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Field-effect transistors with thin ZnO as active layer for gas sensor applications

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Abstract

Zinc oxide based field-effect devices prepared for gas sensing applications are studied. For this purpose, bottom-gate transistors were fabricated using Pd as source and drain interdigitated electrodes with gate lengths varying from 0.3 to 2 μm. Thin (50 nm) zinc oxide films were grown with the aid of pulsed laser deposition (PLD) at room temperature and served as active and sensing layer. AFM and XRD analysis demonstrated the polycrystalline nature of the *c*-axis oriented ZnO films with nanoscale grain size (20–40 nm) with relatively high average roughness. Electrical and gas sensing measurements from the above-mentioned devices are presented.

Keywords: Bottom-gate FETs; Zinc oxide; Gas sensor; Pulsed laser deposition

1. Introduction

Metal–oxide–semiconductors are widely used as gas sensors, because of their inherent good sensitivity to gases like CO, H_2, NO_X and hydrocarbons. Amongst these materials, zinc oxide is one of the most popular ones, mainly due to its good properties even if deposited at lower temperatures, thus giving the possibility to be integrated on cheaper and flexible substrates [1,2]. Moreover, zinc oxide surface presents high sensitivity to both reducing and oxidizing gases as its conductivity is highly dependent on oxygen and/or on zinc interstitials deficiency or abundance, both enhanced by chemical reactions that occur within the grain boundaries [3]. By using field-effect devices it is possible to achieve higher gas sensitivity at relatively low temperatures, thus enabling low-power gas sensor integration in wireless sensor networks for which power consumption is of major importance.

Several methods have been proposed to grow good quality thin zinc oxide films, including chemical vapour deposition [4], spray pyrolysis [5], reactive evaporation [6], DC and RF sputtering [7,8] and pulsed laser deposition (PLD) [9]. For the formation of *c*-axis grown stoichiometric ZnO, all the above-mentioned methods require a substrate temperature higher than 200 °C which in some cases is incompatible with the fabrication process (i.e. cheap substrates, lift-off process etc.). However, compared to the other methods, PLD presents a wider process window that may lead to improved ZnO quality even at temperatures below 200 °C [9], and therefore it is a good candidate for such applications.

In this work, we present our investigations on field-effect transistors having thin ZnO as active layer that was grown at room temperature by pulsed laser deposition. We will also present the first results of the fabricated gas sensors operating at room temperature.

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2. Experimental

Bottom-gate field-effect devices with ZnO as active layer were fabricated. A 100 nm – thick thermal oxide was grown at 1000 °C on highly doped silicon wafers. Backside metallization by RF-sputtering of Ti/Au was performed and patterned Ti/Au contact pads were deposited on the front side via lift-off process. Palladium electrodes were evaporated and lift-off process with E-beam lithography was used to obtain the cross-fingered structure shown in Fig. 1. Several structures were fabricated with interdigitated distance that varied from 0.3 to 2 μm in order to obtain transistors of various gate lengths. As an active layer, a 50 nm-thick zinc oxide layer was grown by pulsed laser deposition at room temperature on the top of the interdigitated electrodes using lift-off process. Finally, devices with channel width of around 1 mm were obtained (21 intra-electrode channels × 50 μm). Several thermal annealing conditions (400–600 °C, in air) were tested in order to optimize the electrical performance of the devices. XRD and AFM investigations allowed us to study the ZnO bulk and surface properties and the electrical measurements were performed with an HP4140B picoamperometer.

3. Results and discussion

3.1. Zinc oxide structural properties

Fig. 2 shows AFM pictures of the as-deposited thin ZnO film that was grown on oxidized silicon wafer. It is demonstrated that these films are polycrystalline ([1 0 1] and [0 0 2] oriented crystallites as supported by XRD analysis) with an average grain size of around 20–40 nm which is not effectively affected by the annealing process, mainly due to the relatively low temperature (400 °C) that was used. This is in accordance with previous studies that have been made at this temperature range [10].

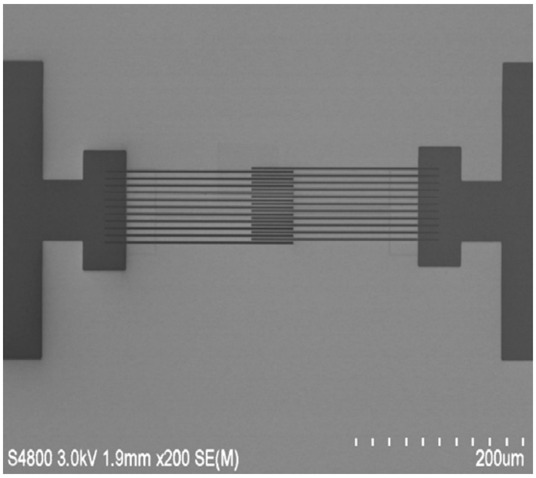

Fig. 1. SEM picture of a ZnO FET structure (top view).

