Vol 18 No 6, June 2009
1674-1056/2009/18(06)/2514-09

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Current-voltage characteristics of individual conducting polymer nanotubes and nanowires*

Long Yun-Ze(龙云泽)[a)†], Yin Zhi-Hua(尹志华)[a)], Li Meng-Meng(李蒙蒙)[a)],
Gu Chang-Zhi(顾长志)[b)], Duvail Jean-Luc[c)], Jin Ai-Zi(金爱子)[b)], and Wan Mei-Xiang(万梅香)[d)]

[a)] *College of Physics Science, Qingdao University, Qingdao* 266071, *China*
[b)] *Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*
[c)] *Institut des Matériaux Jean Rouxel, Université de Nantes, 44322 Nantes, CNRS, France*
[d)] *Institute of Chemistry, Chinese Academy of Sciences, Beijing* 100190, *China*

(Received 10 October 2008; revised manuscript received 4 December 2008)

We report the current-voltage (I–V) characteristics of individual polypyrrole nanotubes and poly(3,4-ethylenedioxythiophene) (PEDOT) nanowires in a temperature range from 300 K to 2 K. Considering the complex structures of such quasi-one-dimensional systems with an array of ordered conductive regions separated by disordered barriers, we use the extended fluctuation-induced tunneling (FIT) and thermal excitation model (Kaiser expression) to fit the temperature and electric-field dependent I–V curves. It is found that the I–V data measured at higher temperatures or higher voltages can be well fitted by the Kaiser expression. However, the low-temperature data around the zero bias clearly deviate from those obtained from this model. The deviation (or zero-bias conductance suppression) could be possibly ascribed to the occurrence of the Coulomb-gap in the density of states near the Femi level and/or the enhancement of electron-electron interaction resulting from nanosize effects, which have been revealed in the previous studies on low-temperature electronic transport in conducting polymer films, pellets and nanostructures. In addition, similar I–V characteristics and deviation are also observed in an isolated $K_{0.27}MnO_2$ nanowire.

Keywords: conducting polymers, I–V curves, nanotubes/wires
PACC: 7280L, 7360R, 8120S

1. Introduction

In recent years, charge transport in low-dimensional organic structures such as conjugated conductive polymer nanowires and nanotubes has attracted considerable attention in view of basic research interest and potential device applications.[1] By now, some interesting results have been reported. For example, it is found that electrical conductivity[2−5] and elastic modulus[6] of the conducting polymer nanotubes and nanowires increase sharply with the decrease of the outer diameter. It is reported that the low-temperature magnetoresistance of isolated polymer nanowires/tubes is much smaller than that of bulk pellets or films.[7,8] Smooth crossover from Mott variable-range hopping (VRH) to Efros–Shklovskii VRH conduction has been observed in individual polyaniline and polypyrrole tubes.[9] Dealing with nonlinear current-voltage (I–V) characteristics of individual polymer nanofibers, Saha[10] and Aleshin *et al*[11] observed single-electron tunneling and Coulomb-blockade transport in conducting polypyrrole and helical polyacetylene nanofibers, separately. In addition, power-law behaviours for both I–V curves and conductance G(T) have been reported recently by Aleshin *et al*[1,12] and Rahman and Sanyal[13] in polyacetylene fibers and polypyrrole wires/tubes, which is characteristic of one-dimensional systems composed of several Lüttinger liquids or Wigner crystals connected in series, owing to electron-electron interactions (repulsive short-range electron-electron interactions or long-range Coulomb interactions). Particularly, Kaiser *et al*[14] recently proposed a generic expression (extended fluctuation-induced tunneling (FIT) and a thermal excitation model) for the nonlinear I–V curves based on numerical calculations for metallic conduction interrupted by small barriers, and showed that the expression could give a very good description of the observed nonlinearities in polyacetylene nanofibers, vanadium pentoxide

*Project supported by the National Natural Science Foundation of China (Grant No 10604038) and the Program for New Century Excellent Talents in University of China (Grant No NCET-07-0472).
†Corresponding author. E-mail: yunze.long@163.com

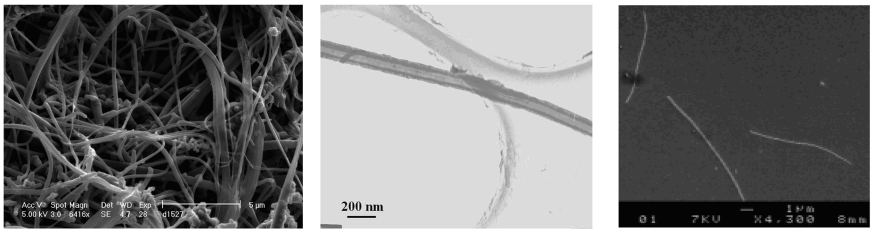
nanofibers, etc. Here, for the Kaiser expression, one question arises: is the Kaiser expression still generic for the nonlinear I–V characteristics of individual polymer nanowires/tubes if the electron-electron interactions are strong and should be taken into account? (as reported by the earlier studies)[1,5,9,11−13]

In our previous studies on low-temperature electrical,[5,9,15−17] thermal[18] and magnetic[19] properties of conducting polyaniline, polypyrrole and poly(3, 4-ethylenedioxythiophene) (PEDOT) nanotubes and nanowires prepared by template-free self-assembly or template-guided synthesis, Long *et al*[18] suggested that the polymer nanotubes/wires be composed of crystalline regions and amorphous regions (namely, the polymer chains be aligned only in small crystallite regions), and the electron-electron interactions in the polymer nanostructures become important especially at low temperatures and dominate the electronic transport processes.[5,9,16,20] For instance, the temperature dependence of resistivity shows crossover from Mott VRH conduction to Efros–Shklovskii VRH conduction at about 70 K. However, the I–V characteristics of individual conjugated polymer nanotubes/wires have not been systematically studied and analysed especially based on numerical calculations.

