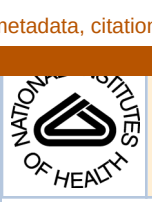

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Photoconductive and polarization properties of individual CdTe nanowires

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1. Introduction

Semiconducting nanowires are attractive materials for optoelectronics and, specifically, cadmium-chalcogenide nanowires have shown promise for future applications [1,2]. Specific types have proven to be useful device components due to their sensitivity to polarization [3], enhanced carrier mobilities [4], and photoconductive properties [5,6] and cadmium telluride is easily made p- or n-type by varying growth conditions during CVD synthesis [7].

Although previous research has demonstrated photoconductance in random mats [8], the photoconductivity of individual CdTe wires has not been investigated. CdTe is a photoconductive II-VI semiconductor with a high optical absorption coefficient [9,10] and a direct band gap in the visible range that makes it an ideal material for photovoltaics.

Previous studies [11,12] have fabricated semiconducting Cd-chalcogenide nanowires in porous AAO templates. Their investigations on electrical transport through CdS and CdSe nanowires focused on the effects of photoelectrically induced *I-V* changes and a coaxial SiO_2 gate dielectric, respectively. In this study the *I-V* relationships of individual metal-$Cd_{0.42}Te_{0.58}$ -metal nanowires are investigated under various photon energy excitations. For individual wires we observed an increase in nanowire current as a function of impinged photon energy, as well as anisotropy in the response to photon polarization. The power conversion efficiency is determined, and information about the phases present in this material is also presented.

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Metal-$Cd_{0.42}Te_{0.58}$ -metal nanowires were electrodeposited into the pores of anodized aluminum oxide (AAO) membranes, and the polarization sensitive photoconductance was analyzed for individual nanostructures. Non-linear *I-V* curveswere observed, and the short-circuit current density, open-circuit voltage, and fill factor were determined. These nanowires exhibited a power conversion efficiency of : 0.56%, which is higher than some comparable nanomaterials of greater complexity.

CdTe nanowire electrodeposition photoconductance

2. Experimental

An electrolyte previously employed by Wang *et al.* [13] was used to deposit wires into the pores of an AAO template with 200nm pores (Whatman Anodisc 13), and $Cd_{0.42}Te_{0.58}$ nanowires were fabricated electrochemically as described elsewhere [14,15,16]. After deposition the Ag working electrode was etched in HNO_3 and the template was dissolved in 1 M NaOH, followed by rinsing (5x) in ethanol. Compositional characterization was performed using an INCA PentaFET energy dispersive spectroscopy system (EDS, Oxford Instruments) attached to a Hitachi S-4700 FE-SEM. Powder X-ray diffraction was performed using CuKα radiation.

Wires were drop cast onto prefabricated 15 μ m gap gold microelectrodes on a p^+ $Si:SiO_2$ substrate [17]. The nanowires were then connected to the microelectrodes using a combination of electron and ion beam induced deposition of Pt between the gold segments of the nanowires and the microelectrodes using an FEI Helios 600 Nanolab Focused Ion Beam (FIB) [16,18]. Electrical measurements were performed in ambient conditions at room temperature with a Keithley 2400 sourcemeter. Photon sources were either a 5 mW unfocused laser diode or a 150 W halogen lamp.

The effect of photon energy E_{ph} on the *I-V* characteristic of individual nanowires was tested with Phillips Lumileds LEDs. Each LED was calibrated to emit 45 lumens. LEDs were turned on and off in succession while a constant potential was applied across the nanowire and the current was measured. Polarization experiments were performed using a high powered (150 W) broad spectrum halogen lamp connected to a fiber optic cable used to direct the light to the polarizer, then onto the nanowire. The polarizer was rotated two degrees between each measurement through a range of 2π radians and the measured photoconductance revealed anisotropy (Figure 4a).

3. Results and discussion

X-ray diffraction data for the $Cd_{0.42}Te_{0.58}$ material shows that both CdTe and a small number of pure Te domains exist, likely because of the Te-rich status of the wires (Figure 1) [19]. The templated electrodeposition technique for nanowire fabrication allows for facile control over various sections of wire length, as evidenced by the EDS data (Figure 2). Clearly defined segments of the Au-$Cd_{0.42}Te_{0.58}$-Au wires allowed $Cd_{0.42}phTe_{0.58}$ segments to be electrically connected to macroscopic leads via contact with the Au wire ends, ensuring that $Cd_{0.42}Te_{0.58}$ sections were not altered or damaged during FIB deposition of Pt.