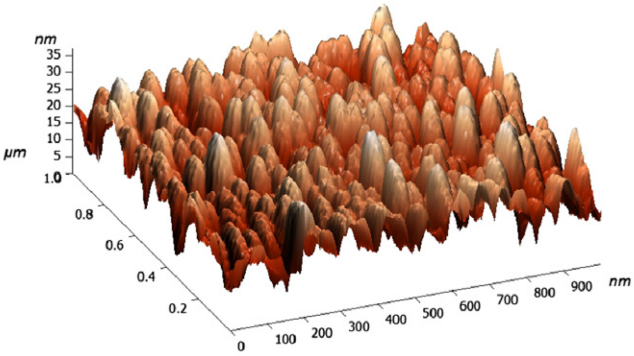

Fig. 2. AFM pictures of Pulsed Laser Deposited ZnO as-deposited.

Concerning surface roughness, it is seen that annealed ZnO exhibits a slightly less rough surface compared to the as-deposited sample. In Fig. 3 we plotted the average surface roughness as a function of the annealing time. The ZnO films exhibit high average roughness of around 22 nm which decreases as annealing time at 400 °C increases, reaching a value of around 15 nm for annealing time more than an hour. Since these films will serve as gas sensors, the high surface roughness of ZnO provides a high surface-to-volume ratio which enhances the chemical active area of the film.

3.2. Electrical properties

Fig. 4 shows the transfer characteristics for devices with various gate lengths (0.6, 1.3, 1.7 and 2 μm). The transistors exhibit n-type conduction, as it is well known for ZnO layers. I_{ON}/I_{OFF} ratio in the order of 10^5–10^6 is achieved for most of the devices. In addition, threshold voltage lies in the range of 5–10 V and the subthreshold swing is higher than 3 V/dec. These last observations indicate the presence of a poor interface between ZnO and SiO_2 and/or the high defect density in the ZnO layer, especially within the grain boundaries. It is known that the work function of Pd is much higher (more than thermal energy) than electron affinity of ZnO, and thus the contact between these two materials is proven to be Schottky one [11].

Thus, a Schottky barrier is formed at ZnO/Pd interface which is dependent on the potential applied at both ends of

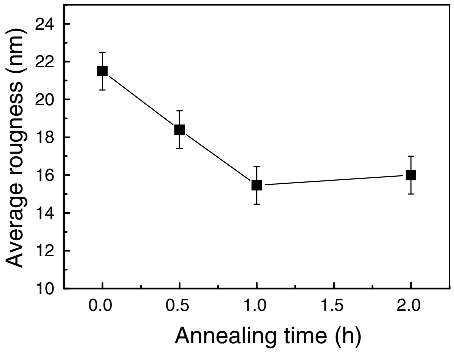

Fig. 3. Average roughness of thin ZnO films measured with AFM as a function of the annealing time at 400 °C in air.

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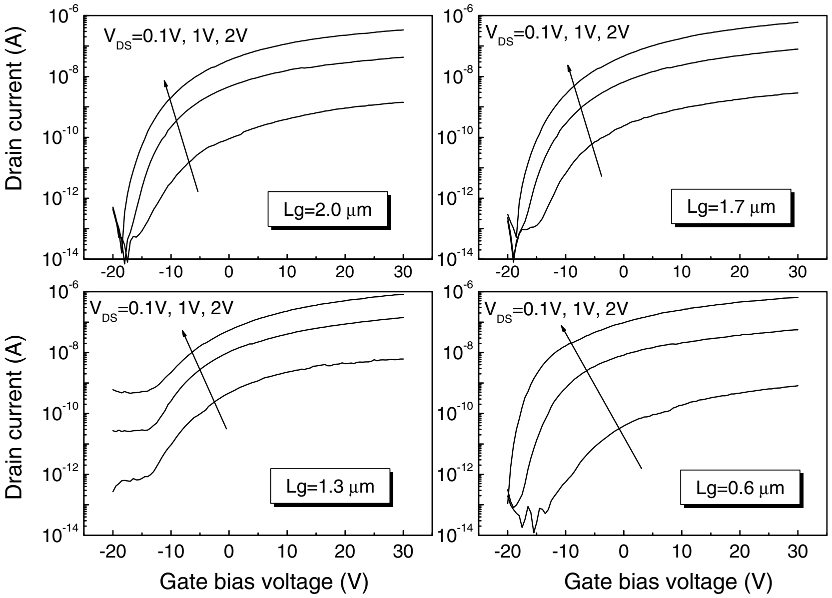

Fig. 4. Transfer characteristics of ZnO FETs for different gate lengths.

the barrier as well as the Fermi level positioning on the semiconductor side (i.e. ZnO). The drain current is limited by the Schottky potential barrier and as the gate bias voltage V_{GS} becomes positive ($V_{GS} = 20$ V) the I_{DS}–V_{DS} curve approaches the ohmic behavior (not shown here). Due to this mechanism, no current saturation was observed at the output characteristics of the fabricated devices.

