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Low leakage current—stacked MgO/$Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ gate insulator—for low voltage ZnO thin film transistors

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The authors report on the role of MgO capping layers in notably reducing leakage currents and improving mobility in ZnO thin film transistors (TFTs) utilizing compatible high-*k* $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ (BZN) gate insulators. All room temperature processed ZnO based TFTs with stacked MgO/BZN gate insulator exhibited a much enhanced field effect mobility of 5.4 $cm^2/V\,s$ with excellent saturation characteristics as compared to that ($\mu_{FE}=1.13\ cm^2/V\,s$) of ZnO based TFTs with BZN gate insulator. This work demonstrates the suitability of MgO/BZN stacked gate insulators in the fabrication of low voltage ZnO based TFTs on plastic substrates. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2387985]

Significant progress has been recently achieved in developing flexible devices such as active matrix organic light-emitting diode (LED) displays, radio frequency identification tags, and sensing devices on polymer substrates by use of organic field effect transistors.[1–3] High-*k* gate insulators for ZnO based thin film transistors (TFTs), as well as organic TFTs, have received increasing attention with the ultimate goal of creating low power/low voltage devices in portable, battery-powered applications.[4–6] High-*k* dielectrics are of particular interest given that gate insulators of more than 200 nm thickness are normally needed to ensure pinhole-free coverage when deposited onto relatively rough plastic substrates. Low voltage organic TFTs (OTFTs) and ZnO based TFTs (<5 V), utilizing room temperature deposited $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ (BZN) thin films were recently reported, pointing to high-*k* gate insulators as a promising route for realizing low voltage operating flexible electronics.[3,5]

A common limitation of room temperature deposited high-*k* dielectrics, e.g., $Ba_{1-x}Sr_xTiO_3$ (BST) and BZN films, is their tendency to suffer from higher leakage currents, detrimental to OTFT operation.[3,4] This is particularly disappointing given that BZN insulators exhibit exceptionally high-*k* values ($k>50$) even when sputter deposited at room temperature. In particular, high leakage currents ($>5\times10^{-5}\ A/cm^2$) were observed in TFTs utilizing BZN gate dielectrics at voltages greater than 6 V. In order to improve the leakage current characteristics of BZN gate insulators, we describe the introduction of a MgO capping layer onto the BZN films. MgO offers a relatively high dielectric constant of ~10, low leakage currents, and good interface characteristics. More importantly, MgO is strongly ionic with a band gap of 8 eV, which can suppress leakage currents due to the formation of high barrier Schottky contacts at the metal electrode/MgO interface.[7] While a number of leakage current mechanisms including Poole-Frenkel emission, space-charge-limited current, and Schottky emission in dielectric materials may apply in the case of room temperature grown dielectric films, Schottky emission is suspected to be the main leakage current mechanism.[8] However, since support for the Schottky emission mechanism comes largely from studies on high temperature deposited BST films, further study is needed to clarify the leakage current mechanism operative in room temperature grown BZN films. In this letter, we report on the role of MgO thin film capping layers in notably reducing leakage currents in BZN high-*k* dielectric thin films. In this regard, the fabrication and characterization of low voltage operating ZnO based TFTs with a MgO/BZN stacked gate insulator is reported.

Disk-type 3 in. BZN, ZnO, and MgO targets were prepared by a conventional mixed oxide method. 200 nm thick BZN thin films were grown on $Pt/Ti/SiO_2/Si$ substrates by rf sputtering with the following operating conditions: power (85 W), working pressure (5 mTorr), and Ar/O_2 [10/10 SCCM (SCCM denotes cubic centimeter per minute at STP)] atmosphere at room temperature. MgO thin films of 15–30 nm thickness were then deposited by pulsed laser deposition with KrF excimer laser (248 nm) operating at a repetition rate of 10 Hz and a fluence of 5 J/cm^2. For electrical measurements, Pt electrodes ($area=2\times10^{-4}\ cm^2$) of 100 nm thickness were deposited through a shadow mask on the BZN and stacked MgO/BZN films by dc magnetron sputtering.

