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Current–voltage characteristics of an individual helical CdS nanowire rope*

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This paper studies the electronic transport in an individual helically twisted CdS nanowire rope, on which platinum microleads are attached by focused-ion beam deposition. The current–voltage ($I-V$) characteristics are nonlinear from 300 down to 60 K. Some step-like structures in the $I-V$ curves and oscillation peaks in the differential conductance ($\mathrm{d}I/\mathrm{d}V-V$) curves have been observed even at room temperature. It proposes that the observed behaviour can be attributed to Coulomb-blockade transport in the one-dimensional CdS nanowires with diameters of 6–10 nm.

Keywords: nanowires, CdS, $I-V$ characteristics, Coulomb blockade
PACC: 7280E, 7335C, 8160C

1. Introduction

Currently, there is intense interest in electrical transport through one-dimensional nanostructures or zero-dimensional quantum dots, since predictable and controllable conductance will be critical to many nanoscale electronics applications. During the last twenty years, Coulomb blockade and single-electron tunnelling (SET) phenomena have attracted much interest due to their potential applications in new nanoelectronic devices such as single-electron transistor circuits,[1] high-precision Coulomb blockade thermometry,[2] supersensitive electrometry, memories and data storage (for a review, see Ref.[3]). The Coulomb blockade and single-electron tunnelling phenomena have been extensively investigated in silicon nanostructures,[4,5] carbon nanotubes,[6,7] and many other metal and semiconductor nanostructures, such as Au nanoparticles or clusters,[8,9] Ag nanocrystals,[10] Pd particles or clusters,[11] Co nanoparticles,[12] PbS/PbSe quantum dots.[13] To observe these effects, a scanning tunnelling microscope (STM) is widely used.[11−14] Another more practical way is that individual nanowires[6,7,15,16] or small numbers of cluster arrays[8,9,17] are dispersed/connected by two micro/nanoscale electrodes. Coulomb blockade effects in template-synthesized nanowire arrays were also reported by several groups.[5,18−20]

In order to observe clear Coulomb blockade effects at higher temperature, usually the size of metal and semiconductor nanostructures is very small (∼10 nm), so that the charging energy of the device can overcome the thermal energy. In this article, we study electronic transport in an individual helical CdS nanowire rope. The helically twisted CdS nanoropes composed of nanowires with diameters of 6–10 nm were prepared by a simple aqueous chemical growth.[21] Focused-ion beam deposition technique was used to attach Pt microleads on the individual nanorope. Nonlinear $I-V$ curves, clear staircase and oscillation peaks were observed even at room temperature for the individual CdS nanorope due to having a smaller diameter and thus a larger Coulomb charging energy.

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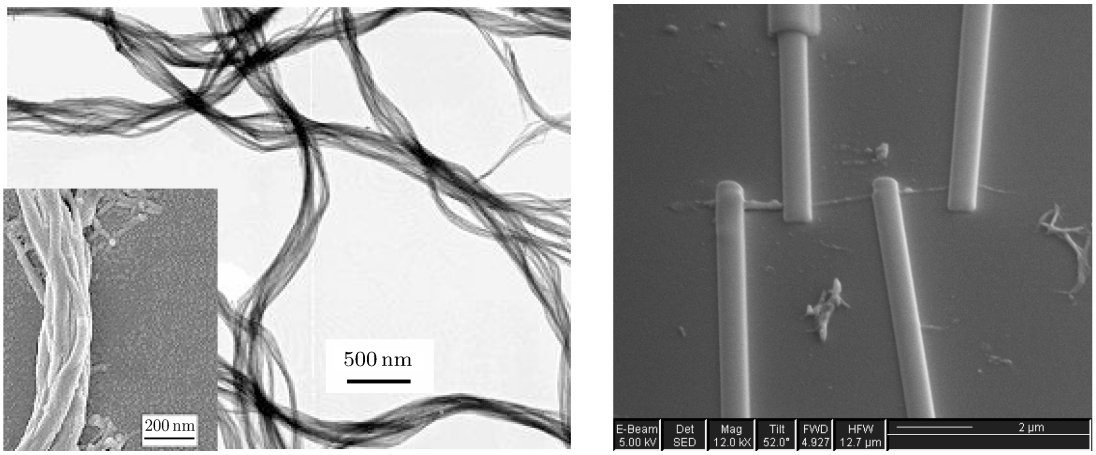
2. Experimental details

