Semiconductor Science and Technology

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To cite this article: Xin'an Zhang *et al* 2010 *Semicond. Sci. Technol.* **25** 045026

Semicond. Sci. Technol. **25** (2010) 045026 (5pp) doi:10.1088/0268-1242/25/4/045026

The fabrication and ultraviolet detecting properties of ZnMgO-based thin film transistor by laser molecular beam epitaxy

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Received 6 October 2009, in final form 12 February 2010
Published 16 March 2010
Online at stacks.iop.org/SST/25/045026

Abstract
Bottom-gate thin film transistors (TFTs) with a ZnMgO film as the channel layer were fabricated on thermally oxidized p-type silicon substrates by laser molecular beam epitaxy. The devices exhibit good electrical properties in dark with the current on/off ratio, threshold voltage and channel mobility of 10^5, 6 V and 0.04 $cm^2\ V^{-1}\ s^{-1}$, respectively. In an accumulation mode with a gate bias of 30 V, the drain current is on the order of 1 μA. However, when exposed to ultraviolet light ($\lambda = 365$ nm) with an intensity of 0.2 mW cm^{-2}, the drain current dramatically increased to 9.4 μA and it was also shown that the photocurrent increased with the increase of photo intensity. The photo-detecting property is more remarkable under a depletion mode of −20 V gate bias with the photo-to-dark current ratio more than 10^4. The spectral and transient responses of the device to ultraviolet illumination were also discussed. These results may open the possibility of employing ZnMgO-based thin film transistors as UV sensors.

1. Introduction

Zinc oxide (ZnO) is an attractive compound semiconductor with a wide and direct band gap of 3.3 eV. It has many unique optical and electronic properties, such as a large exciton binding energy (60 meV) and high radiation hardness, and it can be well-oriented crystalline on various substrates at low temperature [1, 2]. Considerable efforts have been made in the development of electronic and optoelectronics applications based on this material, in which ultraviolet (UV) photodetectors [3], light emitting diodes (LED) [4] and thin film transistors (TFTs) [5] have been realized. Especially, Bae *et al* and Lee *et al* [6] have fabricated TFTs with ZnO as the channel layer and found excellent photo-detecting behavior. It has been demonstrated that the band gap of ZnO can be tailored by alloying with MgO from 3.3 eV to 4 eV [7]. This leads to an increase of the activation energy for defect-related donor states and thus reduces the carrier density in the channel layer. Moreover, the study of Lee *et al* has illustrated that the depletion region in the grains increased with the amount of Mg doping and resulted in almost depleted grains in the channel layer [8]. Recently, high-quality $Zn_{1-x}Mg_xO$ alloy films have been synthesized and used in thin film transistors as active layers, or even insulators according to the Mg content [9, 10]. In the present work, we report on the construction and characterization of ZnMgO-based thin film transistors on SiO_2/Si substrates by laser molecular beam epitaxy (L-MBE). Electrical measurements show that the devices have excellent performance with an *n*-channel enhancement mode operation. For the first time, we investigated the ultraviolet detecting properties of the ZnMgO-based thin film transistors.

2. Experiments

2.1. Deposition of ZnMgO films

The ZnMgO films were deposited on a thermally oxidized p-type silicon wafer (1–10 Ω cm) by L-MBE. The SiO_2 film

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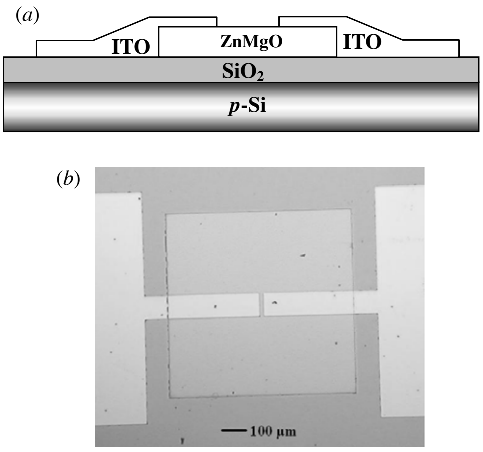