The microstructure and roughness of the BZN and MgO/BZN films were investigated by atomic force microscopy (AFM) and scanning electron microscopy (SEM). The di-

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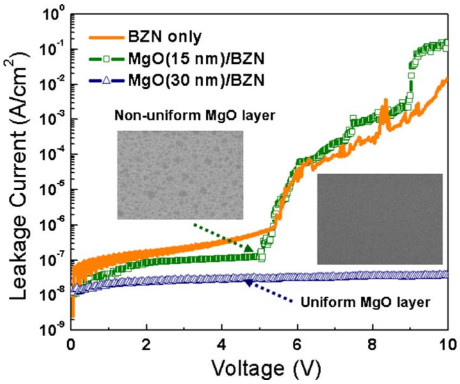

FIG. 1. (Color online) Leakage current densities of BZN and MgO coated BZN thin films.

electric properties were measured at 100 kHz with an applied electric field up to 10 V using an HP4192A impedance analyzer. Current-voltage (*I*-*V*) characteristics were examined with an HP4145B semiconductor parameter analyzer. ZnO based TFTs were fabricated on glass substrates. First, a 100 nm thick Cr gate electrode was deposited by dc sputtering with the aid of a shadow mask. Then, a 200 nm thick BZN gate dielectric film was deposited onto the Cr covered glass substrate by sputtering. This was followed by the room temperature deposition of a very thin (~30 nm) MgO film by pulsed laser deposition to insure the subsequent deposition of a high-quality ZnO film. Some devices on the same substrate were covered with a glass slide to prevent deposition of the MgO capping layer onto them. A ZnO *n*-type channel layer with a thickness of 20 nm was then deposited at room temperature by sputtering using the following conditions: rf power (85 W), working pressure (20 mTorr), and a Ar/O_2 (19/1 SCCM) atmosphere. Transistors were completed by the evaporation of Al top contacts through shadow masks to obtain channel length of 50 μm and width of 2000 μm.

Figure 1 shows the *I*-*V* characteristics of the BZN and stacked MgO/BZN thin films as a function of applied voltage. Two distinctive regions are observed for the BZN film. The leakage current density remains in a relatively narrow band of $10^{-7}-10^{-6}$ A/cm^2 in the low field region (<025 MV/cm, 5 V), and increases rapidly in the high field region (>0.25 MV/cm, 5 V). In order to decrease the BZN film leakage current, thin MgO capping layers were deposited onto the BZN films by pulsed laser deposition. 15 nm thick MgO coated BZN films exhibit similar characteristics to BZN-only films due to the nonuniform islandlike covering of the BZN films by the MgO layer, as shown in Fig. 1, inset (see SEM image). On the other hand, when the MgO film thickness was increased to 30 nm, no distinct increase in leakage current density with increasing applied field up to 0.5 MV/cm (10 V) was observed. The uniform coverage of the thicker MgO films is illustrated in Fig. 1, inset (see SEM image). The measured leakage current density remained on the order of $(\sim 2-3)\times 10^{-8}$ A/cm^2, thereby demonstrating significant improvement in leakage current upon introduction of the 30 nm MgO capping layer.

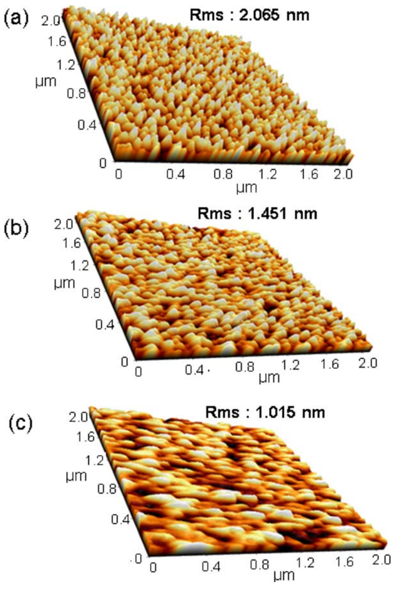

FIG. 2. (Color online) AFM images of the surface morphology of (a) BZN, (b) 15 nm thick MgO/BZN, and (c) 30 nm thick MgO/BZN films.