Since the complex structures in such quasi-one-dimensional systems could be considered as ordered metallic regions in series with disordered conduction barriers, as proposed by Kaiser *et al*,[14] the nonlinear I–V behaviour can be attributed to the charge carrier tunneling through conduction barriers and thermal activation over the barriers. So, in the present paper, we use the Kaiser generic expression (extended FIT and thermal excitation model) to fit the I–V characteristics of individual polypyrrole nanotubes and PEDOT nanowires in a temperature range from 300 K down to 2 K. We find that the I–V data can be well fitted by the Kaiser expression except the data measured at low temperatures and low bias voltages, which is possibly due to the strong Coulomb interactions in the polymer nanotubes and nanowires.

2. Experiment

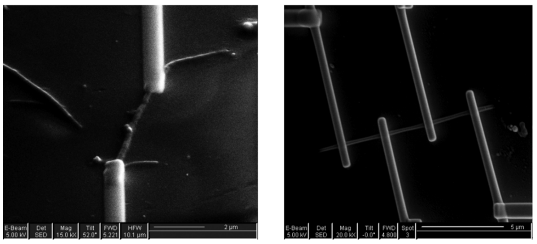
Polypyrrole (PPy) nanotubes used in this work were prepared by using the typical template-free self-assembly method.[8,17,21] Pyrrole monomer (0.002 mol) and *p*-toluene sulfonic acid (PTSA, 0.001 mol) as dopant were mixed in distilled water (10 ml) with stirring. The mixture reacted and formed a transparent solution of PTSA-pyrrole salt and was cooled in an ice bath. Then an aqueous solution of ammonium persulphate (0.002 mol in 5 ml of distilled water) cooled in advance was added slowly into the above cooled PTSA-pyrrole salt solution. After reacting for 15 h in the ice bath, the precipitate was then filtered out from the solution and washed sequentially with distilled water, ethanol, and ether several times, and finally dried for 24 h at room temperature in a dynamic vacuum. PEDOT nanowires with a diameter of about 92 nm were prepared by using the template method according to a typical synthesis procedure as described elsewhere.[5,16,22] The morphologies and the structures of the resulting PPy nanotubes and PEDOT nanowires have been characterized by scanning electron microscopy (SEM), transmission electron microscopy (TEM), elemental analysis, x-ray diffraction and infrared spectroscopy. Figure 1 shows their typical SEM and TEM images. More details about the PPy tubes and PEDOT wires can be found in Refs.[5] and [21] respectively.



(a) (b) (c)

Fig.1. Typical (a) SEM and (b) TEM images of PPy nanotubes prepared by using the template-free method and (c) the SEM image of PEDOT nanowires prepared by using the template-guided synthesis method.

As shown in Fig.2, four platinum microleads on an isolated nanofiber were fabricated by focused ion beam (FIB) deposition (Dual-Beam 235 FIB System from FEI Company, working voltages of the system are 5 kV for the electron beam and 30 kV for the focused-ion beam, the current of the focused ion beam is 1–10 pA) using the following steps. Firstly, polymer nanofibers were ultrasonically dispersed in ethanol, and a droplet of solution was placed on an insulating SiO_2/Si substrate. Secondly, when the solution was dry, we used an electron microscope to find an appropriately isolated nanofiber. Thirdly, four platinum microleads 0.5 μm in width and 0.5 μm in thickness were fabricated by the FIB deposition. Finally, highly conductive silver paste was used to connect Pt microleads and gold wires. I–V characteristics of isolated polymer nanofibers were measured by using a physical property measurement system (PPMS, Quantum Design) and a Keithley 6487 picoammeter/voltage source by scanning bias voltage from –5.0 V to 5.0 V in steps of 0.005 V at temperatures ranging from 300 K to 2 K.



(a) (b)

Fig.2. Typical SEM images of the individual (a) PPy nanotube and (b) the PEDOT nanowire with attaching Pt microleads.

3. Results and discussion

3.1. I–V characteristics of individual PPy nanotubes

Figure 3 shows the I–V characteristics of the individual PPy nanotube from 10 K to 300 K. The highly nonlinear I–V curves can be observed at lower temperatures and the linearity increases as temperature increases. At higher temperatures the Ohmic components become dominant and the linear curves appear at about 200 K as shown in Fig.3(a). The I–V characteristics also show bias-dependent behaviour below 200 K, namely, the nonlinearity appears mainly in low-bias regions and decreases with voltage increasing. It is noted that similar crossover from linear to nonlinear I–V curves with temperature lowering has been widely reported in conjugated polymer nanotubes and nanowires over the past several years.[9,14,16,23,24]

