Quantum Effects At Field Emission From Carbon Quasi-1D Cathodes

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A low threshold voltage and anomalous large currents of field emission from nanotube cathodes was observed by various researchers. Traditionally, current-voltage (I-V) characteristics of field emission of carbon nanocathodes are interpreted by Fowler-Nordheim model.[1-3] It is known that the Fowler-Nordheim model was developed for 3D-metal cathodes with having the quasi-continuous spectre of electrons $f(\varepsilon) = const\sqrt{\varepsilon}$, where $f(\varepsilon)$ and ε are the function of density states (DOS) and the kinetic energy of electrons, respectively. Therefore the Fowler-Nordheim relationship for emission current is continuously rising too on all energy range and grows exponentially.
But carbon nanotube is a quantum wire and a quantum-dimensional effects should be observed in their electron transport. Many various researchers marked a low correlation between data of a field emission from carbon nanotube cathodes and Fowler-Nordheim equation [4-6].This phenomena has not still an explanatory model. In our work the influence of the quantum-dimensional phenomena on field emission from carbon nanotube cathods was studied theoretical and experimental.
It was shown theoretically the full spectrum of electronic states of single wall carbon nanotube (SWNT) includes of the continuous E_{con} and the discrete E_{dis} parts. The distribution function can be written as

$$E_{CNT} = E_{con} + E_{dis} = \frac{\hbar^2 k_z^2}{2m} + \frac{\hbar^2 \pi^2 n^2}{2m\, l^2}, \qquad (1)$$

where $\boldsymbol{k_z}$, ***m*** and ***l*** are the wave function, the electron mass and length of electron's orbit of nanotube, respectively. The general form of DOS for the continuously part of electron spectra can be written as 3D crystal. The general form of DOS of the discrete part is given as

$$f(\varepsilon) = \sum_i \frac{A}{\sqrt{\varepsilon_i - \varepsilon_F}} \qquad (2)$$

ε_F is Fermi energy. The DOS of the quantum electrons contains the Van Hove singularity.. As the electron spectrum is mixed the position of Fermi level will be to determine the domination part of the electron spectrum. The electron density and conductivity of nanotube are increased rapidly near the Van Hove singularity. As the electron spectrum is mixed the position of Fermi level determines the domination part of the electron spectrum (the continuous or the discrete part). In accordance to (2) and (3) the emission current from nanotube catod doesn't correspond to the Fawler-Nordgeim law and can be written as

$$J(E) = e\sum_{i=1,2} \int_{\varepsilon_{min}}^{\varepsilon_{max}} f(\varepsilon_F - \varepsilon_{i(\ )}) D(\varepsilon_z, E)\, d\varepsilon_i \qquad (3)$$

The electron density and conductivity of nanotube are increased rapidly near the Van Hove singularity. The change of emission current conforms with the change of nanotube conductivity and the sharp peaks appear on the current-voltage characteristic
Result of quantization is also presence of the threshold of the start of field emission on the I-V characteristics.
The I-V characteristics at field emission from quasi-1D carbon cathodes (carbon thin multi-walled nanotubes; vertically aligned carbon nanotube arrays; graphene nanoribbons) were experimentally measured using scanning electron microscope Carl Zeiss NEON 40 (Fig.1). For all types of cathodes the voltage thresholds for the start of electron emission are detected in the field emission I-V characteristics (Fig.2). The voltage thresholds are a clearly marked on Fowler-Nordgeim plot (Fig2b). Also when the magnitude of cathode voltage greater-than the voltage threshold we can see the sharp peaks with a small full width (less 100mV) at half maximum on I-V characteristics. The emission current at peak's maximum was several times as much than it follows from Fowler-Nordgeim relationship. The

appearance of sharp peaks on I-V characteristics are connected with the high electron localization near features of Van Hova in the electron spectrum of carbon nanocathodes.
Possible mechanism of field emission from quasi-1D carbon cathodes will be discussed.