The synthesis and structural characterization of the helical CdS nanowire ropes have been described in Ref.[21]. A typical procedure for the CdS nanoropes synthesis is as follows. Firstly, appropriate amount of analytically pure $Cd(CH_3COO)_2{\cdot}2H_2O$ was dissolved into a deaerated 35mol% (by molar concentration) aqueous solution of ethylenediamine in a flask at room temperature. Secondly, under vigorous stirring, stoichiometric analytically pure $Na_2S{\cdot}9H_2O$ was quickly added to this solution, and a milk-white sol was formed soon. Thirdly, the resultant milk-white sol was heated to 50°C, and kept on stirring at this temperature for about one week until the milk-white reaction mixture gradually turned to a yellow colour. At last, the final product was obtained by centrifugation and washed with distilled water and ethanol. The samples obtained were characterized by powder x-ray diffraction (XRD, Rigaku D/max-2400), scanning electron microscopy (SEM) (JEOL JSM-6700F), transmission electron microscopy (TEM) (JEOL JEM-100 CX II), energy dispersive spectroscopy, UV-visible absorption spectra, and circular dichroism spectroscopy.

In order to measure the electrical properties of an individual nanorope, firstly the nanoropes were ultrasonically dispersed in ethanol, and then a drop of dilute solution was placed on an insulating SiO_2/Si substrate. Secondly, a SEM was used to find an appropriately individual nanorope on the wafer. Then, two pairs of Pt microleads with typically 0.8 μm in width and 0.4 μm in thickness were fabricated by focused-ion beam deposition (Dual-Beam 235 Focused-Ion Beam System from FEI Company, the working voltage of the system is 5 kV for the electron beam and 30 kV for the focused-ion beam, respectively, the focused-ion beam current is 10 pA). This method has been widely used to attach microleads on individual carbon nanotubes,[22] conducting polymer microtubes/wires[23−25] and semiconductor nanowires.[26] At last, electrical connection between the Pt microleads and the sample holder was made by highly conductive silver paste and gold wires. Current–voltage characteristics of the single nanorope were measured by using a Physical Property Measurement System from Quantum Design and a Keithley 6487 picoammeter/voltage source in a temperature range from 300 down to 40 K.

3. Results and discussion

Figure 1(a) shows the typical TEM and SEM images of the resulting helical CdS nanowire ropes. The nanoropes have width in a range of 50–200 nm, and have length ranging from a few micrometres to several tens of micrometres. A single nanowire has diameter of 6–10 nm, which has been confirmed by high-resolution TEM studies.[21] It can be seen that the nanoropes are composed of spirally twisted and interstranded nanowire bundles. Figure 1(b) shows the SEM



(a) (b)

Fig.1. (a) TEM and SEM images of the helically twisted CdS nanowire ropes. (b) SEM image of an individual CdS nanowire rope and attached Pt microleads fabricated with focused-ion beam deposition.

image of an individual CdS nanowire rope and attached platinum microleads. The $I-V$ characteristics of a section of the nanorope between the middle two microleads ($\sim$1.7 μm) were measured with a two terminal arrangement by applying bias voltage from 6V to –6V.

