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Fabrication of carbon nanotube lateral field emitters

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Abstract
We report on the fabrication and field emission of carbon nanotube lateral field emitters. Due to its high aspect ratio and mechanical strength, we use vertically aligned multi-wall carbon nanotubes prepared by plasma-enhanced chemical vapour deposition as cathodes, which makes the fabrication of cantilever type lateral field emitters possible. The emission characteristics show that the field emission initiates at 11–17 V. The device has high geometrical enhancement factors (9.3×10^6 cm^{-1}) compared to standard Spindt tips, which may be due to increased field concentration at the nanotube tip and the close proximity of the anode (<1 μm). The relative ease of fabrication compared to vertical field emitters and enhanced field emission characteristics observed makes the carbon nanotube lateral field emitter a good candidate for future integrated nano-electronic devices.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recent progress in carbon nanotube synthesis has made it possible for a carbon nanotube to be grown vertically, as well as laterally, on a substrate at designated sites [1, 2]. This makes application of carbon nanotubes as nano-electronic components possible. However, there is a drawback in carbon nanotubes, which limits application to large-scale integrated devices. Although a method has been developed to selectively destroy metallic nanotubes, leaving only semiconducting ones [3], there is no known method of controlling the chirality of carbon nanotubes during synthesis, making it difficult to select semiconducting carbon nanotubes with a fixed energy gap for high-density integrated circuit application. Therefore it may be useful to have a device that does not rely on the transport properties of the individual carbon nanotubes but still delivers switching capability with gain. One such device is the carbon nanotube gated field emitter [4–6]. It utilizes the geometric enhancement of the nanotube tip structure and the high current density transport capabilities of the carbon nanotubes. Although the reported field emitters show promising characteristics in terms of applications to electron sources for displays and e-beam lithography [7], for nano-electronic applications there are a few drawbacks. It becomes difficult to align multiple layers of insulator and metal, when the nanotube growth is the first stage of fabrication [6]. Also, the integrity of the insulating layer may be difficult to maintain over a large area, at high voltages and may lead to unwanted leakage.

Here we report on the fabrication and operation of carbon nanotube lateral field emitters. Compared to vertical field emitters using carbon nanotube cathodes, they have fewer alignment problems since the anode is fabricated at the same time as the cathode and the gates, and also may have reduced leakage since the electrodes are well separated. The carbon nanotube lateral field emitters may have increased geometrical enhancement due to the ability to design devices with closer distance between the emitter tip and the anode. The field emission measurements reveal good Fowler–Nordheim emission characteristics with field emission achieved with 11 V applied between the anode and the cathode. The geometrical

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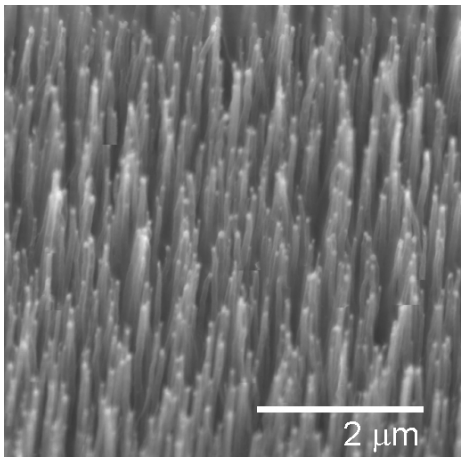

Figure 1. SEM image of vertically aligned MWNTs prepared by plasma-enhanced chemical vapour deposition.

enhancement factors obtained were in the high 10^6 cm^{-1}, which was higher than for standard Spindt field emitters [8]. The results show that the carbon nanotube lateral field emitter may be a good candidate for future nano-electronic applications.

2. Device fabrication

For the lateral field emission cathodes, we use multi-walled carbon nanotubes prepared by plasma-enhanced chemical vapour deposition. A ∼3 nm thin film of Ni catalyst was first deposited onto an oxidized Si substrate. The substrate was then heated to 700 °C at which the Ni catalyst breaks up to form nanoclusters, which seed the nanotube growth [9]. The growth was performed by introducing a mixture of C_2H_2 and NH_3 into the growth chamber and initiating a dc glow discharge by applying −600 V between the sample stage and the anode for 15 min. This process produced vertically aligned nanotubes ∼5 μm long and 50–100 nm in diameter. A ∼6 nm Ni catalyst film yields nanotubes of 100–200 nm in diameter. An scanning electron micrograph (SEM) image of vertically aligned multi-walled carbon nanotubes/nanofibres (MWNTs) is shown in figure 1.

