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Nanowire Ultraviolet Photodetectors and Optical Switches**

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Nanowires and nanotubes may become important building blocks for nanoscale optoelectronics,[1] since they can function as miniaturized devices as well as electrical interconnects. Nano-devices such as field-effect transistors,[2,3] single-electron transistors,[4,5] metal–semiconductor junctions,[6,7] and intermolecular crossed junctions[8,9] have been demonstrated. Many of these devices rely on binary switching, which is critical for important applications such as memory storage and logic circuits. Switching on the nanometer and molecular level has been predominantly achieved through proper electrical gating, as exemplified by nanotube transistors.[2,3] However, no attention has been given to the photoconducting properties of nanowires despite the exciting possibilities for use in optoelectronic circuits. Here, we show the possibility of creating highly sensitive nanowire switches by exploring the photoconducting properties of individual semiconductor nanowires. The conductivity of the ZnO nanowires is extremely sensitive to ultraviolet light exposure. The light-induced conductivity increase allows us to reversibly switch the nanowires between "OFF" and "ON" states, an optical gating phenomenon analogous to the commonly used electrical gating.[2,3,10]

The ZnO nanowires used in the experiments were grown by a vapor phase transport process developed in our lab.[11] The diameters of these wires range from 50 to 300 nm. To characterize their photoconducting properties, the nanowires were dispersed directly on pre-fabricated gold electrodes. Alternatively, electron-beam lithography was used to fabricate gold electrodes on top of the nanowires. Field-emission scanning electron microscopy (FE-SEM) was used to image the ZnO nanowire devices. Electrical resistivity measurements were performed in a four-terminal configuration in air, nitrogen, or vacuum environments.

Four-terminal measurements of individual ZnO nanowires indicate that they are highly insulating in the dark with a resistivity above 3.5 MΩ cm. When the nanowires are exposed to ultraviolet (UV)-light with wavelengths below 380 nm (handheld UV-lamp, 0.3 mW cm^{-2}, 365 nm), the nanowire resistivity decreases by typically 4 to 6 orders of magnitude. Figure 1 compares the current–voltage (*I–V*) curves measured on a

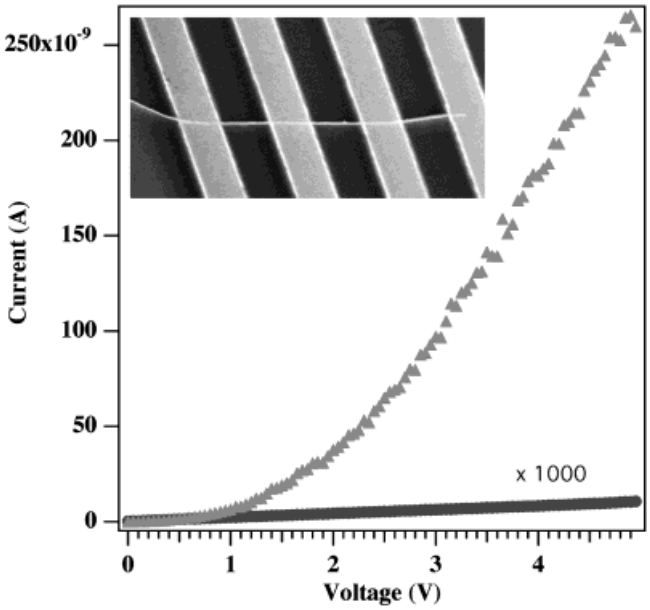

Fig. 1. *I–V* curves show dark current (●) and photocurrent (▲) of a single ZnO nanowire under 365 nm, 0.3 mW cm^{-2} UV-light illumination. The inset reveals an FE-SEM image of a 60 nm ZnO nanowire bridging four Au electrodes. The four-terminal *I–V* measurement is carried out using a Keithley source-measure unit at room temperature.

60 nm nanowire in the dark and upon UV-light exposure. A larger photoresponse was detected at higher bias. We notice that the *I–V* curve for the UV-exposed nanowire exhibits nonlinear behavior. The same nonlinear *I–V* has been observed for both the wire-on-electrode and electrode-on-wire configurations. The four-terminal and two-terminal measurements show essentially identical resistivity values, which suggests that the Au/ZnO contacts may not contribute to the *I–V* nonlinearity. The exact reason for this nonlinearity remains unknown at this stage.[12]

The high sensitivity of the nanowire photoconductors can be seen in Figure 2, which shows the power dependence of the photoresponse. The third harmonic of a Nd:YAG laser was used as the UV light source. Neutral density filters were used to change the incident UV light power. It was found that the photoresponse (I_{pc}) can be expressed by a simple power law

$$I_{pc} \propto P^{0.8} \quad (1)$$

where P is the power of illumination.[13] The non-unity exponent is a result of the complex process of electron–hole generation, trapping, and recombination within the semiconductor.[13] Depending on the power of illumination, the resistivity can be reversibly changed by 4 to 6 orders of magnitude without damaging the nanowires.

