Research Article

Lateral Infrared Photovoltaic Effects in Ag-Doped ZnO Thin Films

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A transient lateral photovoltaic effect has been observed in Ag-doped ZnO thin films. Under the nonuniform irradiation of a 1064 nm pulsed laser, the photovoltaic response shows high sensitivity to the spot position on the film surface. The highest photovoltaic responsivity of 27.1 mV mJ^{-1} was observed, with a decline time of $\sim 1.5 \text{ ns}$ and a full width at half-maximum (FWHM) of $\sim 4 \text{ ns}$. The photovoltaic position sensitivity can reach about $3.8 \text{ mV mJ}^{-1} \text{ mm}^{-1}$. This paper demonstrates the potential of Ag-doped ZnO films in the position-sensitive infrared detection

1. Introduction

ZnO is of technological importance and considerable scientific interest due to its unique properties such as direct wide band gap, large exciton, binding energy, strong emission, large saturation velocity ($3.2 \times 10^7 \text{ cm s}^{-1}$), high radiation resistance, and high breakdown voltage [1]. Therefore, ZnO is a promising candidate for high-power and high-frequency semiconductor devices such as ultraviolet (UV) detectors and laser devices [2–4]. Modification of ZnO properties by impurity incorporation is currently another important issue for possible applications in UV optoelectronics. Doping in ZnO with selective elements offers an effective method to adjust their electrical, optical, and magnetic properties, which is crucial for the practical applications. For example, Al doping in ZnO increased its conductivity without impairing the optical transmission, B doping decreased the resistivity [5], Mn-doped ZnO had ferromagnetism [6], and Ga_2O_3 in ZnO enhanced the near band edge UV emission [7], sulfur doping decreased dramatically the UV emission intensity [8]. The merits of wide band gap and large exciton binding energy of ZnO which lead to the research attentions, and Schottky contact, and p-n junction type of ZnO-based UV photodetectors have been realized and reported [9–11]. However, less attention has been paid to

the infrared characteristics in ZnO. Following up with our previous work, here, we show that Ag-doped ZnO thin film exhibits a lateral laser-induced photovoltage: the saturation values of this photovoltage vary with the position of the laser spot under illumination with the 1064 nm-Nd:YAG-pulsed infrared laser. The lateral photovoltaic property is expected to make the ZnO a candidate for position-sensitive photodetectors, and the possible mechanisms are addressed.

2. Experimental

In our paper the silver-doped ZnO thin film was fabricated on fused quartz substrates ($10 \text{ mm} \times 10 \text{ mm}$) which was prepared from a ZnO mosaic target (1/4 area of the target was uniformly covered with high purity of silver slice in the shape of sector) on fused quartz substrates by pulsed laser deposition (PLD) [12] using a KrF excimer laser with the wavelength 248 nm, pulse duration 30 ms, energy density 1 J/cm^2 in O_2 atmosphere with the pressure $5 \times 10^{-4} \text{ Pa}$ and the substrate growth temperature is 450°C . The films thickness was controlled by the number of laser pulses at 450°C by pulsed-laser deposition. The SEM morphology of Ag-doped ZnO films deposited at substrate temperature of 450°C was reported in [13]. The film surfaces are very

FIGURE 1: The schematic diagram displays the electrode settings, the laser spot, and the laser spot moving direction.

FIGURE 2: Photovoltaic signals PV_{mn} between **m** and **n** electrodes under the irradiation of 1064 nm pulse laser at selected positions of $(-2, 2)$, $(0, 2)$, $(2, 2)$, $(-2, -2)$, $(0, -2)$, and $(2, -2)$, respectively.

smooth, basically silver nanocluster uniformly distributed in the film.

For the measurement of optoelectric behaviors, the 1 mm diameter indium electrodes were made on the film surface. The 1064 nm infrared Nd:YAG laser (pulse duration of 25 ps, repetition rate of 10 Hz) was used as the light source at ambient temperature in air with a pulse energy of 0.23 mJ and a light spot of 2 mm in diameter locked by a diaphragm.

FIGURE 3: Dependence of the PV^P_{mn} on the position of the laser spot in the x direction when laser is irradiated on the ZnO surface.

As shown in Figure 1, the laser irradiated the sample along AA' , BB' , and CC' directions, and the photovoltaic signals from the anode (**m**) to cathode (**n**) were monitored with a sampling oscilloscope terminated into $50\ \Omega$. The square ($ACC'A'$) region as displayed in Figure 1 is chosen in order to avoid the effects from the light illumination on the edge and electrodes.