In order to compare the smoothness of the as-deposited BZN and MgO/BZN stacked films, their root-mean-square (rms) roughnesses were analyzed. Figure 2 shows typical results of three-dimensional AFM images and rms values of BZN and MgO/BZN stacked films. Rms values were 2.065 nm for the BZN film and 1.451 and 1.015 nm for the 15 and 30 nm thick MgO/BZN films, respectively. The smooth surface of the 30 nm think MgO coated BZN films should contribute to good interface characteristics and stable ZnO based TFTs operation.

Figure 3 shows the dielectric constant–electric field characteristics of room temperature grown BZN and stacked MgO/BZN thin films. The BZN films exhibit a relatively high dielectric constant of 55 at 100 kHz. This is nearly the same value as previously reported for BZN films.[3,5] The effective relative dielectric constants of the 15 and 30 nm MgO coated BZN thin films are reduced to 39 and 31.5, respectively, due to the lower dielectric constant (~10) of the MgO films. The measured capacitance, C_{measured} of stacked structures such as MgO/BZN can be evaluated from the series connection of the BZN film capacitance C_{BZN} and the MgO capping layer capacitance C_{MgO},

$$\frac{1}{C_{\text{measured}}}=\frac{1}{C_{\text{BZN}}}+\frac{1}{C_{\text{MgO}}}. \tag{1}$$

Thus, the average dielectric constant ($\epsilon_{\text{average}}$) can be expressed by

$$\frac{d_{\text{total}}}{\varepsilon_{\text{average}}}=\frac{d_{\text{BZN}}}{\varepsilon_{\text{BZN}}}+\frac{d_{\text{MgO}}}{\varepsilon_{\text{MgO}}}, \tag{2}$$

where d_{total}, d_{BZN} and d_{MgO} are the total film, BZN film, and MgO capping layer thicknesses, respectively. The effective dielectric constant of a 200 nm thick MgO film measured in a metal-insulator-metal configuration was 9.4. Accordingly, based on Eq. (2), the 42.7% decrease (from 55 for BZN to 31.5 for MgO/BZN) in measured dielectric constant corresponds to ~36.3 nm thick MgO, in relatively good agreement with thickness measurements (30 nm) by cross-sectional SEM. The small difference between the calculated and measured thicknesses of the MgO film may result from an interface effect, but further study is needed to confirm this. More importantly, the effective dielectric constant ($\varepsilon \sim 31.5$) of the MgO/BZN stacked insulator remains high enough to achieve low voltage operation of less than 5 V in ZnO based TFTs. Furthermore, no measurable dielectric tun-

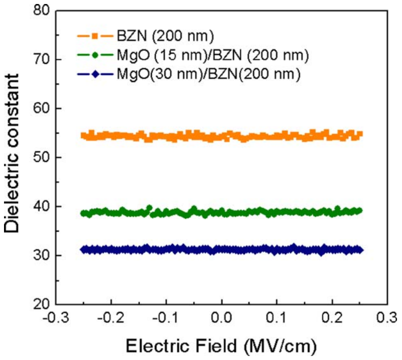

FIG. 3. (Color online) Dielectric constant–electric field characteristics of the BZN and MgO coated BZN thin films.

ability was observed up to an electric field of 0.25 MV/cm, insuring a voltage independent oxide capacitance and, therefore, predictable ZnO based TFTs operation. In order to demonstrate the advantages of stacked MgO/BZN films as gate insulators, all room temperature processed ZnO based TFTs were fabricated on glass substrates.

Figure 4(a) shows the drain-to-source current (I_{DS}) as a function of drain-to-source voltage (V_{DS}) at various gate voltages of the ZnO based TFTs with stacked MgO/BZN gate insulators. The high capacitance of stacked MgO/BZN gate insulators resulted in low voltage operation of less than 4 V. The TFTs normally exhibit off behavior, i.e., it turns on via the accumulation of carriers. The ZnO based TFTs with stacked MgO/BZN gate dielectrics do not conduct at a gate voltage of 0 V. As shown in Fig. 4(a), the TFTs with stacked MgO/BZN gate insulator showed higher on current of 18 μA at V_{GS} and $V_{DS}=4$ V with excellent current saturation in comparison to the TFTs (10 μA at V_{GS} and $V_{DS}=4$ V) with BZN gate insulator.[9] In the case of using stacked MgO/BZN gate insulators, we could expect stable operation at higher voltage level (i.e., on current of 53 μA at V_{GS} and $V_{DS}=5$ V) due to enhanced breakdown strength.

