Mechanism of Low-voltage Field Emission from Carbon Nanotube Cathode

G.G. Kosakovskii[1] , Z.Ya Kosakovskaya[1],
E.V. Blagov[2], Yu.I. Latyshev[1], A.P. Orlov[1], A.M. Smolovich[1].

[1] Kotel'nikov Institute of Radio Engineering and Electronics of RAS, Mokhovaya 11, Moscow, Russia
[2]Institute of Nanotechnology Microelectronics of the RAS, Nagatinskaya 16, Moscow, Russia
German_kos@mail.ru

Already first study of a field emission from carbon nanotube (CNT) were shown the abnormally high density of emission current (up to 2-3 orders) at a low magnitude of electric field intensity [1]. It is known the similar deviation from Fowler-Nordgeim function (FN) have also the flat cathodes, which were coated by films with the low-dimensional structures such as Ge-Si, In-Sn-O and diamond-like films [2, 3]. The object of our work was study the peculiarities of low-voltage field emission (LVFE) from CNT emitter at condition of the dimensional quantization of charge.

For measuring of the current-voltage characteristics the model of nanodiode was assembled in SEM Carl Zeiss 40 (Fig.1 a). As emitters were used the direct nanotubes with diameter of 14 nm and length of 1.4 microns which was synthesized by arc method. The study of the nanotube field emission were conducted in two modes: (i) into electrostatic field by scan of current-voltage characteristics with a voltage step 30 mV; (ii) into microwave field by the scan of frequency.

The following results were obtained at the study of field emission of nanodiode with CNT emitter. Measured value of the emission current is always more the value current calculating by Fowler-Nordheim equation. On F-N plot of CVC curve, we can see the resonance peaks (fig.1b) and the voltage threshold for start emission (U_{thr}) (fig.1c). Emergence of a resonance peaks on the CVC curve near the Van Hove singularities indicates the existence of conduction channels which caused by the size quantization in the nanotube emitter. At $U < U_{thr}$ the conductivity of electric circuit of CNT emitter decreases with increasing voltage. At $U < U_{thr}$ the conductivity decreases with increasing voltage. When $U > U_{thr}$ observed the field electron emission which is always accompanied by IR emission. Resonance peaks on CVC curve correspond to the conduction channels, which always have the negative sections differential conductivity (Fig.2). Study of the charge density distribution along the nanotube axis revealed the appearance of the superlattice into electron gas near the voltage threshold. It was established that the superlattice period decreases with increasing voltage between the anode and the cathode. (Fig.3a -b). The interaction between the electronic systems of individual non-contacting nanotubes was found which could be explained by the collectivization of their electronic states.

By summarizing results, we may make following conclusion. The resonance peaks of I-V characteristic indicate the quantum nature of the of the charge transport in circuit nanotube emitter. Superlattice of electronic gas and the dependence of its period from applied voltage, and the interaction of the electronic subsystems of individual CNTs (Fig. 3), the negative differential conductance indicate on the collective nature of the charge transport near the Van Hove singularities.

There are the potential barriers on both ends of the nanotube emitter, which cause the localization of charge carriers into nanotube (Fig. 4). Ballistic the nanotube conductivity of nanotubes and the potential barriers at both ends thereof are the cause of size quantization electron along the nanotube length nanotube emitter. It is for this reason, increasing the applied voltage ($V < V_{thr}$) causes a decrease of CNTs conductivity and the simultaneous increases of charge density (Fig. 1). When the Fermi level approaching to the Van Hove point the charge density is growing rapidly and the conditions for the condensation of the Fermi electron gas to a Luttinger liquid are appearing. As a result of the Friedel oscillations on the potential barriers are emerged the standing wave of charge density of a localized electrons which formed superlattice along nanotube. At the same time the energy of the potential barriers at both ends of the nanotube have redistributed by the Friedel oscillations. Potential barrier height drops dramatically and the process of collective tunneling of electrons through potential barrier to vacuum collective electron tunneling process through potential barrier to vacuum begins at low voltage. Note that in the emitter circuit together with a DC emission current flows AC current whose frequency depends on the voltage applied.