Figure 1. (*a*) Schematic cross-sectional structure of the ZnMgO-based TFTs. (*b*) The optical micrograph (top view) of a finished device taken by an optical microscope.

with the thickness of 180 nm served as an insulator. Before deposition, the standard photolithography technique was used to define the patterns of the channel layer. The background pressure was pumped to 10^{-6} Pa. The oxygen gas (O_2, 99.99%) was introduced into the growth chamber through a mass flow controller with the velocity of 10 sccm, and the pressure was controlled to be 10^{-3} Pa. A KrF excimer laser ($\lambda = 248$ nm) was used to ablate a ceramic $Zn_{0.9}Mg_{0.1}O$ target (99.99%). The substrate was placed 70 mm away from the target and the deposition was performed at room temperature. Both the target and the substrate were kept rotating to ensure the uniformity of the films. The pulse duration, repetition rate and fluence of the laser beam were 20 ns, 3 Hz and 2 J cm^{-2}, respectively. The film thickness measured by the surface profilometer was ∼100 nm. Then, the films were annealed at 300 °C in oxygen for 1 h in order to increase the crystallinity of the films.

2.2. *Fabrication of ZnMgO-TFTs*

The ZnMgO-based TFTs were fabricated on SiO_2/p-Si substrates. The backside oxide was etched and indium paste ohmic contact was used as a gate. The indium-tin-oxide (ITO) films served as source and drain electrodes, which were fabricated by the lift-off and rf sputtering process. Then all the devices were heated at 300 °C for 30 min to make source and drain form good ohmic contacts to the ZnMgO channel. The thickness and the resistivity of the ITO films was ∼100 nm and 10^{-4} Ω cm, respectively. The channel width (W) and length (L) of TFTs were 100 μm and 20 μm, respectively. The schematic structure of the transistor is shown in figure 1(*a*) and the photograph (top view) of a finished transistor taken by an optical microscope is shown in figure 1(*b*).

2.3. *Characterization techniques*

The crystal structure of ZnMgO films was investigated by x-ray diffractometry (XRD; DX2000) with CuKα radiation ($\lambda = 0.154\,184$ nm) in θ–2θ scan mode. The operation voltage and current were 35 kV and 30 mA, respectively. The surface morphology was characterized by atomic force microscopy

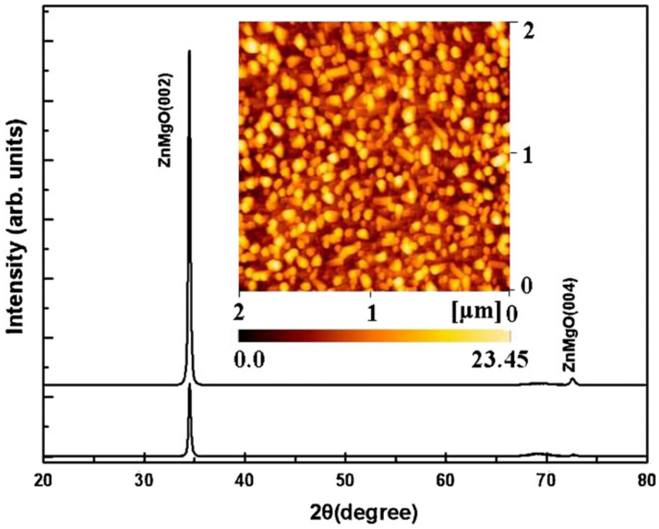

Figure 2. X-ray diffraction patterns of the ZnMgO films. (*a*) Annealed films in oxygen, (*b*) as-deposited films. The inset is an AFM image of the surface of annealed ZnMgO films.
(This figure is in colour only in the electronic version)

(AFM, Seiko SPA400). The electrical characteristics of the transistors were measured by a semiconductor parameter analyzer (KEITHLEY 4200). For the photo-detect measurement, a 500 W Xe lamp (SVX 1450) and a monochromator were used as a light source.

