Thin film transistors with wurtzite ZnO channels grown on $Si_3N_4/SiO_2/Si$ (111) substrates by pulsed laser deposition

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ABSTRACT

Thin Film Transistors (TFT) were made by growing ZnO on $Si_3N_4/SiO_2/Si$ (111) substrates by pulsed laser deposition. X-ray diffraction and scanning electron microscope studies revealed the ZnO to have a polycrystalline wurtzite structure with a smooth surface, good crystallographic quality and a strong preferential c-axis orientation. Transmission studies in similar ZnO layers on glass substrates showed high transmission over the whole visible spectrum. Electrical measurements of a back gate geometry FET showed an enhancement-mode response with hard saturation, mA range Id and a $V_{ON} \sim 0V$. When scaled down, such TFTs may be of interest for high frequency applications.

Keywords: ZnO, Pulsed Laser Deposition, Thin Film Transistor

1. INTRODUCTION

Wurtzite Zinc Oxide (ZnO) is a remarkable multifunctional material with a distinctive property set and a huge range of existing and emerging applications [1]. In particular, it is a direct wide bandgap semiconductor (Eg ~ 3.4eV) with intrinsically high transparency over the whole visible range and a resistivity that can be tuned from semi-insulating right through to semi-metallic by doping. Recently, there has been a surge in interest for Metal Insulator Semiconductor Field Effect Transistors (MISFETs) employing n-type ZnO-based channel layers. Although these Transparent Thin Film Transistors (TTFTs) are not a new concept [2,3], the new generation exhibits a high on-off ratio ($>10^6$) and a higher channel mobility (μ) than current Si-based TFTs. Two main ZnO TTFT variants, employing either wurtzite [4-8] or amorphous [9] ZnO-based alloys as channels, have emerged. The Amorphous Oxide Semiconductor (AOS) variants are being put forward as an alternative to amorphous Si for use in applications such as select transistors in Liquid Crystal Displays (LCD) and Organic Light Emitting Diode (OLED) displays [10]. TFTs with wurtzite ZnO channels, on the other hand, have exhibited GHz range power cut-off frequencies [11] and it has been suggested, therefore, that they may have potential as high frequency devices and thus add increased functionality to future Si integrated circuits.

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2. EXPERIMENT

Back gate MISFET structures were made by growing a layer of ZnO by Pulsed Laser Deposition (PLD) on Si (111) substrates [12] coated with 4.5nm of amorphous Si_3N_4, as shown in Figure 1.

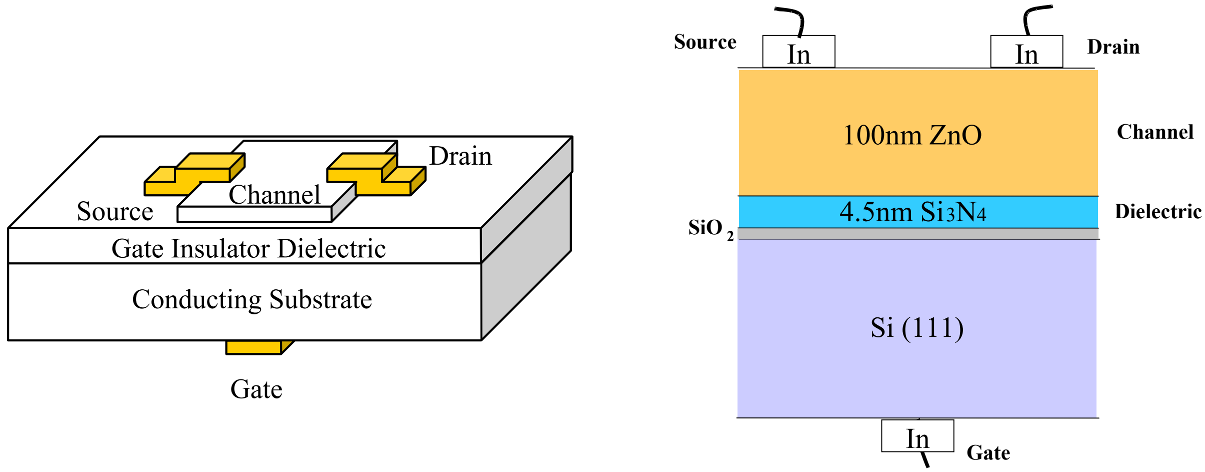

Figure 1. Schematic cross-section and layer detail for the staggered, bottom gate $ZnO/Si_3N_4/SiO_2/Si$ (111) TFT structure employed in this study.

