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Ceramics International 41 (2015) 14641–14644
CERAMICS INTERNATIONAL
www.elsevier.com/locate/ceramint

Epitaxial ZnO thin film transistors on 4H-SiC substrates

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Received 9 June 2015; received in revised form 28 July 2015; accepted 29 July 2015
Available online 6 August 2015

Abstract

Epitaxial ZnO thin film transistors (TFTs) were successfully fabricated on 4H-SiC (0001) substrates and characterized. When compared with conventional ZnO TFTs on glass substrates that were prepared in the same fabrication process, the ZnO TFTs on 4H-SiC substrates exhibited improved characteristics, namely, a saturation mobility of 5.41 cm^2/V s, a threshold voltage of 2.43 V, and a subthreshold swing of 0.61 V/decade. The ZnO TFTs on glass substrates showed 0.44 cm^2/V s, -1.55 V, and 1.13 V/decade. Such improved performance is attributed to the different growth behavior and structural properties of the ZnO channel layers on 4H-SiC substrates. Structural analysis on the ZnO channel layers clearly revealed the epitaxial growth of high-crystalline ZnO along the *c*-axis on 4H-SiC and the polycrystalline growth on glass substrates. The epitaxial ZnO thin films showed a higher Hall mobility of 24.17 cm^2/V s due to less grain boundary and a lower carrier concentration of $6.21 \times 10^{15}/cm^3$ resulting from higher crystalline quality with less defects, whereas the ZnO on glass exhibited 6.24 cm^2/V s and $2.37 \times 10^{17}/cm^3$.
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Keywords: D. ZnO; Thin film transistors; TFTs; Epitaxial growth; 4H-SiC

1. Introduction

ZnO has drawn considerable attention as a compatible material for the channel layer of thin film transistors (TFTs) due to its attractive properties such as high optical transparency, high mobility, potential for low-temperature processing, and relatively low cost. Therefore, ZnO-based TFTs are promising for not only flat panel displays (FPDs) but also next-generation electronic devices [1,2].

4H-SiC is one of the most attractive materials for high-power, high-temperature, and wide band-gap devices. Since 4H-SiC and ZnO both have a hexagonal structure, it is known that high-quality ZnO thin films can be grown epitaxially on 4H-SiC. In general, other insulating substrates with a hexagonal structure such as Al_2O_3 and $LiNbO_3$ have been suggested for growth of high-quality epitaxial ZnO thin films [3–6]. However, 4H-SiC substrates provide advantages over these insulating substrates in terms of a very small lattice mismatch (~5.5%) to ZnO and the feasibility of forming ZnO/4H-SiC hetero-junction semiconductor devices as the need arises. Accordingly, several reports have been published on the epitaxial growth of ZnO thin films on 4H-SiC and the ZnO/4H-SiC hetero-junction device applications [7–10]. Nevertheless, to our knowledge, there has been no report on the fabrication and characterization of TFTs using a ZnO channel layer that is grown on 4H-SiC substrates. As mentioned above, 4H-SiC substrates would allow for high-crystalline ZnO channel layers to be grown, and it may enhance the performance of the TFTs.

In this paper, we demonstrate ZnO TFTs fabricated on 4H-SiC (0001) substrates. For comparison, conventional ZnO TFTs on glass substrates are also prepared in the same fabrication process. Furthermore, the effect of the growth behavior of the ZnO channel layers on the TFT characteristics is systematically investigated.

2. Experimental

Fig. 1 shows the schematic of the epitaxial ZnO TFT on 4H-SiC substrates with the top-gate structure. The fabrication

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http://dx.doi.org/10.1016/j.ceramint.2015.07.185
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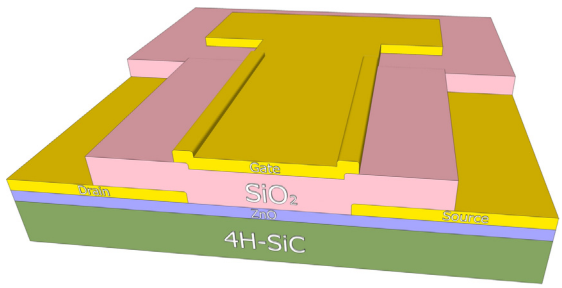

Fig. 1. Schematic of the epitaxial ZnO TFT fabricated on 4H-SiC (0001) substrates.

process is as follows: a ZnO layer was grown on a pre-cleaned 4H-SiC (0001) substrate by pulsed laser deposition (PLD) method as the channel of the TFTs. A ZnO ceramic target (99.999%) was ablated by using a Q-switched Nd:YAG laser with a wavelength of 355 nm, and the deposition was carried out at 200 °C. The drain and source electrodes were formed with Ti/Au metal deposition and conventional photolithography. For the gate dielectric, a 200 nm thick-SiO_2 layer was deposited, and the Ti/Au gate electrode was made on the top of the SiO_2. For the comparison with conventional ZnO TFTs, exactly the same fabrication procedures of the TFTs were executed on glass substrates. In this case, the channel layer is expected to show very different structural and electrical properties compared with that grown on 4H-SiC substrates. The electrical performance of the fabricated devices was measured by using a semiconductor parameter analyzer in a dark box at room temperature.

