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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 (FE) applications. In this paper we will describe the growth of multiwall CNTs and their application in a range of field emission based systems including their use in SEM sources, emitters for use in microwave amplifiers and as emitters in field emission based displays (FEDs).

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1 Introduction

Field Emission (FE) 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 as shown in Fig. 1 below.

Si or W tips were initially used, made by anisotropic etching or deposition. However, a key advantage of CNTs have over these is that they have a very low turn on field which is associated with their high aspect ratio 'whisker-like' shape which provides the optimum geometrical field enhancement [1]. 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 [2], 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 [3]. 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 [4] or aligned arrays of CNTs [5] where the tubes have been spaced optimally to reduce field screening effects in order to increase the emitted current density.

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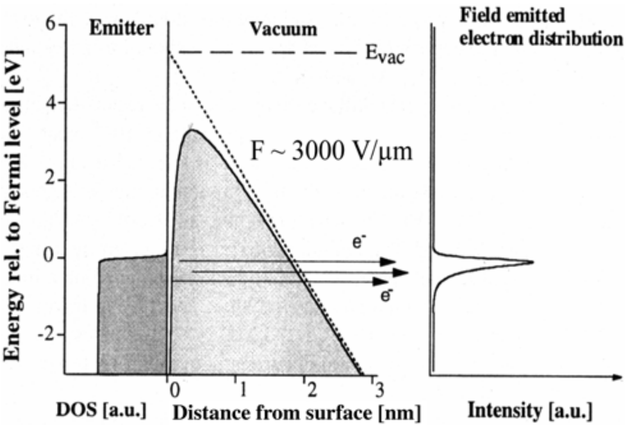

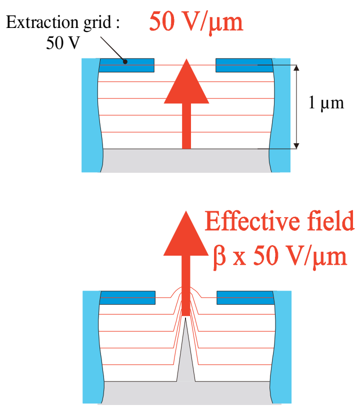

Fig. 1 a) Process of field emission, b) (online colour at: www.pss-a.com) field enhancement.

This paper 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) [6]. The second use of CNTs, which will be described here, is as FE cathodes for high power microwave amplifiers [7]. Their application as the electron emitter in Field Emission Displays will also be described [8]. Finally the use of CNTs in parallel e-beam lithography will also be briefly discussed where an array of parallel electron beams is utilized instead of the normal single beam [9].

2 Applications

2.1 SEM sources

In a low voltage SEM, the largest electron microscope 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 ZrO_2 coated tungsten which is operated at 1800 K, giving an energy width of 0.6–0.7 eV. For this application, a single MWNT FE source is needed and has been found to have a factor of 10 times higher brightness than existing electron sources and a small energy width of ~0.30 eV [6]. One of the major drawbacks to the use of CNTs in this particular application is their integration into present systems. Using plasma enhanced chemical vapour deposition (PECVD), it is possible to directly grow a single, vertically aligned, multiwall carbon nanotube onto a tungsten needle (see Fig. 2a). As

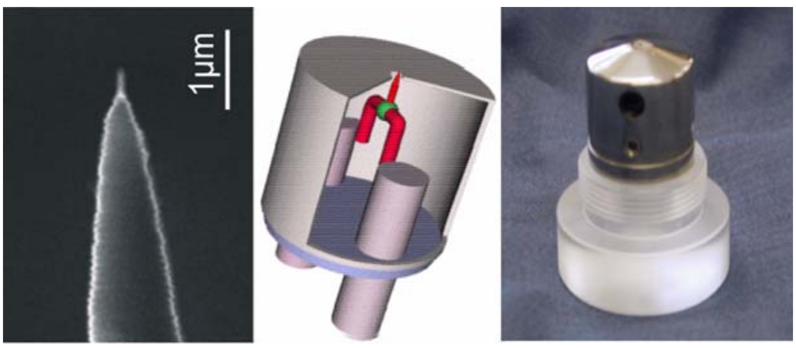

Fig. 2 (online colour at: www.pss-a.com) a) MWCNT on top of a tungsten needle, b) how the tungsten needle is integrated into the electron gun module, c) complete gun ensemble.

