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Coherent field emission from a multi-walled carbon nanotube with two open-ended branches*

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Interference fringes are obtained in a field-emission microscopy (FEM) study of a multi-walled carbon nanotube (MWCNT) with two open-ended branches. The FEM pattern, which is composed of three parallel streaks, can be interpreted by using classical Young's double-slit interference with the ends of the two MWCNT branches treated as two secondary sources of the electron wave. The origin of the coherency of the electron beams from the two branches is discussed on the basis of the quantitative analysis of the FEM pattern. The result suggests a new approach to obtaining a coherent electron source.

Keywords: interference, field emission, carbon nanotube
PACC: 7210, 7360

1. Introduction

The interference of electron waves has been an interesting topic since the wave nature of electrons was experimentally confirmed.[1] Young's double-slit interference is the most classical and straightforward illustration of the wave-like behaviour of electrons.[2,3] As is well known, many nanometer-scale materials can deliver electron beams in a strong electric field.[4−10] In particular, the carbon nanotube (CNT) has offered a new opportunity for studying the interference of electron waves and obtaining high-brightness electron sources.[11−16] Among these studies, most of the coherent emission came from capped CNTs, probably due to the closeness between the emission sites on the caps and the consequent good spatial coherence.[17] In contrast, though field-emission microscopy (FEM) patterns of open-ended CNTs became available no later than the year 1997,[18] to date reports on their coherent field emission are still scarce.

As will be reported in the present paper, the field emission from a CNT with two open-ended branches is studied. Its FEM pattern can be readily interpreted by using Young's double-slit interference. Our experiment is conducted by using less sophisticated instrumentation and under less stringent experimental conditions than previous experiments with a similar mechanism. The present work provides a simple way to observe the wave-like behaviour of electrons and also has significance in developing new-type coherent electron sources.

2. Experiment

The multi-walled carbon nanotubes (MWCNTs) used in the experiment were fabricated by using the chemical vapour deposition (CVD) method.[19] They were assembled onto W tips with a nanofactory system in an FEI Tecnai G20 transmission electron microscope (TEM).[20] The process, whose detail is given in Ref.[21], is briefly described as follows. A number of MWCNTs were adhered to a Pt electrode beforehand. Then, under TEM observation, a W tip was brought into contact with a particular MWCNT. Good Ohmic contact was established by several voltage sweeps between the Pt and W electrodes. Finally, the MWCNT was intentionally broken by the passage of a large current and a W-based MWCNT field emitter was obtained.

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So far, some interesting results have been achieved from the W-based MWCNT emitters made in this way.[21−23] In these previous studies, the field emitters were all individual MWCNTs. On certain occasions, MWCNTs with two parallel branches were also found and then assembled onto W tips. Thus, some double-branched MWCNT field emitters were also available by using this method. The sample used in this experiment is shown in Fig.1. The two branches have approximately the same length (1.13 μm) and diameter (24 nm). Because these geometric parameters are very similar, the field emission capabilities of the two branches are supposed not to differ much.

Also, figure 1 shows that the two branches are both uncapped, which is a natural result of the above fabrication process.

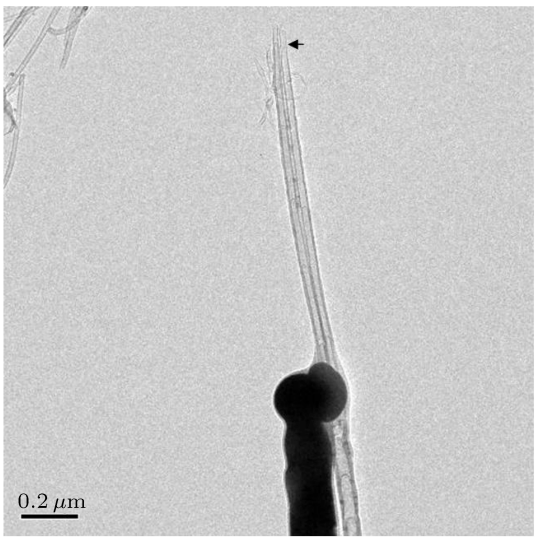


Fig.1. An open-ended double-branched MWCNT on a W tip in a nanofactory system.

