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Field Emission Characteristics of Single Wall Carbon Nanotube Rope at The Presence of Dielectric Medium

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Abstract: An abnormal jump of emission current was observed in a single wall carbon nanotube (SWCNT) rope field emitter, in which two soda-lime glass flakes were set on both sides of SWCNT rope. It gave rise of an apparent enhancement of the emission current after the jump. All these peculiar characteristics of field emission were attributed to the modification of electric field at the presence of glass flakes and its contribution to the selective divergence of electron trajectories. Theoretic analysis and subsequently evidential investigations were carried out to certify the influence of the dimension, separation distance and dielectric constant of the dielectric medium on the I - V characteristics of SWCNT rope, which suggests a feasible way to control the field emission properties from Spindt-type emitters including CNT rope.

Key words: carbon nanotube; field emission; trajectory; dielectric

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介电体围绕下绳束状碳纳米管的场发射特性

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摘要: 在周边环境玻璃薄片介电体的作用下, 绳束状碳纳米管宏观体的场发射电流发生异常跃迁, 同时伴随有场发射电子光斑的横向扩展, 导致跃迁后的场发射电流明显高于正常情况。所有观察到的现象均与介电体存在下的电场重新分布和电子轨迹偏离有关。理论分析及随后的场发射测试检验了介电体几何尺寸、间距、介电常数等因素对场发射 I - V 性能的影响。研究结果提供了一种控制 Spindt 型场发射体电子发射性能的新的可行途径。

关键词: 碳纳米管; 场发射; 电子轨迹; 介电体

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1 Introduction

Carbon nanotube (CNT) is generally considered as one of the best field emitters due to its superb structure and properties including nanoscale radius of curvature, high aspect ratio, excellent electrical conductivity, outstanding mechanical stiffness and chemical inertness. Some electron sources based on CNT field emitters have been developed for the potential applications in field emission display (FED)^[1-3], back light source for liquid crystal display (LCD)^[4-5], cathode-ray lighting element^[6-7], gas-discharge tube^[8], electron gun for scanning electron microscopy (SEM)^[9] or X-ray generator^[10-11].

In these vacuum electron devices, a third electrode, generally named the focusing gate, is used to control the electron trajectories from CNT field emitters^[3, 12-13], which inevitably increases the complexity and cost. In order to simplify the structure for electron trajectory controlling, some self-focusing electron sources have been proposed by positioning the gate electrode parallel with the emitter vicinity^[14] or at the center of cathode^[15]. In previous work, a relative simple way was proposed to control the electron trajectories by selecting presence of dielectric medium such as glass flakes near the single-wall carbon nanotube (SWCNT) rope as field emitter^[16], but the contribution of geometric dimension of the dielectric medium was not investigated and discussed in details up to now. In this work, theoretic analysis and evidential measurements were carried out to reveal the modification of electric field at the presence of dielectric medium in diode structure and its influence on the field emission characteristics of the SWCNT rope. A feasible way is proposed for fabricating electron sources with controllable electron trajectories.

2 Experiments

2.1 Preparation of SWCNT Rope Field Emitter

Macroscopically long ropes of aligned SWCNTs synthesized by a method of arc discharge^[17] were obtained from Advanced Carbon Division, Institute of Metal Research, Chinese Academy of Sciences. Un-

der SEM observations, the SWCNT rope as demonstrated to be made up of tightly packed, roughly aligned bundles of SWCNTs, and few bundles were found to stretch out from the sidewall of the SWCNT rope (Fig. 1 (a)). A simple cut by a razor blade was performed to obtain a great number of SWCNT tips at the emitting surface of SWCNT rope for field emission, as shown in Fig. 1 (b).