In order to investigate the difference between the two channel layers deposited on 4H-SiC and glass substrates, respectively, high resolution X-ray diffraction (HRXRD) analysis was performed. The out-of-plane and in-plane structure of the ZnO thin films in both cases were characterized by θ–2θ scan and pole figure measurements. The surface morphology of the ZnO thin films was observed by atomic force microscopy (AFM). In addition, Hall measurements were conducted to determine the electrical properties including Hall mobility and carrier concentration.

3. Results and discussion

Fig. 2(a) and (b) shows the transfer characteristics of the fabricated TFTs on 4H-SiC substrates and on glass substrates, respectively, at a drain voltage of 10 V. The ZnO TFTs on 4H-SiC substrates clearly show the typical n-channel enhancement mode characteristics. As already known, ZnO is generally exhibits n-type semiconductor behavior, so that the channel of the TFTs is formed by the positive gate voltage. Therefore, the drain current increases under the positive gate voltage and saturates. However, as can be seen in Fig. 2(b), the ZnO TFTs on glass substrates exhibit the depletion mode behavior with current flow at a gate voltage of 0 V. In addition, the extracted device parameters of the ZnO TFTs on 4H-SiC substrates are very different from those of the ZnO TFTs on glass substrates. The on/off current ratio that can be obtained from the largest and smallest drain current in the transfer curve is measured to be around 10^6 for ZnO TFTs on 4H-SiC, while smaller than 10^5 for ZnO TFTs on glass substrates. The saturation mobility and the threshold voltage can be derived from the following equation:

$$I_{DS} = \left(\frac{C_i \mu_{sat} W}{2L}\right)(V_{GS} - V_{TH})^2 \ \text{for}\ V_{DS} > V_{GS} - V_{TH},$$

where I_{DS} is the drain current, C_i is the capacitance per unit area of the gate dielectric, μ_{sat} is the saturation mobility, W is the channel width, L is the channel length, V_{GS} is the gate voltage, V_{TH} is the threshold voltage, and V_{DS} is the drain voltage. The extracted threshold voltage and saturation mobility of the ZnO TFTs fabricated on 4H-SiC substrates are 2.43 V and 5.41 cm^2/V s, respectively. In the case of the ZnO TFTs on glass substrates, the saturation mobility is more than 10 times lower (0.44 cm^2/V s), and the threshold voltage is calculated to be negative (−1.55 V). The subthreshold swing that is defined as the gate voltage required to change the drain current by one order of magnitude in the subthreshold region can be extracted from the equation:

$$SS = \frac{dV_{GS}}{d \log I_{DS}}$$

where SS is the subthreshold swing. The subthreshold swing of the ZnO TFTs on 4H-SiC is 0.61 V/decade, which is much lower than that of the ZnO TFTs on glass substrates (1.13 V/decade).

These differences in the device performance between the ZnO TFTs on 4H-SiC and on glass substrates seem to be attributed to the different characteristics of the ZnO channel layers. In order to clarify the difference and its effect on the device performance, structural, morphological, and electrical analysis were carried out. Fig. 3(a) shows the XRD θ–2θ spectra of the ZnO thin films on 4H-SiC substrates. The diffraction peak around 34.4° corresponding to ZnO (0002) appears. The *c*-plane growth of ZnO thin films with a hexagonal wurtzite structure due to its lowest surface free energy has been well known [11]. The reflection from 4H-SiC (0004) shows up as well at around 35.6°. The XRD pattern of the ZnO thin films on glass substrates is also shown in Fig. 3(b). Similarly, it is confirmed that the diffraction peak of ZnO (0002) appears without any additional peak corresponding to glass substrates. However, the intensity of the peak is clearly lower than that from the ZnO thin films on 4H-SiC substrates. The ratio of the intensity of the ZnO (0002) peak on 4H-SiC to that on glass is measured to be 10.4. Focusing on the diffraction angle (2θ) of the ZnO (0002) peaks, while the peak from the ZnO on 4H-SiC substrates is located at 34.4° that is very close to the angle of bulk ZnO (0002), the diffraction angle of ZnO (0002) on glass substrates is observed at a lower angle of 34.1°. According to the Bragg law, it is clear that planar compressive stress exists in the ZnO thin films grown on glass substrates, which might be attributed to intrinsic defects in ZnO lattice. From these results, it can be understood that the crystalline quality of the ZnO thin films grown on 4H-SiC substrates is higher than that of the ZnO on glass substrates.

More detailed structural properties of the ZnO thin films can be determined from pole figure measurement of ZnO ($10\bar{1}1$) diffraction for both samples. The inset (left) of Fig. 3(a) depicts the result of the pole figure measurement of ZnO ($10\bar{1}1$) on 4H-SiC substrates. The strong six-fold symmetrical poles separated by 60° and one central pole are obviously observed.

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