The field emission properties of the double-branched MWCNT were studied by using a field-emission microscope (FEM) with a base pressure of 3.1×10^{-8} Pa. In the FEM, a negative high voltage was applied to the tip. An assembly of a fluorescent screen and a microchannel plate (MCP), placed 172 mm in front of the MWCNT emitter, was used to collect the emission current and image the electron emission patterns. The emitter was welded on a W loop, so that it could be heated by the current passing through the loop.

3. Results and discussion

The dependence of the emission current of the MWCNT on the applied voltage (I–V behaviour) was studied at different stages. First, as shown in Fig.2(a), it was measured before any heat treatment. Obvious fluctuation and even abrupt current drop were observed. Then the sample was subjected to repeated heat treatment. Each time the treatment lasted about 2 min and the temperature of the W tip rose to around 1×10^3 °C. Then, as shown in Fig.2(b), the I–V behaviour was recorded before, during and after the acquisition of the FEM pattern sequentially. The current differences under the same voltages were smaller than 1.8%, suggesting that the heat treatment had established a stable emission and the FEM study did not bring about any serious change in electron emission. This result is in agreement with our previous result.[23] Generally, the establishment of stable field emission is attributed to the removal of the adsorbate and the blunting of the tip.[23−25] Moreover, a typical I–V behaviour of a W tip free from any CNT is also given in Fig.2(b) to confirm that the above I–V behaviours arose from the MWCNT instead of the W tip. The Fowler–Nordheim (FN) plots, whose abscissa