The MWNTs were then physically removed from the substrate and mixed with PMMA. This is done by immersing the substrate in a vial containing PMMA and using magnetic stirring rods, physically breaking the MWNTs from the substrate. A detailed description of the PMMA suspended dispersion technique is discussed elsewhere [10].

We used thermally oxidized Si as the substrate. Initially, Cr/Au alignment marks were deposited to use as reference markers. Then a thin layer (50–100 nm) of Al was evaporated, which acted as the sacrificial layer. The thickness of the Al layer determines the minimum suspension height of the nanotube and also the required thickness of the sputtered Nb. The mixture of PMMA and MWNTs was spin-coated onto the Al surface (figure 2(a)). Then the positions of the MWNTs relative to the alignment marks were mapped using a high resolution optical microscope. Next electron beam lithography was used to define the anode, gates and the cathode contact patterns of the device in the PMMA (figure 2(b)). Then the exposed Al was chemically etched. As illustrated in figure 2(c), the etching was isotropic and it produces an undercut profile in the exposed area, which helps facilitate lift-off. After Nb metal sputter deposition (thickness ∼ 500 nm) and lift-off (figure 2(d)), the sacrificial Al was etched away leaving the carbon nanotube suspended (figure 2(e)).

3. Results and discussion

An SEM image of a carbon nanotube lateral field emitter is shown in figure 3. As can be seen an MWNT was suspended by Nb sputtered contacts to one end. The diameter of the MWNT was ∼200 nm. The Ni catalyst particle was visible, confirming that the emitter tip was the growth terminated end and not the end that has been broken off the substrate. The distance between the nanotube tip and the anode was ∼300 nm.

The field emission characteristics of the carbon nanotube lateral field emitter are shown in figure 4. The measurement results were obtained from the device shown in figure 3. The measurement was performed at room temperature inside an SEM machine specimen chamber, which had a pressure of $\sim 10^{-8}$ mbar. This was done to make possible investigation of the device structure before and after each measurement and also to measure the device in high vacuum. The limited number of electrical feed-throughs to the SEM specimen chamber limited the use of the fabricated gate electrodes in this experiment and gated lateral field emission should be investigated in future measurements by increasing the number of electrical connections. The electron beam of the SEM was blanked during measurement, which reduces charging of the substrate and contamination due to carbon deposition. The applied voltage between the carbon nanotube emitter cathode and the anode was ramped from 0 to 40 V in steps of 50 mV. It can be seen that field emission initiates around 17 V and the increase in emission current has an exponential dependence on the applied bias. The characteristics show a noticeable hump near 25 V. Emission current of ∼240 nA was obtained at a bias of 40 V.

The emission characteristics exhibit Fowler–Nordheim behaviour, as shown in the inset of figure 4. The emission current density given by Fowler and Nordheim is as follows:

$$J = aV^2 \, \mathrm{e}^{(-b/V)}, \tag{1}$$

where J is the emission current density, V is the applied voltage and a and b are Fowler–Nordheim parameters. Parameter b ($=6.44 \times 10^7 \phi^{3/2}/\beta$; where ϕ is the work function ∼5 eV) is commonly used for comparing emitter characteristics as it provides information regarding the geometrical enhancement factor β of a field emitter. The β value is inversely proportional to b. Thus the design of an emitter typically aims towards lower values of b and higher β, which may reduce the turn-on voltage of the device.

The inset Fowler–Nordheim plot shows that the data may be divided into two sections and evaluated separately by fitting the data to equation (1). This results in similar values of $\beta \sim 7.86 \times 10^6$ cm^{-1} for both parts. The β value for the characteristics below 25 V was slightly lower than that above 25 V, indicating that the hump in the field emission characteristics may represent a physical change in the emitter.

