Charge Carrier Transport Properties in Single-Walled Carbon Nanotube Fibers

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Transport properties via temperature dependences of sample resistance $R(T)$ and influence of microwave field of 10 GHz on the conductivity of the single-walled carbon nanotubes fibers are investigated. The $R(T)$ dependences studied within 4.2–300 K can be well approximated by the Mott law for 3D variable range hopping below $T = 80$ K and by typical law for fluctuation-induced tunnelling model within the temperature range 80–300 K. We associate the observed increase in the conductivity with microwave power by increase in hopping probability of the charge carriers between single-walled carbon nanotubes.

PACS numbers: 73.63.Fg

1. Introduction

Transport properties of single-walled carbon nanotubes (SWCNTs) are of particular interest from a point of view of both basic physics and applications. On the one hand, the material allows a study of a large variety of different quan-

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tum phenomena like single-electron tunnelling [1], Luttinger liquid behaviour [2], ballistic transport [3], etc. On the other hand, carbon nanotube-based electronics has promising application starting from antistatic shielding, transparent conductive layers, interconnections and heat sinks in integrated circuits as well as gas, bio- and chemical sensors. For the latter aims a particular role is played by arrays (fibers) of carbon nanotubes. Hence, the understanding of charge carrier properties is one of the key-topics in the development of new devices.

2. Experimental results

The SWCNTs fibers were synthesized using wet spinning process from solutions comprising nanotubes, surfactant and water. This process provides polymer-free nanotubes fibers without the need for super acid. The fabrication procedure was described in detail in Ref. [4]. The SWCNT raw material itself was prepared by laser ablation. The fibers consist of a great number of individual nanotubes and typically have a diameter of $50-100$ μm. Scanning electron microscopy investigations of the structure of the fibers surface suggest a certain degree of individual nanotubes alignment inside the fibers.

In order to determine transport mechanisms, the temperature dependences of resistance $R(T)$ of SWCNT fibers were measured in the range of 4.2–300 K. To complete charge carrier transport picture in strong electric fields, we have applied microwave (MW) field of 10 GHz to measure change of the conductivity averaged over the MW field period. The dependences were recorded at temperatures 77 K and 300 K.

3. Discussion

The $R(T)$ dependence of the SWCNT fibers is shown in Fig. 1. In the low-temperature range (4.2–80 K) the resistance as a function of temperature exhibits a classical 3D variable range hopping Mott conduction, following the law [5]:

$$R = R_0 \exp(T_0/T)^{1/4}. \tag{1}$$

In the temperature range $T = 80-300$ K $R(T)$ dependences can be approximated by a typical law for fluctuation-induced tunnelling conductivity mechanism [6, 7]:

$$R = R_0 \exp\left(\frac{T_1}{T + T_0}\right), \tag{2}$$

where parameters T_0 and T_1 are defined by the following equations:

$$T_0 = 16\varepsilon_0 \hbar A V_0^{3/2} / \left[\pi e^2 k_{\mathrm{B}} (2m_{\mathrm{e}})^{1/2} w^2\right], \tag{3}$$

$$T_1 = 8\varepsilon_0 A V_0^2 / (e^2 k_{\mathrm{B}} w), \tag{4}$$

where w is the width of the tunnel junction, A labels its area, and V_0 is the height of the contact potential; k_{B} stands for the Boltzmann constant, e is the electronic charge and m_{e} denotes the electron's effective mass, and ε_0 the vacuum permittivity.
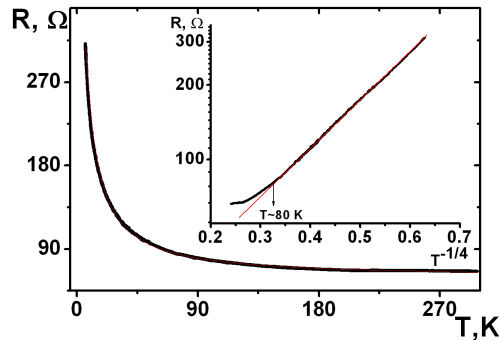
Fig. 1. The temperature dependence of the resistance of the SWCNT fibers. The inset shows the log $R - T^{-1/4}$ plot.

Differently from systems with hopping charge carrier transport between localized sites, the fluctuation-induced tunnelling conductivity model was proposed for disordered heterogeneous systems. As it is known [6], the conduction electrons are delocalized here and free to move over distances very large as compared to atomic dimensions. In these systems (for example, conductor–insulator composites, granular metals, disordered semiconductors) electron transfer between large conductive segments separated by small insulating gaps dominates electrical conductivity. In our case fitting results agree well with experiment data indicating thus importance of intertube contacts between individual carbon nanotubes. We assumed that the area A of the junction equals the cross section of a SWCNT with diameter of about 1.5 nm. Using the expressions (3) and (4) the effective junction width is estimated to be 4.6 nm and the effective barrier height to be 0.172 eV.

The conductivity of SWCNT fibers increased when the microwave field of 10 GHz was applied to the samples. The dependences of the variation of the conductivity of SWCNT fibers on applied MW field power at the temperatures 77 and 300 K are shown in Fig. 2.
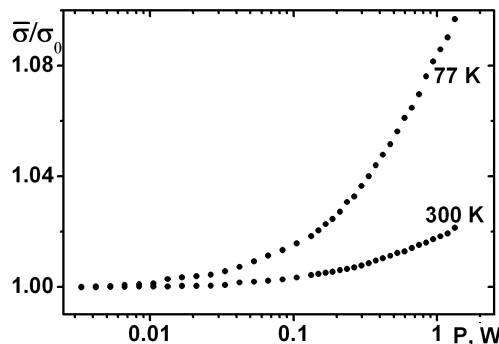

Fig. 2. The dependence of the conductivity variation on applied MW power.

The $R(T)$ dependences indicate that the conduction of the SWCNT fibers can be considered as a combination of two mechanisms: variable range hopping [5] which prevails in the low-temperature range and fluctuation-induced tunnelling due to existence of the contact barriers between individual nanotubes inside the fibers [7]. The energy barriers can exist as a result of contacts either between metallic and semiconductive nanotubes or between semiconductive nanotubes with different band gap.

The increase in the conductivity on MW power becomes more essential with the temperature decrease as one can see from Fig. 2. At the same MW power of about 1 W the relative conductivity increase was about 2% and 10% at 300 K and 77 K, correspondingly. According to R(T) dependences the VRH starts to prevail at temperatures below 80 K. Therefore we associate the increase in the conductivity by increase in the hopping probability of charge carriers in MW field.

In conclusion, charge carrier properties in SWCNT fibers were studied. Experimental data are consistent both with the charge transport model for homogeneously disordered materials due to low-temperature localization of charge carriers arising from the defects in the tubes themselves and with the model for heterogeneous materials that emphasises the role of energy barriers between the nanotubes.

Acknowledgments

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