Si_3N_4 was chosen as the dielectric insulator because of its' relatively high dielectric constant (~7.5) and resistivity (10^{14} Ω.cm). TFTs with a gate length (L) of 150 μm and gate widths (W) of 75, 150, 350 and 700 μm were fabricated using photolithography. X-ray diffraction (XRD) studies were conducted with a 4-circle Philips X-Pert MRD PRO system. Images of fracture cross-sectional samples were obtained using a Hitachi S-4800 field-emission scanning electron microscope (SEM). Electrical characteristics were made using a dual-source dc power supply, a Fluke multimeter and a Keithley 2400 source-meter. Resistivity was measured using a four-point system. Transmittance spectra were acquired for a ZnO layer grown on a Corning glass substrate using similar growth conditions to the $ZnO/Si_3N_4/SiO_2/Si$ (111).

3. RESULTS & DISCUSSION

Figure 2 shows an SEM image of a fracture cross-section of the $ZnO/Si_3N_4/SiO_2/Si$ (111).

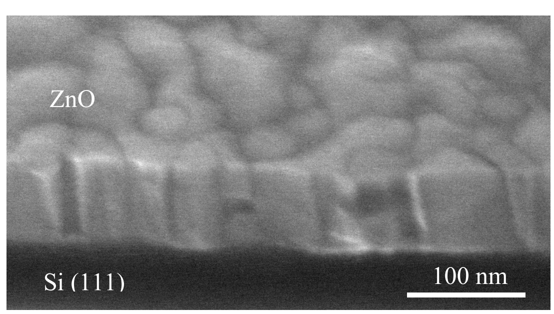

Figure 2. An SEM image of a fracture cross-section of the $ZnO/Si_3N_4/SiO_2/Si$ (111).

The image shows that the film thickness was about 100 nm and indicates that the average grain size was about 50 nm. Figure 3 shows the (0002) peak XRD 2θ/ω and ω rocking curve scans for the $ZnO/Si_3N_4/SiO_2/Si$ (111).

