

# Synthesis and electrical properties of p-type CdTe nanowires

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Published in Micro & Nano Letters; Received on 13th March 2013; Revised on 27th April 2013; Accepted on 1st May 2013

CdTe nanowires (NWs) are synthesised via a thermal evaporation process, and the structure characterisations reveal that the as-synthesised NWs are single crystalline with a zinc blende structure and a crystal growth direction of [111]. Nano-field-effect transistors are fabricated based on individual CdTe NWs, and the electrical properties demonstrate that the CdTe NWs have p-type conductivity with a mobility ( $\mu_h$ ) of  $6.8 \times 10^{-2} \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1}$  and carrier concentration ( $n_h$ ) about  $3.6 \times 10^{19} \text{ cm}^{-3}$ . This significant p-type conductivity is attributed to the intrinsic defects of Cd vacancies in NWs, and then, the high-aspect ratio and nearly perfect single-crystalline quality in one-dimensional NWs are conducive to excellent electron transfer characteristics. The synthesised NWs with significant p-type conductivity will be very attractive candidates for nanoelectronic devices.

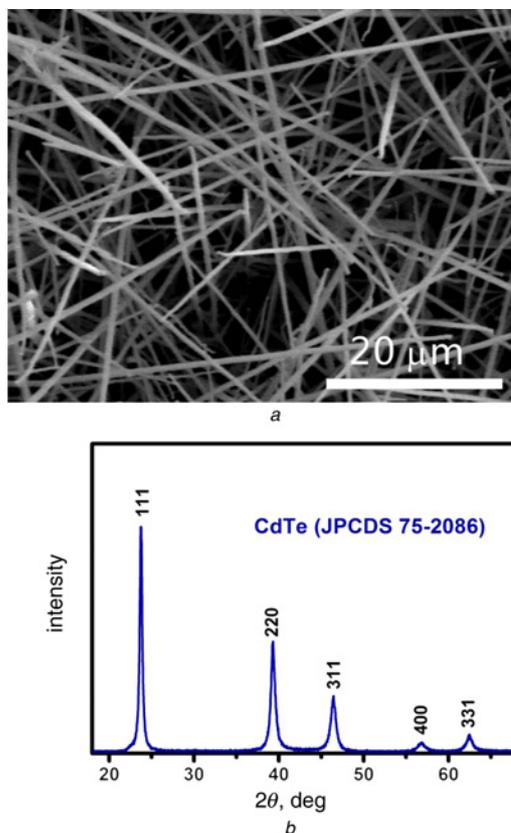
**1. Introduction:** As direct wide bandgap semiconductors, one-dimensional (1D) II–VI group semiconductor nanostructures with unique geometries and size-confinement effects present distinct electronic and optical properties making them an important class of materials in nanoelectronics and nanooptoelectronics [1–9]. Enormous efforts have been made to synthesise and characterise 1D II–VI group nanostructures in the last decade, such as nanowires (NWs) [10–16], nanoribbons/nanobelts [4, 17–19], nanorods [20–22] etc. However, because of the strong self-compensation effect, most of the 1D II–VI group nanostructures present n-type conductivity and p-type is hard to achieve [23, 24]. To realise the practical applications of 1D semiconductors in nanodevices, p-type conductivity is as important as n-type conductivity. Up to now, some studies on p-type ZnTe [6, 25, 26], ZnSe [13], ZnS [27] and ZnO [28], are reported representing considerable progress. Nevertheless, p-type doping still remains a major challenge, and more researches are needed to develop the synthesis process and nanodevices in practical applications.

CdTe is an important II–VI group semiconductor material and has a direct bandgap of 1.51 eV at room temperature [29]. Owing to the high optical absorption coefficient for photons in the whole solar spectrum, CdTe is suggested to be optimum material for photovoltaic solar energy conversion [2]. With the development of nanotechnology, 1D CdTe nanostructures have been synthesised. One-step hydrothermal synthesis of CdTe NWs with amorphous carbon sheaths was reported by Yong *et al.* [14]. Ye *et al.* [30] reported high-quality CdTe NWs: synthesis, characterisation and application in photoresponse devices. Hackney *et al.* [31] reported the photoconductive and polarisation properties of individual CdTe NWs, and the as-synthesised CdTe nanowires exhibited a power conversion efficiency of 0.56%, which is higher than some comparable nanomaterials. However, the electrical properties of 1D CdTe NWs have been rarely discussed up to the present, particularly in the case of nanofield-effect transistors (nano-FETs).

