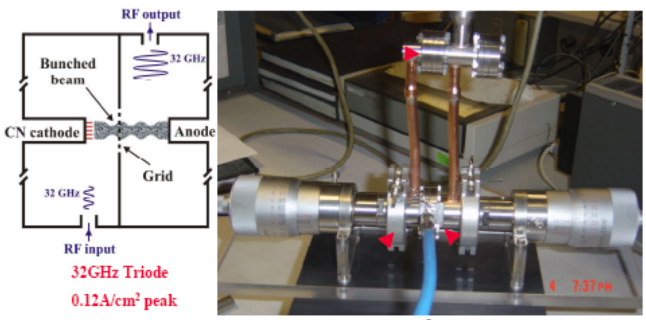

Figure 6: 32 GHz triode.