3.3. Gas sensing experiments

FET sensors were placed in a chamber with a continuous flow of nitrogen. An external heater was adjusted to the sensor and NO was introduced when the drain current was stabilized. Fig. 5 demonstrates the normalized drain current with ($V_{DS} = 0.1$ V and $V_{GS} = 0$ V) as a function of time when 100 ppm of NO were introduced in the chamber at various temperatures. The drain current decrease is observed at all temperatures while this decrease is more pronounced at the higher temperature of 150 °C. At this temperature range it is known that [12] gaseous NO is chemisorbed at the ZnO surface and grain boundaries following the reaction:

$$NO_{gas} + V_O \rightarrow V_O - O_{ads} + 1/2N_2 \qquad (1)$$

where V_O is the oxygen vacancy and O_{ads} the adsorbed oxygen atom.

As a result, when ZnO FET is in NO environment, oxygen vacancy concentration is reduced, leading to a decrease of electrons in the conduction band. This mechanism is reflected to the drain current decrease. Finally, it has to be mentioned that drain current reduction seems to be depended on the NO concentration and that for NO concentration values more than 100 ppm, device surface seems to be saturated, at least for the temperature range studied.

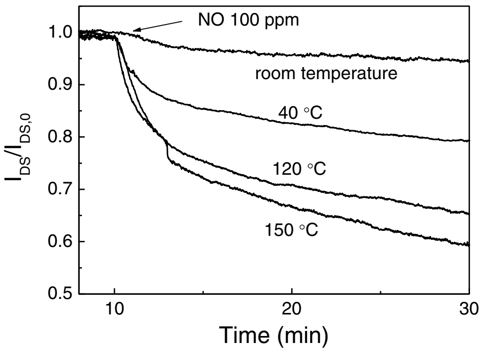

Fig. 5. Normalized drain current as a function of time for various sensor temperatures at presence of nitric oxide in nitrogen.

4. Conclusion

Field-effect transistors have been developed having thin zinc oxide as active layer and palladium as source/drain electrodes for gas sensor applications. ZnO was grown by pulsed laser deposition at room temperature. Transistors with gate lengths from 2 μm down to 0.6 μm were studied in terms of electrical and gas sensing performance. It was found that the devices exhibit a high I_{ON}/I_{OFF} ratio, even though the drain current is strongly limited by the Pd/ZnO Schottky contact. Finally, the sensors demonstrated good sensitivity on nitrogen monoxide within moderate temperature range.

Acknowledgments

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References

[1] S.J. Pearton et al., J. Vac. Sci. Technol. B 22 (2004) 932.
[2] J. Xu, Q. Pan, Y. Shun, Z. Tian, Sensor. Actuat. B 66 (2000) 277.
[3] Y. Ma, W.L. Wang, K.J. Liao, C.Y. Kong, J. Wide Bandgap Mater. 10 (2002) 113.
[4] G.L. Mar, P.Y. Timbrell, R.N. Lamb, Thin Solid Film 223 (1993) 341.
[5] O. Yamazaki, T. Mitsuyu, K. Wasa, IEEE Trans. Sonic. Ultrason. 27 (1980) 369.
[6] J. de Klerk, Ultrasonics 8 (1970) 159.
[7] T. Yamamoto, T. Shiosaki, A. Kawabata, J. Appl. Phys. 51 (1980) 3113.
[8] S. Ghosh, A. Sarkar, S. Bhattacharya, S. Chaudhuri, A.K. Pal, J. Cryst. Growth 108 (1991) 534.
[9] N.J. Ianno, L. McCnville, N. Shaikh, S. Pittal, P.G. Snyder, Thin Solid Film 220 (1992) 92.
[10] M.K. Puchert, P.Y. Timbrell, R.N. Lamb, J. Vac. Sci. Technol. A 14 (1996) 2220.
[11] H.V. Wenckstern, G. Biehne, R.A. Rahman, H. Hochmuth, M. Lorentz, M. Grundmann, Appl. Phys. Lett. 88 (2006) 092102.
[12] F. Boccuzzi, E. Guglielminotti, A. Chiorino, Sensor. Actuat. 7 (1992) 645.

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