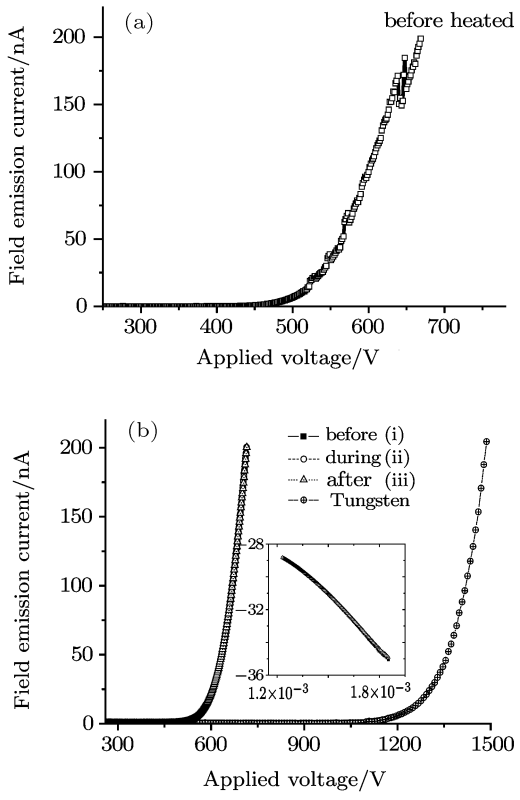
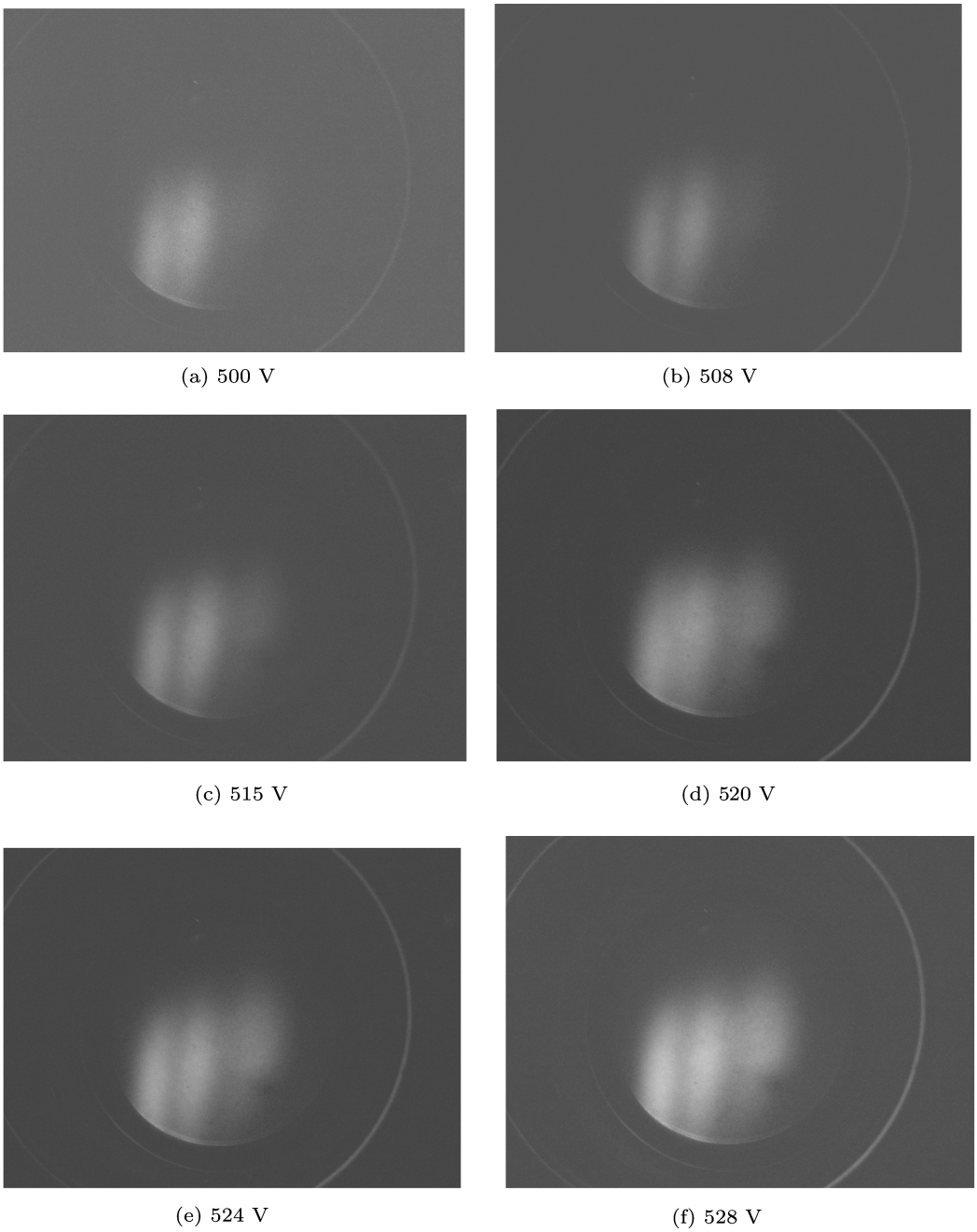


Fig.2. I–V behaviours of MWCNT shown in Fig.1. (a) The unstable behaviour before any heat treatment; (b) The stable behaviour after the heat treatment. (The inset shows the FN plots. Curves (i), (ii) and (iii) are obtained before, during and after the acquisition of the FEM images, respectively. Since the emission is stable, the three curves almost coincide).

and ordinate are respectively $1/V$ and $\ln(I/V^2)$, are given in the inset of Fig.2(b). They are approximately straight lines and thus the electron emission from the MWCNT is confirmed to be the consequence of the tunneling effect.