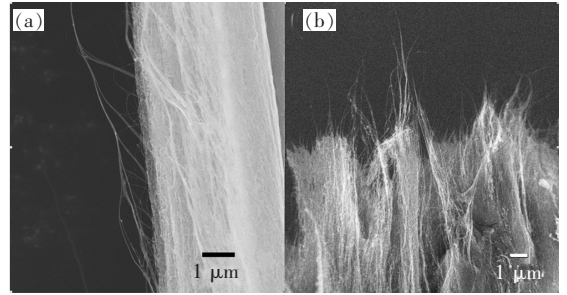


Fig. 1 Typical SEM images of SWCNT ropes. (a) The sidewall. (b) The emitting surface.

2.2 Field Emission Measurements of SWCNT Rope

Fig. 2 shows the diode structure we used to determine the field emission performance from a freestanding rope of SWCNT, in which the SWCNT rope was fixed perpendicularly onto a copper plate cathode. An indium-tin-oxide (ITO) glass was employed as the anode to collect emission electrons, and the gap between the SWCNT tips and the anode was about 1mm. Two flakes of soda-lime glass (12 mm × 9 mm × 1 mm in dimension) were symmetrically positioned on each side of the SWCNT rope, and the separation distance and thickness of the glass flakes could be adjusted arbitrarily. The diode structure was transferred into a high vacuum chamber, in which the working pressure was typically of the order of 10^{-5} Pa. Keithley PS350 High Voltage

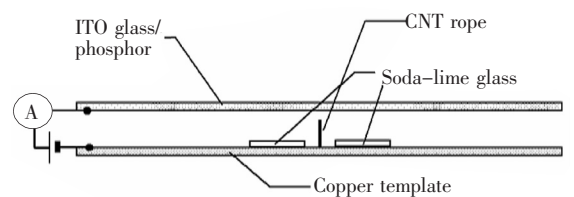


Fig. 2 Diode structure used for the field emission measurements of a freestanding SWCNT rope surrounded by glass flakes

Supply and 2000 Multimeter were used to provide the bias voltage with a step of 3 V and to record the emission current, respectively.

3 Results and Discussion

Fig. 3 shows the shifts of field emission characteristics from the same SWCNT rope with and without the presence of glass flakes. From Fig. 3, an abrupt jump of the emission current (2.5 ~ 141.5 A) at a threshold voltage of ~ 670 V can be easily distinguished from the I - V curve at the presence of glass flakes (see the opened squares in Fig. 3), which gave rise of a relative high current after the current jump. Meanwhile, a selective expansion of the electron patterns was found with the current jump, indicating the divergence of electron trajectories due to the modification of electric field at the presence of glass flakes.

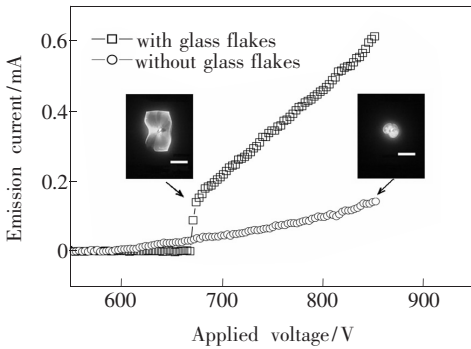


Fig. 3 Comparisons of the I - V alternations from the same SWCNT rope with (opened square) and without (opened circle) glass flakes, along with the corresponding electron patterns at an equivalent current of ~ 145 A. The length of the SWCNT rope was 3.15 mm, and a scale bar of 12 mm was involved into the optical insets.

With the application of Gauss theorem in electrostatic field, once a sheet of dielectric substance is introduced into the plate electrodes under a constant potential of U , the electric field strength (E) between the dielectric sheet and the electrode can be roughly estimated by the following equation,

$$E = \frac{U\varepsilon_r}{\varepsilon_r d + (1 - \varepsilon_r)h} = \frac{U}{d + \left(\frac{1}{\varepsilon_r} - 1\right)h}, \quad (1)$$

