Field-effect transistors and photodetectors based on solution-synthesized nanowires

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Various semiconductor nanostructures, including nanotubes and nanowires have been grown and studied recently. The primary growth technique has been chemical vapor deposition (CVD)-based, such as the rather popular vapor-liquid-solid (VLS) technique. [1] Growth techniques utilizing solution-based synthesis, on the other hand, have a number of advantages over the CVD technique such as low cost, scaling of production, ability to passivate the semiconductor surface chemically during growth, and the ease of transfer to any substrate. One such synthetic method is the solution-liquid-solid (SLS) technique, which has been used by various groups to produce colloidal quantum dots or nanocrystals.[2] Rudimentary photodetectors have been demonstrated using closed-packed "solids" of the SLS-grown nanocrystals. Though photon absorption and electron-hole pair generation in nanocrystals is efficient, the extraction of carriers is difficult, involving hopping transport between the dots before being collected by the electrodes.

In this work, we demonstrate photodetectors based on CdSe nanowire networks, or "quantum-wire solids". Nanowires allow band-transport along their axes, therefore potentially offering a drastic improvement over nanocrystals for the efficient collection of optically generated carriers. To evaluate the transport properties of the nanowires, we have fabricated field-effect transistors using both single nanowires and networks of nanowires as channels on SiO_2/Si substrates with back gates. For single nanowire FETs, focused ion beam has been employed to define Pt source-drain contacts. Typical nanowires diameters are 10nms, and lengths vary from 1-10 microns. For multiple nanowire channels, we have used ac dielectrophoretic alignment for precise placement of the nanowires between the source-drain contacts (Figure 1, right).[3] The nanowires FETs thus fabricated require a negative gate bias for pinch-off indicating that the wires are n-type, and drain-source current on/off ratios of 10^5 are observed for FETs with dense nanowires network channels, as opposed to ~10 for single nanowires FETs (Figure 2, right). The temperature-dependence of the source-drain current (Fig 3, left) indicates that the charge transport is dominated by thermally generated carriers in the dark.

Metal-semiconductor-metal photodetector devices are then fabricated using conventional optical lithography and metal deposition. The photodetectors are found to have very low dark currents (~ 10 nA at 5 V), indicating very few free carriers in the nanowires at room temperature. The spectroscopic photoresponse of these photodetectors is measured using a xenon lamp coupled with a monochromator, and a lock-in amplifier in a photon energy range of 1.4 - 3.5 eV. We observe a sharp turn-on in the photocurrent, at 1.80 eV, near the absorption edge of the nanowires measured independently using an UV-Vis spectrophotometer (Figure 3, center). The photoresponse is estimated to be higher than 50 mA/W at a bias of 5 V at 550 nm (2.25 eV) illumination. With increasing photon energy, the responsivity of the NW-based photodetectors shows a very slow decrease, ~ 18% drop at 3.4 eV compared to that at 2.25 eV. This is in sharp contrast to traditional photodetectors, where the photoresponse decays rapidly with increasing photon energy. The photoresponse, and the resultant quantum efficiency can be enhanced for particular wavelengths by a cavity effect by tuning the thickness of the underlying SiO_2 layer and using multiple reflections from the SiO_2/Si interface, as demonstrated in Figure 3 (right).

In conclusion, we have demonstrated that solution-synthesized semiconductor nanowires can be used as channels in traditional FET structures, and their high optical absorption and high quantum efficiencies can be exploited for fabrication of photodetectors. With solution synthesized narrow bandgap semiconductor (PbS, PbSe) nanowires, the photodetector spectral range can be extended into the IR regime, and can be transferred to flexible substrates in the future.[4]

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[3] R. Zhou, H.-C. Chang, V. Protansenko, M. Kuno, A. Singh, and D. Jena, unpublished (2006).
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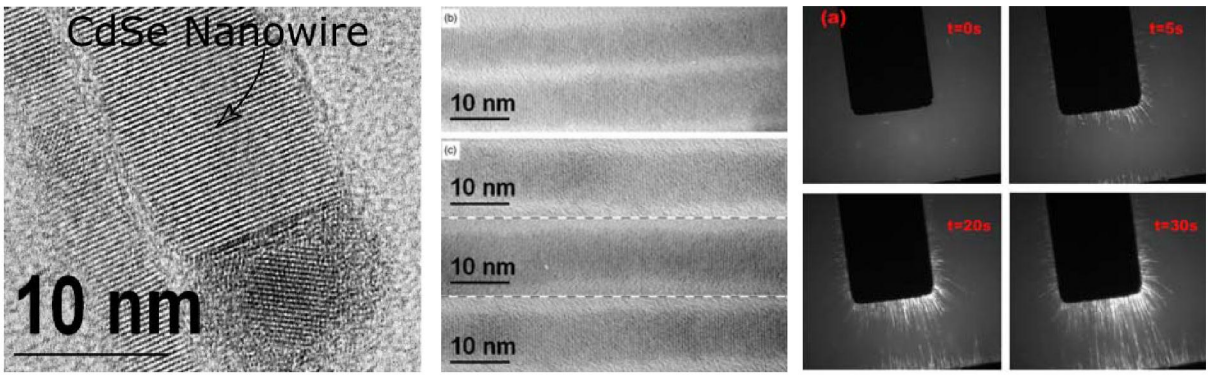