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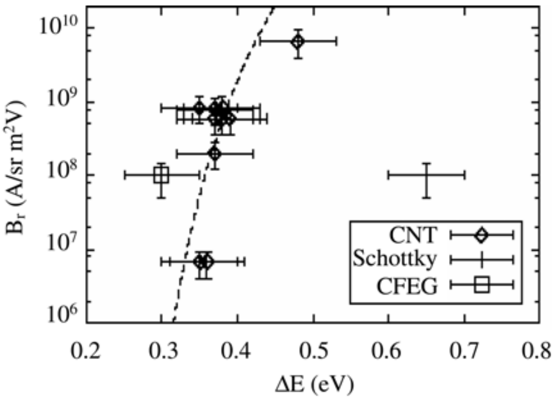

Fig. 3 Field emission brightness, B_r, as a function of the energy spectrum, ΔE, for several MWCNTs. Data for a Schottky emitter and a tungsten cold field emission gun (CFEG) are also included [6].

PECVD is a parallel process, CNTs can be deposited onto several such tips in one deposition run. MWNTs are preferred to SWNTs because of their greater mechanical stiffness.

The brightness of a series of CNTs is shown in the next figure and is compared with that of a state of the art Schottky emitter and tungsten cold field emission gun (CFEG). Being cold emitters, the CNT and the CFEG have almost identical energy spread (ΔE) values. However, the CNTs have a much more stable emission than the CFEGs and also the CNT has a much higher brightness than the CFEG at high currents [6]. Our results also show a significant improvement over Schottky emitters where our CNTs either have a lower ΔE at similar B_r or a higher B_r at a similar ΔE value. The significant performance advantage of CNT electron sources should see them implemented in the very near future in this high-value niche market where cost is not critical.

2.2 High power/frequency amplifiers

With the requirements for higher bandwidth and more channels, microwave links are increasingly using the 30 GHz and above frequency range. In order to satisfy the power (tens of Watts) and bandwidth requirements (30 GHz), satellites are using travelling wave tubes (TWT's) based on thermionic cathodes. Present day TWTs, however, are bulky and heavy, and take up valuable space and weight budget in a satellite, and any miniaturization of the current TWT would give rise to cost savings in a satellite launch,

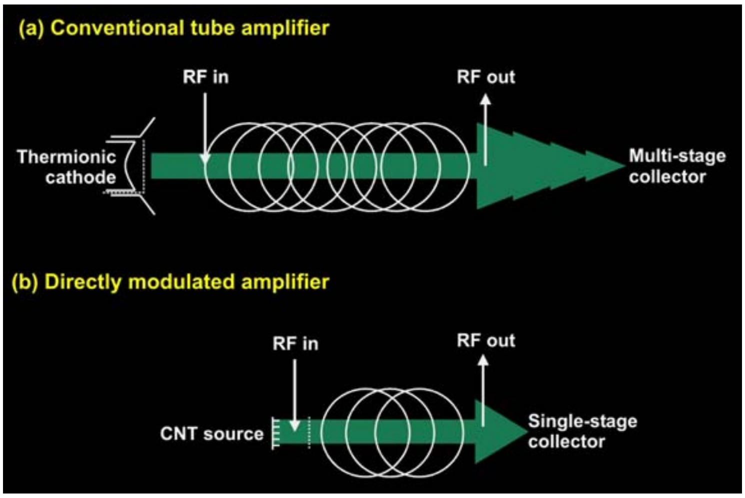

Fig. 4 (online colour at: www.pss-a.com) a) Conventional travelling wave tube, b) directly modulated CNT based TWT.

