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2-D Numerical Simulation of High Performance Amorphous In-Ga-Zn-O TFTs for Flat Panel Displays

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We reported the latest results on two-dimensional (2-D) simulation of high performance amorphous In-Ga-Zn-O (a-IGZO) TFTs for flat panel displays. Our RF sputter a-IGZO TFT has following properties: field-effect mobility (μ_{eff})=12cm^2/Vs, threshold voltage (V_{TH})=1.15V, sub-threshold swing (S)=0.13V/dec and on/off ratio over 10^{10}. A density-of-states model is developed, for the first time, to accurately simulate the measured transistor properties. The oxygen vacancy states are also included to simulate the high temperature TFT behavior.

1. Introduction

Recently, there is an increasing interest in using amorphous In-Ga-Zn-O thin-film transistors (a-IGZO TFTs) to replace a-Si:H TFTs for next generation flat-panel displays. This is especially important for high-resolution displays. The pulse-laser-deposition (PLD) and RF sputter a-IGZO TFT with high μ_{eff} was successfully fabricated by several groups.[1,2] Despite all the success in device fabrication, no numerical simulation was reported that is essential for full understanding of device operation and optimizing of its electrical performance and structure needed for pixel design. In this paper, we report, for the first time, results on a-IGZO TFTs 2-D simulation based on proposed density-of-states (DOS) model to describe electronic properties of the a-IGZO thin-film.

2. TFT Structure and a-IGZO DOS Model

A 2-D, inverted-staggered a-IGZO TFT structure used for numerical simulation is shown in inset of Figure 3. The structure consists of a 20nm thick a-IGZO channel layer and a 100nm thick SiO_2 gate insulator layer. The TFT channel length (L) is 30μm. The contacts between source/drain (S/D) electrodes and a-IGZO channel are either assigned as Schottky or ohmic in nature in this work.

To develop the proper DOS model, we referred to several published results. Takagi *et al.* have extracted the conduction band effective mass (m_c) to be ~0.34 m_e (m_e is the mass of free electron) in their early work on a-IGZO.[3] We further calculated the effective conduction band density of states (N_c) to be $5x10^{18}$cm^{-3}.[4] The structural disorder within a-IGZO is represented as band tail states within band gap, as a function of energy (E) by following expressions (cf. Fig. 1, Table 1):

$$g_{CBa} = g_{ta} \exp\left((E - E_C)/E_a\right) \quad (1)$$

$$g_{VBd} = g_{td} \exp\left((E_V - E)/E_d\right) \quad (2)$$

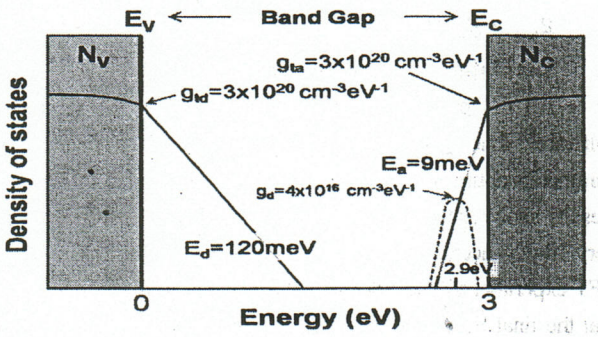

Fig. 1. Proposed density-of-states (DOS) model for a-IGZO.

where E_C and E_V are conduction and valence band edge energy.[5] To determine the proper range for g_{ta}, we refer to the fact that the DOS has a continuous distribution from tail states to extended states. Therefore, it is reasonable for N_C (or N_V) and g_{ta} (or g_{td}) to have a proportional relation. Since N_C of a-IGZO is about an order smaller than a-Si:H (N_C for a-Si:H is ~$3x10^{19}$cm^{-3}), we assume g_{ta} of a-IGZO should be around 10^{20} cm^{-3}eV^{-1} (g_{ta} for a-Si:H is 10^{21} cm^{-3}eV^{-1}).[5] The band gap (E_g) and valence-band-tail slope (E_d) were further determined by optical absorption measurement on a-IGZO thin film.[6]

It is well known that due to the unique conducting mechanism through metal ion's spherical s-orbital, band conduction can still exist in a-IGZO TFT even it is an amorphous phase. Therefore, we set the band mobility (μ_n) to be the maximum differential μ_{eff} obtained from TFT measurement (in this study, its 15 cm^2/Vs). Oxygen vacancy can also alter the electrical properties of oxide semiconductors. It is commonly believed that the vacancy created additional states near the conduction-band edge (CBE)[7,8]. We include a Gaussian- distributed donor-like states located near the CBE to phenomenologically model the oxygen vacancies in oxide