In addition to the high sensitivity, the nanowire photoconductors also exhibit an excellent wavelength selectivity. Figure 3a shows the evolution of the photocurrent when a nanowire was exposed first to highly intense light at 532 nm (Nd:YAG, second harmonic, 532 nm) for 200 s and then to

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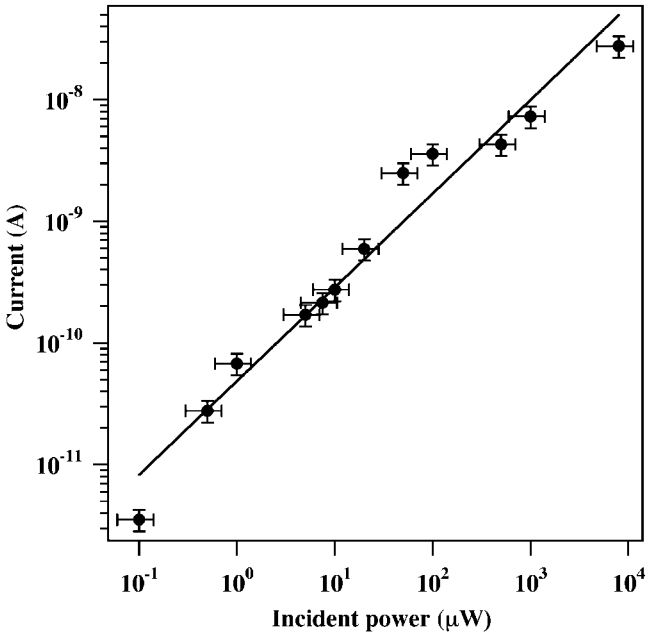

Fig. 2. Variation of the photocurrent with the intensity of illumination at 355 nm for a ZnO nanowire. The third harmonic of a Nd:YAG laser was used as the UV-light source. Several neutral density filters were used during the power-dependent measurement. The UV laser power is measured using a Melles Griot power meter. The bias on the nanowire is 1 V.

UV-light at 365 nm. Green light does not induce a photoresponse, while exposure to less intense UV-light increases the conductivity by 4 orders of magnitude. Measurements of the spectral response show that our ZnO nanowires indeed have a response cut-off wavelength of ~370 nm, which is expected from the wide bandgap (3.37 eV) of ZnO. In fact, a measurable photoresponse has been observed even with a small percentage of UV-light from a broadband light source such as indoor incandescent light or sunlight.

It is known that oxygen chemisorption plays a central role in regulating the photosensitivity of bulk or thin film ZnO, where a UV-sensitivity of similar magnitude has been observed.[13–15] We believe that a similar mechanism is applicable to our nanowire system. In the dark, oxygen molecules adsorb on the nanowire surface as negatively charged ions by capturing free electrons from the n-type ZnO, thereby creating a depletion layer with low conductivity near the nanowire surface:

$$O_2(g) + e^- \longrightarrow O_2^-(ad) \quad (2)$$

Upon exposure to UV-light, photo-generated holes migrate to the surface and discharge the adsorbed oxygen ions through surface electron–hole recombination:

$$h^+ + O_2^-(ad) \longrightarrow O_2(g) \quad (3)$$

At the same time, the photo-generated electrons significantly increase the conductivity of the nanowire. This photo-

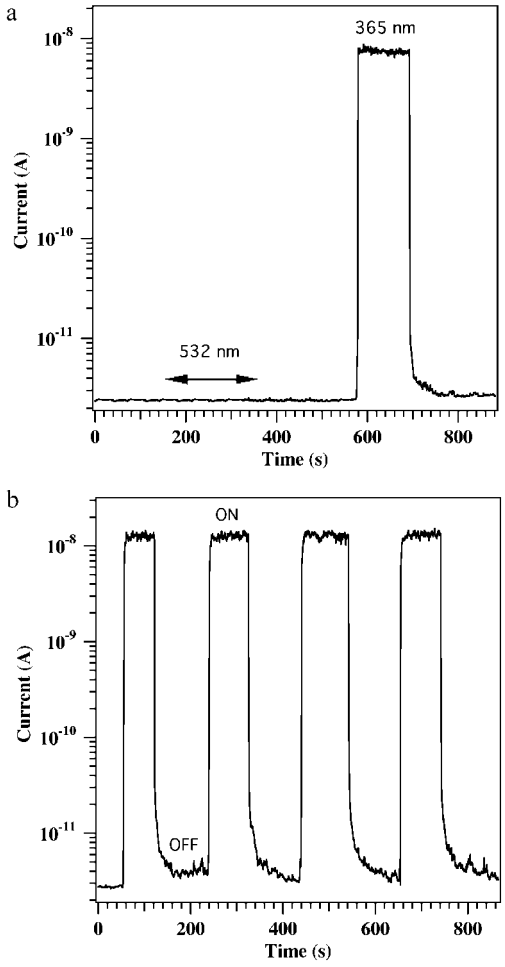

Fig. 3. a) Sensitivity of the photoresponse of a ZnO nanowire to light exposure at wavelengths of 532 nm and 365 nm. Second harmonics of a Nd:YAG laser and a handheld UV-lamp were used as visible and UV-light sources, respectively. b) Reversible switching of a ZnO nanowire between low and high conductivity states when the handheld UV-lamp was turned on and off. The bias on the nanowire is 1 V.

electric gain suggests that an optical gating (analogous to the conventional electrical gating) is operating within these nanowires rather than a simple light harvesting process. It is expected that thinner nanowires may further enhance the sensitivity of the devices due to an increased surface to volume ratio, which may lead to the realization of single photon detection. In addition, the photoresponse is strongly dependent on the ambient gas conditions, being slow in vacuum and inert gases (up to several minutes), and fast in air (<1 s). Further optimization of the nanowire composition, e.g., through doping or surface modification, could improve these characteristics.

The characteristics of the photoconductive ZnO nanowires suggest that they are good candidates for optoelectronic switches, with the dark insulating state as "OFF" and the UV-exposed conducting state as "ON". Figure 3b plots the photoresponse as a function of time as the UV-lamp was switched on and off. It is evident that the nanowires can be reversibly switched between the low and the high conductivity

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state. The rise and decay times of the fastest nanowire switches are below our detection limit, which is roughly 1 s. These photoconducting nanowires could serve as highly sensitive UV-light detectors, chemical and biological sensors, and switching devices for nanoscale optoelectronic applications, where the binary states can be addressed optically.

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