3. Results and discussion

The XRD patterns of the as-grown and annealed ZnMgO films on SiO_2/Si substrates are shown in figure 2. The films clearly have wurtzite crystal structures and show a preferred *c*-axis orientation normal to the substrates. No diffraction peaks for a cubic crystal structure MgO or impurity phases appeared. The intensity of the peaks was greatly increased after annealing in oxygen, indicating that the crystal property of the film was improved [11]. The surface morphology of the ZnMgO film was observed by means of AFM, and the image is shown in figure 2. The AFM worked in a tapping mode and the scanning area was 2 μm × 2 μm. In light of the image, the film possessed granular morphology with the grain size ranging from 30 nm to 50 nm and the root-mean-square roughness was calculated to be 2.35 nm.

Figure 3(*a*) displays the output characteristics for different gate voltages of ZnMgO-based TFTs measured in dark at room temperature, which clearly indicates pinch-off, linear and saturated regions. The active channel is n-type because a positive gate-to-source voltage (V_{GS}) is required to induce the conducting channel. The drain currents increased markedly with increasing positive gate bias. The device is operated in enhancement mode because the saturated drain current is only 10^{-7} A at a gate voltage of 0 V. With the V_{GS} varied from 0 to 30 V in step of 5 V, the device exhibits clear current saturation and pinch-off characteristics, which indicate that the entire channel region could be depleted of electrons [12]. Figure 3(*b*) shows the transfer characteristics of ZnMgO-based TFTs measured at a fixed drain voltage of 25 V.

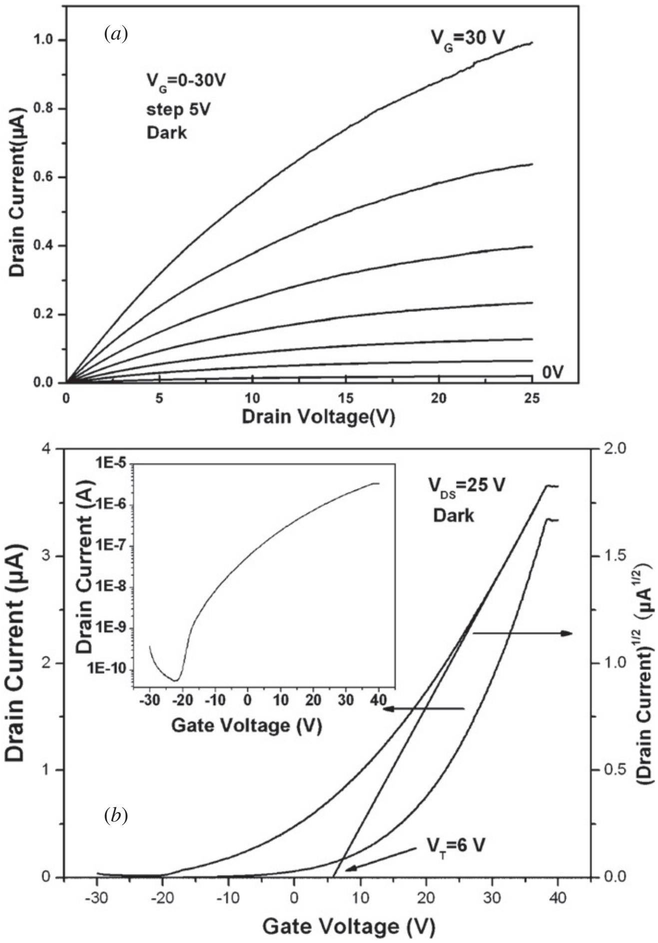

Figure 3. Electrical properties of ZnMgO-based TFTs in dark. (*a*) Output characteristics (I_{DS}–V_{DS} curves), (*b*) transfer characteristics (I_{DS}–V_{GS} curves).