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and aid the implementation of micro-satellites. Solid state devices are not used in this high frequency regime because the maximum power attained by solid state devices today at 30 GHz is ~1 W. Attempts have been made to replace the hot thermionic cathode in a TWT with a Spindt tip cathode [10] delivering the dc electron beam – however, the bulk of the TWT device is still there, since it is the tube (in which the electron beam modulation takes place) that is physically large. 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 as shown in Fig. 4b. 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 [11]. 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 which generate a dc beam which then travels in a helical coil (indicated schematically by the white circles). It is in this helical coil that the electrons are velocity modulated to form bunches. The energy from the bunches of electrons is then extracted from an output helix. As the velocity modulation of the dc beam is inefficient, the input helix is very long, usually 2/3rd the length of the tube. Furthermore, the large energy spread in the electrons mean that a multi stage collector is required at the end of the tube to collect the electrons. In our proposed amplifier (b), the directly modulated CNT emitter produces electron bunches at the source, and hence no input helix is required. Hence only a short output helix is required to couple out the RF energy.

High temperatures (>1000 °C) are needed to facilitate electron emission in the conventional thermionic emitters and they can generate a dc current density of 1–2 A/cm^2. From the post modulation of this beam, diffuse electron bunches and the RF power saturates at about 30% of the beam power and to optimize output a long interaction line is required. The use of CNTs here significantly reduces the amplifier size leading to significant cost savings. This is because the CNTs are cold emitters where no heating is supplied. The cathode can be directly pulsed to generate short well defined bunches of electrons. There are no saturation effects due to well defined bunches, c.f. diffuse electrons in the conventional case and this means a much shorter interaction tube can be used. At present we have produced CNT based cathodes which can be directly modulated at 1.5 GHz and 32 GHz.

2.3 Field emission displays (FEDs)

The use of CNTs as the electron emitter in Field Emission Displays has been investigated by several groups and most recently Samsung have announced a large area 38″ prototype FED based television based on the screen-printing of the CNT emitter material. FEDs operate on the same principle as cathode ray tubes (CRTs) except in this instance an array of electron emitters is used instead of the single electron emitter used in the CRT. By using a separate electron gun for each sub-pixel the depth of the display can be substantially reduced as shown in Fig. 5.

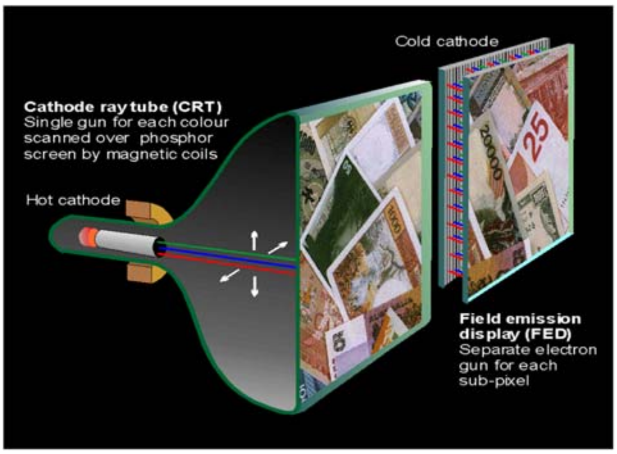

Fig. 5 (online colour at: www.pss-a.com) Schematic of a CRT (uses a thermionic emitter) and FED (uses an array of cold cathode emitters).

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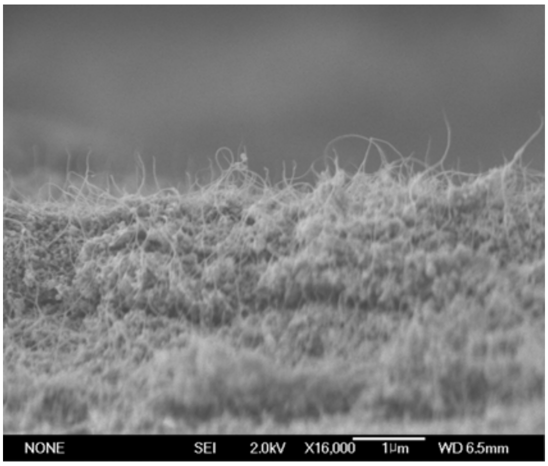

Fig. 6 Non aligned CNTs.