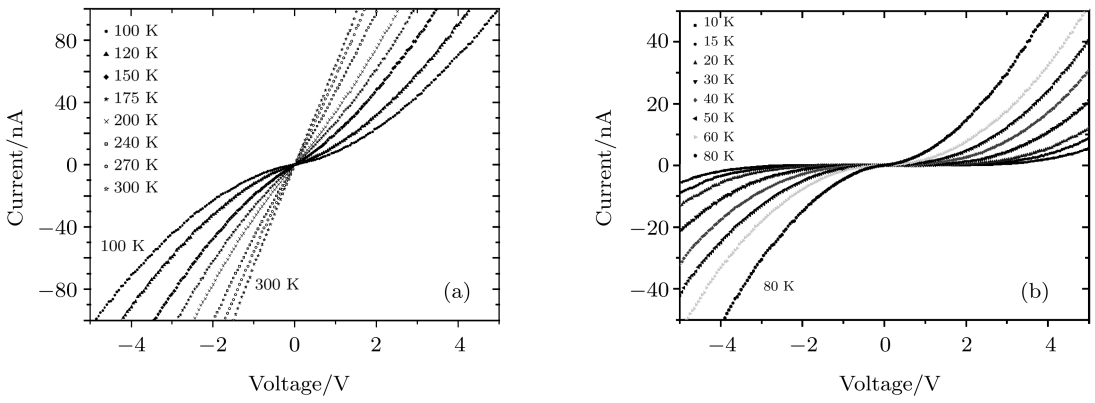


Fig.3. I–V characteristics of an individual PPy nanotube at temperatures ranging (a) from 100 K to 300 K and (b) from 10 K to 80 K.

Up to now, several theoretical models such as space-charge limited current, FIT, Coulomb gap, Coulomb blockade, Luttinger liquid, Wigner crystal models, etc. have been considered to explain the conduction mechanism of low-dimensional polymer materials.[9−14,23−25] Considering that the measured polymer nanotubes and nanowires are composed of small crystalline regions and amorphous regions, namely, the polymer nanofibers can be viewed as the quasi-one-dimensional systems with an array of ordered metallic regions separated by

conduction barriers,[14,25] we try to fit the measured I–V data by using the generic expression presented by Kaiser *et al*[14] according to the fluctuation-assisted tunneling and thermal activation model (extending Sheng's work,[26]) with which the conduction through small barriers between metallic regions, i.e.

$$G = \frac{I}{V} = \frac{G_0 \exp(V/V_0)}{1 + h[\exp(V/V_0) - 1]} \tag{1}$$

can be numerically calculated. Here, G_0,V_0 and h are parameters: G_0 is the temperature-dependent low-field ($V \to 0$) conductance; V_0 is the voltage scale factor, which depends strongly on the barrier energy; parameter $h = G_0/G_\mathrm{h}$ (where $h < 1$), which yields a decrease of G below the exponential increase at higher values of voltage V (the saturation of G at a high-field value, G_h, as $V \to \infty$ given by expression (1) is an extrapolation of the calculations).

Firstly, the I–V characteristics in Fig.3(a) are fitted to expression (1) at temperatures ranging from 300 K to 100 K as shown in Fig.4(a). Here we note that the measured I–V characteristics are symmetric upon reversal voltage, i.e. the measured I–V characteristics are axially symmetric with respect to the longitudinal axis, so only positive voltage curves are used to show the fits more clearly. Apparently, the model can give a good account of the changing shape of curves at higher temperatures above 100 K. According to the FIT theory, essentially, the nonlinearity of curves responds to tunneling through the conduction barrier with small fluctuations to the barrier height. As temperature increases, the thermal fluctuations become comparable to the barrier height and linearity becomes dominant. Table 1 gives the fitting parameters. The low-field conductance G_0 increases substantially from 5.6957 nS to 59.9711 nS as temperature increases from 100 K to 300 K. The parameter h increases from 0.2301 to 0.5267 with the increase of temperature corresponding to a decrease of G below the exponential increase at higher voltages. The voltage scale factor V_0 also increases from 1.9058 V at $T = 100$ K to 8.5050 V at $T = 300$ K, indicating the lessening of nonlinearity in the I–V characteristics as temperature increases. Secondly, we also have tried to fit the low temperature I–V characteristics to expression (1) in a temperature range from 80 K to 10 K as shown in Fig.4(b) and Table 2, only the data measured at high bias voltages can be fitted very well just like those above 100 K, namely, there are obvious deviations between I–V and fitting plots below a specific voltage (V_s) separately. The value of V_s can be easily estimated by determining the demarcation point between the I–V and fitting plots. Furthermore, V_s shows temperature dependence features with values ranging from 2.9 V at $T = 10$ K to 0.9 V at 80 K.

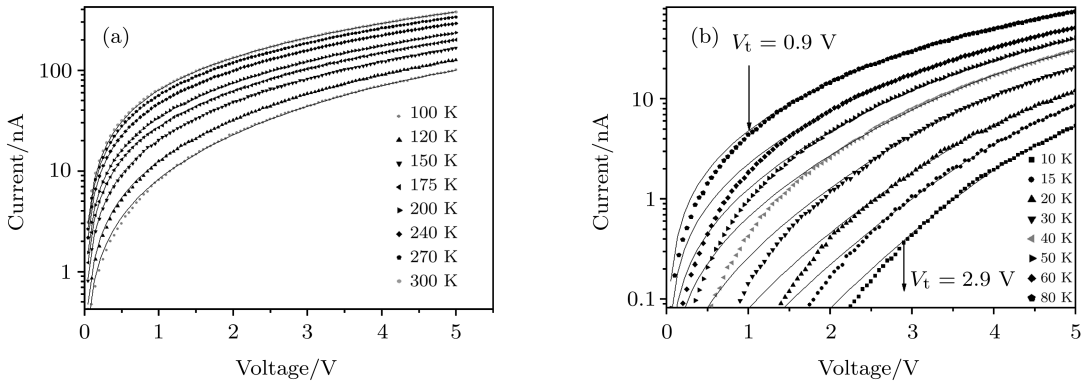


Fig.4. I–V characteristics (log-linear curves) of the PPy nanotube with fits to expression (1), at temperatures ranging from 300 K to 100 K (a) and from 80 K to 10 K (b).

