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Hopping Hall effect in multi-walled carbon nanotubes

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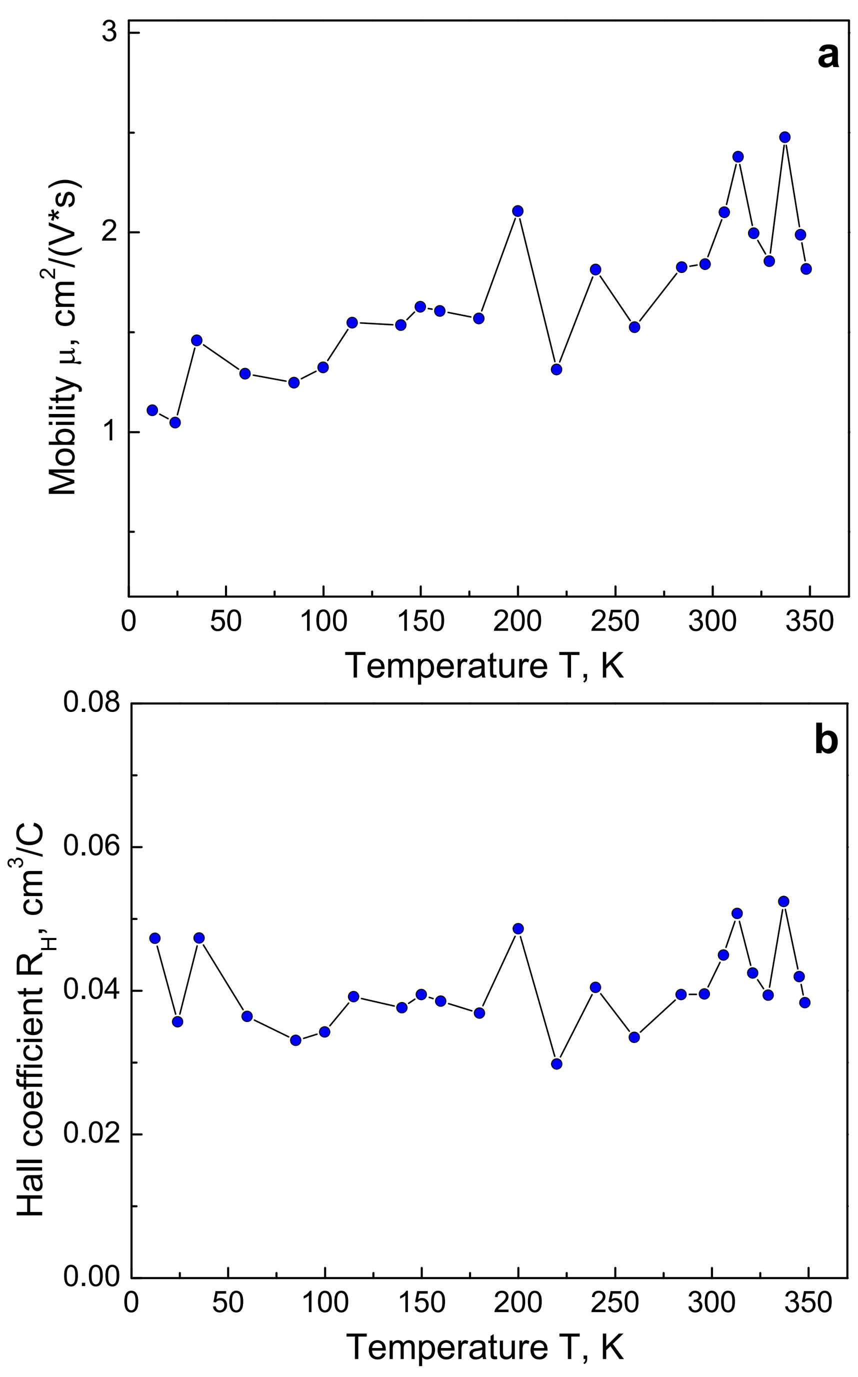

Fig. 1. Temperature dependences of the Hall mobility μ_H and the Hall coefficient R_H.