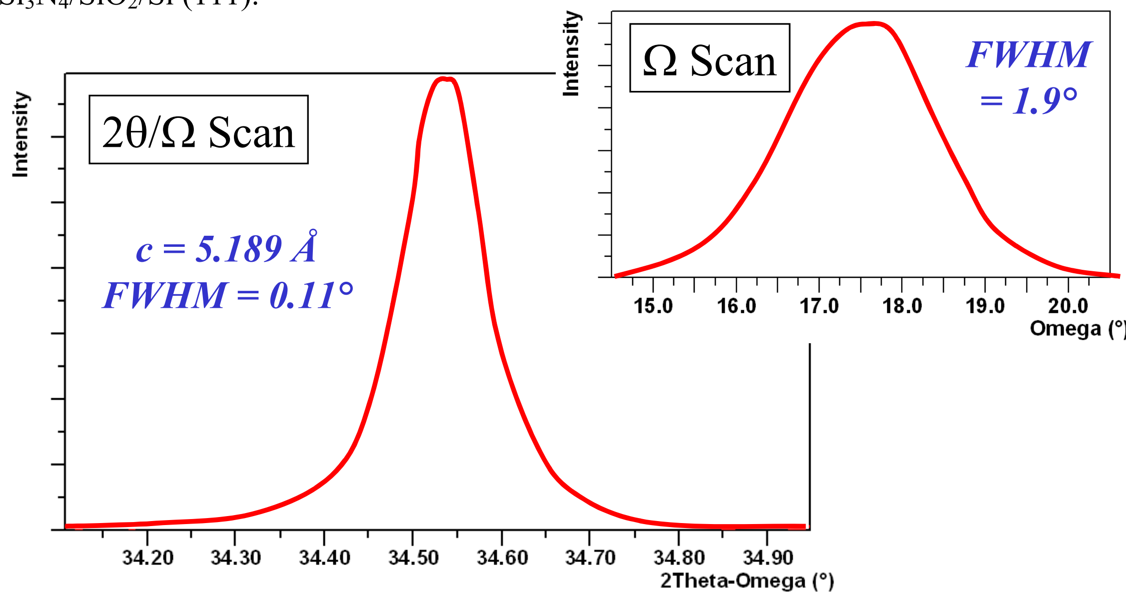

Figure 3. XRD 2θ/ω and ω scans for the (0002) peak of the $ZnO/Si_3N_4/SiO_2/Si$ (111).

XRD revealed a wurtzite crystal structure for the ZnO with a preferential c-axis orientation along the growth direction. The 2θ/ω scan had a Full Wave Half Maximum (FWHM) of 0.11º and a peak position corresponding to a c lattice parameter of 5.189 Å, which is a little smaller than would be expected for relaxed wurtzite ZnO. This implies that the layer was under tensile strain in the film plane. The ω scan FWHM was 1.9º. Thus, although the ZnO film grown had preferential c-axis orientation, there was more dispersion than typically observed for films grown on c-sapphire substrates [13].

Figure 4 shows the optical transmission spectrum for the ZnO/glass sample grown under similar conditions to the $ZnO/Si_3N_4/SiO_2/Si$ (111).

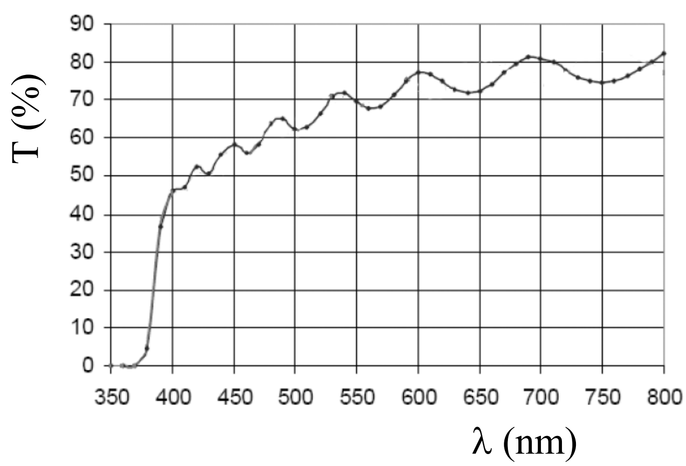

Figure 4. Optical transmission spectrum for a ZnO/glass sample.

The spectrum shows a transmittance, for the ZnO plus the glass substrate, over 70% for visible wavelengths above about 500 nm.

Four point electrical resistance measurements of the ZnO gave an estimate of the film resistivity at about 0.08 Ω.cm. In contacts gave a good ohmic response. Figure 5 shows the output characteristic for a MISFET structure with an L of 150 µm and a W of 700 µm, for various Vgs.

