A comparative study of field emission from single- and double-wall carbon nanotubes and carbon peapods

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Abstract. In this work field electron emission was studied for a variety of single-wall carbon nanotube-based nanostructures (arc and HipCO nanotubes, C_{60} -and C_{70}-based carbon peapods, double-wall nanotubes) in the same conditions. A comparable surface roughness for all samples was confirmed by a scanning electronic microscopy, while distribution of emission centers was visualized with a phosphorescent anode screen. We developed an original approach that improves a reliability of the field emission threshold measurements. All materials showed the emission threshold values ranging from 0.5 to 2.5 V/μm. The lowest threshold was observed for HipCO and double-wall materials that contain thinner nanotubes than other studied materials.

INTRODUCTION

Carbon peapods and double-wall carbon nanotubes (DWNT) are novel nanostructures [1, 2] based on single-wall carbon nanotubes (SWNT). Since SWNT is an efficient field emission (FE) electron source [3-7], one may expect that both carbon peapods and DWNT should also show strong FE performance. However, since until now these materials have been obtained in rather small volumes and FE measurements have been performed in different geometries, the quantitative comparison has not been made yet. In this work we in the first time report on the comparative study of the FE in a variety of SWNT-based nanostructures (arc and HipCO SWNT, C_{60} -and C_{70}-based carbon peapods, DWNT) using the same experimental setup.

EXPERIMENTAL

Field emission measurements were performed in a vacuum diode configuration with the flat cathode and anode. The nanotube-based cathodes were placed on the holder, which position and tilt with respect to the anode can be changed. In our experiments, anode was made of either metal or glass with conductive ITO electrode covered by the phosphor layer. In the latter case we were able to visualize distribution

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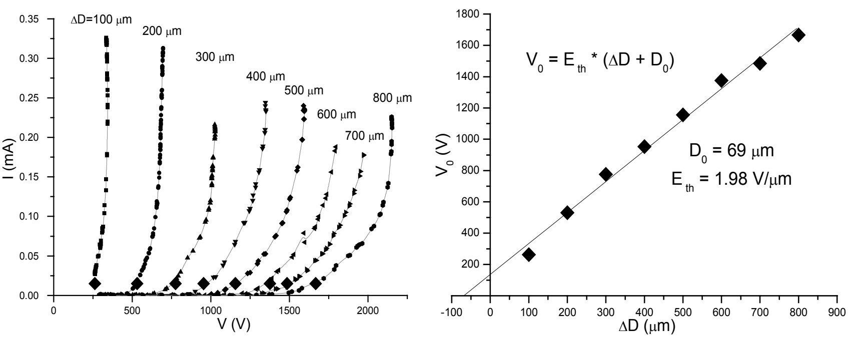
of emission sites over the cathode surface. The current-voltage measurements were performed at room temperature, residual pressure of 10^{-5} Torr and bias up to 20kV. In order to observe the sample during the measurement process and to capture light emitted by the phosphor layer, we employed a measuring cell with a bell glass.

SWNT were synthesized by arc-discharge method with Ni/Co or Ni/Y_2O_3 catalyst. Commercially available raw and purified HipCO nanotubes were used. The peapods were formed from SWNT (arc-produced with Ni/Co) by filling them with C_{60} or C_{70} molecules at elevated temperature. The double-wall carbon nanotubes were synthesized by heating in vacuum of C_{60}-filled peapods.

In order to compare the FE properties of cathodes made from different nanocarbon materials, we prepared samples of the same shape and thickness and glued them onto Ni substrates. The morphology of each sample was examined by using Scanning Electron Microscope LEO-15500.

RESULTS AND DISCUSSION

Field emission measurements were performed in a vacuum diode configuration with the flat cathode [8]. In order to compare the FE efficiency in different materials we developed a new method that enabled to determine the threshold electric field ($\boldsymbol{E_{th}}$) at cathode surface for all materials. This field can be found from $\boldsymbol{E_{th} = V_{th}/D}$, where $\boldsymbol{V_{th}}$ is the "switch on" threshold voltage and $\boldsymbol{D}$ is an inter-electrode distance. However, in the experiment, we can directly measure only a relative displacement $\boldsymbol{\Delta D}$ of the cathode rather than its distance from the anode, i.e. $\boldsymbol{D=D_0+\Delta D}$, where $\boldsymbol{D_0}$ is *a priori* unknown. In order to overcome this difficulty, for each nano-carbon cathode we measured a current I as a function of $\boldsymbol{V}$ at several displacements $\boldsymbol{\Delta D}$ (see *Figure 1 a*).



(a) (b)

FIGURE 1. (a)A family of ***I-V*** dependences for the carbon peapods, fully filled with C_{60}, measured with different distances between electrodes ***D*** (mm). The emission threshold points are marked at the current level of 0.02 mA. (b) The emission threshold voltage dependence on the distance between electrodes. Points - experiment, line - its linear approximation.

From these measurements, we determined the voltage V_0 that corresponds to the current of $\boldsymbol{I_0}$ = 0.02 mA. This voltage is slightly above the "switch on" threshold V_{th} for the particular sample at a given ΔD. Since the FE threshold $E_{th} = V_{th}/D$ is an intrinsic parameter of the cathode material that does not depend on applied voltage and distance between the cathode and anode, V_{th} is a linear function D. Correspondingly, the measured in the experiment V_0 should be a linear function of ΔD. Therefore, the offset of the measured dependence $V_0(\Delta D)$ in the horizontal axis (see Figure 1b) gives us the value of D_0 and the FE threshold E_{th} [8].

