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Top-gate thin-film transistors based on GaN channel layer

Rongsheng Chen,[a] Wei Zhou, and Hoi Sing Kwok
Center for Display Research, Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

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Gallium nitride (GaN) thin films were utilized as active channel layer to produce top-gate n-type thin-film transistors (TFTs). GaN thin films with wurtzite structure were deposited by reactive DC magnetron sputtering technique at room temperature using liquid gallium target. The GaN TFTs exhibit good electrical performance such as field effect mobility of 1 cm^2/Vs, threshold voltage of -0.4 V, on/off current ratio of 10^5, and subthreshold swing of 0.8 V/decade. © *2012 American Institute of Physics*. [doi:10.1063/1.3676447]

Gallium nitride (GaN) has emerged as one of the most promising compound semiconductor during the last few years. The current deposition techniques for high quality GaN related thin films are mainly metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). One of the current directions in GaN research is to deposit high quality GaN thin film using inexpensive substrate under low temperature. Recently, amorphous and polycrystalline GaN thin films were deposited using magnetron sputtering technique[1–4] or pulsed laser deposition technique.[5] For the mass production in industry, DC magnetron sputtering technique for the thin film deposition has the potential of high deposition rate, large area, good uniformity, and low cost.

Transparent zinc oxide (ZnO)-based thin-film transistors (TFTs) have attracted considerable attention for application in flat panel displays, imaging, electronic paper, and other consumer electronics due to their better uniformity and performance including high mobility, excellent subthreshold swing, and high on/off current ratio, as compared to a-Si TFTs and poly-Si TFTs.[6–8] However, the poor electrical stability of ZnO-based TFTs is still a main issue preventing from commercialization.[9] Bottom-gate type and top-gate type TFTs using reactive radio frequency sputtering GaN film as channel layer has been demonstrated.[10,11] But they showed poor performance such as low mobility (6×10^{-2} cm^2/Vs) and low on/off current ratio (3×10^3), due to localized gap states in GaN thin film and large series resistance at the interface between GaN film and Al electrode.

In this work, as an alternative to ZnO-based TFTs, top-gate n-type TFTs with heavily doped source/drain region were fabricated utilizing GaN thin film as active channel, which was deposited by reactive DC magnetron sputtering technique using gallium target at room temperature. The properties of the GaN thin films and the proposed top-gate GaN TFTs are studied and discussed in detail.

GaN thin film was deposited by reactive DC magnetron sputtering using a liquid gallium target in a mixed Ar and N_2 ambient at room temperature. The deposition pressure and the power were 5 mTorr and 80 W, respectively. The structure of the films was analyzed by XRD experiments in grazing incidence geometry using Cu Kα1 radiation at 40 kV, 40 mA. The optical transmittance measurements were performed with a spectrophotometer in the wavelength range from 320 nm to 1050 nm. Atomic force microscopy (AFM) measurement was done in order to investigate the surface topography.

The cross-sectional schematic of the proposed top-gate GaN TFTs is shown in Figure 1. A 150 nm thick GaN thin film as active layer were first sputtered on thermally oxidized silicon wafer substrate. The GaN active layer was defined by photolithography and lift-off process. Source and drain regions were selectively implanted with silicon at dose of $3 \times 10^{15}/cm^2$ and an energy of 190 keV through 25 nm plasma-enhanced chemical vapor deposition (PECVD) oxide. Annealing at 1100 °C for 5 min in N_2 ambient was performed to activate the implanted silicon dopant. A 150 nm thick SiO_2 layer was deposited as gate dielectric by PECVD at 300 °C. Then, a 100 nm thick indium tin oxide (ITO) layer, used as gate electrode, was sputtered at room temperature and patterned by photolithography and lift-off technique, followed by the dry etching of gate dielectric SiO_2 using ITO as a mask. The ohmic contacts on source and drain region were formed using Ti/Al double metal layers deposited by sputtering. The Ti/Al double metal layers were defined by photolithography and lift-off process. The proposed GaN TFTs have a width to length ratio (W/L) of 5, with $L = 2\,\mu m$. The electrical properties of the GaN TFTs were measured at room temperature using an Agilent 4145B semiconductor parameter analyzer.