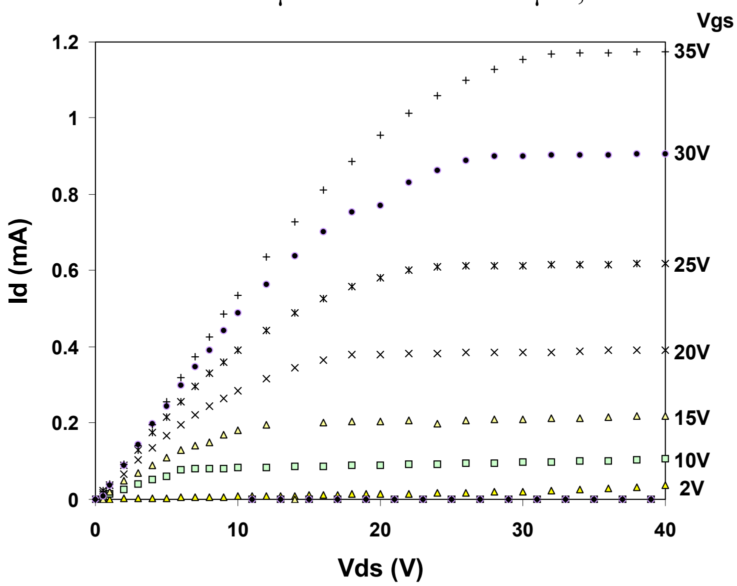

Figure 5: Output characteristic of an $ZnO/Si_3N_4/SiO_2/Si$ (111) TFT with L =150µm & W = 700µm.

The devices exhibited enhancement-mode TFT behaviour. This is preferable to the depletion mode alternative, since the off-state is the power-down condition, which is good for both energy efficiency and simplified circuit design. The characteristics all showed "pinch-off" and "hard-saturation" (a plateauing of Id above a certain Vds), which suggests that the whole channel could be depleted of electrons. Finally, the Id was in the mA range, which is relatively large/good for a ZnO-based TFT. Figure 6 shows transfer characteristics, of the same TFT as shown in Figure 5, for Vds of 100mV and 1V.

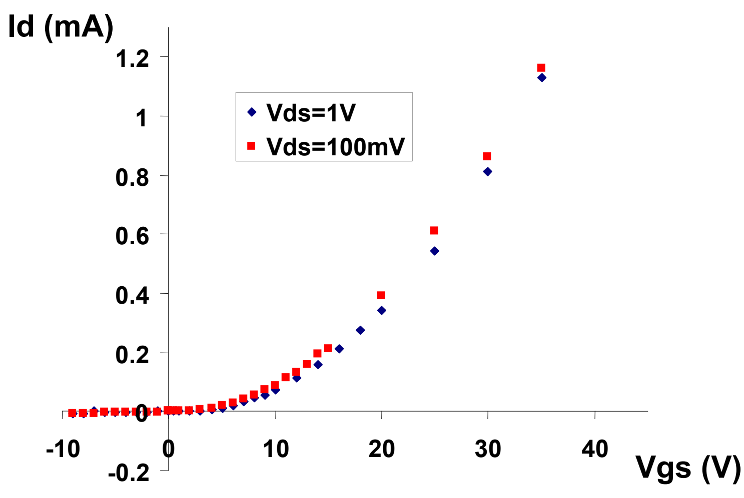

Figure 6. Transfer characteristic of $ZnO/Si_3N_4/SiO_2/Si$ (111) TFT.

The transfer characteristics are rectifying, confirming transistor behaviour in the device. The V_{ON} is about 0V, which suggests that neither the electron nor the trap densities in the channel were too high. The characteristics for the two different Vds are similar. The gate leakage current could not be measured because the detection limit of the ammeter was insufficient and I_{ON}/I_{OFF} could not be calculated.

4. CONCLUSION

Thin Film Transistors (TFT) structures were made by growing n-type ZnO on $Si_3N_4/SiO_2/Si$ (111) by PLD. XRD and SEM studies indicated that the ZnO layers had a polycrystalline wurtzite structure, a smooth surface and a strong preferential c-axis orientation. Optical transmission studies of similar ZnO layers on glass substrates showed good transparency over the whole visible spectrum. Electrical measurements of a back gate $ZnO/Si_3N_4/SiO_2/Si$ (111) FET with ohmic In contacts, revealed rectifying transfer characteristics, with a V_{ON} ~0V, and enhancement-mode output characteristics showing hard saturation and a mA range Id. When scaled down, TFT devices based on such structures may be of interest for high frequency applications.

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