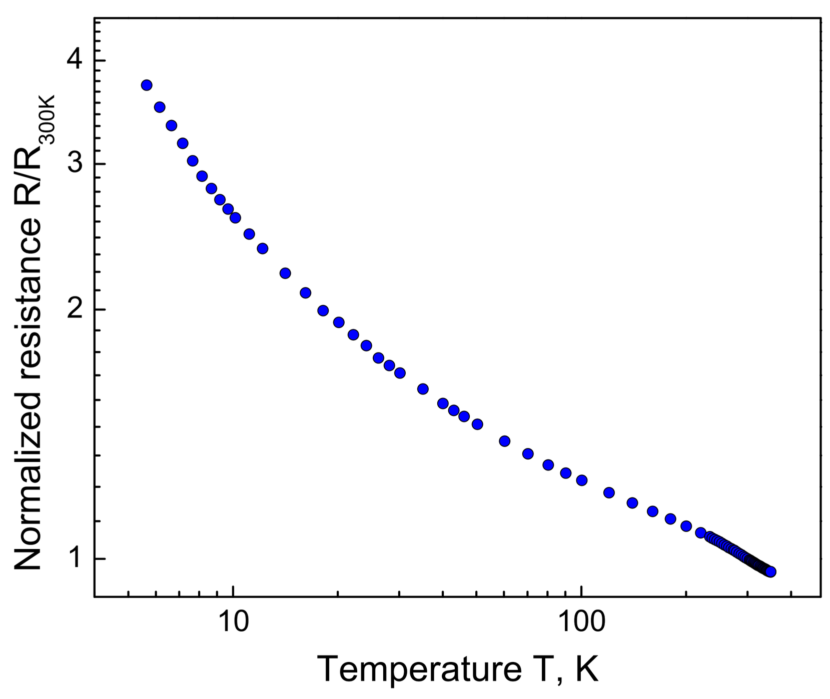

Fig. 2. Temperature dependence of MWCNT resistance normalized to its value at 300 K.