Figure 4(b) shows transfer characteristics of the ZnO based TFTs with stacked MgO/BZN gate insulators. The threshold voltage (V_{th}) was calculated from x-axis intercept of the square root of I_{DS} vs V_{GS} plot. Field effect mobility (μ_{FE}) modeled by the equation $I_D=(WC_i/2L)\mu_{FE}(V_{GS}-V_{th})^2$ can be calculated from the slope of the plot of $|I_{DS}|^{1/2}$ vs V_{GS} in the saturation region ($V_{GS}=4$ V), where L is the channel length, W is the channel width, C_i is the capacitance per unit area of the insulating layer, V_{th} is the threshold voltage, and μ_{FE} is the field effect mobility. In our previous report, the measured V_{th} and μ_{FE} were, respectively, +2.4 V and 1.13 cm^2/V s for ZnO based TFTs with BZN only gate insulator.[9] On and off currents were 1.36×10^{-5} and 5.54×10^{-10} A, respectively, giving an on/off current ratio of 2.4×10^4. On the other hand, the ZnO based TFTs with stacked MgO/BZN gate insulators exhibited a much enhanced field effect mobility of 5.4 cm^2/V s and an improved on/off ratio of 8.2×10^5 when operating at same voltage of 4 V. A similar threshold voltage of +2.8 V was obtained with the stacked gate insulator. The improved mobility is suspected to be related to the decreased roughness of the interface between the semiconducting layer and the gate insulator. By covering the BZN top layer with a MgO film, the surface roughness was decreased from 2.065 to 1.015 nm, as shown in Fig. 2. On the other hand, the surface morphology of the ZnO semiconductor layer was not changed with the introduction of MgO (not shown). The very smooth stacked MgO/BZN films ensure both high-quality ZnO layers and ZnO/MgO interfaces, resulting in improved carrier mobility due potentially to both reduced disorder in the ZnO film as well as reduced interfacial scattering. Smoother MgO/BZN films also ensure more uniform electric fields within the dielectric.

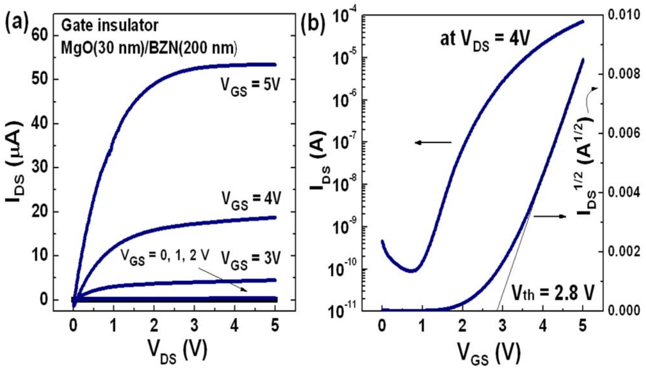

FIG. 4. (Color online) (a) Drain-to-source current (I_{DS}) vs drain-to-source voltage (V_{DS}) curves at various gate-to-source voltages (V_{GS}) for ZnO TFTs with stacked MgO/BZN gate insulators and (b) log drain-to-source current (I_{DS}) and square root of drain-to-source voltage (V_{DS}) of 4 V for ZnO TFTs with stacked MgO/BZN gate insulator.

In conclusion, 30 nm MgO coated BZN films were prepared at room temperature as a gate insulator. The stacked MgO/BZN gate oxide showed a high relative dielectric constant of 31.5 with greatly reduced leakage currents, i.e., $(\sim 2-3)\times10^{-8}$ A/cm^2 at an applied electric field of 0.5 MV/cm. The decrease in leakage current is believed to be due to the suppression of charge carrier emission from the electrode. The ZnO based TFTs with stacked MgO/BZN gate insulators exhibited a high field effect mobility (5.4 cm^2/V s) and excellent current saturation with a low operating voltage of less than 4 V. The results of this work demonstrate that room temperature processed ZnO based TFTs with stacked MgO/BZN gate insulators provide a promising route for the development of a wide range of logic circuits as well as active matrix organic LEDs.

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