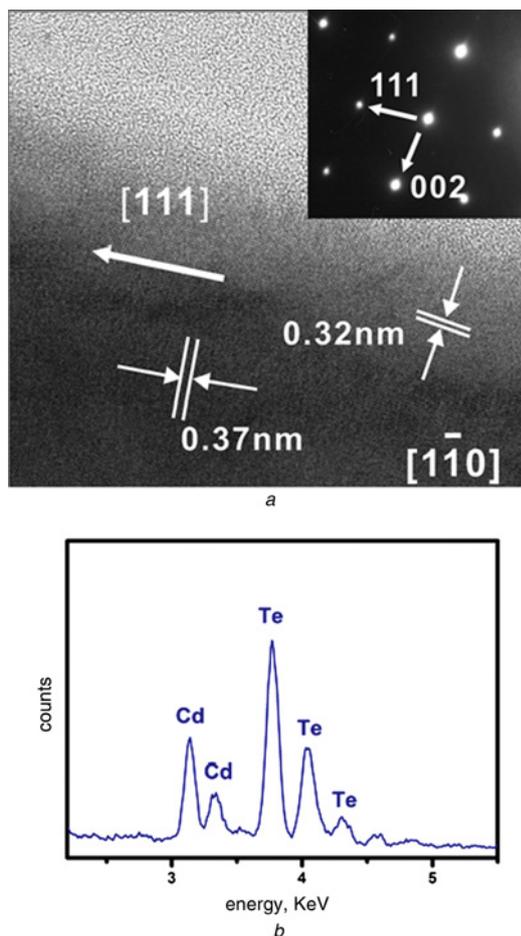
In this Letter, the synthesis of p-type CdTe NWs is explored, and the crystal structure properties of NWs are characterised by using field-emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM) and selected-area electron diffraction (SAED). Then, p-type electrical conductivity and transfer properties based on nano-FET are investigated. The results will develop the application of CdTe NWs in generation of nanoelectronic devices.

**2. Experimental:** The CdTe NWs are synthesised in a quartz tube furnace via a thermal evaporation method. High purity CdTe

powder (99.999%) is loaded into an alumina boat and is placed at the centre of the tube furnace; Si substrate precoated with a layer of 10 nm gold catalyst is placed in the downstream direction 26 cm from the centre. The tube is then evacuated to 900 Torr, and then the tube is heated at a rate of 20 K/min to a target temperature of 920 K. A mixed flow of H<sub>2</sub> (5%) and Ar (95%) is used as the carried gas with a constant flow rate of 30 sccm, and the growth duration is 2 h.



**Figure 1** SEM image of typical as-synthesised CdTe NWs, and XRD patterns of CdTe NWs  
a SEM image  
b XRD patterns



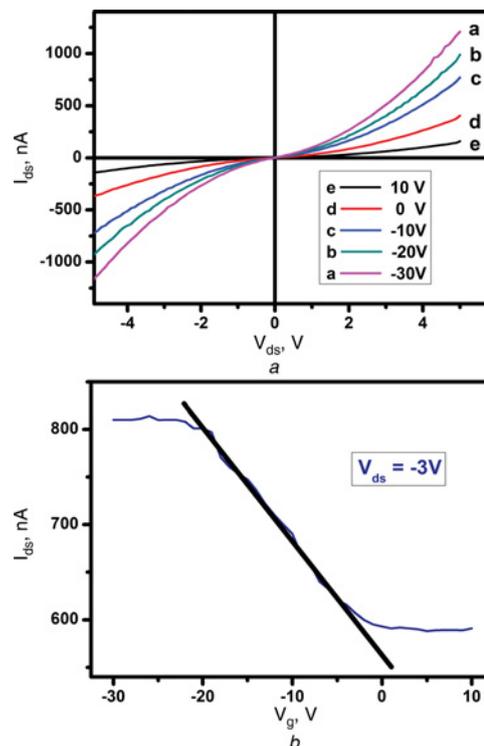
**Figure 2** HRTEM image of CdTe NW, inset is corresponding SAED pattern recording along  $[1-10]$  zone axis, and EDS spectrum of CdTe NWs  
 a HRTEM image  
 b EDS spectrum

CdTe NWs are characterised by FESEM (SIRION 200, FEI), X-ray diffraction (XRD, D/max- $\gamma$ B), HRTEM (JEM-2100F, 200 kV) with SAED. The chemical compositions of the NWs are analysed by energy-dispersive X-ray spectroscopy (OXFORD, equipped on the TEM).

To assess the electrical properties of CdTe NWs, nano-FETs based on individual NWs are fabricated. The NWs are dispersed on a heavily doped Si substrate with a SiO<sub>2</sub> layer (300 nm) serving as the back-gate and the gate dielectric. Patterned Au (100 nm) electrodes are successively deposited on the NWs in high-vacuum by e-beam evaporation with the assistance of a mesh-grid mask composed of tungsten wires (diameter of 5  $\mu$ m). The electrical measurements are conducted by using a semiconductor characterisation system (Keithley 4200).