Figure 2 shows the $I-V$ characteristics of the individual nanorope for a series of temperatures from 300 down to 60 K. It is evident that all the $I-V$ curves are not linear even at room temperature and show signature of Coulomb blockade effect (suppression in tunnelling current around zero bias voltage). A voltage threshold to charge transport becomes apparent below 200 K and increases in magnitude with lowering temperature. Similar $I-V$ profiles have been widely observed in a number of ultrasmall structures in metals and semiconductors in which tunnel barriers have been formed and the conductance is Coulomb blockade limited. For example, Ozturk *et al*[17] reported a transition from linear to nonlinear $I-V$ curves for a 500 μm long interconnect dielectrophoretically assembled from the gold nanorods. The nonlinear $I-V$ characteristics of an individual helical polyacetylene nanofibre were also reported.[27]

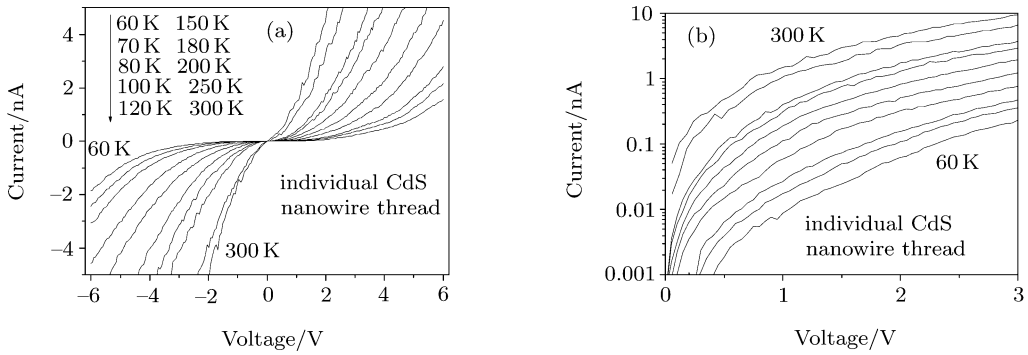


Fig.2. $I-V$ characteristics of the individual helical CdS nanowire rope measured at different temperatures from 300 down to 60 K. (a) Linear-linear plot. (b) Log- linear plot.

It is interesting to note that some step-like structures are observed in the $I-V$ curves and some oscillations are observed in the differential conductance curve ($\mathrm{d}I/\mathrm{d}V-V$), which was numerically derived from the corresponding $I-V$ curve. In order to show the staircase more clearly, Fig.3(a) gives an expanded region (0–3V) of the $I-V$ characteristics at 250 and 300 K. Fig.3(b) represents the conductance oscillation peaks at 300 K. As we know, 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}=$e^2/2C > k_{\mathrm{B}}T$, C is the capacitance of the island) and the tunnel resistance is much greater than the resistance quantum (25.6 kΩ), the single-electron tunnelling phenomena can be observed at a temperature T: suppression of the tunnelling current around zero bias voltage, step-like behaviour of the $I-V$ characteristic at higher bias, and conductance oscillation peaks in the $\mathrm{d}I/\mathrm{d}V-V$ curves. To date, a few works on room-temperature SET in carbon nanotubes,[6,7] metal nanoparticles,[12] and conducting polymer nanotubes[18] have been reported. In these cases the sizes of the metallic islands must be small enough ($\sim$10 nm) so that the charging energy can overcome the thermal energy at room temperature (25.9 meV). For example, room-temperature SET phenomena were observed in carbon nanotubes[6,7] or partially crystalline polymer nanotubes[18] which were separated by nanoscale junctions/barriers. For the present case, the CdS nanowires have been confirmed to be crystalline through the selected electron diffraction pattern recorded on a section of a single bundle of nanorope.[21] However, the CdS nanowire with diameter of 6-10 nm does not tend to be a single crystal in the whole length due to many kinks (as shown in Fig.1(a) or Ref.[21]) and some defects (observed by high-resolution TEM). According to the orthodox theory of single electronics, if one-dimensional arrays are inhomogeneous, the arrays will exhibit Coulomb staircase due to space correlation of SET events.[28] Furthermore, the Coulomb charging energy of the CdS nanowire island is estimated to be $E_{\mathrm{c}} = e^2/2C \sim 23$ meV (for a cylinder,[29] $C \approx \pi\varepsilon\varepsilon_0 L/\ln(L/r)$, where ε_0=8.8$\times10^{-12}$F/m, dielectric constant $\varepsilon\sim5$ for CdS,[20] nanowire radius r $\sim$7 nm,

island length is assumed to be $L \sim 50\,\mathrm{nm}$), which is comparable with the room-temperature thermal energy 25.9 meV. In addition, the device resistance is about 200MΩ at room temperature, which is also much greater than the resistance quantum. So we propose that the observed staircase and oscillation peaks in Fig.3 could be ascribed to Coulomb-blockade transport in the one-dimensional CdS nanowires with diameters of 6–10 nm.