The FEM pattern of the two-branched MWCNT was studied. The result shown in Fig.3 was obtained at room temperature. When the voltage was below 500 V, the FEM pattern was hardly visible on the screen. When the voltage was raised to 500 V, two bright streaks emerged and a third streak was also dimly visible. As the voltage was further raised, the contrast of the streaks was improved. The FEM image with the optimal quality was obtained under a voltage of 528 V. In Fig.3(f), the three streaks are very clear. They are separated by a spacing of 8.3 mm. The spatial distribution of the imaging intensities along a direction approximately perpendicular to the streaks is given in Fig.4, in which the three peaks correspond to the three streaks in Fig.3. In our previous work, the field emission from an individual CNT only gave rise to an FEM pattern of a round spot,[23,26] thus the FEM pattern reported here is believed to be the consequence of interference between the electron waves from the two coherent sources on the MWCNT.



(a) 500 V (b) 508 V

(c) 515 V (d) 520 V

(e) 524 V (f) 528 V

Fig.3. FEM patterns at 500 (a), 508 (b), 515 (c), 520 (d), 524 (e) and 528 V (f), respectively.

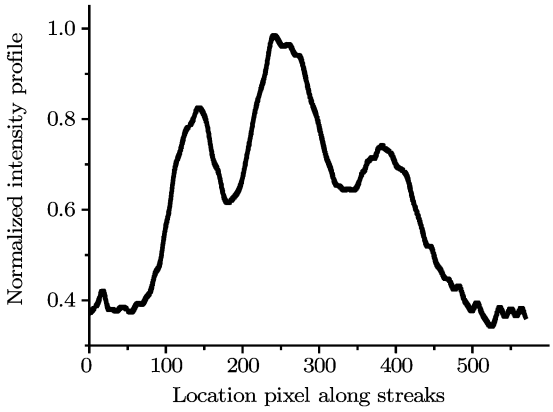


Fig.4. Intensity distribution along the direction approximately perpendicular to the streaks.

Lowering the temperature of the emitter down to liquid nitrogen temperature did not lead to obvious improvement in the quality of the streak pattern. In contrast, when the temperature of the tip was raised to 1×10^3 °C, the streaks disappeared and the FEM pattern turned into a bright spot.

The observed pattern can be well interpreted as a consequence of Young's two-beam interference. It is possible that the sources of the two electron beams were two individual protrusions on the open ends of the MWCNT. Nonetheless, the sample had undergone a blunting process before the FEM patterns were acquired. That is, the heating and the extraction of the field emission current had probably removed the protrusions at the end of the MWCNT. Moreover, it is interesting to make a comparison between the pattern in Fig.3 and the interference patterns obtained by other researchers. In the coherent field emission results reported by previous researchers, the whole patterns were often a superposition of an ordinary FEM pattern and interference fringes. In most cases, the sources of the coherent electron beams were two separate sites on a capped end of a CNT. For instance, the observed fringes could arise from the interference between the emissions from two adjacent pentagons.[11] In contrast, the pattern shown in Fig.3 contains interference fringes only. No individual sites on the CNT end were imaged. Therefore, it seems to be more reasonable to believe that the two entire ends of the double branches, instead of some individual sites on them, behaved as the two beam sources. That is, the two branches are considered to have divided the wavefront of the electron wave and served as two secondary coherent wave sources, which are termed as two "pinholes" in the book by Born and Wolf.[27]

As shown in Fig.1, the two branches are not completely separated from each other. Actually their walls are in contact between the W tip and the position indicated by the arrow. Therefore, it is assumed that the electron wave was not divided into two wave-fronts until it reached the arrowed position. The part above the arrowed position in each branch, which is around 0.1 μm in length, is referred to as the 'branch tip' here.

There have already been a number of reports that an MWCNT is a ballistic conductor and in some cases the mean free path of electrons in it can be as long as about 10 μm.[28−31] Of course, whether an MWCNT can become a ballistic conductor depends remarkably on its fabrication condition, and there are also reports showing that an MWCNT appears to be a diffusive conductor.[32] Although it cannot be guaranteed that every MWCNT is a ballistic conductor, obtaining a relatively long mean free path in it is not difficult when the fabrication condition is properly controlled. Since the two branch tips are about 0.1 μm in length, it is assumed that the electrons in them experience a ballistic transport before the emission. Ballistic transport consists of single electron conduction with no phase and momentum relaxation.[33] Consequently, the two electron beams retain their respective phases in the branch tips, thus they are coherent.

