Angle-sensitive and fast photovoltage of silver nanocluster embeded ZnO thin films induced by 1.064-μm pulsed laser*

Zhao Song-Qing(赵嵩卿)[a)†], Yang Li-Min(杨立敏)[a)], Liu Wen-Wei(刘闻炜)[a)], Zhao Kun(赵 昆)[a)], Zhou Yue-Liang(周岳亮)[b)], and Zhou Qing-Li(周庆莉)[c)]

[a)] *Department of Mathematics and Physics, China University of Petroleum (Beijing), Beijing* 102249, *China*

[b)] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*

[c)] *Beijing Key Laboratory for Terahertz Spectroscopy and Imaging, Key Laboratory of Terahertz Optoelectronics, Ministry of Education, Department of Physics, Capital Normal University, Beijing* 100048, *China*

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Silver nanocluster embedded ZnO composite thin film was observed to have an angle-sensitive and fast photovoltaic effect in the angle range from –90° to 90°, its peak value and the polarity varied regularly with the angle of incidence of the 1.064-μm pulsed Nd:YAG laser radiation onto the ZnO surface. Meanwhile, for each photovoltaic signal, its rising time reached ∼2 ns with an open-circuit photovoltage of ∼2 ns full width at half-maximum. This angle-sensitive fast photovoltaic effect is expected to put this composite film a candidate for angle-sensitive and fast photodetector.

Keywords: angle-sensitive detector, ZnO thin film, silver nanocluster, fast photovoltage

PACC: 7240, 8115I, 0762, 7360F, 7865K

1. Introduction

Zinc oxide (ZnO) film, a II–VI semiconductor with wide band gap of 3.37 eV and large exciton binding energy of 60 meV,[1,2] is technologically important due to its special electrical and optical properties, which make it suitable for a variety of applications such as ultra-violet (UV) light-emitters or LEDs, and UV detectors, transparent conducting electrodes and gas sensors, etc.[3−14] Regarding the photoelectric properties of the ZnO, UV detectors based on ZnO photoconducting layers,[6,7] metal–semiconductor Schottky barriers[2,8] or heterojunctions[12] have been reported. For these detectors, the attention was mainly paid to their properties in the UV or visible range. Metallic nanoparticles, such as Ag or Au, can be used as the building clusters for photonic or microelectronic devices. Extensive work has been done on different metal nano-composite systems. Recently, metallic nano-particle embedded in oxide films exhibited fascinating properties, such as large nonlinearity, photocatalysis, etc.[15−18] In this article, we apply a silver–ZnO mosaic target in obtaining Ag-nanocluster embedded ZnO composite thin films by pulsed laser deposition (PLD) technique.[19,20] We found that this composite thin film has a fast and angle-sensitive laser-induced photovoltaic effect. This effect was expected to make this composite film suitable for a new type fast-responded photodetector to detect changes in angular position.

2. Experimental details

The films were prepared on fused quartz substrates by pulsed laser deposition technique. A KrF excimer laser (wavelength: 248 nm, pulse width: 30 ns, energy density: 1 J/cm^2) was used for ablation of ZnO mosaic target (1/4 area of the target was covered with high purity (99.99%) silver slice in the shape

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†Corresponding author. E-mail: zhaosongqing@yahoo.com.cn

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of sector). In our experimental processing, the repetitive frequency of laser was 4 Hz, the O_2 pressure was 5×10^{-4} Pa, and the temperature of substrates was 450 °C. All the samples were cooled to room temperature under O_2 pressure of 5×10^{-4} Pa in the chamber.