in which, U and d is the potential and distance

between two electrodes, respectively, while h and ε_r is the thickness and relative dielectric constant of the dielectric medium. Since the value of ε_r is higher than 1, *i. e.* $\left(\frac{1}{\varepsilon_r} - 1\right) < 0$, it is obviously that the E value obtained from Equation (1) is higher than that without the presence of dielectric medium ($E_0 = \frac{U}{d}$ while $h = 0$). Therefore, an assumed distribution of the electric field at the presence of dielectric medium can be illustrated as Fig. 4 (a), in which the edge effect of induced charge distribution has been also taken into account. On the other hand, a SWCNT rope field emitter placed between the plate electrodes would generate an electric field roughly following the simple quadratic distribution^[3] (Fig. 4 (b)), and consequently, by making use of the superposition principle, the distribution of electric field near a SWCNT rope at the presence of glass flakes was obtained and shown in Fig. 4 (c). The modification of electric field shown in Fig. 4 (b) ~ (c) can be used to explain the peculiar phenomena

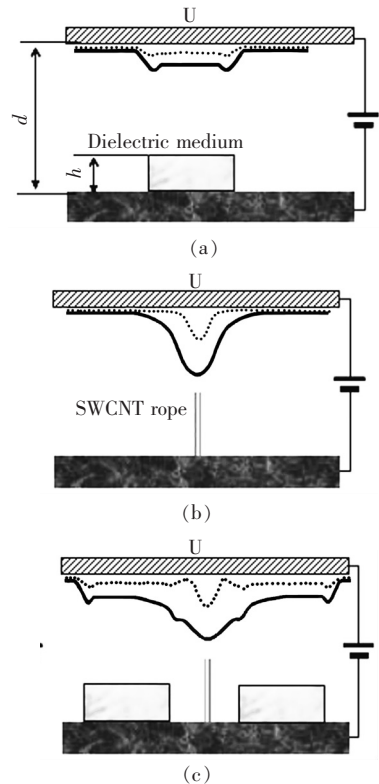


Fig. 4 Schematic diagrams of the electric field distribution in a diode structure at the presence of dielectric medium only (a), isolated SWCNT rope (b), and a SWCNT rope positioned between two dielectric flakes (c).

mentioned above. While the simple quadratic distribution of electric field around the isolated SWCNT rope (Fig. 4(b)) aroused a circle-like electron pattern, the separated peaks of electric field distribution in Fig. 4(c) would result in the divergence of electron trajectories at high fields and thus give rise of the expanded patterns of electron patterns at the presence of dielectric medium. Since the spreading of emitting electrons over a relatively large region is helpful to reduce the adverse influence of space charge effect on electron emission^[18], the corresponding emission current would increase to some extent, as shown in Fig. 3. In the meanwhile, it should be pointed out that the small trough of electric field distribution near the SWCNT rope at low fields (see the dotted line in Fig. 4(c)) could be taken as an activation barrier for electrons to emit from the SWCNT tip. Only when the applied voltage is high enough to overwhelm this activation barrier, part of the emitted electrons would fly towards the glass edge and then generate the expanded emission patterns shown in Fig. 3.

It is suggested by equation (1) that the electric field E must be strongly dependent upon the parameters of h and ϵ_r . In an evidential investigation, while the thickness of glass flakes (h) near a SWCNT rope (3.15 mm in length) was increased step by step, the amplitude and threshold voltage for the current jump were found to increase apparently until the glass flakes were higher than the SWCNT rope, as shown in Fig. 5(a). According to equation (1), any increase of the glass thickness (h) would result in an increment of the electric field E , and thus generated a deeper barrier and a higher threshold voltage for the occurrence of current jump. On the other hand, since the region for electron pattern expansion kept unchanged with increasing glass thickness, the space charge density around the SWCNT tip did not change apparently, and thus result in the similar I - V alternations after the current jump (Fig. 5(a)). Once the glass thickness ($h = 4.0$ mm) was larger than the height of SWCNT rope (3.15 mm), the existence of so thick glass flakes would partly block the paths of electron emission, and consequently

result in a less amplitude and relative low threshold voltage for the current jump.