For large area displays (and also for backlight units for AMLCDs [12]) thick film screen printing methods can be used to produce the emitters (see Fig. 5) but for smaller higher resolution displays CVD processes are required to produce well aligned arrays of CNTs. A typical screen printed CNT film is shown in Fig. 6.

2.4 Parallel electron-beam lithography

There is a continuing need to find efficient techniques for sub-100 nm semiconductor lithography and mask production. Electron-beam direct write is considered to be a candidate for these applications because sub 100 nm beam sizes are "easily" obtained. The present drawback associated with this technique however is the low throughput due to serial writing with a single electron beam. To solve this problem, a relatively straightforward concept is to use an array of parallel electron beams. Several groups have de-

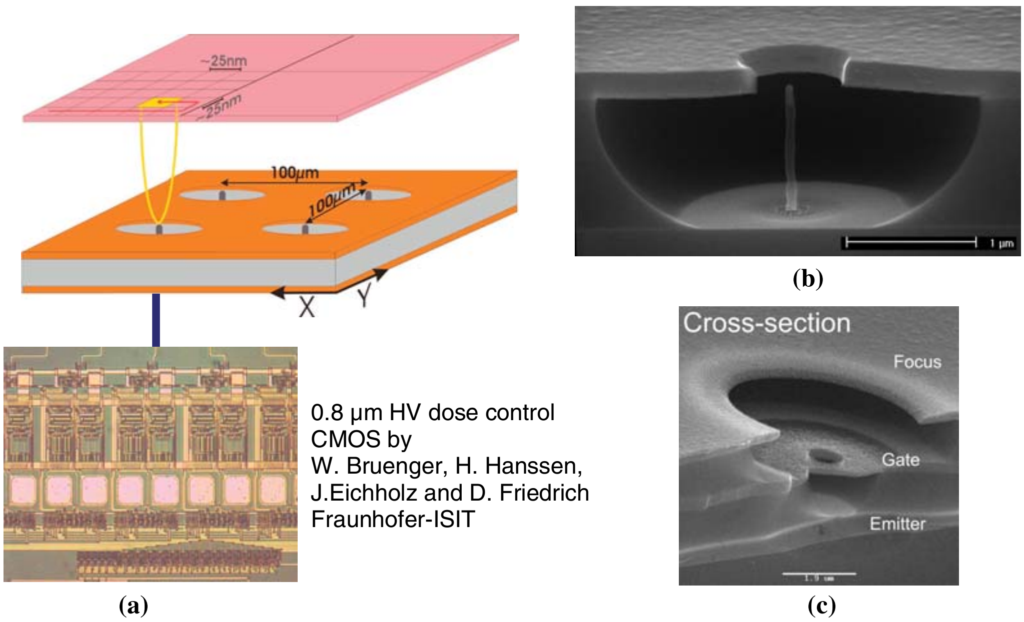

Fig. 7 (online colour at: www.pss-a.com) a) Schematic of the e-beam lithography system, b) gated CNT, c) cross section of the electron gun.

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monstrated the feasibility of this approach and we have over the past several years investigated the use of CNT emitters for such an application. Figure 7a provides a schematic of the system where the emitted current is controlled via a CMOS feedback circuit designed and built in the Frauhofer Institute. For such micro-electron sources a "triode" type arrangement with an additional integrated extraction gate electrode is needed (see Fig. 7b). 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. Figure 7c shows a completed e-beam gun where the focus electrode is also integrated. This reduces the power, complexity, and cost of the gate drive/modulation circuitry.

The field emission behaviour from an array of such microguns has been investigated. For a 100×100 array the emitted current that can reach the anode is 10 μA (equivalent to ~1 nA per emitter). Guillorn et al. at Oakridge have also fabricated cathodes based on CNTs using an alternative manufacturing technique [13].

3 Conclusions

The high electrical conductivity of MWCNTs allied to their remarkable thermal stability has made them one of the most intensely studied material systems for field emission (FE) applications. In this paper, we have described the growth of multiwall CNTs and their application in a range of field emission based systems including their use in SEM sources, emitters for use in microwave amplifiers, in parallel e-beam lithography systems and as emitters in field emission based displays (FEDs).

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