The film thickness was fixed at 500 nm and the film area was 10×10 mm^2. The crystal structure and the composition analyses were characterized by x-ray diffraction (XRD), scanning electron microscopy (SEM) and x-ray photoelectron spectroscopy (XPS). The combined use of XRD, SEM and XPS allowed us to elucidate that the silver doped into the ZnO films was in the form of nanoclusters.[19] The schematic setup for the laser-induced photovoltage (LPV) measurement was shown in the inset of Fig. 1. A small area of 5 mm in diameter was irradiated on the Ag-doped ZnO thin film surface by pulsed laser beam with energy density ∼0.06 mJ/mm^2. The pulse duration was ∼20 ps. The lateral photovoltage between the indium electrodes was measured and recorded by a 500-MHz sampling oscilloscope terminated into 1 MΩ at ambient temperature. All electrodes were always kept in the dark to prevent the generation of any electrical contact photovoltage.

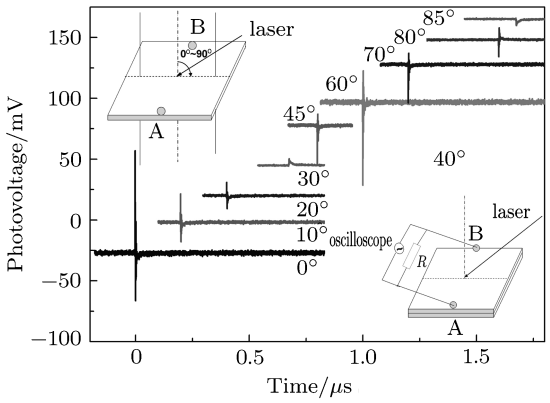


Fig. 1. Different photovoltaic signals for different incident angles of laser pulse plotted as functions of time. Photovoltaic signals shown here are given according to their sizes when the incident angles of laser pulse are set at 0°, 10°, 20°, 30°, 45°, 60°, 70°, 80° and 85°.

3. Results and discussion

As displayed in the top inset of Fig. 1, the LPV is obtained through two indium electrodes which are named A and B, and located in the middle of the two opposite film sides. The photovoltaic signal, obtained when the film is irradiated by a laser pulse, is plotted as a function of time. Different signals for different angles of incidence of laser pulse are presented separately. Here, angles of incidence of laser pulse shown in the inset of Fig. 1 vary from 0° to 90°. Signal for different angles of incident laser has different peak value. When the angle is less than 33°, the peak value decreases linearly as the angle of incidence increases. The peak value reaches zero when the angle is about 33°. After the angle is greater than 33°, the signal changes its sign, though the peak values vary linearly with the angle of incidence approximately. The peak value reaches maximum when the laser angle of incidence is increased up to 60°. Then the peak of the signal decreases as the angle further increases. As the incident angle reaches ∼85°, the photovoltaic signal becomes almost a smooth line.

Figure 2 exhibits the LPV signals when the laser irradiates on the film from other side of the normal line of the film surface. The sketch map of the irradiating laser pulse is shown in the inset of Fig. 2. The angle of incidence of the laser irradiation on this side of normal line is defined as –90°∼0°. The main part of Fig. 2 illustrates signals for different incident angles plotted as a function of time. The peaks of all the signals we are concerned about vary linearly with the angles when the angle is larger than –60°. The peak reaches its maximum when the incident angle reaches –60°. Then the peak of the signal begins to decrease linearly as the incident angle decreases.

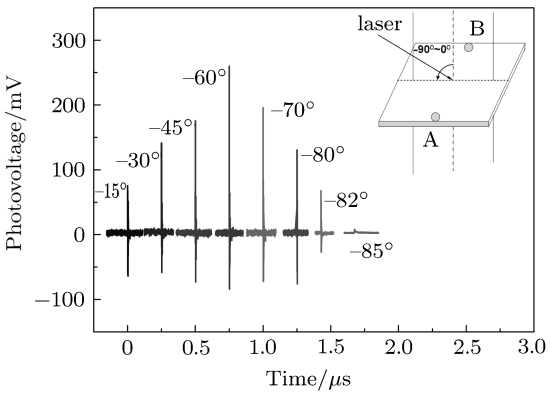


Fig. 2. Different photovoltaic signals with different incident angles of laser pulse plotted as a function of time. Photovoltaic signals shown here are given according to sizes when the incident angles of laser pulse are set at –15°, –30°, –45°, –60°, –70°, –80°, –82° and –85°.