Fig. 1: Solution-synthesized CdSe nanowires (left, center), and their ac electric-field assisted dielectrophoretic alignment between contact pads in solution (right).

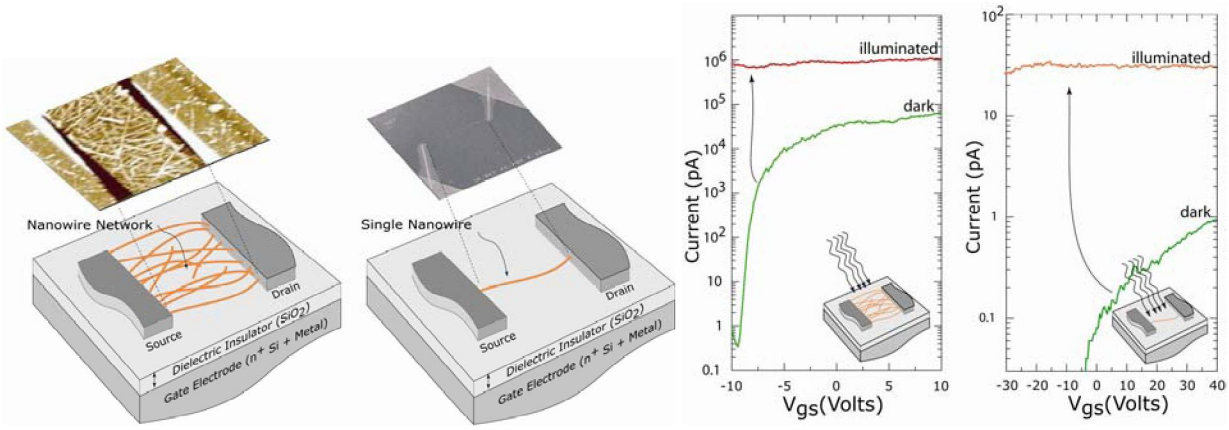

Fig. 2: AFM & SEM images of (left) multiple nanowires FET and (center) single nanowires FETs assembled on conductive Si/SiO_2 substrates with back-gates. The single nanowires FETs are fabricated by focused-ion-beam inscribed Pt contacts written from isolated wires to larger metal pads. The figure on the right compares the current-voltage characteristics of the two FETs in dark and under illumination.

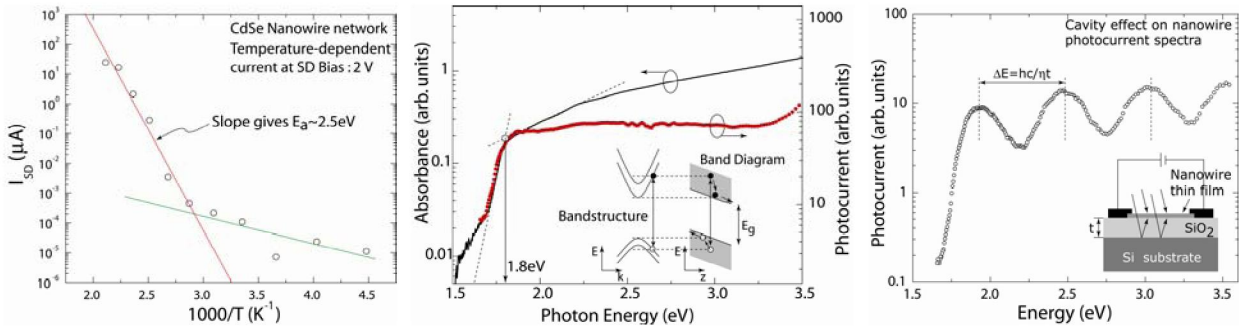

Fig. 3: (Left): Temperature dependent source-drain current indicating that thermally generated carriers dominate the transport in dark. (Center): 300K photocurrent spectra superposed on the absorption spectra of the nanowires showing sharp band-edge onset of photocurrent. The photoresponse does not decrease with increasing photon energy in sharp contrast to bulk semiconductor photoconductive photodetectors. (Right): Cavity-induced oscillations in the nanowires photocurrent spectra.