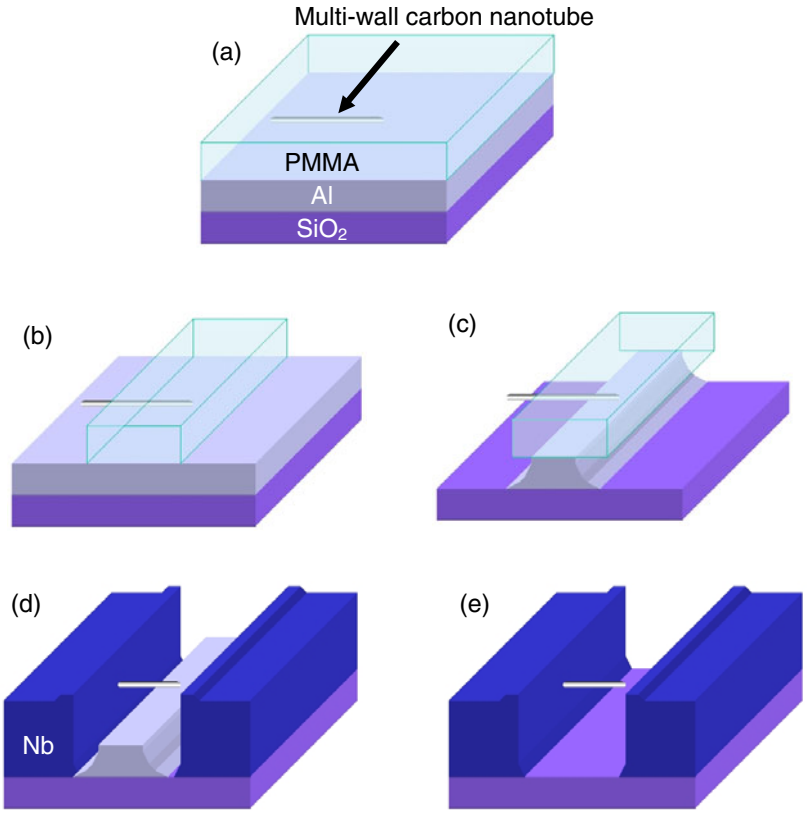

Figure 2. Schematic diagram of the carbon nanotube lateral field emitter fabrication steps. (a) PMMA suspended dispersion. (b) e-beam lithography. (c) Al sacrificial layer etching. (d) Nb electrode deposition and lift-off. (e) Al pillar etching.

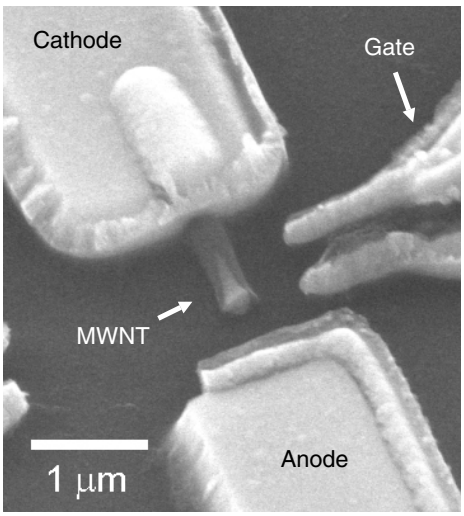

Figure 3. SEM image of a carbon nanotube lateral field emitter. The MWNT diameter was ∼200 nm. The distance between the emitter tip and the anode was ∼300 nm. The sample was tilted by 40°.

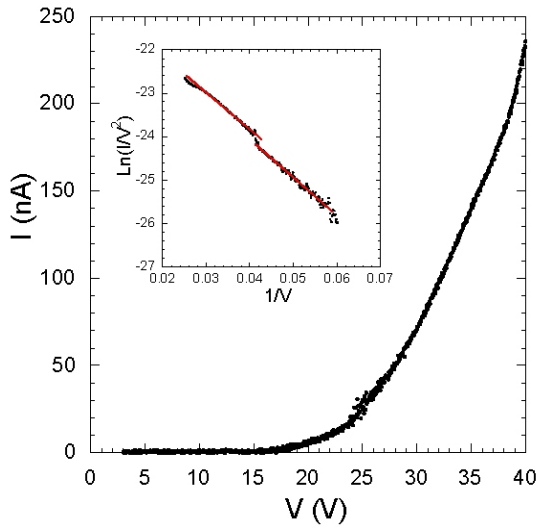

Figure 4. Field emission characteristics of carbon nanotube lateral field emitter. The measurement was performed at a pressure of ∼3 × 10^{-8} mbar and at room temperature inside an SEM specimen chamber. The emission voltage was ∼17 V. The inset shows the Fowler–Nordheim plot of the measurement.