References

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Figures

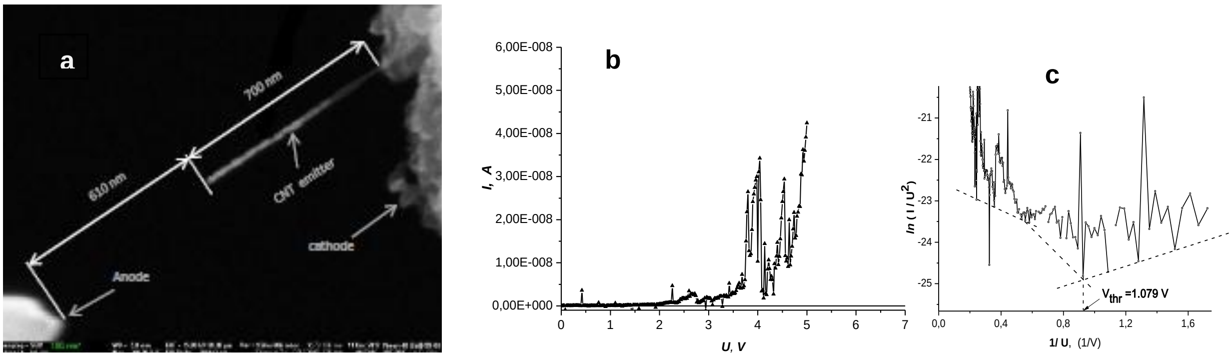

Figure 1. SEM image of nanodiode with CNT emitter (a) and its I-V characteristic of field emission in traditional (a) and Fowler-Nordgeim plot (c).

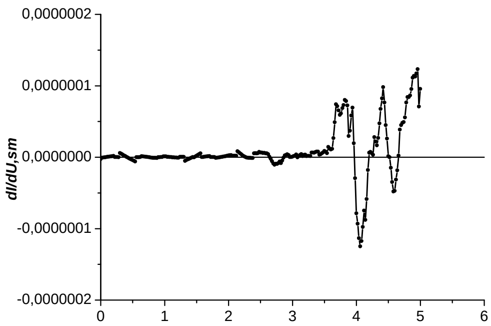

Figure 2. The differential conduction of CNT emitter

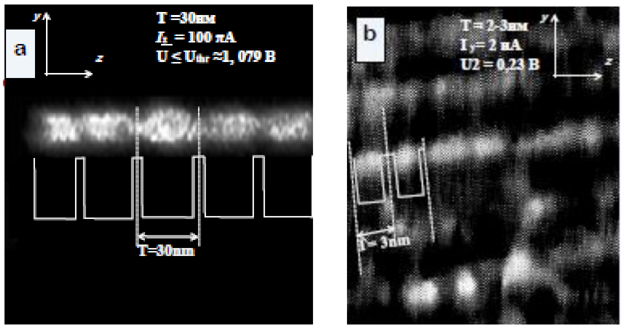

Figure 3. SEM image of nanotube emitter at U ≤ U_{thr} (a) and STM image of nanotube bundle (b)

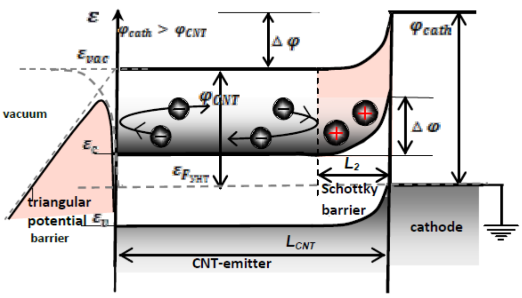

Figure 4. The energy scheme of the CNT emitter in contact with 3D metal cathode