Table 1. Fitting parameters to expression (1) for the PPy nanotube at temperatures ranging from 300 K to 100 K.

T/K	100	120	150	175	200	240	270	300
G_0/nS	5.6957	9.3517	16.7153	23.9491	30.5414	43.0448	53.0629	59.9711
h	0.2301	0.2883	0.4007	0.4411	0.4536	0.5057	0.5438	0.5267
V_0/V	1.9058	2.3161	2.8850	3.9544	4.8845	6.5367	7.7996	8.5050

Table 2. Fitting parameters to expression (1) for the PPy nanotube at temperatures ranging from 80 K to 10 K.

T/K	10	15	20	30	40	50	60	80
G_0/nS	0.00257	0.01058	0.02734	0.10292	0.30492	0.6336	1.2537	2.9671
h	0.00148	0.00363	0.00726	0.01718	0.03337	0.05595	0.0883	0.1586
V_0/V	0.72021	0.84051	0.91803	1.04301	1.23446	1.34696	1.52279	1.6720

Particularly, as shown in Fig.3(b), there is a threshold voltage (V_t), below which a little current flows through the nanotube. The value of V_t can be determined by locating the intersection between the voltage axis and the line describing the linear portion of I^*dV/dI versus V plots at high voltages.[11,20] Figure 5 exhibits the threshold voltage V_t and the specific voltage V_s determined from Fig.4(b). It is found that the values of V_s and V_t at a fixed temperature are very close to each other and both of them decrease with the increase of temperature and vanish above 80–100 K. Consequently, we conclude the depletion of fitting curves at low temperatures, below 80–100 K in this case, corresponds to the anomalous low-bias I–V behaviour, which cannot be explained by the fluctuation-induced tunneling and thermal excitation model. In addition, we also compare the values of zero-bias conductance determined from the fitting parameter (G_0) with that determined from experimental measurements (G_0', obtained from the I–V curve or differential conductance). As shown in Fig.6, G_0' sharply decreases below 80–100 K and deviates from G_0, and becomes superposable to G_0 with temperature increasing. We will discuss this deviation in the following context.

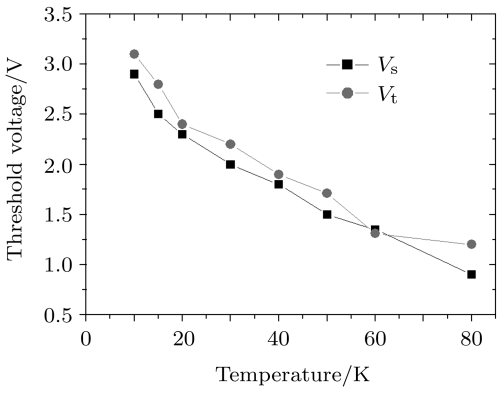


Fig.5. Temperature dependence of specific voltage V_s and threshold voltage V_t.

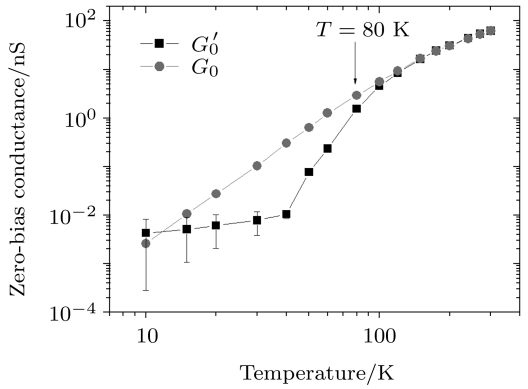


Fig.6. Low-field conductance with temperature varying, where G_0 is the fitting data and G_0' is determined from the experimental data.

3.2. I–V characteristics of individual PEDOT nanowires

The measured I–V characteristics of the single PEDOT nanowire are shown in Fig.7(a) in a temperature range from 300 K to 2 K (I–V data above 100 K are not shown here.). It is obvious that the I–V curves are linear above 100 K and gradually become nonlinear with lowering temperature. Once again, the I–V curves are fitted to expression (1) as shown in Fig.7(b), where log-linear plots show the low-bias and low-current regions more clearly. Here we note that I–V characteristics are symmetric upon reversal voltages, i.e. I–V characteristics are axially symmetric with respect to the longitudinal axis, so only positive voltage parts are shown in the figure. Apparently, the model can give a good account of the changing shape of curves above 30 K. According to the fluctuation-assisted tunneling and thermal activation model,[14] essentially, the nonlinearity of curves responds to tunneling through the conduction barrier with small fluctuations to the barrier height. As temperature increases, linearity becomes dominant and corresponding thermal fluctuations become compara-

ble to the barrier height. In this case, it is at about 100 K that the linear component becomes dominant as shown in Fig.7(a) and coincides with the fitting parameter $h = G_0/G_h$ increasing to 0.91995 from 0.13752 at $T = 2$ K and the parameter V_0 increasing to 3.03416 from 0.24606 at $T = 2$ K as shown in Table 3. However, in discordance with the previous results,[14] obvious deviations appear below 30 K. Furthermore, we find the value of specific voltage V_s (demarcation point between the I–V data and the fitting curves in Fig.7(b)) is inversely proportional to temperature. Interestingly, just below 30 K, a little current flows only above the threshold voltage V_t as shown in Fig.7(a). We also find that the values of V_s are very close to the values of corresponding V_t at each fixed temperature, just like the results shown in Fig.5.