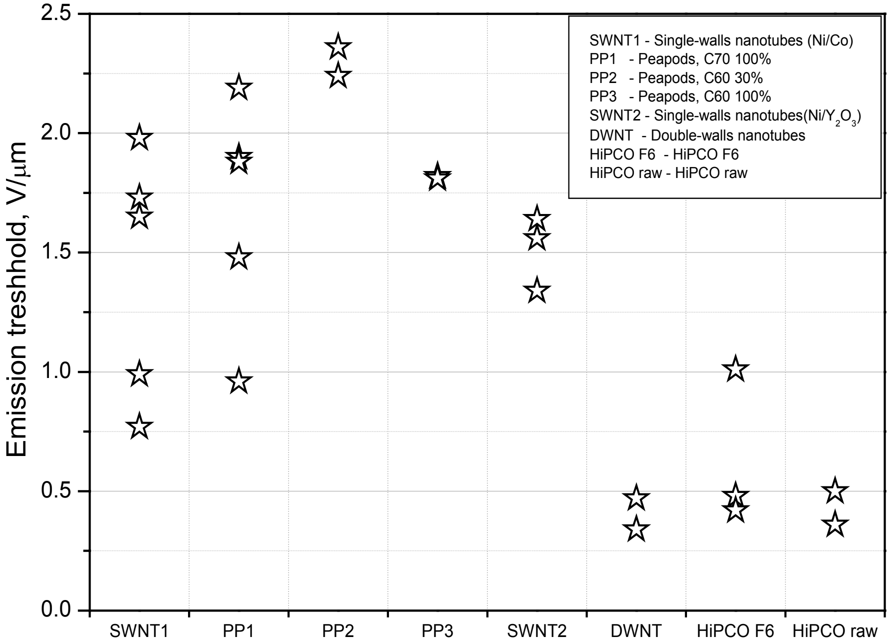
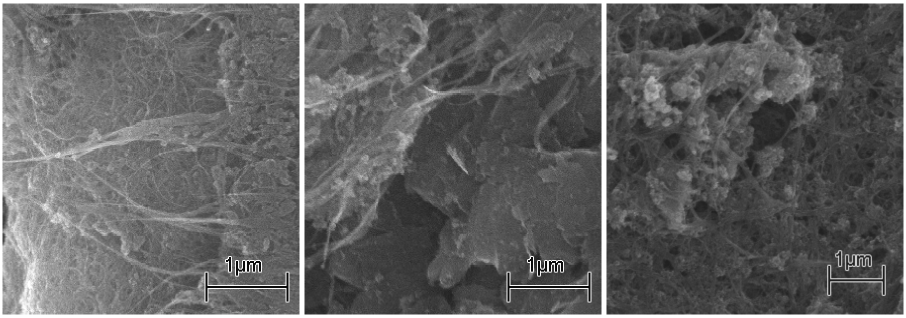


FIGURE 2. The emission threshold values measured for different carbon materials. The legend is in the insert.



(a) (b) (c)

FIGURE 3. SEM images for SWNT synthesized by arc technique with Ni/Co catalyst (a), peapods filled with C_{70} (b) and SWNT synthesized with Ni/Y_2O_3 catalyst (c).

We employed the developed method to measure the FE threshold for all studied nanotube-based materials (see insert to Figure 2) and using several samples for each material. One can observe that the obtained threshold values are spreaded in the range

0.5-2.5 V/μm. The lowest threshold was observed for samples containing (both raw and purified) HipCO nanotubes and double-wall SWNT. The latter material was manufactured by heating of arc-SWNT based on C_{60} peapods. We suggest that such a reduction of the FE threshold is due to the presence of the nanotubes with the smallest diameter (0.6-1.0 nm) in HipCO nanotubes and double-wall SWNT.

CONCLUSION

We developed a novel approach that allows us to improve a reliability of the FE threshold measurements. This approach was demonstrated for nanocarbon cathodes made of different SWNT-based materials. The surface roughness of cathodes was investigated with a scanning electronic microscopy, while the phosphorescent anode screen was used to visualize a distribution of emission centers on the cathode surface. The nano-carbon films investigated showed the FE threshold values ranging from 0.5 to 2.5 V/μm. We suggest that the thinnest SWNT in HipCO- and DWNT-based cathodes are responsible for the relatively low FE threshold of 0.5 V/μm in these materials.

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REFERENCES

1. W. Smith, M. Montioux, et al., *Nature, 396 (1998) 323.*
2. R. Pfeiffer, H. Kuzmany, Ch. Kramberger, et al., *PRL 90 (2003) 225501.*
3. L.A. Chernozatonskii, Yu.V. Gulyaev, Z.Ya Kosakovskaya, et al., *Chem. Phys. Lett. 233 (1995) 6.*
4. W.A. de Heer, A. Chatelain, D. Ugarte, *Science 270 (1995) 1179.*
5. J.M. Bonard, J.P. Salvetat, W.A. de Heer, et al., *Appl. Phys. Lett. 73 (1998) 918.*
6. A.N. Obraztsov, I. Pavlovsky, A.P. Volkov et al., *J. of Vacuum Science & Tech. B 18 (2000) 1059.*
7. E.D. Obraztsova, A.S Pozharov, S.V. Terekhov et al., *Proc. of Material Research Society, Symp., 2002, vol. 706, p. Z6.7.1-Z6.7.6.*
8. A.N. Obraztsov et al., *Appl. Surf. Sci., 215 (2003) 214.*