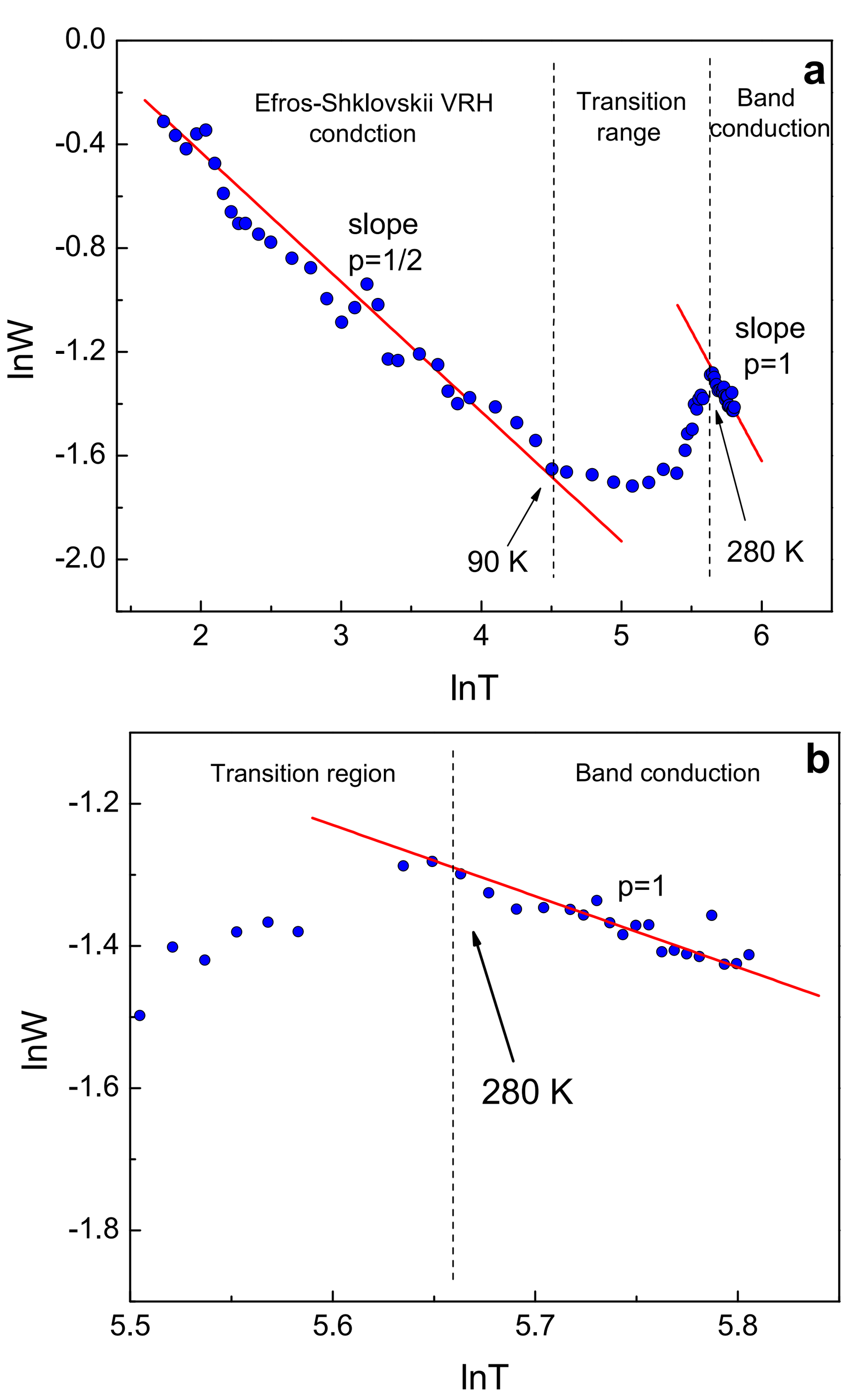

Fig. 3. Temperature dependence of logarithmic derivative W for MWCNT in the temperature ranges of 4.2–340 K (a) and of 245–340 K (b).

MOTIVATION

Carbon nanotubes are promising material for applications in many fields, including electronic devices, due to their unique physical and electrical properties. Hall effect is a valuable tool for the investigation of charge transport in materials. Despite this, only a small number of works have studied the Hall effect in carbon nanotubes.

AIM

The current work aimed to investigate the mechanisms of charge transfer and the Hall effect in multi-walled carbon nanotubes in a wide temperature range of 4.2–340 K.

EXPERIMENTAL DETAILES

Investigated multiwall carbon nanotubes (MWCNT) were produced by Arkema, France. Typical nanotube sizes are 10-15 nm in diameter (5-15 walls) and 1-10 μm in length. The measurements of the Hall effect were performed by the van der Pauw method in a helium cryostat. The studied MWCNT samples had the shape of a rectangular parallelepiped with dimensions 5x5x0.3 mm3, obtained under pressure conditions of ~100 MPa. The magnetic field induction was B=0.3 T. Raman and IR spectra for the studied MWCNTs can be found in our previous work [1].

DISCUSSION

The resistivity of the studied MWCNT sample is about $2*10^{-4}$ Ohm*m at room temperature. Fig. 1 shows the temperature dependence of the Hall mobility μ_H and the Hall coefficient R_H. Over the entire temperature range studied, $R_H>0$. Hall mobility shows a slight increase from ~1 cm^2/V*s to ~2 cm^2/V*s with increasing temperature from 12 K to 340 K.

Discussion of the observed Hall effect requires a detailed consideration of the charge transfer mechanisms in MWCNT. Fig. 2 shows the temperature dependence of the resistivity $\rho(T)$ for MWCNT. In order to find conduction mechanisms and the corresponding temperature intervals, it is convenient to use the logarithmic derivative W:

$$W = -\frac{\partial \ln \rho(T)}{\partial \ln T} \qquad (1)$$

Fig. 3 shows the temperature dependence lnW on lnT. There are two linear sections in the plot, which reveal two different conduction mechanisms at different temperatures.