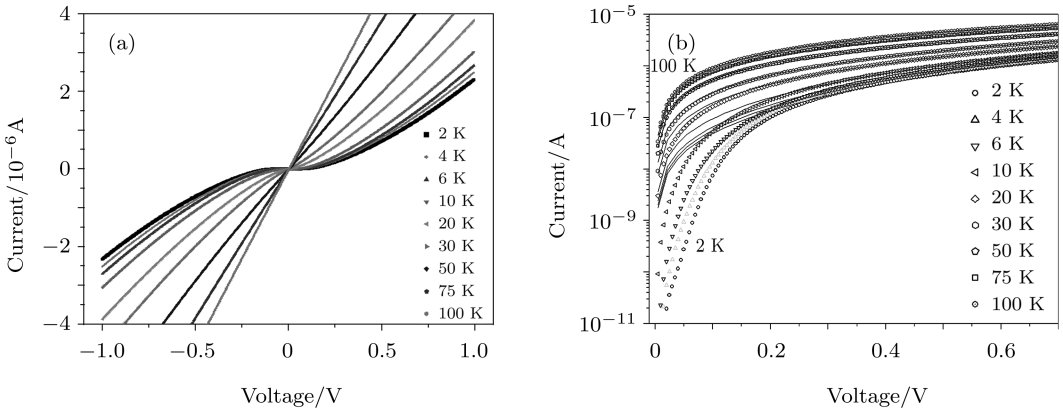


Fig.7. Measured I–V characteristics of the PEDOT nanowire in a temperature range from 2 K to 100 K (a), and log-linear plots corresponding to I–V characteristics (dotted curves) with fitting curves (solid line) to Eq.(1) (b).

Table 3. Fitting parameters to expression (1) for the PEDOT nanowire at different temperatures.

T/K	2	6	10	30	50	100
G_0/s	3.466×10^{-7}	4.718×10^{-7}	7.157×10^{-7}	2.729×10^{-6}	5.167×10^{-6}	9.046×10^{-6}
h	0.13752	0.16277	0.2178	0.53854	0.73696	0.91995
V_0/V	0.24606	0.25033	0.27588	0.45408	1.0689	3.03416

3.3. Further discussion

Our results above indicate that the Kaiser generic expression can give a good description of I–V characteristics of individual polymer nanotubes/wires except for the I–V data measured at low temperatures and low bias voltages, because the Kaiser expression (extending the Sheng model[26] or FIT and thermal excitation model[14]) has included well the microstructure feature and the conduction feature of conjugated polymer nanofibers (quasi-one-dimensional metallic conduction interrupted by small barriers). Kaiser *et al*[14] have also shown that this generic expression can interpret the observed nonlinearities in carbon nanotube networks, vanadium pentoxide nanofibres, polyacetylene nanofibres, and granular Sr_2FeMoO_6. However, apparent deviation from Kaiser expression has been evidenced in the low-temperature I–V curves as shown in Figs.4(b) and 7(b). Here we note that log-linear plots have been used in Figs.4(b) and 7(b) in order to show the deviation at low energies much more clearly; if the I–V curves are plotted in linear-linear scale as done in Ref.[14], the deviation will not be so apparent (please see Fig.8). We propose that one possible reason for the deviation is that the Kaiser expression does not include the contributions from the Coulomb-gap occurring in the density of states near the Femi level[27−30] and/or enhanced electron-electron interaction due to nanosize effects,[9,20] which become important at low enough temperatures and voltages.

The concept of Coulomb gap introduced by Pollak, Efros and Shklovskii *et al*,[27] describes the effect that localized states with Coulomb interactions cannot have a finite density of states at the Fermi level,

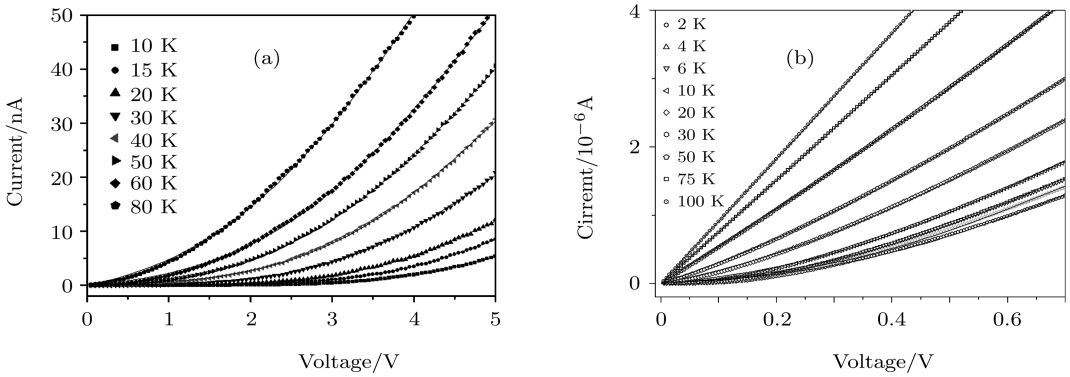


Fig.8. Linear-linear plot of I–V curves (dotted) of the individual (a) PPy nanotube and (b) the PEDOT nanowire and the corresponding fitting curves (solid) to expression (1).