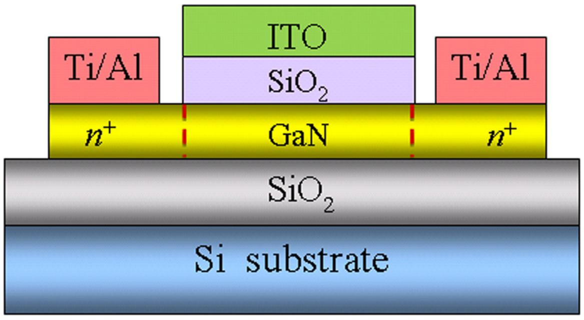

FIG. 1. (Color online) A cross-section schematic of the proposed GaN TFT with top gate structure.

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[a] Author to whom correspondence should be addressed. Electronic mail: rschen@ust.hk.

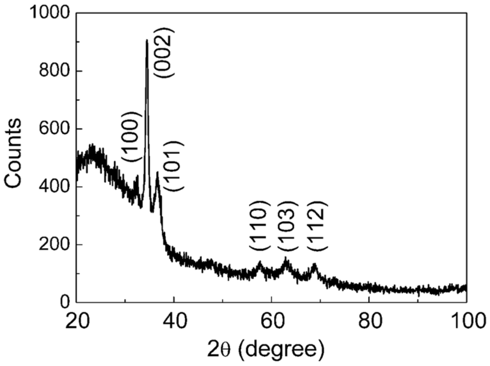

FIG. 2. The XRD pattern of the GaN thin film deposited at room temperature.

Figure 2 shows the XRD pattern of the GaN thin film. Several diffraction peaks were obtained and the strongest 2θ peak corresponding to (002) was observed at 34.5°, indicating that the GaN film is polycrystalline with a wurtzite structure and has a *c*-axis orientation. Calculated from the Scherrer formula, the estimated average grain size of the deposited GaN thin film is around 10 nm. The relatively smooth surface, reasonably uniform, and ultrafine microstructure of the GaN thin film were confirmed by AFM measurement, as shown in Figure 3. The root mean square (rms) roughness of the GaN film was only about 1.4 nm.

The transmittance curves of the 150 nm thick GaN thin film is shown in Figure 4(a), where it can be seen that the film shows 80%–93% optical transmission in the visible range. This high transmittance is important for transparent electronics applications. The optical band gap has been derived from Eqs. (1) and (2), as shown in Figure 4(b). The optical absorption coefficient α is determined from the following relation:

$$T = (1 - R)^2 e^{(-\alpha d)}, \tag{1}$$

where T, R, and d are the transmittance of the films, the reflectance of the films, and the film thicknesses, respectively. The optical band gap of the film is calculated by applying the Tauc model and the Davis and Mott model in the high absorbance region,

$$\alpha = D(h\upsilon - E_g)^n, \tag{2}$$

where $h\upsilon$, E_g, and D are the photon energy, the optical band gap, and a constant of proportionality, respectively. In this work, the value of n is 0.5 because the GaN film is a direct band gap material. The optical band gap for the GaN film is determined to be about 3.3 eV by extrapolating the linear portion of α^2 versus the $h\upsilon$ plot onto the energy axis, as shown in Figure 4(b). It agrees well with reported values, i.e., 3.2–3.4 eV (Refs. 2–4) for polycrystalline and 3.39 eV (Ref. 12) for single crystal material.

The typical output characteristics of the n-type GaN TFTs with a channel width to length ratio of 10 μm/2 μm are shown in Figure 5(a). The drain-source current (I_{DS}) exhibits pinch-off and saturation indicating that the TFTs follows standard field effect transistor characteristics. I_{DS} of the GaN TFTs increased when a positive V_{GS} was applied. It indicates typical n-channel depletion mode characteristics. The output characteristic shows clear linear regions and does not show significant current crowding at low V_{DS}, indicating that low series resistance in source/drain contacts were obtained. This low series resistance was caused by the heavily doped GaN in source/drain region and the activation of the silicon dopant. This low series resistance in source/drain contacts is the main reason for much better performance of the proposed GaN TFTs, as compared to previous reports.[10,11]

The field effect mobility induced by the transconductance at a low drain voltage is given by,

$$\mu_{FE} = \frac{Lg_m}{WC_{OX}V_{DS}}, \tag{3}$$

where g_m and C_{OX} are the transconductance and the gate insulator capacitance per unit area, respectively. The transfer characteristics with $V_{DS} = 0.2$ V and 5 V for the GaN TFTs