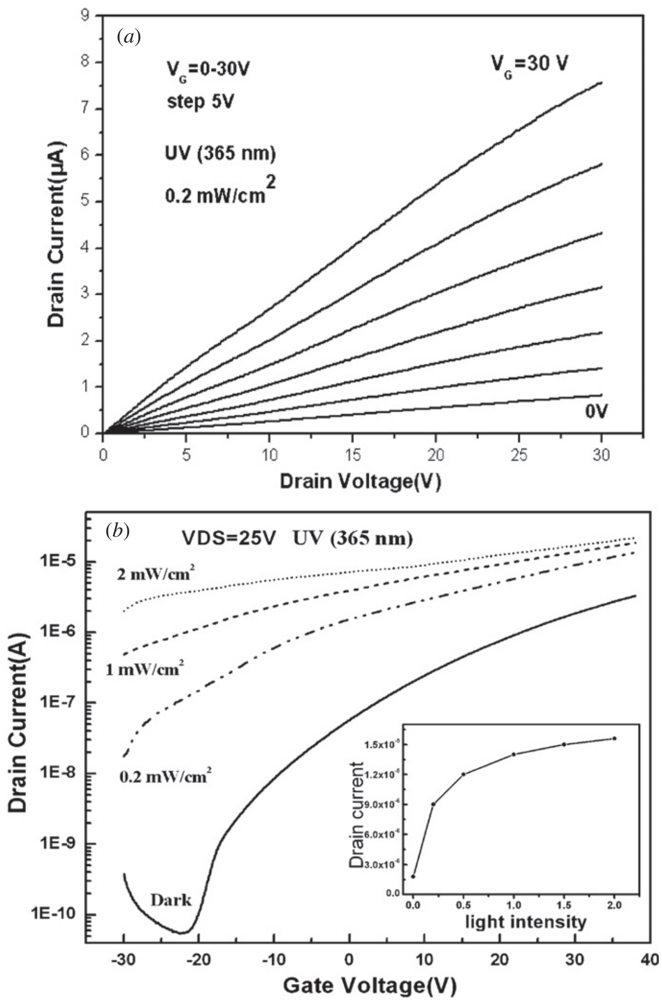

Figure 4. Ultraviolet detecting properties of ZnMgO-based TFTs. (*a*) Output characteristics, (*b*) transfer characteristics ($\log_{10} I_{DS}$–V_{GS} curves with different illumination power).

The drain current (I_{DS}) is governed by the relation $I_{DS} = \frac{1}{2}\mu_{FE} C_{ox} \frac{W}{L}(V_{GS} - V_T)^2$, where C_{ox} is the capacitance per unit area of the gate insulator, W and L are the width and length of the channel respectively, V_T is the threshold voltage and μ_{FE} is the field effect mobility [13]. The V_T is extracted by fitting a straight line to the plot of the square root of I_{DS} versus V_{GS} of 6 V. The inset in figure 3(*b*) shows the $\log_{10} I_{DS}$–V_{GS} curve. The device exhibited an on/off ratio of 10^5 and the off current was approximately 10^{-10} A. The field effect mobility was determined on the order of 0.04 cm^2 V^{-1} s^{-1} and the values were smaller than that of the device with a ZnO channel layer because of the scattering property of the substituted Mg ion.

Figure 4(*a*) shows the output properties of the ZnMgO-based TFTs when exposed to ultraviolet light ($\lambda = 365$ nm) with an intensity of 0.2 mW cm^{-2}. The saturation properties of the drain current were degraded, while the value of the drain current was greatly increased up to about 9.4 μA, which is about an order of magnitude higher than the maximum dark saturation current. The observed change is clearly due to photoelectric effect in the ZnMgO channel. If the TFTs operate in the dark, the charges injected by applying appropriate positive V_{GS} are located close to the ZnMgO/SiO_2 interface. As the light is applied to the devices (in this case directly onto the active films), the photons with energies larger than the band gap of ZnMgO are absorbed in the material. As a result, a bound electron–hole pair or exciton is formed. Furthermore, these resulting excitons are eventually dissociated into photogenerated electrons and holes. Once generated, photogenerated electrons and holes begin to move under the influence of the electric field according to the transistor operation. As the gate and drain biases are positively applied relative to the source, the photogenerated holes move away from the gate and drain and toward the source, while the photogenerated electrons move toward the gate and drain and away from the source. Therefore, the concentration of holes becomes larger because the contributions come from the gate-induced effect and from the photogenerated holes due to light effect. As a consequence, it leads to an increase in the drain current. However, the resulting photogenerated charges are probably more populated near the active channel as the gate electric field is larger than the drain electric field due to gradual channel approximation formalism [14].

