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COMMENT

Comment on 'Electrical transport via variable range hopping in an individual multi-wall carbon nanotube'

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Abstract
The temperature dependence of the conductance of an individual multi-wall carbon nanotube (MWNT) measured over a temperature range of (297–4.8 K) by Khan *et al* (2008 *J. Phys.: Condens. Matter.* **20** 475207) is interpreted in the framework of the phonon-assisted tunnelling model. It is shown that our presented model describes more adequately the peculiarities of the temperature dependence of the conductance in individual MWNTs supposing that in the process of tunnelling phonons of 1 and 2 meV energy are invoked.

Recently, Khan *et al* [1] presented results on the temperature dependence of the conductance of an individual multi-wall carbon nanotube (MWNT) measured over a temperature range of (297–4.8 K). Three-dimensional variable range hopping (3D VRH) has been applied for conduction in the temperature range 297–70 K, and the 2D VRH mechanism has been invoked for the temperature range 70–4.8 K. With the help of these models, various Mott parameters have been estimated. We want to emphasize that some parameters, such as hopping distance, calculated based on the 3D VRH and 2D VRH mechanism, significantly differ from each other. Indeed, the hopping distance R calculated at 150 K (3D VRH), was found to be 4.66×10^{-6} cm, while R calculated using the 2D VRH model, varied from 0.269×10^{-10} to 0.647×10^{-10} cm as the temperature decreased from 70 to 4.8 K. It is inexplicable why R at 150 K is four orders higher than R at 50 K. Furthermore, the value of 6×10^{-11} cm is much smaller than the atomic radius. Thus, the explanation of the temperature dependence of the conductance presented in reference [1] is doubtful. Therefore, we propose an alternative explanation of the temperature dependence of conductance based on the phonon-assisted (PhAT) model, which has already been used to describe the temperature behaviour of conductance in single-wall carbon nanotubes [2].

The PhAT model is based on the assumption that the temperature-field-dependent conductivity is caused by a thermally activated charge carrier generation process, which is an electric field initiated phonon-assisted tunnelling of electrons from the discrete centres (traps) to the conduction band. Due to the interaction of phonons with electrons, the tunnelling is essentially a temperature-dependent process. If the current is governed by electrons released from the traps, then the current I through the nanowire will be proportional to the electron release rate W and the density of the traps N, i.e. $I \propto NW$. Since G is defined as $G = I/V$, the temperature dependence of the conductivity could also be described by the tunnelling rate dependence on temperature $W(T)$. In order to confirm the workability of the PhAT model for explanation of the temperature behaviour of the conductance G in the MWNT, a comparison of the temperature-dependent tunnelling rate $W(T)$, computed using the PhAT theory with $G(T)$ dependence could be performed. For the computation of the transition rate dependence on field strength E and temperature $W(E, T)$, a relatively simple equation for electron tunnelling from the centre to the conduction band, presented in [2, 3], is

used:

$$W(E,T) = \frac{eE_{\square}}{(8m^*\varepsilon_T)^{1/2}}[(1+\gamma^2)^{1/2}-\gamma]^{1/2}[1+\gamma^2]^{-1/4} \times \exp\left\{-\frac{4}{3}\frac{(2m^*)^{1/2}}{eE_{\square}\hbar}\varepsilon_T^{3/2}[(1+\gamma^2)^{1/2}-\gamma]^2 \times \left[(1+\gamma^2)^{1/2}+\tfrac{1}{2}\gamma\right]\right\}, \quad (1)$$

$$\gamma = \frac{(2m^*)^{1/2}\Gamma^2}{8e\hbar E_{\square}\varepsilon_T^{1/2}}$$

where $\Gamma^2 = 8a(\hbar\omega)^2(2n+1)$ is the width of the centre absorption band, $\hbar\omega$ is the phonon energy, $n = [\exp(\hbar\omega/k_{\mathrm{B}}T)-1]^{-1}$, ε_T is the energetic depth of the centre, e is the electronic charge unit, m^* is the electron effective mass, and a is the electron–phonon coupling constant.

The $W(E,T)$ was computed for a centre of 5 meV depth, which was estimated from the straight line at higher temperatures in the plot of $\ln G$ versus $1/T$ from [1] using the relation $G \sim \exp(-\varepsilon_T/kT)$. For the effective mass, the value of $m^* = 0.2m_{\mathrm{e}}$ [4] was used.