The peak value of the signal versus the angle of incidence in the range from –90° to 90° is plotted in Fig. 3. It can be seen from Fig. 3 that in the range of –60°–60°, the peak value varies almost linearly with the angle of incidence of the laser irradiation, though

the peak changes its sign when the angle exceeds 33°. An inflection point occurs when the angle of incidence is 60°. In the range of –60°∼85°, the peak value changes very regularly with the angle of incidence of laser irradiation. Clearly, a difficulty may arise if such films are used as an angle detector: the peak values might be equal if the incident angle is set in the ranges of –90°∼–60° and –60°–30°. Such a problem could be solved by distinguishing the upward or downward trend when the incident angle of the laser increases. So the film could be used as low-cost and easy-operated angle-sensitive photodetectors.

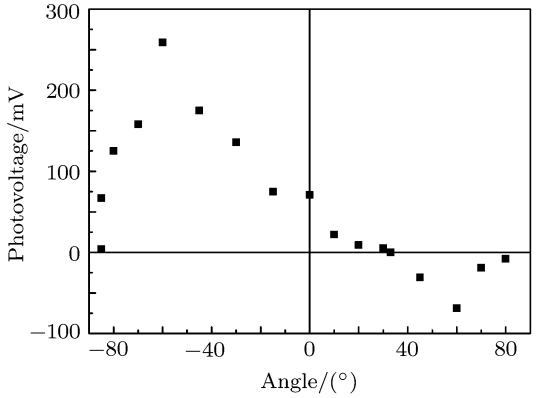


Fig. 3. The peak value of the signal as a function of the angle of incidence in the range from –90° to 90°.

Figure 4 shows a laser-induced photovoltaic signal as a function of time according to its size when the incident angle is set at –60°. Under such a condition, the peak value of the signal reaches maximum, ∼260 mV. Meanwhile, similar to all photovoltaic signals, its rising time reaches ∼2 ns with an open-circuit photovoltage of ∼2 ns full width at half-maximum (FWHM). As all the photovoltaic signals measured and recorded by a 500-MHz oscilloscope, the maximum time resolution of it is only ∼2 ns, thus the rising time and FWHM of all signals are about 2 ns. Obviously, such a fast response to laser irradiation could make the ZnO a candidate for fast photodetector. When we change the energy of laser pulse from 0.5 mJ to 4 mJ, we find that the rising time and FWHM have nothing to do with the pulse energy while the peaks of photovoltage vary linearly with the laser energy.

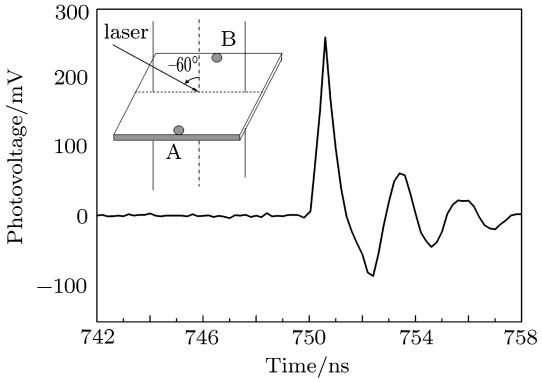


Fig. 4. The temporal photovoltaic response of silver nanocluster embedded ZnO film to 1.064-μm laser pulse when the angle of incidence of the laser is set at –60°.

It can be deduced that the angle-sensitive and fast photovoltaic property of this composite film should have a certain relationship with its microstructure or some other properties. Our film is polycrystalline. However, the growth of ZnO thin films has a tendency to grow with strong [0001] preferential orientation on various kinds of substrates even on glass. During the film growing process, the [0001] preferentially oriented grain may become tilted to an angle (such as 30°) with respect to the substrate surface. Then the photovoltaic signals would be related to the angle of incidence of laser irradiation. Further studies are still in progress.