i.e., the density of states at the Fermi level is suppressed (the density of states is parabolic around the Fermi level, exhibiting a "soft gap"), and the Coulomb gap occurs. Materials with a Coulomb gap exhibit particular characteristics. For example, the temperature dependence of resistivity appears in the form of $\log \rho \sim T^{1/2}$ in a lower temperature range, where the exponent 1/2 is independent of the dimensionality of the disordered system (this is the Efros–Shklovskii VRH). To date there exist a number of forms of experimental evidence in which hopping is indeed influenced by the presence of the Coulomb gap at sufficiently low temperatures. For example, the previous studies[28−30] on electronic transport in conducting polyaniline, polypyrrole, PEDOT, etc. have shown that the Coulomb gap can result in a smooth crossover from three-(or two-)dimensional Mott VRH conduction to Efros–Shklovskii VRH conduction. The crossover temperature is usually less than 30 K for polymer bulk films and pellets.[28−30] However, for individual polymer nanotubes, the crossover temperature can be enhanced to 60 K or even 96 K.[9]

In addition, Coulomb blockade as a physical phenomenon, dealing with a specific role of Coulomb interaction in a mesoscopic system, was first predicted by Kulik and Shekhter.[31] When the following two conditions can be fulfilled to avoid thermal and quantum smearing, namely, charging energy E_c of a small conducting isolated island must exceed the available thermal energy ($E_c = e^2/2C > k_B T$, where C is the capacitance of the island) and the tunnel resistance is much greater than the resistance quantum (25.6 kΩ), the single-electron tunneling phenomena can be observed at temperature T: suppression of the tunneling current around zero bias voltage ($-e/2C < V < e/2C$, "Coulomb blockade"), and step-like behaviour of the I–V characteristic at higher bias ("Coulomb stairs"). Up to now, the single-electron tunneling phenomena have been extensively investigated in carbon nanotubes and many metal and semiconductor nanostructures.[32,33] For conjugated polymer nanotubes and nanowires, Saha[10] and Aleshin *et al*[11] have reported single-electron tunneling or Coulomb-blockade transport in conducting polypyrrole and helical polyacetylene nanofibers because the quasi-one dimensional polymer nanofiber can also be considered as an array of small conducting regions (quantum dots) separated by nanoscale barriers where quantum confinement and Coulomb charging effect may play an important role.

The above results and discussion indicate that the influence of Coulomb gap and/or Coulomb blockade on electronic transport in isolated nanofibers should be taken into account. In the present case, in order to show the low-bias anomalies on the I–V curves of an individual polymer nanofiber more clearly, their corresponding differential conductance $\mathrm{d}I/\mathrm{d}V$ curves at low temperatures are shown in Fig.9. For the measured PEDOT nanowire, obvious Coulomb-gap-like structures expand gradually at low voltages below 30 K, which means that a little current can flow through the nanowire below the threshold voltage, and the zero-bias conductance is suppressed by several orders of magnitude with decreasing temperature. Such a depletion of the differential conductance at low energies has been widely observed in inorganic and organic semiconductors,[9,20,27,29,30,34−36] and generally regarded as a signature of electron-electron interaction.[27] Figure 9 also indicates that the low-bias anomaly disappears at higher temper-

atures possibly because the Coulomb gap becomes "filled up" with thermal excitations as temperature increases. Here we note that both the Coulomb gap and the Coulomb blockade in principle can lead to a reduced zero bias conductance at low temperatures, in the present paper we have not excluded the possibility of Coulomb-blockade transport in the polymer nanowires and nanotubes especially at low temperatures as reported by Aleshin *et al.*[11] For instance, as shown in Fig.5, the specific voltage V_s, below which the numerical calculations begin to deviate from the experimental I–V data, is quite close to the threshold voltage V_t. It is possible that both the Coulomb gap in Efros–Shklovskii law and the Coulomb blockade make contributions to the reduced zero bias conductance at low temperatures. Anyway, the occurrence of Coulomb gap and/or Coulomb blockade can suppress the low-temperature current or conductance at low energies as shown in Fig.6, thereby making the measured I–V data deviate from the Kaiser generic expression. Finally, it is worthwhile noting that such a deviation is observed not only in individual polymer nanofibers, but also in isolated nanowires of inorganic compound such as $K_{0.27}MnO_2$ nanowires[20] as shown in Fig.10.

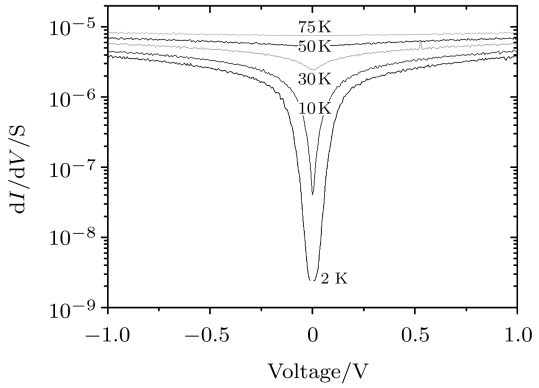


Fig.9. Corresponding differential conductance dI/dV spectra of a single PEDOT nanowire.