Figure 4(*b*) shows the $\log_{10} I_{DS}$–V_{GS} curves of ZnMgO-based TFTs measured at a fixed drain voltage of 25 V

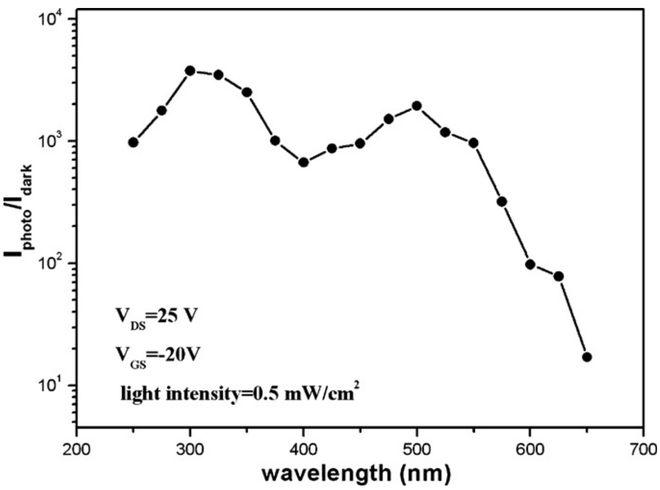

Figure 5. Spectral response of the ZnMgO-based TFT in the depletion mode operation.

with different ultraviolet light intensity. The amount of photocurrent clearly increases with the illumination power. It is notable that the photo response was more sensitive in the depletion mode than in the accumulation mode. Under the gate bias of −20 V for the depletion mode operation, the photo/dark current ratio was more than 10^4 (normalized power density 2 mW cm^{-2}), which is much larger than the value of accumulation mode as shown in figure 4(*b*). The reason may be that the initial dark depletion state draws almost no charge carriers in the ZnMgO channel layer, which lead to low background signals. In photoconductive metal-semiconductor-metal (MSM) ultraviolet detectors, it is also important to reduce the background carriers for high sensitivity [15]. So the results open a way to modulate the carrier concentration in the active channel by adding a gate bias. The inset of figure 4(*b*) shows the curve of the drain current plotted as a function of light intensity. The drain current clearly increased nonlinearly with the light intensity. At a low light intensity, the increased number of photogenerated carriers causes the channel to have a higher conductivity; the drain current increased remarkably. At the higher irradiance values, phenomena such as exciton–exciton annihilation and electron–hole recombination occur; the drain current increased slowly [16].

Figure 5 shows the spectral response of the ZnMgO-based TFT measured under a gate bias of −20 V for the depletion state, where photocurrent/dark current (I_{photo}/I_{dark}) ratios are plotted as a function of the wavelength. The device exhibits obvious response in the UV region around 360 nm corresponding to band-to-band transitions. The responses in visible region are due to the photo carriers generated from the deep-level defects within the band gap [7]. Additional works are needed to improve the crystalline properties of the ZnMgO films and to reduce the intrinsic defects for practical visible–blind application.