Each nanowire had a non-linear *I-V* characteristic for a -10 V to 10 V sweep. Under illumination the conductance of the nanowire increased compared to measurements in ambient or dark conditions. Impinging laser light decreased the typical nanowire resistance from 42 ± 2 k to 30 ± 2 k (assessed at *V : eq* -7*V* in Figure 2). Various LEDs (E_{ph} = 2.69 eV, 2.34 eV, 2.10 eV, 1.97 eV, peak width of 0.1 eV) were impinged on the wire while a constant potential was applied across the wire (Figure 3). The 2.69 eV LED increased the conductivity of the nanowire most significantly, over twice as much as the 1.97 eV LED. For direct gap absorption, the data $I(E_{ph})$ can be fit to $\alpha = A(E_{ph} - E_g)$ $3/2/E_{ph}$, where α is the adsorption coefficient and E_g is theband gap, as expected for CdTe [20]. Fitting $I(E_{ph})$ to the excitation data (Figure 3) resulted in a band gap of 1.17 eV, which is consistent with previous reports on Te-rich CdTe materials [19].

1. Pure Te peaks are expected due to the as-grown stoichiometry of these wires. Phase separation between Te clusters and the CdTe matrix has been previously explored by Lepiller *et al.* [19]

2. Comparison between dark and illuminated (150 W halogen lamp) *I-V* curves. Top inset: SEM image of a Au-Cd $_{0.42}Te_{0.58}$ -Au nanowire with EDS data indicating the multicomponent structure of the nanowires. Bottom inset: SEM image of a single Au-Cd $_{0.42}Te_{0.58}$ -Au nanowire connected to microelectrodes via Pt-deposited films [18].

3. Incident photon energy and corresponding currents for three different nanowire samples. V_{SD} = 1 V. The data fit the equation

$$\alpha = A(\mathrm{E}_{ph} - E_g)3/2/E_{ph} \text{ with } A = 1.15E - 8 \text{ and } E_g = 1.17eV$$

When the polarization was parallel to the nanowire the increase in current was maximized and minimized when it was perpendicular (Figure 4a). This agrees with the expected absorption by a cylinder of diameter $D \ll \lambda$ [21]. The polarization ratio, $\rho = (I_{\mathrm{P}} - I_{\perp})/(I_{\mathrm{P}} + I_{\perp})$, of the intensities parallel (I_{P}) and perpendicular ($I_{\perp}$) yields $\rho = 0.38 \pm 0.03$, which, when fitted to cos 2(θ), yields $R^2 = 0.86$.

4. (a) Polarization angle with respect to the long axis versus current through a single nanowire shows current maximization when polarization was parallel to the long axis of the nanowire with V_{SD} = 1 V. (b) The Fourier Transform of (a). Note the harmonics at twice and three times the fundamental frequency. Data from two wires is represented.

The Fourier transform (Figure 4b) contained strong harmonics in addition to the fundamental oscillation. The harmonics contain approximately 25% of the spectral weight. We speculate that the extra harmonics might arise from misalignments in the polarizer, scattering from the metal leads, or the finite aspect ratio of the CdTe segment [21].

The short-circuit current density I_{sc}, open circuit voltage V_{oc}, along with maximum voltage V_{max}, and current max I_{max} between I_{sc} and V_{oc} were determined. Fill factor *FF* was used to calculate the energy conversion efficiency $\eta = (I_{max}V_{max}FF)/P_{in}$, where $FF = I_{max}V_{max}/I_{sc}V_{oc}$ (extracted from Figure 2), I_{max} and V_{max} are the current and voltage maxima, respectively, and P_{in} is the incident power intensity [22]. $\eta = 5.6\times10{-}3\pm 0.5\times10{-}3$ was obtained; this value is somewhat higher than what has been previously reported for more complicated materials [23]. Further improvements in the conversion efficiency may be realized by improvements in the fill factor, which can be achieved by reducing the series resistance of the device through the creation of graded interfaces between the metal and semiconductor segments of the nanowire, as has been demonstrated [18].