4. Summary

In summary, silver nanocluster embedded composite ZnO thin film showed an angle-sensitive and fast photovoltaic effect. The peak value and the sign of photovoltaic signal varied regularly with the angle of incidence in the range from –90° to 90° when the 1.064-μm pulsed Nd:YAG laser irradiated onto the film surface. And for all photovoltaic signals, the rising time reaches ∼2 ns with an open-circuit photovoltage of ∼2 ns FWHM. This angle-sensitive and fast photovoltaic effect is expected to make the composite ZnO thin film a candidate for angle sensitive and fast photodetectors.

References

[1] Özgür Ü, Alivov Ya I, Liu C, Teke A, Reshchikov M A, Doğan S, Avrutin V, Cho S J and Morkoc H 2005 *J. Appl. Phys.* **98** 041301

[2] Yang W, Hullavarad S S, Nagaraj B, Takeuchi I, Sharma R P, Venkatesan T, Vispute R D and Shen H 2003 *Appl. Phys. Lett.* **82** 3424

[3] Gonzáles A E J, Soto Urueta J A and Parra R S 1998 *J. Cryst. Growth* **192** 430
[4] Yang Z Y 2009 *Chin. Phys.* B **18** 1253
[5] Natsume Y and Sakata H 2000 *Thin Solid Films* **372** 30
[6] Sharma P, Sreenivas K and Rao K V 2003 *J. Appl. Phys.* **93** 3963
[7] Sharma P, Mansingh A and Sreenivas K 2002 *Appl. Phys. Lett.* **80** 553
[8] Liang S, Sheng H, Liu Y, Huo Z, Lu Y and Shen H 2001 *J. Cryst. Growth* **225** 110
[9] Cao H, Zhao Y G, Ong H C, Ho S T, Dai J Y, Wu J Y and Chang R P H 1998 *Appl. Phys. Lett.* **73** 3656
[10] Dietl T, Ohno H, Matsukura F, Cibert J and Ferrand D 2000 *Science* **287** 1019
[11] Cao H, Zhao Y G, Ho S T, Seelig E W, Wang Q H and Chang R P H 1999 *Phys. Rev. Lett.* **82** 2278
[12] Jeong I S, Kim J H and Im S 2003 *Appl. Phys. Lett.* **83** 2946
[13] Guo J P, Li K Z, Liang R S, Liao C J, Liu S H, Wang J D, Wei Z J and Zhou P 2008 *Chin. Phys.* B **17** 4142
[14] Liu H W, Ma D M, Shi W, Tian L Q, Wang X M, Xie W P, Xu M and Zhou L J 2009 *Acta Phys. Sin.* **58** 1219 (in Chinese)
[15] Lü Z Q, Zhao H, Zhao K, Zhao S Q and Zhou Q L 2009 *Chin. Phys.* B **18** 4521
[16] Zhang L, Lu K Q, Zhang M Z, Liu X M and Zhang Y P 2008 *Chin. Phys.* B **17** 2539
[17] Wang W T, Chen Z H, Yang G, Guan D Y, Yang G Z, Zhou Y L and Lü H B 2003 *Appl. Phys. Lett.* **83** 1983
[18] Tsuji H, Sugahara H, Gotoh Y and Ishikawa J 2003 *Nucl. Instrum. Meth.* B **206** 249
[19] Zhao S Q, Zhou Y L, Zhao K, Liu Z, Han P, Wang S F, Xiang W F, Chen Z H, Lü H B, Cheng B L and Yang G Z 2006 *Physica* B **373** 154
[20] Qiu J, He M, Liu G Z, Lü H B and Xing J 2008 *Acta Phys. Sin.* **57** 1236 (in Chinese)