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**Contact Resistance Reduction of ZnO Thin Film
Transistors (TFTs) with Saw-Shaped Electrode**

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Abstract

We report a saw-shaped electrode architecture ZnO thin film transistor (TFT) for effectively increase channel width. Such a saw-shaped electrode has ~2 times longer contact line at the contact metal/ZnO channel junction. We experimentally observed an enhancement in the output drive current by 50% and reduction in the contact resistance by over 50%, when compared to a typical shaped electrode ZnO TFT consuming the same chip area. This performance enhancement is attributed to extension of channel width. This technique can contribute to device performance enhancement and especially reduction in the contact resistance which is a serious challenge.

Keywords: Zinc Oxide (ZnO); Thin Film Transistor; Contact Resistance; Saw-shaped Electrode

1. Introduction

Zinc oxide (ZnO), an amorphous oxide semiconductor is prominent for its low cost, low temperature process capabilities, non-toxicity, high performance, and flexibility/transparency [1-10]. ZnO has been extensively explored for various applications, such as nano-generators, sensors, flexible devices, memory devices, and logic circuits [11-16]. In particular, ZnO has been widely investigated for back-plane thin film transistor (TFT) enabling display technology. When compared to amorphous silicon (a-Si), which is used for low-resolution display, ZnO has benefits in terms of higher saturation mobility, showing a similar performance that of poly silicon TFT [17].

However, to translate its potential for display industry as backplane transistor, it is important to increase the driving current value to improve the device performance for a high-speed circuit design. So far, it is well-known that channel length (L_g) scaling is one of the most effective approaches to increase drive current. This correlation can be understood by the transit frequency, f_T , which can be defined by the following equation for a digital circuit design [9].

$$f_T = \frac{g_m}{2 \times \pi \times C_{ox}} \sim \frac{\mu \times (V_{GS} - V_T)}{2 \times \pi \times L_g^2} \quad (1)$$

C_{ox} is the gate oxide capacitance, L_g is the gate length, μ is the field-effect mobility, and $(V_{GS} - V_T)$ is the gate overdrive voltage of the TFT. This empirical correlation shows that the development of semiconductor industry has been mostly driven by geometrical L_g scaling. In turn, not only increases circuit integration, but also improves circuit operation speed by $\tau_{delay} = CV/I$. Reduction in L_g is possible with several ways including a top-down lithographic scaling and a vertical channel TFT structure without a lithography process [18-19]. However, as L_g scaling approaches to the sub-100 nm regime, industry has confronted technological barriers such as serious gate leakage current. L_g scaling can induce V_{TH} shift, which can result into a high off-state

current, I_{OFF} , and can degrade output swing and thus increases the power consumption [20]. Because of these problems, it may be effective to consider other factors besides L_g scaling to improve device performance. For example, reduction in contact resistance can be expected to improve device performance while avoiding the short channel effect (SCE), which is a problem arising from device scaling.

Recently, reduction in contact resistance is an important concern for device performance improvements with scaling in the conventional Silicon devices and nano-material based transistors including ZnO TFTs [21-23]. Since the nano-device has a contact system between the metal electrode and the semiconductor that generates the Schottky-barrier, the device operation can greatly be influenced by the state of the contact region. This indicates that efforts to reduce contact resistance are more effective in nano-material based transistors including ZnO TFTs. Therefore, reduction in contact resistance can be suggested as an effective approach to achieve higher drive current, avoiding serious current leakage problems.

Here we suggest a structural reconfiguration of contact electrodes into saw-shaped to increase effective channel width. However, the idea of interdigitated electrodes has been employed mostly for enhancement of photo-generation in photo-detectors without investigating an advantage of contact resistance reduction [24]. Compared to the typical electrode, the saw-shaped electrode increases channel width by nearly 2 times without consuming extra chip area. As mentioned above, ZnO TFT is one of Schottky-barrier type transistors, meaning that overall device operation can be determined by the contact region. Electric field from the gate terminal has strong influences on the extended contact line with the saw-shaped electrode, enhancing gate field electrostatics. As a result, contact resistance was reduced by over 2 times, which in turn drive current increases $\sim 50\%$ per unit chip area without more device area consumption.