4. Conclusions

Metal-$Cd_{0.42}Te_{0.58}$ -metal nanowires were fabricated via sequential electrodeposition into the pores of AAO. These wires produced non-linear *I-V* curves and were photoconductive. Both photon energy and polarization angle modulatedthe amount of photoconductance in single wires. Higher photon energies caused an increase in conductivity of : 2.5×. These measurements showed that there is strong potential for metal-CdTe-metal nanowires in photovoltaic applications.

Acknowledgments

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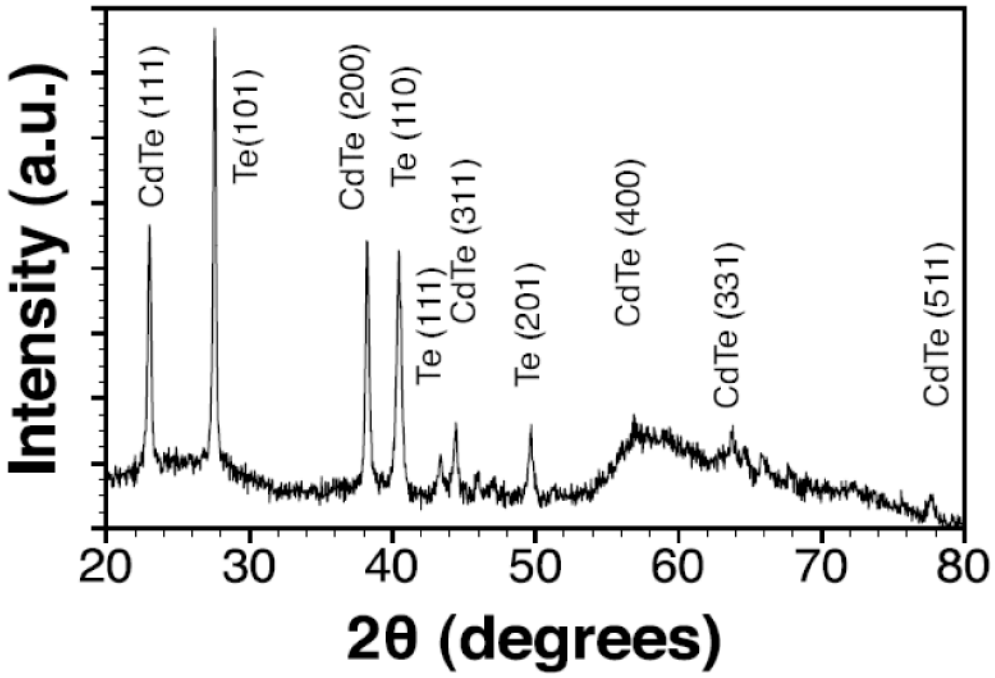

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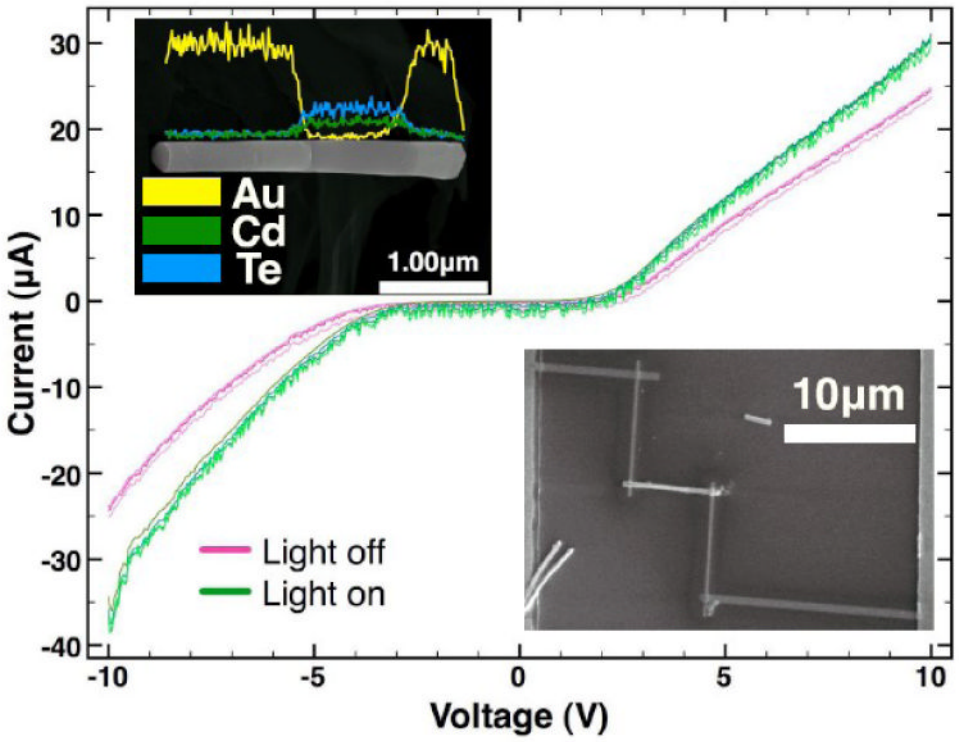