References

[1] Forbes R.G., Sol. State Electronics, **45** (2001) 779–808.
[2] Wang X., Lin Z. et al., J. Phys. D: Appl. Phys., **40** (2007) 4775–4778.
[3] Sveningsson M., Morjan R.-E. et. al. Appl. Phys., **A73** (2001) 409–418.
[4] D. Lovall et al., Phys. Rev. B, **61(8)** (2000) 5683
[5] M.J. Fransen, Th.L. van Rooy, P., Kruit., Applied Surface Science, **146** (1999) 312–327
[6] Stetsenko B.V., Shchurenko A.I. Problems of Atomic Sci.and Techn., **1,** Plasma Physics.(2009)136

Figures

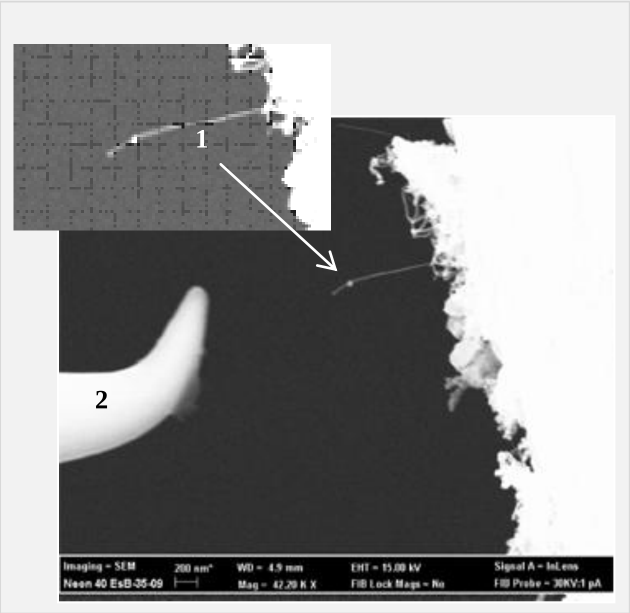

Fig.1. SEM image of the experimental setup for field emission: (1) is single multi-walled nanotube with 14 nm diameter and length 1,5 mkm; (2) is tungsten anode

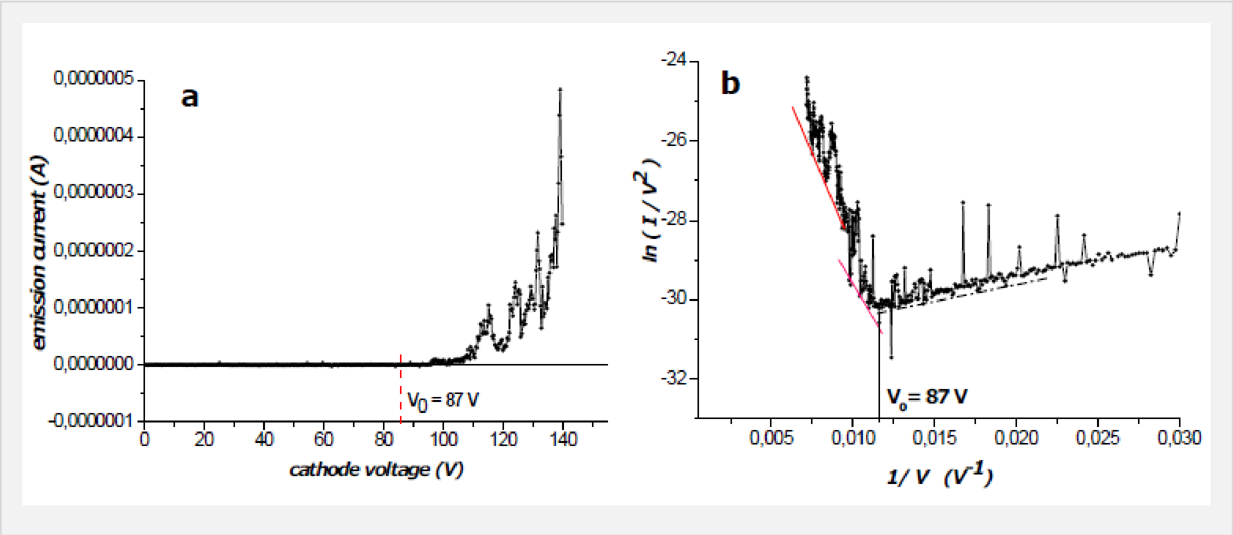

Fig.2. Field-emission current vs voltage curve from single multi-walled carbon nanotubes(a) and Fowler–Nordeim plot (b).