Figures 6(*a*) and (*b*) show the transient responses of the transistor measured at $V_{GS} = V_{DS} = -10$ V when the light source was switched on and switched off, respectively. Figure 6(*c*) shows the I_{DS} measured in the dark for 300 s and it is 40 pA. The switching-on process reached a maximum photocurrent of 1.8 μA, and the corresponding transient curve can be fitted by a single exponential quite well, giving a time constant of 20.6 ± 0.2 s. On the other hand, the

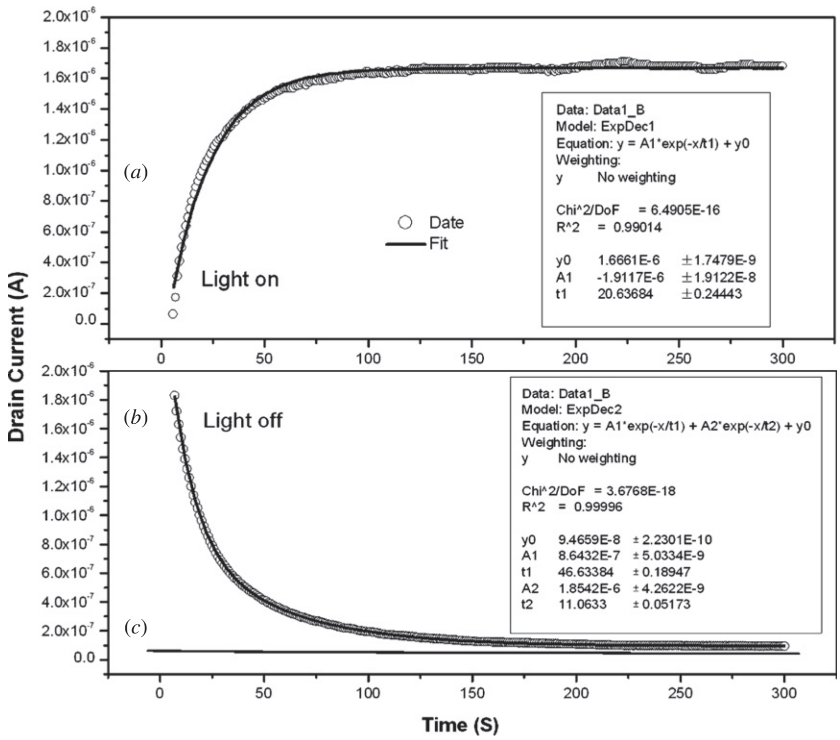

Figure 6. The transient response of the ZnMgO TFT to ultraviolet illumination.

switching-off process can be described by a combination of a slow decrease of photocurrent at the beginning and a second, faster process in the end. For the slow response, the time constant is approximately 46.6.1 ± 0.2 s. The faster process has a relatively short time constant of 11.1 ± 0.1 s. The slow response times are mainly attributed to the deep levels from defects in the ZnMgO channel or the surface damage during the device processing. The electrons are trapped during their relaxation in the deep level states, thereby increasing the minority hole carriers lifetime, and hence, the response time [17]. In addition, the oxygen adsorption at the surface and the grain boundaries of ZnMgO may also affect the response time [18]. So the enhancement of the crystalline quality of the ZnMgO films and reduction of the interface trap density are two critical issues in our future work. On the other hand, increasing the channel width (W) and decreasing the channel length (L) of the device are also the effective ways to accelerate the collection of photogenerated carriers. The minimum current reached after the light source was switched off for 300 s is ∼119 pA. This value is three times higher than the dark current. Therefore, persistent photoconductivity was observed in this experiment. This effect is probably caused by the existence of defects and such a behavior has also been observed in other systems [19].

4. Conclusion

A thin film transistor with ZnMgO as the channel layer was fabricated by L-MBE. Electrical measurements have shown that the devices have excellent performance in dark with the current on/off ratio, threshold voltage and channel mobility of 10^5, 6 V and 0.04 $cm^2\ V^{-1}\ s^{-1}$, respectively. Illuminated by the ultraviolet light, the device displayed a high photo-to-dark current ratio of more than 10^4 at the depletion mode operation and it was also shown that the photocurrent increased with the increase in UV intensity. The transient response of the transistor to ultraviolet illumination was also discussed. The results indicate that the ZnMgO-based TFTs can be a promising UV photo-detecting device.

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