**3. Results and discussion:** The typical SEM image as shown in Fig. 1a reveals that the as-synthesised CdTe NWs have a uniform wire-like geometry with a diameter of about 100–180 nm and length > 40  $\mu$ m. Fig. 1b shows the XRD patterns of the CdTe NWs samples, all the diffraction peaks are assigned to CdTe with a zinc blende structure (JPCDS No. 75–2086).

Fig. 2a depicts the HRTEM image of a CdTe NW, the lattice spacing can be estimated to be 0.37 and 0.32 nm corresponding to the (111) and (002) planes, respectively. The inset is the corresponding SAED pattern recorded along the  $[1-10]$  zone axis, which reveals that the CdTe NW is single crystalline with a growth direction of  $[111]$ . Interestingly, in our experiments, the as-synthesised CdTe NWs have the same morphology and crystal configuration



**Figure 3** Electrical properties measurements  
 a  $I_{ds}$  against  $V_{ds}$  curves for different  $V_g$  that range from 10 to  $-30$  V  
 b  $I_{ds}$  against  $V_g$  curve measured at  $V_{ds} = -3$  V

under similar growth conditions. Fig. 2b shows the energy dispersive spectrum (EDS) of CdTe NWs, the atomic ratio of as-synthesised intrinsic CdTe NWs is estimated to be 44:56 and the content of Te is more than Cd revealing non-stoichiometry of the product and implying that a large number of Cd vacancies ( $V_{Cd}''$ ) may exist in NWs.

The electrical properties of CdTe NWs are evaluated based on nano-FETs. As shown in Fig. 3a, from the source–drain current against voltage ( $I_{ds}$ – $V_{ds}$ ) curves obtained at the gate voltages ( $V_g$ ) varied from 10 to  $-30$  V in steps of 10 V, it can be observed that the conductance of the NW monotonously increases with decreasing  $V_g$ , revealing a typical p-type semiconductor character [18, 23, 29]. The resistance ( $R$ ) of the CdTe NW can be estimated to be  $8.6 \times 10^8 \Omega$  and the resistivity ( $\rho$ ) 270  $\Omega$ cm. Fig. 3b depicts the  $I_{ds}$ – $V_g$  curve at  $V_{ds} = -3$  V. The hole mobility ( $\mu_h$ ) can be deduced to be about  $6.8 \times 10^{-2} \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1}$  [32]. The hole concentration ( $n_h$ ) thus can be estimated to be  $3.6 \times 10^{19} \text{ cm}^{-3}$ . By extrapolating the  $I_{ds}$ – $V_g$  curve to the  $V_g$  axis as shown in Fig. 3b, the threshold voltage ( $V_{th}$ ) is estimated to be 2 V.

According to the self-compensation effect of II–VI group compound semiconductors, each element constituting the compounds usually has different dissociation pressure and sublimating temperature, thus leading to deviation of the product from stoichiometric composition during the sublimation and deposition processes. The p-type behaviour of intrinsic CdTe NWs is probably attributed to the intrinsic defects of Cd vacancies in NWs. The defect theory could be used to explain this p-type conductivity [18], and then the neutral Cd vacancy  $V_{Cd}^{\times}$  and the ionised vacancies will bring about acceptor energy levels in the forbidden energy gap. In addition, the as-synthesised CdTe NWs with a high-aspect ratio and nearly perfect crystalline structure will enable the electrons to suffer less scattering through such a narrow zone.

**4. Conclusion:** In conclusion, the CdTe single-crystalline NWs are synthesised via the thermal evaporation method, the morphology and structure characterisations demonstrate that CdTe NWs have a

zinc blende structure with growth direction of [111]. The electrical properties measurements of the single CdTe NW FET reveal that the NWs have good p-type conductivity with a mobility of  $6.8 \times 10^{-2} \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1}$  and carriers concentration of  $3.6 \times 10^{19} \text{ cm}^{-3}$ . The significant p-type conductivity is attributed to the intrinsic defects of Cd vacancies in NWs, and the high-aspect ratio and nearly perfect single-crystalline quality in the 1D nanostructures can present excellent electron transfer characteristics. The as-synthesised CdTe NWs with novel electrical properties will develop application in the generation of nanoelectronic devices.

**5. Acknowledgments:** We are thankful for financial support from Pingdingshan Science and Technology Bureau Science Research Programmes (No. 2012C039). We also thank Henan Province Scientific and Technological Department Programmes (Nos. 092102210198 and 122102210171), Henan Province Scientific and Technological Department Key Programmes for Science and Technology Development (No. 102102210439), Henan Province Education Department Natural Science Research Programmes (No. 2010B150002).

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