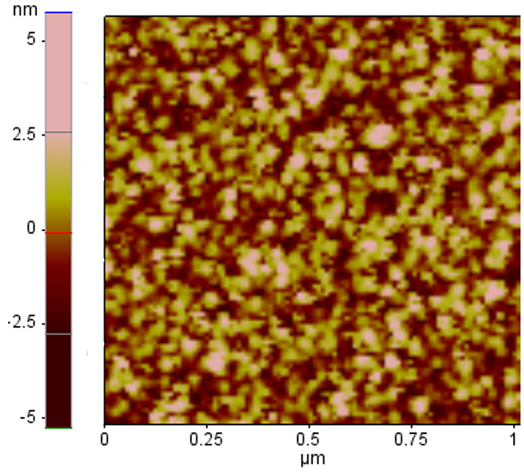

FIG. 3. (Color online) The AFM image for the polycrystalline GaN thin film.

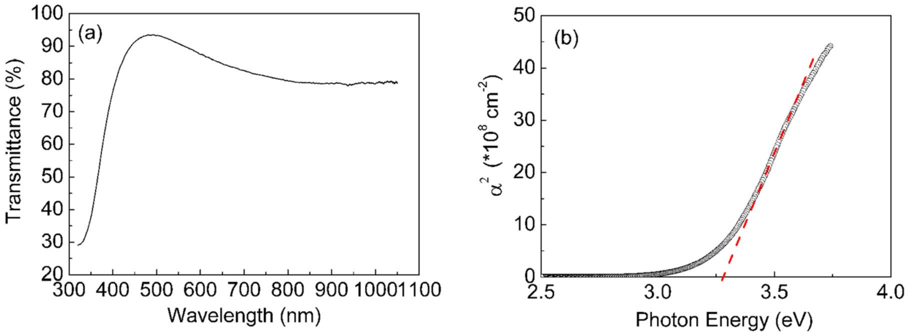

FIG. 4. (Color online) (a) Optical transmittance spectrum for the GaN thin film with a thickness of 150 nm and (b) the square of absorption coefficient as a function of photon energy for the GaN films.

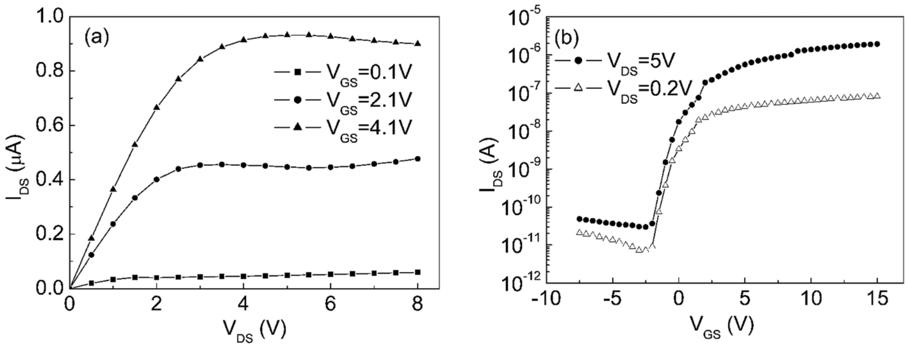

FIG. 5. (a) Output characteristics and (b) transfer characteristics of the GaN TFTs ($W/L = 10/2\ \mu$m).

with the same channel width to length ratio are shown in Figure 5(b). They exhibit good transfer TFT characteristics at a drain voltage of 0.2 V such as field effect mobility of 1 cm^2/Vs, threshold voltage of −0.4 V, subthreshold swing of 0.8 V/decade, and on/off current ratio of 10^5.

In general, the subthreshold swing value is an indicator of the trap density in the active GaN channel layer and at or near the interface between GaN and SiO$_2$ gate dielectric. These trap states are filled or empty depending on the location of Fermi-level. The relative large subthreshold swing may be caused from a nonoptimized dielectric and semiconductor interface, which should be improved in the future.

In conclusion, top gate n-type TFTs using GaN thin film as active channel layer were fabricated in this work. GaN thin film was deposited by reactive DC magnetron sputtering at room temperature and the film exhibits a polycrystalline structure with a strongest (002) orientation. Concerning the optical properties, the films have an average optical transmission around 85% in the visible range and the optical band gap is determined to be about 3.3 eV. The proposed GaN TFTs have field effect mobility of 1 cm^2/Vs, threshold voltage of −0.4 V, subthreshold swing of 0.8 V/decade, and on/off current ratio of 10^5. The proposed top gate GaN TFTs in this paper can be a potential candidate as driving devices in the next generation flat panel displays.

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