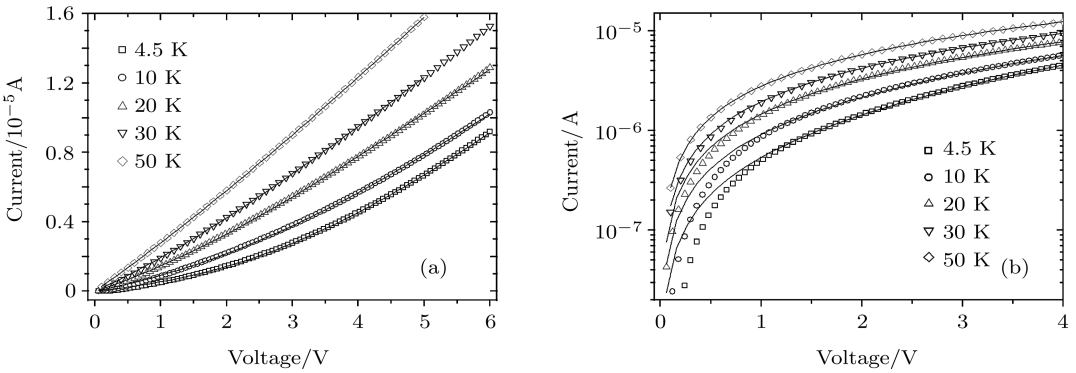


Fig.10. (a) Linear-linear plot and (b) log-linear plot of I–V characteristics (dotted curves) of an isolated $K_{0.27}MnO_2$ nanowire and their corresponding fitting curves (solid lines) to expression (1).

4. Conclusions

The electronic transport properties of isolated polymer nanotubes and nanowires are investigated in a temperature range from 300 K down to 2 K. For the complex structures with ordered metallic regions in series with disordered conduction barriers in such quasi-one-dimensional systems, the nonlinear I–V characteristics are well fitted to the extended FIT and thermal activation model (Kaiser expression) except for the low-energy region at low temperatures corresponding to the anomalous I–V behaviour. We attribute this low-bias anomaly to the occurrence of the Coulomb-gap in the density of states near the Femi level and/or the enhancement of electron-electron interaction due to nanosize effects.

References

[1] Aleshin A N 2006 *Adv. Mater.* **18** 17 and references therein

Bao L H, Li C, Tian Y, Tian J F, Hui C, Wang X J, Shen C M and Gao H J 2008 *Chin. Phys.* B **17** 4585