Below 90 K, experimental data show a slope of p=1/2. It indicates that at low temperatures, Efros-Shklovskii variable range hopping (ESVRH) charge transfer occurs through localized states. Conductivity below 90 K can be described by the expression:

$$\rho = \rho_{0VRH} \cdot \exp\left(\left(\frac{T_0}{T}\right)^{1/2}\right) \qquad (2)$$

where ρ_{0VRH} is a perfactor, T_0 is a characteristic temperature T_0=11 K (Fig. 4a).

The ESVRH mechanism is also confirmed by the behavior of MWCNT resistance in a sufficiently high electric field according to:

$$\rho \propto \exp\left(\left(\frac{E_0}{E}\right)^{1/2}\right) \qquad (3)$$

where E_0 is a characteristic electric field, E_0=3.5*10^4 V/m (Fig. 4b).

At temperatures above 280 K, the logarithmic derivative W has a linear slope equal to p=1 (Fig. 3b). It indicates that at room temperatures and above, electric charge transfer occurs due to band conduction according to:

$$\rho = \rho_{0A} \cdot \exp\left(\frac{E_a}{k_B T}\right) \qquad (4)$$

where ρ_{0A} is the prefactor, E_a is the activation energy, E_a=7 meV (Fig. 5).

Between 90 K and 280 K there is a transition range where the effects of hopping and band conduction are superimposed.

It was found that for MWCNTs the temperature dependence of the Hall mobility can be described by the exponential law (Fig. 6) theoretically predicted for hopping conduction [2]:

$$\mu_H \propto \exp\left(-\alpha \cdot \left(\frac{T_0}{T}\right)^{1/2}\right) \qquad (5)$$

where α is a numerical coefficient, T_0 is a characteristic temperature for ESVRH (2)

It is clear to see in Fig. 6 that experimental data demonstrate linear behavior right up to room temperatures, which exceeds the upper limit of hopping conductivity of 90 K. It indicates that the contribution of hopping conduction to the Hall effect may remain significant up to room temperatures. The deviation from linear behavior (Fig. 6) at temperatures above 280 K is consistent with a change in the charge transfer mechanism (Fig. 3). At temperatures above 280 K, band conduction occurs. It makes it possible to estimate the carrier concentration n in MWCNTs at near room temperatures:

$$R_H = \frac{C}{n \cdot |e|} \qquad (6)$$

where e is elementary charge, C is a certain constant, the value of which depends on the scattering mechanism, C≈1.

It was found that n≈1*10^{20} cm^{-3} at 300 K.

In our case, data analysis (Fig. 4a and Fig. 6) indicates that the numerical coefficient is α=0.65 (see expression (5)).

The obtained data on the hopping Hall effect for MWCNT are in good agreement with the results of our previous work [3], where we observed the Hall effect in the hopping conduction regime for the reduced graphene oxide films with different contents of the sp^2-carbon fraction.

CONCLUSSIONS

1. For the studied MWCNTs (Arkema, France), a positive Hall effect is observed. The mobility of charge carriers increases from ~1 cm2/V*s to ~2 cm2/V*s with increasing temperature from 12 K to 340 K.
2. The investigation of the temperature dependences of electrical resistance and Hall mobility indicates that the hopping conductivity makes the main contribution to the Hall effect in the wide temperature range up to room temperatures.
3. Below 280 K, the temperature dependence of mobility follows an exponential law $\mu_H \sim \exp(-\alpha \cdot (T_0/T)^{1/2})$ theoretically predicted for disordered semiconductors in hopping conduction regime.
4. In the studied MWCNTs, band conduction occurs at temperatures above 280 K, which makes it possible to estimate the charge carrier concentration n≈1*10^{20} cm^{-3} at 300 K.

