Temperature dependence of photoconductivity and persistent photoconductivity of single ZnO nanowires

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Abstract Photoelectrical properties of single ZnO nanowires have been investigated using photocurrent–voltage characteristics measurements varying with excitation photon energy and temperature. It is found that persistent photoconductivity (PPC) exists, and the PPC decreases with decreasing temperature. The temperature dependence of the PPC effect indicates that thermally activated return of electrons from shallow traps is responsible for the PPC phenomenon. The photosensitivity is found to be linear with the applied voltage, and it increases with decreasing temperature. A temperature dependence of photoconductivity gain was introduced to explain the experimental results.

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One-dimensional materials are promising building blocks for high-performance nanoscale electronic and photonic devices. Wide band gap semiconductor ZnO nanowires have attracted increasing attention in recent years for their potential application for gas sensors [1–3], light-emitting diodes [4, 5], photovoltaic devices [6, 7], ultraviolet (UV) lasers [8] and UV detectors [9–12]. Photodetectors of ZnO nanowires are candidates as low-cost UV detectors with high gain and photoresponsivity. However, a negative aspect is that ZnO photodetectors often display a strong persistent photoconductivity (PPC) [13, 14], and typical relaxation times for the PPC were in the range of tens of minutes to several days. Additionally, the mechanisms of ZnO photodetectors are more complex than the generation of electron–hole pairs across the band gap, because the as-grown ZnO is generally an n-type semiconductor with abundant trap states and surface states. Therefore, it is important to understand in depth the photoelectrical properties of ZnO nanowires. Based on understanding the photoelectrical properties, the physical effect may be extended, the mechanism may be addressed and new functions may be found, which in turn helps to improve the device performances. Although photoelectrical properties of ZnO nanowires have been investigated intensively at room temperature [4–16], we are unaware of published papers about the temperature dependence of photoconductivity of single ZnO nanowires. The temperature-dependent behavior of the photoconductivity can yield more information about the carrier generation, transport and recombination. In this work, we report the temperature dependence of PPC and photoconductivity of single ZnO nanowires. The underlying mechanisms related to the carrier generation, trapping, detrapping and recombination are discussed.

Individual ZnO nanowires contacted by Ti (10 nm)/Au (50 nm) electrodes were fabricated on a Si substrate with a 500-nm SiO2 layer using an e-beam lithography technique [15]. Figure 1 shows the scanning electron microscopy (SEM) image of a single ZnO nanowire device. The devices were placed in a Janis micro-cryostat with \( \sim 10^{-6} \) Torr vacuum. The electrical measurements were performed by a Keithley 6430 Sub-fA Remote SourceMeter.
The photoelectrical properties of the ZnO nanowire device were studied in detail through employing incandescent light from a bulb and an ultraviolet (UV) laser beam (325 nm) from a He–Cd laser as the excitation light sources, respectively. Figure 2a displays the typical current–voltage ($I–V$) characteristics of the device measured at a temperature of 300 K. A slight increase of photoconductance under the irradiation of the bulb is observed. Because the photon energy of the bulb light is smaller than the ZnO band gap energy, the photoconductance is ascribed to the transition of carriers from defect states to the conduction band. It is found that the photoconductance increases with increasing bulb power. Thus, the photoconductance can be simply tuned via controlling the illumination power. As the sample was illuminated by a 325-nm (corresponding to 3.8-eV) laser, the photoconductance was almost two orders of magnitude enhanced. Because the photon energy of the laser is larger than the 3.3-eV band gap of ZnO, the significant enhancement of photoconductance may mainly originate from the photogenerated electron–hole pairs across the band gap.

An important phenomenon is that after switching off the laser shutter a persistent photoconductance (PPC) is maintained, which is much higher than the initial dark conductance, as shown in Fig. 2a. The PPC decreases greatly with decreasing temperature, and the PPC has only a small value at a temperature of 100 K, as seen in Fig. 2b. Moreover, it is found that the PPC almost disappears as the temperature further decreases to 70 K, as shown in Fig. 2c. The physical mechanisms responsible for the persistent photoconductance are still under debate. Generally, the irradiation with the UV laser can result in the desorption of gas molecules from the ZnO nanowire surface, and after switching off the laser the surface gas adsorption cannot be recovered quickly in the vacuum, which will induce the PPC effect. However, the effect of gas desorption only cannot sufficiently explain the temperature dependence of the PPC. Here, we attribute the temperature dependence characteristics of the PPC to the variations of emptying of charged trap states in the ZnO nanowire. For the n-type ZnO, the recombination probability of the shallow traps near the conduction band may be very low because a thermally activated return of electrons to the conduction band may occur. The free-carrier concentration $n$ at thermal equilibrium depends on the position of traps $E_t$ in the forbidden gap and the effective state density $N_c$, and is given by [17]

$$n = N_c \exp\left(-\frac{\Delta E_t}{kT}\right),$$

where $\Delta E_t = E_c - E_t$ is the energy distance between the trap energy level and the conduction band. At high temperatures, a certain time is necessary to fill the traps at the beginning of irradiation, and after switching off the light a persistent photoconductance appears until the traps are thermally