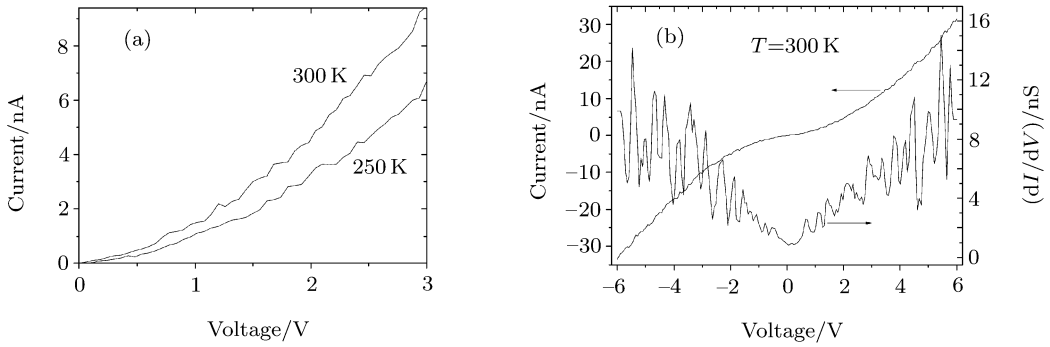


Fig.3. (a) $I-V$ curves expanded between 0–3 V to show the Coulomb staircases. (b) $I-V$ curve and corresponding differential conductance of the individual CdS nanowire rope at 300 K.

Here there are four points should be addressed. Firstly, the step-like structures in the $I-V$ curves were repeated in other single CdS nanowire ropes (data not shown) and not caused by the noise of the instrument because the used Keithley 6487 picoammeter source with a high resolution of 0.001 nA was very stable during experiments. Secondly, according to the $I-V$ curves shown in Fig.2(a), the amplitude of the fluctuating peak seems much higher at room temperature than at low temperatures. This is not true due to the linear-linear plot of the $I-V$ curves in Fig.2(a). Figure 2(b) shows the log-linear plot of the $I-V$ curves, the step-like structures could be observed clearly at low temperatures. Thirdly, it should be noted that the oscillation peaks in Fig.3(b) are not periodic due to the fact that the CdS nanowires could be considered as more-barrier-tunnel-junction structures like silicon nanowire[4] or polymer nanofibre,[27] because it is evident that the peaks are periodic for simple two-barrier-tunnel-junction structures[30] and not strictly periodic for complicated three- or more-barrier-tunnel-junction structures[14] (e.g. a silicon nanowire[4] and a single helical polyacetylene nanofibre.[27]) At last, we note that single-electron transport phenomena have been reported in individual bundles, or ropes, of single-walled carbon nanotubes.[31] Our ropes of CdS nanowires are quite similar to the above mentioned bundles of single-walled carbon nanotubes.

4. Conclusion

In summary, we have studied the current–voltage characteristics of an individual helically twisted CdS nanorope composed of nanowires with diameters of 6–10 nm. The nanowire rope shows nonlinear $I-V$ curves, step-like structures and oscillation peaks even at room temperature. We propose that the observed results could be ascribed to Coulomb-blockade transport in the one-dimensional CdS nanowires due to the fact that the CdS nanowires have a smaller diameter (6–10 nm) and thus a larger Coulomb charging energy. The helical CdS nanowire ropes, similar to bundles of single-walled carbon nanotubes or other polymeric or inorganic nanofibres, can be viewed as a one-dimensional array of small crystalline grains made of nanowire separated by multiple tunnelling junctions.

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