In the PhAT theory, the energy of phonons taking part in a tunnelling process is very important. We want to note that there exists a grand variety of vibration modes in carbon nanotubes in the energy range from about 1 to 200 meV [5], and phonons of various energies may take part in the tunnelling process. Since the temperature dependence of the conductivity persists into low temperatures (4 K) and the centre's depth is low, the energy of phonons should not be large. The phonons of higher energy, which probably dominate at higher temperatures, can be frozen in the low temperature range, therefore the phonons of low energy must be effective. For the calculation of $W(T)$ in this comment, we used phonons of 1 meV and 2 meV energy, and the total $W(T)$ was expressed as a sum of $W_1(T)$ and $W_2(T)$ with $\hbar\omega_1 = 1$ meV and $\hbar\omega_2 = 2$ meV, respectively. The electron–phonon coupling constants a_1 and a_2 were chosen so that the best fit of the experimental data with the calculated dependences could be achieved. The fit of the $\ln G(T)$ dependence on T extracted from figure 8 in [1] with the theoretical dependence $\ln[0.1W_1(T)+W_2(T)]$ on temperature is shown by the solid line in figure 1. Apparently, the theoretical curve describes well the temperature behaviour of the conductivity in the entire range of the measured temperatures.

It should also be pointed out that a verdict about the conduction mechanism could not be realized only from the curve of the temperature dependence of the conductivity. The conductance mechanism can be definitely determined from the current–voltage measurement determined at different temperatures. However, the VRH model fails in explaining the conductivity dependence on the applied field strength [2].

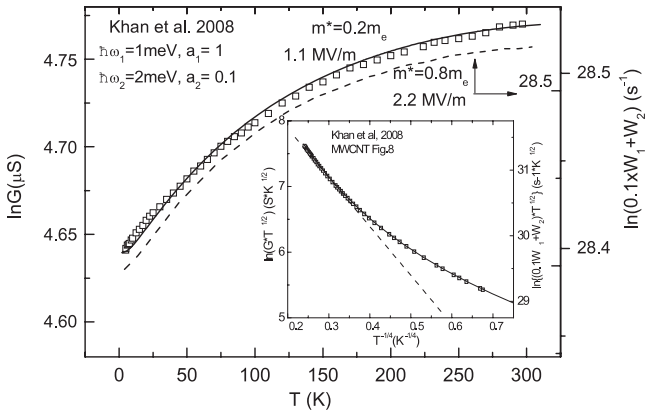

Figure 1. Experimental $G(T)$ dependence on the temperature of individual MWNTs from figure 8 in [1] (symbols) fitted to the theoretical $\ln[0.1W_1(T)+W_2(T)]$ dependences (lines), computed using the parameters: $\varepsilon_T = 5$ meV, $\hbar\omega_1 = 1$ meV, $\hbar\omega_2 = 2$ meV, $a_1 = 1$, $a_2 = 0.1m^* = 0.2m_{\mathrm{e}}$ (solid curve), and $m^* = 0.8m_{\mathrm{e}}$ (dashed curve). Note that the value of effective mass only changes the value of the tunnelling rate but not the shape of the $W(T)$ curve. In the inset of the figure, the plot of $\ln(G^*T^{1/2})$ (symbols) and $\ln[(W^*T^{1/2})]$ (solid line) against $T^{-1/4}$ for the temperature range 4.8–297 K is shown. The dashed line represents 3D VRH behaviour.

In conclusion, the observed conductance can be consistently interpreted in the framework of the model based on the phonon-assisted tunnelling process, initiated by an electric field. An advantage of the PhAT model over the VRH models used in [1] is the possibility of using the behaviour of the $G(T)$ data to describe the same set of parameters: ε_T, $m*$, T, E, $\hbar\omega$, and a, at both low and high temperatures. Out of the aforementioned parameters, only the electron–phonon coupling constant a and the phonon energy $\hbar\omega$ are the fitting parameters, estimated according to the best fitting of the experimental data and the theory. Other parameters are known from experiments or from literary sources. Therefore, the PhAT mechanism could be dominant in the conductance of the individual carbon MWNTs, as previously shown in the case of single-wall carbon nanotubes [2].

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