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UV photoresponse of single ZnO nanowires

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ABSTRACT ZnO nanowires grown by site-selected molecular beam epitaxy (MBE) were contacted at both ends by Al/Pt/Au ohmic electrodes. The current–voltage (I–V) and photoresponse characteristics were obtained both in the dark and with ultraviolet (UV, 254 or 366 nm) illumination. The I–V characteristics are ohmic under all conditions, with nanowire conductivity under UV exposure of 0.2 Ω cm. The photoresponse showed only a minor component with long decay times (tens of seconds) thought to originate from surface states. The results show the high quality of material prepared by MBE and the promise of using ZnO nanowire structures for solar-blind UV detection.

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1 Introduction

ZnO nanowires may have application in a variety of areas, including gas and chemical sensing, data storage or polarized light emitters [1–4]. While most of the work to date has focused on the synthesis of a wide variety of one-dimensional nanostructures based on ZnO [5–27], there has been less done on the electrical transport properties and photoconduction in ZnO nanowires. Recent reports have shown the sensitivity of ZnO nanowires to the presence of oxygen in the measurement ambient and to ultraviolet (UV) illumination [1–3]. In the latter case, above band gap illumination was found to change the current–voltage (I–V) characteristics of ZnO nanowires grown by thermal evaporation of ball-milled powders between two Au electrodes from rectifying to ohmic [3]. By contrast, there was no change in the effective built-in potential barrier between the ZnO nanowires and the contacts for below band gap illumination. The slow photoresponse of the nanowires was suggested to originate in the presence of surface states which trapped electrons with release time constants from milliseconds to hours [3].

In this paper we report the photoresponse characteristics of single ZnO nanowires grown by site-selective molecular beam epitaxy (MBE). These nanowires have relatively fast photoresponse and show electrical transport dominated by bulk conduction.

2 Experimental

The site-selective growth of the nanowires has been described in detail previously [14, 15]. For nominal Ag thicknesses of 20 Å, discontinuous Ag islands are realized. ZnO nanowires were deposited by MBE with a base pressure of 5×10^{-8} mbar using high-purity (99.9999%) Zn metal and an O_3/O_2 plasma discharge as the source chemicals. The Zn pressure was varied between 4×10^{-6} and 2×10^{-7} mbar, while the beam pressure of the O_3/O_2 mixture was varied between 5×10^{-6} and 5×10^{-4} mbar. The growth time was ~ 2 h at 400–600 °C. The typical length of the resulting nanowires was ~ 2 μm, with typical diameters in the range of 15–50 nm. Selected-area diffraction patterns showed the nanowires to be single crystal. They were released from the substrate and then transferred to SiO_2-coated Si substrates. E-beam lithography was used to pattern sputtered Al/Pt/Au electrodes contacting both ends of a single nanowire. The separation of the electrodes was ~ 0.3 μm. A scanning electron micrograph (SEM) of the completed device is shown in Fig. 1. Au wires were bonded to the contact pad for current–

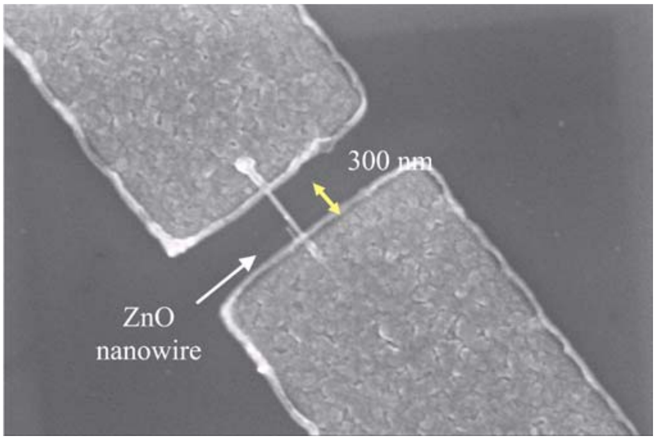

FIGURE 1 SEM micrograph of ZnO nanowire between two ohmic contact pads of Al/Ti/Au

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voltage (I–V) measurements performed at 25 °C in air. In some cases, the nanowires were illuminated with above band gap light at 254 or 366 nm from a Hg arc lamp with a power density of 0.1 W cm^{-2}.