This increase in geometrical enhancement above 25 V may be attributed to field sharpening of the nanotube tip [11].

The field emission characteristics of another carbon nanotube lateral field emitter are shown in figure 5. The lower inset shows the SEM image of the device. The Ni catalyst particle observed at the end of the tip of the device shown in figure 3, was not present in this device. Also the diameter of the MWNT suddenly decreases around the tip area, from ∼50 nm in the regions starting from the cathode contact to <10 nm at the tip. This may be due to the fact that the emitter tip was the broken end of the MWNT. The turn-on voltage for this device was ∼11 V, which was lower than that of the previous device. The emission characteristics were less stable than the previous device; however, it can be seen that the emission currents were

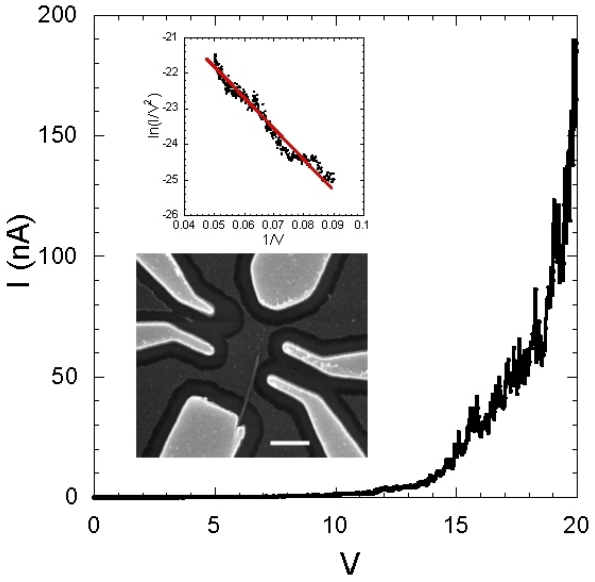

Figure 5. Field emission characteristics of a broken end carbon nanotube lateral field emitter. The diameter of the nanotube tip was less than 10 nm. The distance between the emitter and the anode was ∼1 μm. The emission voltage was ∼11 V. The lower inset shows an SEM image of the device. The upper inset shows the Fowler–Nordheim plot of the measurement.

much higher for the same applied voltages than the previous device. The Fowler–Nordheim plot, shown in the top inset of figure 5, also confirms that the emission was less stable. However, the β value for this device is $\sim 8.55 \times 10^6$ cm^{-1} giving increased geometrical enhancement from the previous device. The fluctuation in the emission characteristics may be attributed to possible desorption of surface adsorbates [12].

When we compare these results to other known emitters, the carbon nanotube lateral field emitters have lower turn-on voltages and a lower b value ∼80 V. Good Mo Spindt tip field emitters have turn-on voltages of ∼25 V and a b value of 240 V [8]. Although the difference in geometry does not allow a direct one-to-one comparison the results obtained from carbon nanotube vertical field emitters fabricated by nanotubes grown directly on the substrate by plasma-enhanced chemical vapour deposition (PECVD) shows similar turn-on voltages and b values for the initial emission cycle [4].

4. Conclusions

We have successfully fabricated carbon nanotube lateral field emitters using MWNTs prepared by PECVD and have tested their field emission characteristics. The emitters have turn-on voltages of 11–17 V. The evaluation of the Fowler–Nordheim plots shows that the device has high geometrical enhancement factors (9.3×10^6 cm^{-1}) compared to standard Spindt tips, which may be due to increased field concentration at the nanotube tip and the close proximity of the anode (<1 μm). The relative ease of fabrication compared to vertical field emitters and enhanced field emission characteristics observed may make the carbon nanotube lateral field emitter a good candidate for future integrated nano-electronic devices.

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