2. Experimental details

A P⁺⁺ Si/300 nm SiO₂ wafer was prepared through a chemical cleaning (mixture of Aceton, IPA, DI water). Atomic layer deposition (ALD) was used to deposit ZnO film (300 cycles). The source is a precursor combination of diethylzinc as metal-precursor and pure oxygen. To observe the ZnO channel surface, scanning electron microscope (SEM, NovaNano) and atomic force microscopy (AFM, SPM-5500) were used. ZnO film root means square (RMS) and thickness was estimated as ~3.2 nm and ~58 nm with an AFM measurement. Raman spectroscopy (ARAMIS, laser wavelength: 473 nm, 50 mW) was used to evaluate the optical characteristics of the transferred representative ZnO film. Photoluminescence (PL) measurement (ARAMIS, laser wavelength: 325 nm) was conducted to estimate the band-gap and defect-level for ZnO film. Photolithography and chemical etching with buffered oxide etchant was conducted to define ZnO channel. Photolithography process was conducted again to form source and drain electrodes. Physical vapor deposition (PVD) was done with e-beam evaporator to deposit metal electrode. Titanium (Ti) was used as contact metal since it has small band offset with ZnO channel. Finally, device fabrication was completed with a lift-off process, followed by thermal annealing at 200 °C for an hour in a vacuum chamber. Transfer/output characterization and transmission line measurement (TLM) of ZnO TFTs were done using a Keithley 4200-SCS semiconductor parameter analyzer at room temperature in an ambient air.

3. Results and discussion

We studied the physical properties of a ZnO film using atomic force microscopy (AFM), Raman, photoluminescence (PL), scanning electron microscope (SEM), and transmission electron microscope (TEM).

To observe the surface roughness and thickness of a ZnO film, AFM measurements were conducted (Figure 1(a)). Root mean square (RMS) of ZnO surface is ~ 3.3 nm, showing a smooth

surface with underlying the contact metal. Since surface status has a strong influence on the electrical properties, we can expect that our devices can be operated well [25]. The thickness of the ZnO film is ~ 58 nm, hence, our device can be defined as a nano-material based field effect transistor. (Figure 1(b)). The values of RMS and thickness were calculated through Gwyddion program.

Figure 1(c) shows the typical Raman spectrum of the ZnO film with 473 nm laser source. The Raman data shows the E_2 (high) phonon frequency with respect to that of a ZnO film, $436 \sim 438 \text{ cm}^{-1}$. The band-gap of ZnO can be confirmed by photoluminescence (PL) measurement. Figure 1(d) shows the PL data of the ZnO film with 325 nm laser source. Usually, the PL spectrum of ZnO consists of an ultraviolet (UV) emission band (~ 370 nm, narrow band) and a defect-level (DL) emission band (broad band), indicating that the band-gap of ZnO semiconductor is ~ 3.4 eV. The energy bandgap of the material can be estimated from the UV emission band, while the deep-level surface defects can be estimated from the DL emission band. In the PL data, the DL emission peak is too weak to be observed, meaning that it has a very small ratio of surface defect density to the total volume. Therefore, we cannot identify the defect-level for the ZnO film. We calculated the intensity ratio of I_{DL}/I_{UV} (~ 0.11) which is much smaller than that of a ZnO nanowire structure [12].

Figures 2(a) and (b) show high-resolution transmission electron microscopy (HRTEM) images for a Ti-ZnO stack and a ZnO film crystallinity. We observed 50~60 nm thickness of ZnO channel from the image, which is corresponding to the result of the AFM measurement. From the image of the ZnO film crystal, it was observed that the film consists of poly and single crystal. In the single crystal region, lattice constant is ~ 0.52 nm in the structure of a Wurtzite structure with a direction of [0001]. Figure 2 (c) exhibits that fast Fourier transform (FFT) of the ZnO film. The mixed dot and ring pattern is observed from the ZnO film, showing the combination of poly and single crystal structures. Energy dispersive spectroscopy (EDS) for the ZnO film was also

investigated in the supplementary information, showing the peaks for Zn and O species (Figure S1).

Figure 2 (d) shows SEM images of completed ZnO TFT with TLM electrode. The scale bar is 200 nm. Each channel (from channel 1 to channel 5) has different channel length for calculation of contact resistance from the TLM method. We used each electrode for the electrical measurement with different channel length. Two different TLM electrodes are exhibited in SEM images; a normal (bottom left) and a saw-shaped (bottom right).

Figures 3(a) and (b) show the electrode shape of the normal electrode and the saw-shaped electrode. We patterned various channel width of 30, 40, 60, 80 μm . The normal and the saw-shaped electrodes were compared with 60 μm of channel width as an example. The normal electrode has 60 μm of contact line width, which is contacted to the ZnO channel, while the saw-shaped electrode has extended to ~ 130 μm (60 μm and additional 70 μm , increase in channel width by ~ 2 times). It can be expected that increased electrode width provides extended carrier injection line from the source to the ZnO channel, increasing the carrier transport and drain current value. The difference can be explained by the 3D schematics of band diagrams in Figures 3(c) and (d).