3. Result and Discussion

Initial photoconductive infrared (IR) detectors have been developed utilizing band-band transitions or dopant-to-band transitions. Here, we have the Ag as a dopant in ZnO, and we make it exposed to IR laser. Figure 2 showed the photovoltaic responses to the 1064 nm-pulsed laser irradiation varying with the laser spot along the AA' , BB' , and CC' directions. Two significant characteristics of the photovoltaic signals were found: (i) the maximum photovoltage is obtained when the laser spot is very close to the **m** electrode; (ii) moving the laser spot between the **m**, **n** electrodes leads to the photovoltage dropping. The highest photovoltaic responsivity of $27.1\ \text{mV}\ \text{mJ}^{-1}$ was observed, with a decline time of $\sim 1.5\ \text{ns}$ and a full width at half-maximum (FWHM) of $\sim 4\ \text{ns}$, along the BB' direction close to the **m** electrode. The x direction-position sensitivity, which means the variation of the photovoltage in $\text{mV}\ \text{mJ}^{-1}$ for a 1 mm displacement of the spot along x direction, is about $3.8\ \text{mV}\ \text{mJ}^{-1}\ \text{mm}^{-1}$.

As displayed in Figure 3, the lateral photovoltage was obtained through two indium electrodes named **m** and **n** located in the middle of the two opposite film sides. The peak values of the laser induced photovoltages (PV^P_{mn}) were plotted as a function of the laser spot position x (along AA' , BB' , and CC' , the coordinate origin O was set at the centre between B and B') on the ZnO surface. In the region between the electrodes along the x -axis (shown in Figure 1), when the laser irradiated on the ZnO surface, the PV^P_{mn} varied very linearly with laser position x . It is clear that the absolute

FIGURE 4: Three-dimensional plot for the PVP_{mn} as a function of the laser spot position.

PVP_{mn} value depends on the position of the spot on the x -axis and undergoes a sign drop while the laser spot travels from m to n . The biggest absolute signal value occur when the light spot is close to B .

Figure 4 summarizes the spatial distribution of the PVP_{mn} . The schemae looks like an open book with the ridge toward X - Y plane. The photovoltaic signals are almost symmetrical. The dependence of the photovoltage of laser spot position shows a higher value for the laser spot close to the m electrode while a lower value close to the n electrode. The result indicated the potential in position-sensitive detection at room temperature.

Ag-doped ZnO thin film exhibits a sharp absorption edge at 370 nm [12] in agreement with its band gap of 3.37 eV and photocarrier can be easily generated under UV light illumination. However, the photon energy of 1064 nm laser is 1.165 eV, and it is impossible for the 1064 nm photons to excite the electron-hole pairs in either the Ag-doped ZnO thin film or the insulating quartz substrate. The above fact demonstrates the other aspects playing a crucial role in the photoresponse process in the present sample.

The lattice mismatch between the ZnO and quartz (major component is SiO_2 and high concentration traps exist resulting from impurities or defects) lead to the Ag doping on the fused quartz as surface plasmon at the interface which plays the role of capping buffer layer. So, many microdomains originated from the interface between the film and substrate and even run through the thickness of the whole film, resulting into nanorods, nanowires, and nanoclusters [13]. Thus, there are many metal-insulator (MI) contact structures in Ag-doped ZnO/quartz film. Based on MI contact theory [14], the Fermi level (E_f) of Ag immediately after contact is higher than that of SiO_2 , and electrons will be transferred from the Ag into SiO_2 to equalize the E_f . During the transmission, a portion of electrons are trapped by positively charged centres in the crystal and are accumulated in traps as discussed by Terner [14] and Liu et al. [15]. The contact potential difference in the equilibrium state is estimated as ~ 0.64 eV being determined by the metal

and insulator work functions, which is smaller than the 1064 nm photon energy of 1.165 eV. Under 1064 nm laser irradiation, a number of trapped electrons are freed into the conduction band of SiO_2 and removed by the built-in electric field. Eventually, the photovoltages were induced. Further experiments, such as polarization, doping concentration, interface, and tilting angle dependences, are in progress in order to clarify the underlying detection mechanism of the Ag-doped ZnO thin film.

4. Conclusions

In summary, we have observed the lateral photovoltaic effects in the Ag-doped ZnO thin film under the irradiation of the 1064 nm pulse laser. The largest photovoltaic responsivity is $\sim 27.1 \text{ mV mJ}^{-1}$ with the decline time of $\sim 1.5 \text{ ns}$ and a FWHM of $\sim 4 \text{ ns}$. The peak photovoltage shows a high sensitivity of laser spot position between the contacts on the film surface. In addition, avoiding cryogenic cooling not only reduces the cost and weight but also simplifies the infrared detector system, allowing widespread usage. ZnO is a feasible solution to the future of uncooled IR detection, and the promising initial results demonstrate the possibility of Ag-doping ZnO as a candidate of IR position detector.

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