Electron field emission from a single carbon nanotube: Effects of anode location

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Electron field emission from an isolated carbon nanotube (CNT) was performed *in situ* in a modified scanning electron microscope, over a range of anode to CNT tip separations, D , of 1–60 μm . The threshold field required for an emission current of 100 nA was seen to decrease from a value of 42 V μm^{-1} at an anode to CNT tip separation of 1 μm , asymptotically, to approach 4 V μm^{-1} at a separation of 60 μm . It is proposed that at low D , the electric field enhancement factor (β) reduces as the anode electrode approaches the CNT mimicking a parallel plate configuration. Under “far field” conditions, where $D > 3h$, where h is the CNT height, the CNT enhancement factor is no longer dependant on D , as shown by the asymptotic behavior of the threshold field, and is purely a factor of the CNT height and radius. For each CNT to tip separation, measured emission current data together with the threshold field and enhancement, are consistent with a Fowler-Nordheim analysis for the far field conditions, and dispels the need for a novel emission mechanism to explain the results as has been proposed recently. © 2005 American Institute of Physics.

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Since the identification of carbon nanotubes¹ (CNT), there has been sustained research academically and industrially into numerous potential applications.^{2–7} Much effort has been invested in the study of their application for electron sources by the process of electron field emission,^{7–9} leading to the fabrication of possible next generation flat panel displays.¹⁰ Carbon nanotubes are promising candidates for cold cathode electron field emitters due to their electrical properties, chemical inertness, tensile strength, and high aspect ratio, which enable them to alter the local electric field around the tip due to a field enhancement factor, often denoted by β . It is important, therefore, in designing and fabricating field emission displays or future cold cathode sources, to understand fully the emission properties and characteristics of not just arrays and mats of CNT, but of individual CNTs. To date, various studies have been performed on field emission from a single CNT.^{11–13} Measurements of field emission often attempts to quantify the behavior in terms of the applied electric field and the local electric field at the tip, via β . For an emitter not operating in the high current space charge regime, the local electric field required for emission should not be a function of the electrode separation, D , and one would expect that measurements of the applied threshold field not to be dependent on the relative separation of the electrodes, with the applied electric field given simply as V/D , where V is the applied potential difference. In this letter, we report that the position of the anode electrode in field emission from a single CNT is important, and furthermore that redefining the manner in which the applied field is described gives rise to a better understanding of the CNTs field emission properties.

Multiwalled carbon nanotubes were synthesized by a plasma arc discharge between two graphite electrodes. The subsequent carbon deposit was purified by microfiltering and oxidation at 500 °C to remove any amorphous carbon and

carbon particles, leaving purified CNTs. The CNTs were mixed into a polymer solution of polystyrene, which was dissolved in toluene. An ultrasonic treatment was used to improve the dispersion of the CNT within the polymer. Vacuum casting methods were then used and the as cast films were hot pressed to remove any residual solvent. To expose a single CNT, the sample was physically broken and the broken edge studied in a scanning electron microscope (SEM). An exposed and isolated CNT was found, vertically aligned to the substrate, with a height of 8 μm and a radius of approximately 40 nm. Figure 1 is a SEM micrograph of the exposed CNT, prior to a field emission experiment, and it can be seen that there are no neighboring CNTs that would alter the field emission properties by the effect of field screening.¹⁴ The conduction through the bulk of the CNT

FIG. 1. Scanning electron microscope image of a single isolated CNT with height 8 μm and radius 40 nm protruding from a CNT polymer sample. The etched tungsten tip anode can be seen suspended above the CNT at a distance 10 μm away. Dotted lines and arrow illustrate where separation, D , is measured.

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polymer sample is believed to follow a power law with nanotube concentration.¹⁵ Conduction is believed to be by tunneling between nanotubes which are closely spaced together. It is worth noting that during SEM imaging neither the CNT nor the polymer exhibit any charging, which suggests they are both conductive.

Field emission (FE) experimentation was performed in a modified Cambridge Stereoscan 250 III SEM that includes electrical feed throughs connected to a sharp tungsten tip (FE anode) and the CNT substrate. The tip can be moved independently of the SEM stage by three-axis piezoslides with a minimum step size of 40 nm and up to 5 mm travel, see Fig. 1. A FE testing system, comprising of a Labview program running a Keithley 237 source meter, was then connected to the FE stage and anode, to measure field emission characteristics with a 100 fA resolution.

FE testing was conducted within the SEM chamber at a vacuum of better than 10^{-5} Torr. The sample was mounted on the isolated FE stage with silver epoxy and FE was performed at CNT tip to anode separations of 1, 2, 4, 10, 20, 40, and 60 μm and due to the experiments being conducted in the SEM, these separations could be established very accurately. The FE voltage cycling and current/voltage measurements were computer controlled to ensure repeatability of the testing procedure. The applied voltage was increased in 0.5 V steps (smoothed by a RC circuit) until an emission current of 1 μA was measured and then the voltage was reduced to 0 V in similar steps. A limit of 1 μA was employed to ensure that damage to the single CNT due to filament current heating was not a possibility. Emission current was plotted against applied electric field for each of the CNT tip-anode separations. The resulting plots are shown in Fig. 2(a). It can be seen that for a CNT to anode separation of 1 μm , the threshold field, E_T , defined here as the applied field required for an emission of 100 nA, is 42 $\text{V } \mu\text{m}^{-1}$. As the separation is increased to 2 μm , the threshold field reduces to 27 $\text{V } \mu\text{m}^{-1}$. Subsequent increasing of the separation to 4, 10, 20, 40, and 60 μm (60 μm being the largest as beyond this, accurate measurement of the distance became difficult as the CNT was no longer resolved at that magnification) gave threshold fields of 19, 10, 7, 5, and 4 $\text{V } \mu\text{m}^{-1}$, respectively. Figure 2(b) shows $1/E$ against $\ln(I/E^2)$ Fowler-Nordheim plots for the seven CNT tip to anode separations listed earlier. All plots are approximately a straight line indicating that the emission mechanism is likely to be of the Fowler-Nordheim Fermi level tunneling type. A plot of threshold field for an emission current of 100 nA against CNT to anode separation is shown in Fig. 3, where it is observed that the threshold reduces asymptotically. This can be explained by the fact that as the anode approaches the tip of the CNT, the tip to anode approximates a parallel plate configuration and the geometric field enhancement factor of the CNT decreases. As the anode electrode is moved away from the CNT tip, the parallel plate approximation diminishes and the geometric properties of the CNT reduce the threshold field required by its field enhancement. A plot of the enhancement factor which was extrapolated from the Fowler-Nordheim equation using a work function of 4.5 eV is also shown in Fig. 3. Enhancement is seen to reduce as the anode approaches the tip of the CNT, further suggesting that the system approximates to a parallel plate configuration at low D , and at higher values of D , enhancement is seen to level out in accordance to the threshold field. From this we