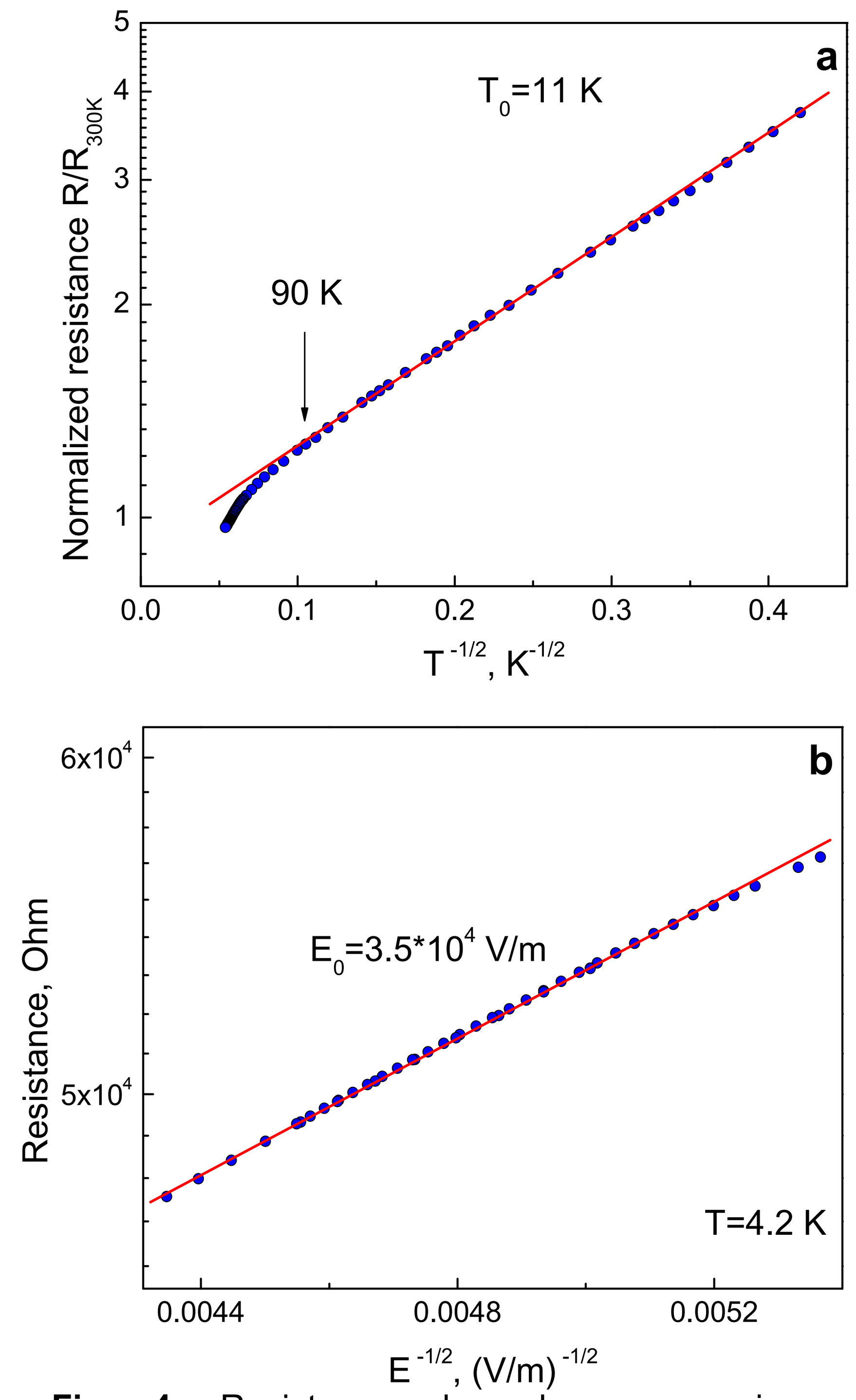

Fig. 4. Resistance dependences on inverse temperature $T^{-1/2}$ (a) and electric field $E^{-1/2}$ (b) for studied MWCNT. Electric-field dependences were obtained at temperature of 4.2 K.