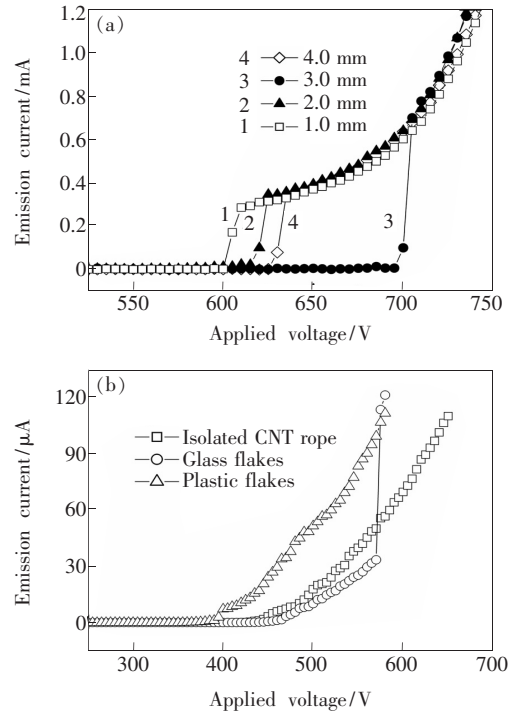


Fig. 5 Shifts of the I - V alternations from the same SWCNT rope in terms of the glass thickness (a), and the presence of dielectric mediums based on PE plastic or Soda-lime glass (b), respectively.

Moreover, equation (1) suggested that a relatively low dielectric coefficient ϵ_r would give rise of a decreased electric field of E , and thus make a less contribution to the corresponding I - V alternations. Accordingly, several dielectric medium, whose value of dielectric constant has been determined by using a bridge measurement, was employed to take the place of glass flakes. In Fig. 5(b), the glass flakes ($\epsilon_r = 5.45$) was substituted by polyethylene flakes ($\epsilon_r = 2.26$) in similar size for the I - V measurements, in which only a slight jump of the emission current could be observed at the presence of plastic flakes. In other investigations, quartz glass ($\epsilon_r = 3.72$), alumina ($\epsilon_r = 6.86$), or ceramic mat ($\epsilon_r = 6.11$) behaved similar current jump to that of soda-lime glass, while the presence of soft materials with low dielectric constant, such as plastic or rubber flakes in similar size did not arouse notable jump of the emission current.

Additionally, it should be pointed out that only

while the dielectric medium is close enough to the field emitter, the shifts of I - V alternations can be detected obviously. Fig. 6 shows the influence of the enlarged separation distance between two glass flakes on the I - V alternations from the same SWCNT rope, in which a gradually decreased amplitude for the current jump, along with a higher threshold voltage and a much less enhanced emission current at higher field, can be observed.

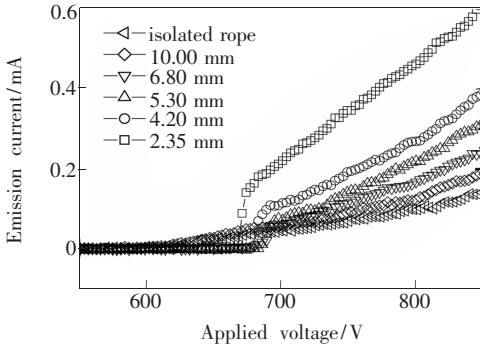


Fig. 6 Shifts of the I - V alternations in terms of the separation distance between glass flakes

The phenomena described above indicate an interesting and feasible way to control the field emission characteristics including emission current and electron patterns from Spindt-type field emitters including SWCNT ropes by adjusting the dielectric

constant or configurations of surrounding substance. It is very promising for the fabrications of electron sources used in back light source for LCD, cathode lighting elements and X-ray generators.

4 Conclusion

In the diode structure for field emission measurements of SWCNT rope, the introduction of dielectric medium such as glass flakes aroused an intriguing jump of the emission current, along with a selective expansion of the electron patterns and an enhanced current after the jump. The phenomena were attributed to the modification of electric field at the presence of dielectrics, which is strongly depending on the dielectric constant and configurations of dielectric medium. This result gives a possibility of designing a new vacuum device with high emission current and controllable electron patterns.

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