FIG. 2. (a) Emission current against applied electric field for anode to CNT tip separations of 1 ($\blacksquare$), 2 ($\square$), 4 ($\bullet$), 10 ($\circ$), 20 ($\blacktriangle$), 40 ($\triangle$), and 60 μm ($\blacklozenge$). A peak emission current of 100 nA was employed to ensure no damage to the CNT. (b) Plot of $1/E$ against $\ln(I/E^2)$ for all seven voltage-current measurements. Fit is to a Fowler-Nordheim theory.

can deduce that at high D , the enhancement factor is dependant on the geometrical properties of the CNT alone and not the location of the anode, as enhancement reaches an asymptotic value. But at low D the enhancement factor of the single CNT is dependant on its geometrical properties and the location of the anode electrode. Using the two-dimensional theoretically obtained expression from Ref. 16, for electric field enhancement factor of a single, isolated CNT, where the anode electrode is sufficiently far away, we can now fit to this expression based on three-dimensional

FIG. 3. Threshold field against anode to CNT tip separation ($\blacksquare$). Threshold field for an emission current of 100 nA can be seen to reduce from 42 $\text{V } \mu\text{m}^{-1}$ at a separation of 1 μm to a value of 4 $\text{V } \mu\text{m}^{-1}$ at a separation of 60 μm . Calculated enhancement factors using the Fowler-Nordheim equation ($\circ$), shows decreasing enhancement with decreasing D which ties in with increasing threshold field with decreasing D . Dotted line is a fit from Eq. (1).

experimental results and show it to be best represented by

$$\beta/100 = 1 + \sqrt{\frac{h}{\alpha r}}, \quad (1)$$

where $h=8\text{ }\mu\text{m}$, $r=40\text{ nm}$, and $\alpha=2$. The enhancement factor is seen to be 807, which is the value that the enhancement factor approaches from our data of Fig. 3 as D increases and is denoted by the dotted line in Fig. 3. While the trends of threshold field and enhancement factor of Fig. 3 are in contradiction to other reported work of field emission from single CNT,¹⁷ we feel that the manner in which we are defining the applied electric field as anode to CNT tip, rather than the more commonly used anode to cathode (or CNT base/substrate) is more applicable and gives a more realistic insight into the field emission properties of emission from a single CNT. The derivation of this empirical fit to the field when D is greater than three times the height of the tube is to be explored in future work. As the Fowler-Nordheim analysis of Fig. 2(b) showed approximations to a straight line, it was possible for an emission current to be calculated using the well known and widely accepted Fowler-Nordheim equation¹⁸

$$I = \frac{aA\beta^2 E^2}{\phi} \exp\left(\frac{-b\phi^{3/2}}{\beta E}\right), \quad (2)$$

where a and b are constants with values $1.54 \times 10^{-6}\text{ eV V}^{-2}$ and $6.83 \times 10^7\text{ eV}^{3/2}\text{ V cm}^{-1}$, respectively. A is the emission area which has been calculated as $5 \times 10^{-13}\text{ cm}^2$ using the CNT radius of 40 nm. β is the enhancement factor which was taken from the data of Fig. 2(b). E is the applied electric field in V cm^{-1} and ϕ is the work function which was estimated at 4.5 eV. Figure 4(a) shows the I - E curves for the seven values of D and Fig. 4(b) is the extracted threshold field for an emission current of 100 nA and the threshold fields found experimentally and shown in Fig. 3. It can be seen that the obtained trends and values of Fig. 4(a) are comparable to that of Fig. 2(a) and that the calculated threshold fields are a close match to that found experimentally.

In conclusion, we have shown electron field emission from a single isolated CNT in a modified SEM. Accurate anode to CNT tip separations down to 1 μm were made possible by manipulating the anode electrode and sample stage within the SEM. We have shown that as the separation of the CNT to anode increases from 1 to 60 μm , the threshold field decreases to an asymptotic value dependant on the geometric properties of the CNT, and the enhancement factor increases to an asymptotic value in accordance with the decreasing threshold field. This is due to the CNT tip and anode approximating a parallel plate at low D .

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FIG. 4. (a) Calculated emission current for an anode to tip separation of 1 ($\blacksquare$), 2 ($\square$), 4 ($\bullet$), 10 ($\circ$), 20 ($\blacktriangle$), 40 ($\triangle$), and 60 μm ($\blacklozenge$). The Fowler-Nordheim emission current equation was used. (b) Experimental threshold field ($\circ$) and calculated threshold field from the Fowler-Nordheim emission currents of Fig. 4(a). ($\blacksquare$)

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