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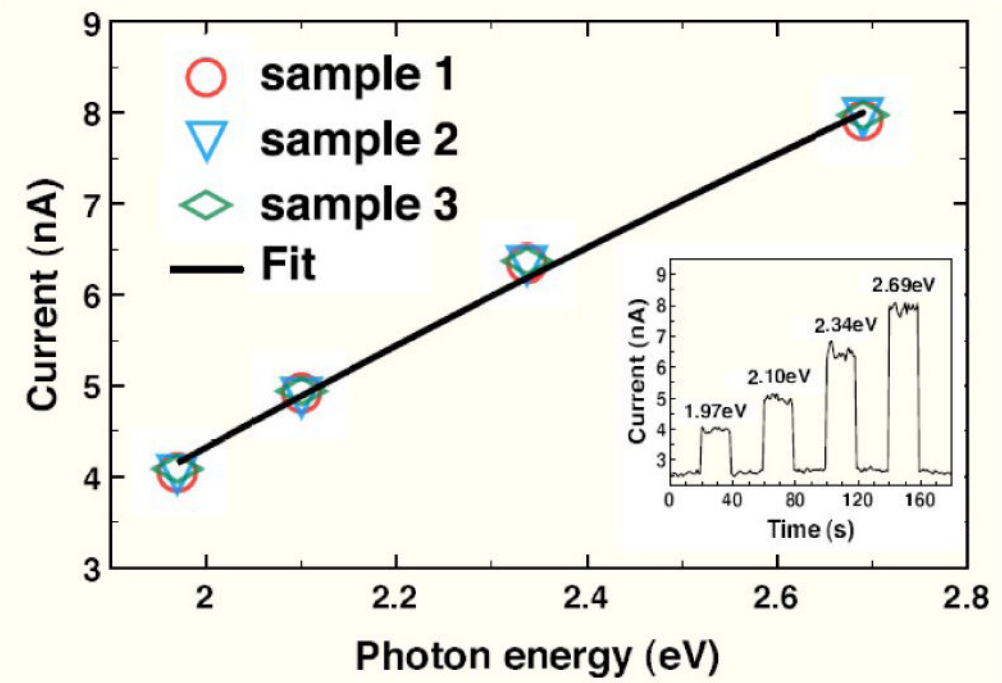

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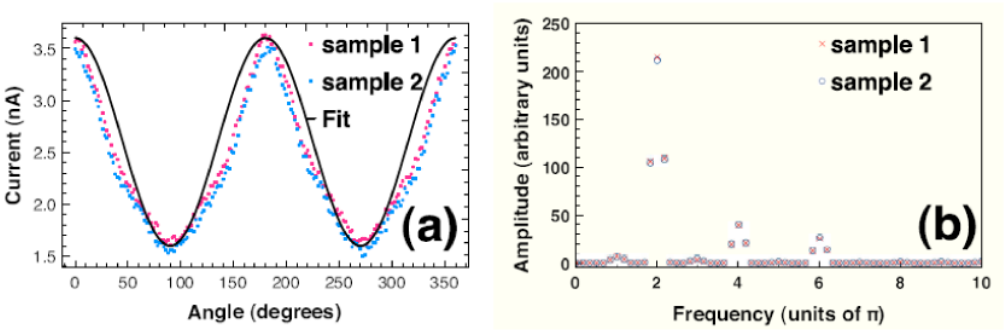
Incident photon energy and corresponding currents for three different nanowire samples. *VSD* = 1 V. The data fit the equation _ = *A*(*Eph* − *Eg*)3/2/*Eph* with *A* = 1.15*E* − 8 and *Eg* = 1.17 *eV*.



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