The dependence of the image quality on temperature can also be readily interpreted by using the above assumption of ballistic transport. If the lengths of the two branch tips are already smaller than the mean free path of an electron, lowering the tip temperature will not further obviously reduce the scattering undergone by electrons in their journey from the arrowed position to the ends of the MWCNT. In contrast, the raising of temperature can result in more scattering events, thus leading to a shorter mean free path. Therefore, the phase of the electron wave cannot be retained any longer during the transport in the two branch tips, and the coherency is damaged.

It is well known that a Young's interference gives rise to, in the paraxial approximation, a series of parallel fringes separated by

$$\delta x = \frac{D\lambda}{d}, \tag{1}$$

where δx is the separation between two adjacent bright fringes, D is the distance between the line joining the two pinholes and the plane of observation, λ is the wavelength of the electron wave, and d is the separation between the two pinholes.[27]

It should be noted that the situation for the electron wave in an FEM differs slightly from that for monochromatic light in a typical Young's experiment. Actually, after exiting from the two MWCNT branches the electrons were in an accelerating field. Thus, strictly speaking, the electron wavelength was not a constant from the MWCNT tip to the screen. Nonetheless, the electrostatic force imposed on an electron was strong only in the vicinity of the tip and attenuated rapidly when the electron moved away from the tip. Even for a traditional W tip, electrons pick up almost their full kinetic energy in a distance of a few tip radii.[34] Thus, the space between the MWCNT and the screen was almost field free due to the fact that the MWCNT–anode separation was much larger than the radius of the emitter. As a result, the electron wave can be well approximated by a plane wave, whose wavelength is determined by the accelerating voltage

$$\lambda = \frac{h}{p} \approx \frac{12.25}{\sqrt{V_{\mathrm{a}}}}, \tag{2}$$

where h is the Planck constant, p is the electron momentum and V_{a} is the accelerating voltage between the anode and the tip. Here V_{a} and λ are in volt and in angstrom, respectively.[35] By inserting the value of the voltage with the best image quality, one obtains $\lambda = 0.53$ Å (1 Å=0.1 nm). Of course, the value of λ depends on that of V_{a}. Since the accelerating voltage did not change too much during the acquisition of the interference fringes, the change of λ is neglected.

As mentioned above, $\delta x = 8.3$ mm and $D = 172$ mm. Thus, d is calculated to be 1.1 nm. As argued above, the field emission under which a stable interference pattern was attainable did not seem to come from several particular sites on the MWCNT end. Thus it is reasonable to believe that the whole end of each branch made a contribution to the field emission. Under such a circumstance, each branch tip was equivalent to a virtual source, which is defined as an area from which the electrons seem to originate when they are traced back along their trajectories.[36] As is clear in Fig.1, the diameters of the two branches were of the order of 10 nm. Since the electron beams emitted from the two branch tips did not follow parallel trajectories, probably the separation of their virtual sources was of the order of 1 nm. That is, the Young's interference-based interpretation of the FEM pattern obtained here is self-supporting.

4. Conclusion

An MWCNT field emitter with two open-ended branches is fabricated in a TEM study and its field emission is studied in an FEM. Its FEM pattern is composed of three parallel streaks that can be interpreted as fringes of a Young's interference. As suggested by the quantitative analysis of the result, the open ends of the two branches are believed to serve as two coherent virtual sources. Compared with previous results on the coherent electron emission from CNTs, the result described here features a pure interference pattern that contains exclusively interference fringes. It indicates that coherent electron emission can occur not only between different sites on a capped CNT end, but also sometimes between different CNT branches.

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