The 3D schematics of band diagram and the difference of carrier injection line for the normal and the saw-shaped electrodes are shown in Figures 3(c) and (d). The normal line electrode has the limited narrow carrier transport path. On the other hand, for a saw-shaped electrode, there is an additional path for carriers from the source to the channel, offering enhanced carrier transport flow. Therefore, it can be expected that additional drain current is achieved from the saw-shaped electrode due to the longer transport line. We theoretically compared the electric field distribution for the normal and the saw-shaped electrodes using high frequency structure simulator (HFSS) in the supplementary information (Figure S2). When the saw-shaped electrode was used, a relatively higher current density was achieved at the contact. To understand if the

electrode modification can have a benefit on the device performances experimentally, various electrical characterizations were conducted.

Figure 4 (a) displays the transfer characteristics (I_{DS} - V_{BG}) of the normal and the saw-shaped electrode ZnO TFTs. Each measurement was done at room temperature in an ambient air. Drain current was calculated by the following conventional drain current equation.

$$I_{DS} = \frac{1}{2} \mu_{FE} C_{ox} \frac{W}{L} (V_G - V_{TH}) V_D \quad (2)$$

I_{DS} is the drain current, μ_{FE} is the field-effect mobility, C_{OX} is the oxide capacitance, W is the channel width, L is the channel length, V_G is the gate bias, V_{TH} is the threshold voltage, and V_D is the drain bias. Gate bias was swept ranging from -30 V to 30 V and drain bias was applied at 20 V. The transfer curve shows a typical unipolar n-type behavior with a depletion-mode (D-mode). It is well-known that the majority carrier is electron in ZnO and the source is oxygen vacancies in the crystal structure. I_{ON}/I_{OFF} ratio is over 10^4 for both cases, indicating that our ZnO device has enough switching performance to be used for integrated circuits. Nano-material based transistors including ZnO TFT are Schottky-barrier type transistors which is different with conventional silicon metal-oxide-transistors (Si MOSFETs) in operations [26-28]. Since the operation of Schottky-barrier type transistors is mostly determined by the status of contact region and barrier height dimension, increasing in contact line length at the junction can has advantages of device performance enhancement. By using the saw-shaped electrode, both I_{ON} and I_{OFF} increased. Although there is concern about increased standby power, the increase of I_{OFF} is much smaller than that of I_{ON} . ΔI_{OFF} and ΔI_{ON} is 1.21 pA and 15.1 nA, respectively.

Figure 4(b) shows the output characteristics of ZnO TFT with the normal and the saw-shaped electrode. During electrical measurements, 30 V of back-gate bias was applied with drain bias sweep range of $0 \sim 5$ V. Drain current was compared with different channel lengths. As expected, drain current increases as channel length reduced. From the output characteristics, the

difference of contact resistance (R_{CO}) can be expected. The clear difference between the normal and saw-shaped electrode can be observed. The normal line electrode shows a relatively low differentiation value (dI_{DS}/dV_{DS}) in the linear region where the voltage is low (small drain bias region). When using the saw-shaped electrode, higher drain current and low contact resistance can be expected from the output characteristics. The details of contact resistance will be described below.

In order to compare the normal and the saw-shaped electrodes statistically, average drain current was calculated in Figure 5. Drain current values for devices were normalized with channel length to make a fair comparison. We compared three cases; (i) normal electrode (L_W), (ii) 2 times channel width, $2 \times L_W$ (calculation), (iii) saw-shaped (experiment). When comparing the theoretical value of $2 \times L_W$ case and the saw-shaped case, it was expected that 2 times increase in drain current would be achieved with the saw-shaped electrode. However, the drain current increased by ~ 1.5 times. This discrepancy can be understood by the calculation of total resistance.

$$R_{TOT} = R_{CH} + 2R_{CO} \quad (3)$$

R_{TOT} is total resistance, R_{CH} is channel resistance, and R_{CO} is contact resistance. By using saw-shaped electrode, it was expected that R_{CO} can be reduced 2 times since contact line between the contact metal and the channel increases, while there is no change of R_{CH} . The saw-shaped electrode can partially contribute to reduction in R_{TOT} by reducing R_{CO} . Even though the saw shape electrode does not show 2 times increase in drain current of the normal electrode, it offers an advantage of $\sim 50\%$ increase without device area consumption.