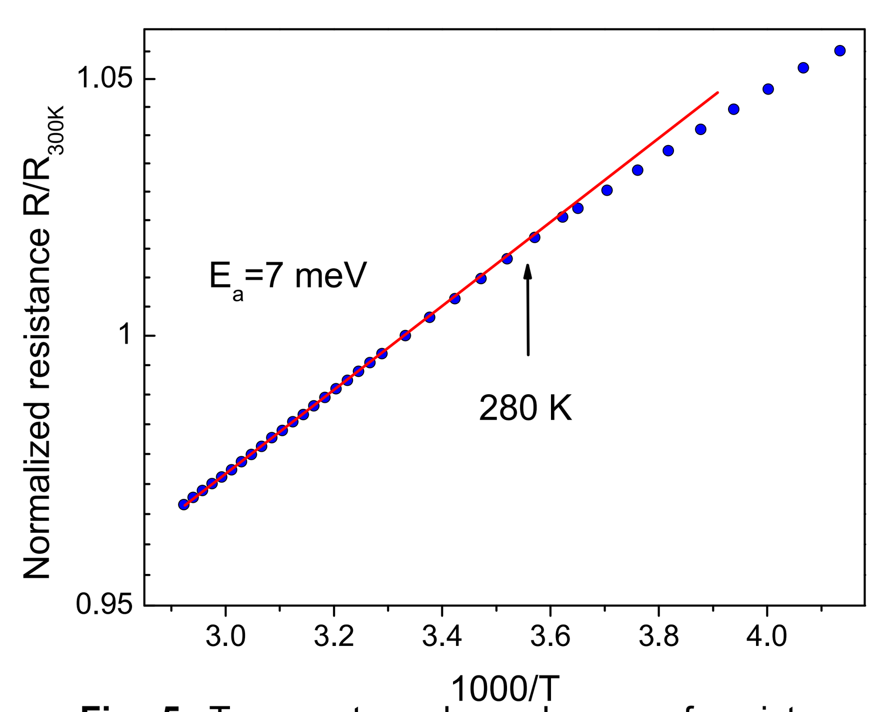

Fig. 5. Temperature dependences of resistance on inverse temperature 1000/T in the range 210–340 K.

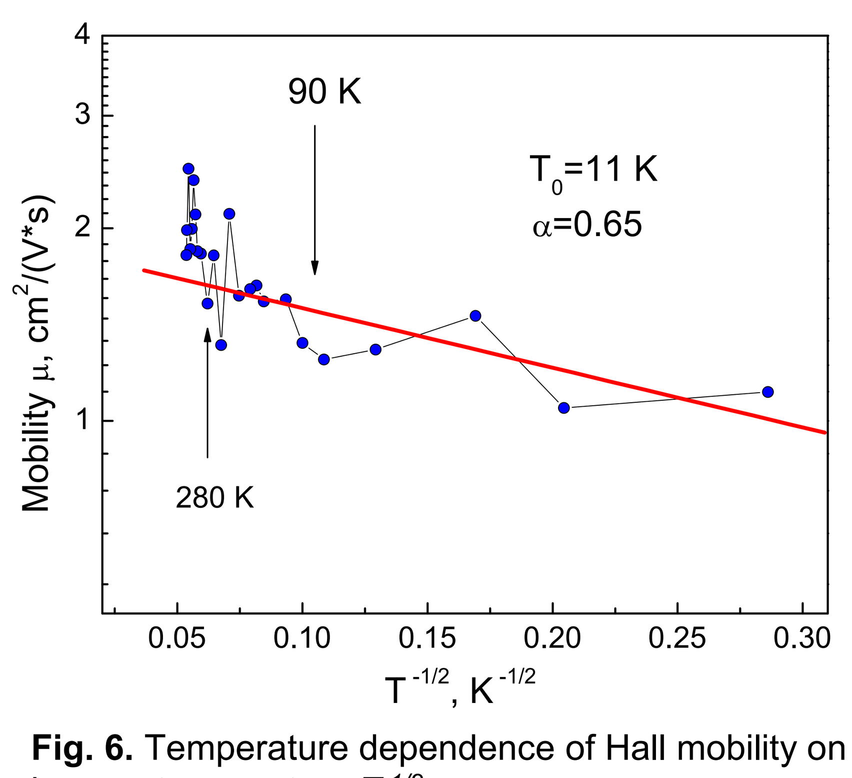

Fig. 6. Temperature dependence of Hall mobility on inverse temperature $T^{-1/2}$.

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