3 Results and discussion

Figure 2 shows the I–V characteristics of the nanowires in the dark and under illumination from 366-nm light. The conductivity is greatly increased as a result of the illumination, as evidenced by the higher current. No effect was observed for illumination with below band gap light. Transport measurements to be reported elsewhere show that the Pt Schottky diodes formed on the nanowires exhibit an ideality factor of 1.1, which suggests that there is little recombination occurring in the nanowires. Note also the excellent ohmicity of the contacts to the nanowires, even at low bias. On blanket films of n-type ZnO with carrier concentration in the 10^{16} cm^{-3} range we obtained a contact resistance of 3–5 × 10^{-5} Ω cm^{-2} for these contacts [28]. In the case of ZnO nanowires made by thermal evaporation, the I–V characteristics were rectifying in the dark and only became ohmic during above band gap illumination [3]. The conductivity of the nanowires during illumination with 366-nm light was 0.2 Ω cm.

Figure 3 shows the photoresponse of the single ZnO nanowire at a bias of 0.25 V under pulsed illumination from a 366-nm-wavelength Hg lamp. The photoresponse is much faster than that reported for ZnO nanowires grown by thermal evaporation from ball-milled ZnO powders [3] and likely is due to the reduced influence of the surface states seen in that material. The generally quoted mechanism for the photoconduction is creation of holes by the illumination that discharge the negatively charged oxygen ions on the nanowire surface, with detrapping of electrons and transit to the electrodes [3, 29, 30]. The recombination times in high-quality ZnO measured from time-resolved photoluminescence are short, on the order of tens of ps [31–33], while the photoresponse measures the electron-trapping time [34]. There is also a direct correlation reported between the photoluminescence lifetime and the defect density in both bulk and epitaxial ZnO [33]. In our nanowires, the electron-trapping times are on the order of tens of seconds and these trapping effects are only a small fraction of the total photoresponse recovery characteristic. Note also the fairly constant peak photocurrent as the lamp is switched on, showing that that any traps present have discharged in the time frame of the measurement.

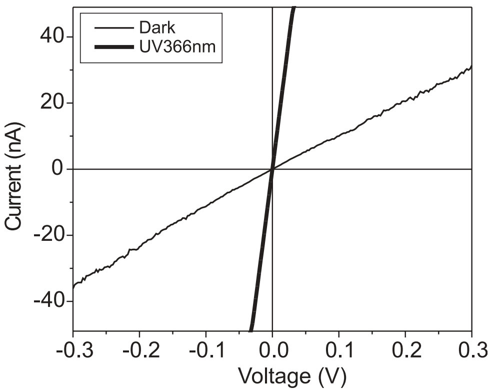

FIGURE 2 I–V characteristics from single ZnO nanowire measured at 25 °C in the dark or under illumination from a 366-nm Hg lamp

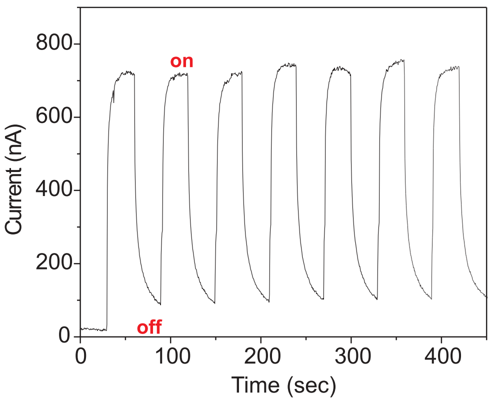

FIGURE 3 Time dependence of photocurrent as the 366-nm light source is modulated

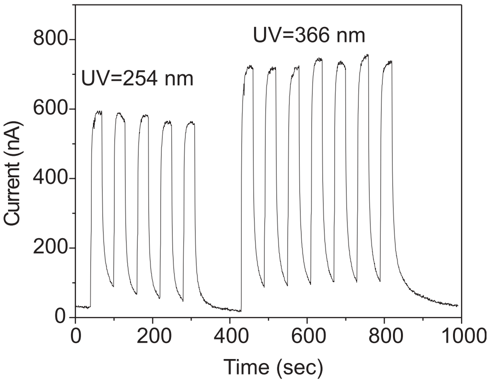

FIGURE 4 Time dependence of photocurrent in the nanowire as either a 254-nm or a 366-nm light source is modulated

Figure 4 shows the photoresponse from the nanowires during pulsed illumination from either 254- or 366-nm light. The lower peak photocurrent in the former case may be related to the more efficient absorption near the surface of the nanowires. Once again we see an absence of the very long time constants for recovery seen in nanowires prepared by thermal evaporation [3].

4 Summary and conclusions

In conclusion, single ZnO nanowires with excellent photocurrent response and current–voltage characteristics have been prepared by site-selective MBE. The I–V characteristics are linear even when measured in the dark and the photoconduction appears predominantly to originate in bulk conduction processes with only a minor surface-trapping component. These devices look very promising for UV detection.

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