Li P J, Zhang W J, Zhang Q F and W J L 2007 *Acta*

Phys. Sin. **56** 1054 (in Chinese)
[2] Martin C R 1995 *Acc. Chem. Res.* **28** 61 and references therein
[3] Granström M and Inganäs O 1995 *Polymer* **36** 2867
[4] Delvaux M, Duchet J, Stavaux P Y, Legras R and Demoustier-Champagne S 2000 *Synth. Met.* **113** 275
Duchet J, Legras R and Demoustier-Champagne S 1998 *Synth. Met.* **98** 113
[5] Duvail J L, Long Y Z, Cuenot S, Chen Z J and Gu C Z 2007 *Appl. Phys. Lett.* **90** 102114
[6] Cuenot S, Demoustier-Champagne S and Nysten B 2000 *Phys. Rev. Lett.* **85** 1690
[7] Kim G T, Burghard M, Suh D S, Liu K, Park J G, Roth S and Park Y W 1999 *Synth. Met.* **105** 207
Park J G, Kim G T, Krstic V, Kim B, Lee S H, Roth S, Burghard M and Park Y W 2001 *Synth. Met.* **119** 53
[8] Long Y Z, Chen Z J, Shen J Y, Zhang Z M, Zhang L J, Huang K, Wan M X, Jin A Z, Gu C Z and Duvail J L 2006 *Nanotechnology* **17** 5903
[9] Long Y Z, Zhang L J, Chen Z J, Huang K, Yang Y S, Xiao H M, Wan M X, Jin A Z and Gu C Z 2005 *Phys. Rev.* B **71** 165412
[10] Saha S K 2002 *Appl. Phys. Lett.* **81** 3645
[11] Aleshin A N, Lee H J, Jhang S H, Kim H S, Akagi K and Park Y W 2005 *Phys. Rev.* B **72** 153202
[12] Aleshin A N, Lee H J, Park Y W and Akagi K 2004 *Phys. Rev. Lett.* **93** 196601
[13] Rahman A and Sanyal M K 2007 *Phys. Rev.* B **76** 045110
[14] Kaiser A B, Rogers S A and Park Y W 2004 *Mol. Cryst. Liq. Cryst.* **415** 115
Kaiser A B and Park Y W 2005 *Synth. Met.* **152** 181
[15] Long Y Z, Huang K, Yuan J, Han D, Niu L, Chen Z J, Gu C Z, Jin A Z and Duvail J L 2006 *Appl. Phys. Lett.* **88** 162113
Long Y Z, Chen Z J, Peng H L and Liu Z F 2008 *Chin. Phys.* B **17** 2251
[16] Long Y Z, Duvail J L, Chen Z J, Jin A J and Gu C Z 2008 *Chin. Phys. Lett.* **25** 3474
Yin Z H, Long Y Z, Gu C Z, Wan M X and Duvail J L 2009 *Nanoscale Res. Lett.* **4** 63 doi: 10.1007/s11671-008-9203-8
[17] Long Y Z, Chen Z J, Wang N L, Ma Y J, Zhang Z, Zhang L J and Wan M X 2003 *Appl. Phys. Lett.* **83** 1863
Zhou Y, Long Y Z, Chen Z J, Zhang Z M and Wan M X 2005 *Acta Phys. Sin.* **54** 228 (in Chinese)
Yin Z H, Long Y Z, Huang K, Wan M X and Chen Z J 2009 *Chin. Phys.* B **18** 298
[18] Long Y Z, Luo J L, Xu J, Chen Z J, Zhang L J, Li J C and Wan M X 2004 *J. Phys.*: *Condens. Matter* **16** 1123
Xu J, Luo J L, Chen Z J, Long Y Z, Bai H Y, Wan M X and Wang W L 2003 *Acta Phys. Sin.* **52** 947 (in Chinese)
Long Y Z, Yin Z H, Hui W, Chen Z J and Wan M X 2008 *Chin. Phys.* B **17** 2707
[19] Long Y Z, Chen Z J, Shen J Y, Zhang Z M, Zhang L J, Xiao H M, Wan M X and Duvail J L 2006 *J. Phys. Chem.* B **110** 23228
Long Y Z, Chen Z J, Zhang Z M, Wan M X, Zheng P and Wang N L 2003 *Acta Phys. Sin.* **52** 175 (in Chinese)
Long Y Z, Chen Z J, Liu Z X, Zhang Z M, Wan M X and Wang N L 2003 *Chin. Phys.* **12** 433
[20] Long Y Z, Yin Z H, Chen Z J, Jin A Z, Gu C Z, Zhang H T and Chen X H 2008 *Nanotechnology* **19** 215708
[21] Yang Y S, Liu J and Wan M X 2002 *Nanotechnology* **13** 771
Long Y Z, Xiao H M, Chen Z J, Wan M X, Jin A Z and Gu C Z 2004 *Chin. Phys.* **13** 1918
Huang K, Wan M X, Long Y Z, Chen Z J and Wei Y 2005 *Synth. Met.* **155** 495
[22] Duvail J L, Dubois S, Demoustier-Champagne S, Long Y and Piraux L 2008 *Int. J. Nanotechnol.* **5** 838 and references therein
[23] Gence L, Faniel S, Gustin C, Melinte S, Bayot V, Callegari V, Reynes O and Demoustier-Champagne S 2007 *Phys. Rev.* B **76** 115415
Joo J, Kim B H, Park D H, Kim H S, Seo D S, Shim J H, Lee S L, Ryu K S, Kim K, Jin J I, Lee T J and Lee C J 2005 *Synth. Met.* **153** 313
[24] Park J G, Lee S H, Kim B, Yu H Y, Park J H, Kabir M S, Kubatkin S, Persson M and Park Y W 2002 *Current Appl. Phys.* **2** 23
Kaiser A B and Park Y W 2003 *Synth. Met.* **135-136** 245
Samitsu S, Iida T, Fujimori M, Heike S, Hashizume T, Shimomura T and Ito K 2005 *Synth. Met.* **152** 497
[25] Zimbovskaya N A, Johnson Jr A T and Pinto N J 2005 *Phys. Rev.* B **72** 024213
[26] Sheng P 1980 *Phys. Rev.* B **21** 2180
[27] Efros A L and Shklovskii B I 1975 *J. Phys.* C **8** L49
Shklovskii B I and Efros A L 1984 *Electronic Properties of Doped Semiconductors* (Berlin: Springer)
Pollak M and Shklovskii B I 1990 *Hopping Transport in Solids* (Amsterdam: North-Holland)
[28] Skotheim T, Elsenbaumer R and Reynolds J 1998 *Handbook of Conducting Polymers* (New York: Marcel Dekker) p 85
[29] Ghosh M, Barman A, De S K and Chatterjee S 1998 *J. Appl. Phys.* **84** 806
[30] Maji S, Mukhopadhyay S, Gangopadhyay R and De A 2007 *Phys. Rev.* B **75** 73202
[31] Kulik I O and Shekhter R I 1975 *Sov. Phys. JETP.* **41** 308
[32] Postma H W Ch, Teepen T, Yao Z, Grifoni M and Dekker C 2001 *Science* **293** 76
[33] Long Y Z, Wang W L, Bai F L, Chen Z J, Jin A Z and Gu C Z 2008 *Chin. Phys.* B **17** 1389
Zhang Y, Cao J X and Yang W 2008 *Chin. Phys.* B **17** 1881
Zhang W, Li M K, Wei Q, Cao L, Yang Z and Qiao S S 2008 *Acta Phys. Sin.* **57** 5887 (in Chinese)
[34] Massey J G and Lee M 1995 *Phys. Rev. Lett.* **75** 4266
Sandow B, Gloos K, Rentzsch R, Ionov A N and Schirmacher W 2001 *Phys. Rev. Lett.* **86** 1845
[35] Kang N, Hu J S, Kong W J, Lu L, Zhang D L, Pan Z W and Xie S S 2002 *Phys. Rev.* B **66** 241403
Kong W J, Lu L, Zhang D L and Pan Z W 2005 *Chin. Phys.* **14** 2090
Shen J Y, Chen Z J, Wang N L, Li W J and Chen L J 2006 *Appl. Phys. Lett.* **89** 153132
Fang J H, Liu L W, Kong W J, Cai J Z and Lu L 2006 *Chin. Phys.* **15** 1071
[36] Ma Y J, Zhang Z, Zhou F, Lu L, Jin A Z and Gu C Z 2005 *Nanotechnology* **16** 746
Wang D Q, Zhou Z Y, Zhu R and Ye X Y 2008 *Chin. Phys.* B **17** 3875
He X B, Yang T Z, Cai J M, Zhang C D, Guo H M, Shi D X, Shen C M and Gao H J 2008 *Chin. Phys.* B **17** 3444