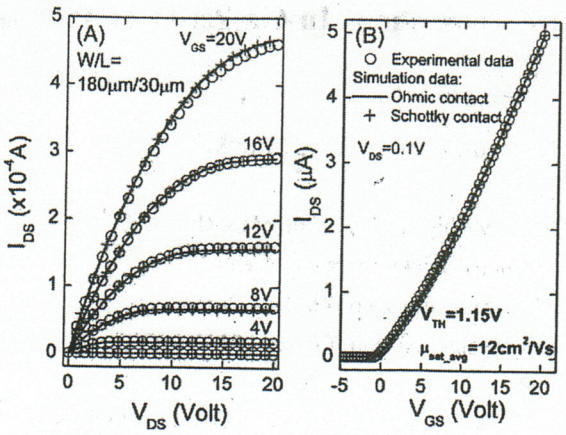

Fig. 2. (A) Output and (B) transfer characteristics for 20nm thick a-IGZO TFTs. Threshold voltage (V_{TH}) and average field-effect mobility (μ_{sat_avg}) are also indicated.

semiconductor with equation:

$$g_{Gd} = g_d \exp\left(-(E-\lambda)^2/\sigma^2\right) \qquad (3).$$

3. Simulation Results and Discussion

All the parameters are then inputted into the simulation software[9] that was modified for this study. The final set of parameters optimized for our a-IGZO TFT are listed in Table I. Results show that our physics based model can reproduce with a very highly accurate output, transfer and sub-threshold a-IGZO TFT experimental characteristics (Figure 2,3). It is worth to notice that the final E_a we obtain (9 meV) is lower than common a-Si:H value (~25meV) and agree fairly well with what Kamiya *et al.* predicted in their original work.[8] Both Schottky and ohmic contact models have been considered, and give similar simulation results. This suggests that the S/D metal (in this study, it's Ti) is forming an ohmic-like contact with the a-IGZO layer. On another a-IGZO TFT (with lower g_{ta} value), we measured the electrical properties at a high temperature (90°C) and observed a shift in turn-on voltage. Since there is no electrical stressing involved, it is more reasonable to assume that the physical origin of such shift is due to increasing oxygen vacancy in a-IGZO at the higher temperature. Figure 4 shows that our model can simulate such observation by increasing oxygen vacancy states g_{Gd} (cf. eq.3 and Table.I).

Table I. Key simulation parameters used in this study

Symbol	Value	Unit	Description
N_c	$5x10^{18}$	cm^{-3}	Effective conduction band DOS
N_v	$5x10^{18}$	cm^{-3}	Effective valence band DOS
g_{ta}	$3x10^{20}$	$cm^{-3}eV^{-1}$	Density of tail states at E=Ec
g_{td}	$3x10^{20}$	$cm^{-3}eV^{-1}$	Density of tail states at E=Ev
E_a	9	meV	Conduction-band-tail slope
E_d	120	meV	Valence-band-tail slope
E_g	3.05	eV	Band gap
Φ	4.3		Electronic affinity
ε	10		Permittivity
μ_n	15	cm^2/Vs	Band mobility (electron)
μ_p	0.1	cm^2/Vs	Band mobility (hole)
m_c	0.34	m_e	Conduction band effective mass
g_d	$4x10^{16}$	$cm^{-3}eV^{-1}$	Peak of oxygen vacancy (OV) states
λ	2.9	eV	Mean energy of OV states
σ	0.1	eV	Standard deviation of OV states

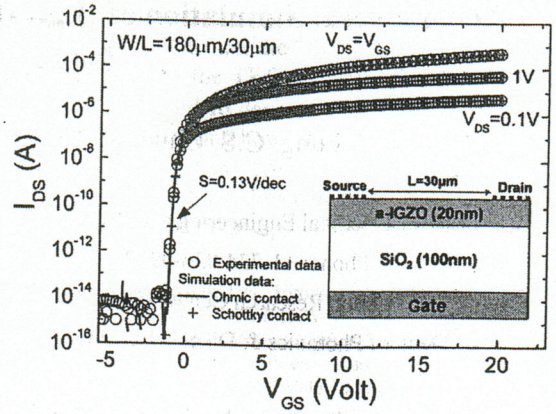

Fig. 3. I_{DS}-V_{GS} curves of a-IGZO TFT. Sub-threshold swing (S) is also indicated. Inset: TFT structure used in simulation.

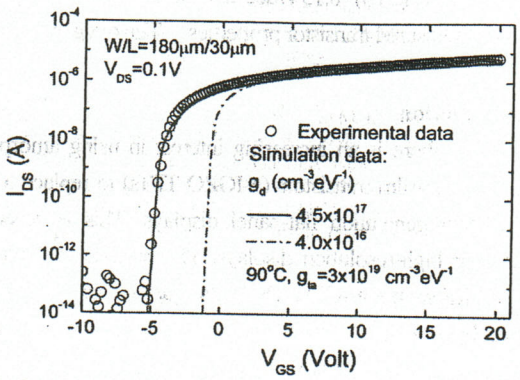

Fig. 4. Example of using oxygen vacancy states (g_{Gd}) to simulate a-IGZO TFT shifting behavior at high temperature.

4. Conclusion

We demonstrated that the device physics based on 2-D numerical simulation can be use to precisely predict a-IGZO TFT electrical performance. In addition, simulation results suggest that a high performance of a-IGZO TFT can be partially due to an ohmic S/D contact and a sharp conduction tail states distribution. Such device is very desirable for a high resolution flat panel displays.

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