A modified saw-shaped electrode offers a benefit of increasing in channel width at the contact junction for carriers to pass through the Schottky-barrier easier. As a result, we could observe the reduction in contact resistance. To calculate contact resistance (R_{CO}), there are several approaches such as transmission line measurement (TLM) and using the ratio of two linear DC curves [29-30]. We could calculate R_{CO} from the TLM method with several different channel

length since large area ZnO semiconductor area was achieved. R_{CO} was estimated at $L_{CH} = 0 \mu m$ by an extrapolation method from various resistance values of devices which have different channel lengths (Figure S3).

Figure 6 (a) shows R_{CO} values for each case from TLM method. Each measurement was conducted at room temperature. R_{CO} values were also compared for three cases; (i) normal electrode, L_W , (ii) 2 times channel width, $2 \times L_W$ (calculated), (iii) saw-shaped (experiment). When we consider 2 times ((ii) $2 \times L_W$) channel width of the normal electrode, calculated R_{CO} is reduced to 50 %, since the contact line between the contact metal and the channel increases by 2 times. Interestingly, the R_{CO} value of the saw-shaped electrode case was also reduced by $\sim 50 \%$, showing $100 M\Omega \cdot \mu m$ of R_{CO} which is similar value with that of the case of $2 \times L_W$. The results suggest that the saw-shaped electrode offers almost same contact resistance reduction rate compare to the case (2) ($2 \times L_W$) with a benefit of device area efficiency.

Figure 6 (b) shows the average contact resistance as a function of gate bias for the normal and the saw-shaped electrode. The contact resistance has a strong correlation with the back gate bias. The correlation between the gate bias and the contact resistance can be explained by two reasons: (i) a Schottky-barrier at the metal/ZnO junction is determined by the electric field from the gate terminal, modulating carrier tunneling efficiency through the barrier; (ii) the electrical doping which induces a smaller R_{CO} in the ZnO channel can be determined with the gate bias, which is similar phenomena as in graphene [31]. Overall, average R_{CO} of the saw shape electrode is lower than that of the normal electrode. Average R_{CO} of the normal and the saw-shaped electrode is $\sim 167 M\Omega \cdot \mu m$ and $\sim 100 M\Omega \cdot \mu m$ at the saturation region (at $V_{BG} = 30 V$).

4. Conclusions

In summary, we have shown a saw-shaped electrode can increase effective channel width. Additional effective channel width and widened carrier transport region from the source

to the ZnO channel were expected from mask design and band diagram. As a result, reduction in contact resistance and increasing in drain current were observed with the saw-shaped electrode.

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Figure captions

Figure 1 AFM images showing (a) root mean square (RMS) value of ZnO film surface and (b) ZnO film thickness. The RMS and the thickness are estimated as ~ 3.266 nm and ~ 58 nm, respectively. (c) Raman spectrum for ZnO film showing E_g (high) peak. The laser source of 473 nm was used (d) Photoluminescence (PL) data for ZnO film with 325 nm of laser source. It has ultra-violet (UV) emission band and deep-level (DL) emission band. Band-gap of ZnO can be estimated ~ 3.4 eV.

Figure 2 HRTEM for (a) a Ti-ZnO stack and (b) ZnO crystallinity. (c) Fast Fourier transform (FFT) pattern for a ZnO film. (d) SEM image of a ZnO TFT with TLM electrode. Normal (bottom left) and saw-shaped (bottom right) are exhibited in the SEM images.

Figure 3 Thin film transistor structure from the top view and electrode shape of (a) the normal and (b) the saw-shaped electrode. 3D schematics of band diagram for (c) the normal and (d) the saw-shaped electrode.

Figure 4 (a) Transfer curves ($I_{DS}-V_{BG}$) measured with a gate bias sweep range from -30 V to 30 V at a fixed drain voltage of 20 V for a ZnO TFT made with the normal electrode (black dashed line) and ZnO TFT made with the saw-shaped electrode (blue solid line). ZnO TFTs show the typical n-type depletion-mode behavior. (b) Output curves ($I_{DS}-V_{DS}$) for ZnO TFTs with the normal and the saw-shaped electrode.

Figure 5 Statistical average drain current for (1) normal (L_w), (2) $2L_w$ (calculated), and (3) saw-shaped electrode (experiment). Each drain current was normalized to give a fair comparison. The saw-shaped electrode offers a benefit of $\sim 50\%$ of drain current increase.

Figure 6 (a) Total resistance as a function of the channel length for (1) normal (L_w), (2) $2L_w$ (calculated), and (3) saw-shaped electrode (experiment). The saw-shaped electrode shows $\sim 50\%$ reduction of the normal electrode in contact resistance (b) Average contact resistance as a function of the back gate bias for the normal and the saw-shaped electrode.

Fig. 1 Park et al.

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Fig. 5 Park et al.

Fig. 6 Park et al.