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Modeling of amorphous InGaZnO thin-film transistors based on the density of states extracted from the optical response of capacitance-voltage characteristics

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In order to model dc characteristics of *n*-channel amorphous InGaZnO thin-film transistors from experimentally obtained density of states (DOS), the acceptorlike DOS is extracted from the optical response of capacitance-voltage characteristics and confirmed by the technology computer-aided design (TCAD) simulation comparing with the measured data. Extracted DOS is a linear superposition of two exponential functions (tail and deep states), and its incorporation into TCAD model reproduces well the experimental current-voltage characteristics over the wide range of the gate and drain voltages. The discrepancy at higher gate voltage is expected to be improved by incorporating a gate voltage-dependent mobility in the model. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3013842]

With advantages of the low cost room temperature (RT) fabrication process, higher mobility than those of covalent semiconductor thin-film transistors (TFTs), and compatibility with rollable transparent electronic applications, multicomponent oxide semiconductor (i.e., InGaZnO (IGZO), InZnO, and GaZnO)-based TFTs have attracted much attention. In as much as both the free carrier density (n_{free}) in the conduction band and the localized trapped carriers (n_{loc}) play a major role in determining the effective mobility (μ_{eff}) of IGZO TFTs, a simple and fast extraction of the density of states (DOS) $[g(E)]$ in IGZO TFTs is strongly required for characterization applicable to their modeling and design of devices and integrated circuits. Whereas the process parameter dependences of the carrier density (n_{Hall}) and the mobility (μ_{Hall}) by Hall measurement in IGZO thin film have been well understood by many research groups [i.e., the oxygen partial pressure and/or the radio frequency (rf) power during RT sputtering process],[1–4] $g(E)$ of *n*-channel IGZO TFTs has been obtained by the numerical simulation-based fitting from the experimental results.[5,6] Very recently, the donorlike states near the valence band maximum were analyzed by using the x-ray photoelectron spectroscopy.[7]

In this letter, a simple and fast extraction of the acceptorlike $g(E)$ near the conduction band minimum (CBM) of *n*-channel amorphous IGZO (*a*-IGZO) TFTs is demonstrated based on the experimental optical response of the capacitance-voltage characteristics. In addition, the validity of the extracted $g(E)$ is verified by its incorporation into the technology computer-aided design (TCAD) model and comparison with the measured current-voltage characteristics.

The integrated IGZO TFTs have the most commonly used back-channel-etch staggered bottom gate structure for active-matrix liquid crystal displays and/or active-matrix organic-light-emitting-diode displays. Devices are fabricated as follows: on a thermally grown SiO_2/Si substrate, the first sputtered deposition at RT and patterning of molybdenum (Mo) gate are followed by plasma-enhanced chemical vapor deposition (PECVD) of SiO_2 (100 nm) at 300 °C. An active layer ($Ga_2O_3:In_2O_3:ZnO=2:2:1$ at. %) is then sputtered by rf magnetron sputtering at RT in a mixed Ar/O_2 [100:1 at SCCM (SCCM denotes cubic centimeter per minute at STP)] and wet etched with diluted HF to get IGZO pattern with the thickness of $T_{\text{IGZO}}=70$ nm. For the source/drain (S/D), a 200-nm-thick layer of Mo is sputtered at RT and then patterned by dry etching. After N_2O plasma treatment on the channel surface of the IGZO active layer, a SiO_2 passivation layer is continuously deposited at 150 °C by PECVD without a vacuum break. All the samples were finally annealed for 1 h in the furnace at 250 °C. The channel length (L), the channel width (W), and the length of the overlap region between the gate and S/D (L_{ov}) are designed to be 50, 200, and 10 μm, respectively. An amorphous phase of the fabricated IGZO layer was confirmed by x-ray diffraction and transmission electron microscopy.

Figure 1 illustrates the concept of extracting the acceptorlike $g(E)$ from an optical response of capacitance-voltage (C-V) characteristics between gate and S/D electrodes. The measured capacitance as the function of the gate voltage V_G (S/D electrodes are grounded in C-V measurement) in the dark (C_{dark}) and photon-illuminated state (C_{photo}) can be described as

$$\frac{1}{C_{\text{dark}}}=\frac{1}{C_{\text{ox}}}+\frac{1}{C_B}, \tag{1}$$

$$\frac{1}{C_{\text{photo}}}=\frac{1}{C_{\text{ox}}}+\frac{1}{C_B+C_{\text{IGZO}}}, \tag{2}$$

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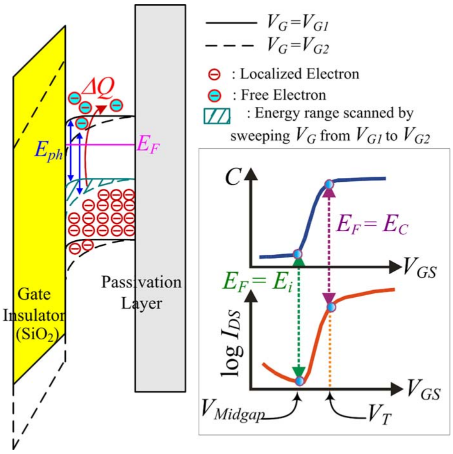

FIG. 1. (Color online) The schematic diagram illustrating the concept of extracting the accepterlike DOS $[g(E)]$. Capacitance (C_{IGZO}) due to photoresponsive charge (ΔQ) is converted into $g(E)$ at a specific energy level $[E_C(V_{\mathrm{G}})-E_{\mathrm{ph}}]$. The inset illustrates the relationship between V_{G} and $E_F(V_{\mathrm{G}})$.

$$C_{\mathrm{IGZO}}=\frac{\Delta Q}{\Delta V_{\mathrm{GS}}}=\frac{q\Delta N}{\Delta V_{\mathrm{GS}}}$$

$$=C_{\mathrm{ox}}\left[\frac{C_{\mathrm{photo}}}{C_{\mathrm{ox}}-C_{\mathrm{photo}}}-\frac{C_{\mathrm{dark}}}{C_{\mathrm{ox}}-C_{\mathrm{dark}}}\right], \qquad (3)$$

where C_{ox}, C_B, and C_{IGZO} are the gate oxide insulator capacitance, the capacitance due to V_{G}-responsive localized trapped charge in a-IGZO active layer in a dark state, and the capacitance due to photoresponsive charge (ΔQ) and/or electrons (ΔN) at a specific V_{G}, respectively. When an optical source with a photon energy $E_{\mathrm{ph}}=1.9$ eV ($<E_{g,\mathrm{IGZO}}\approx 3.2$ eV) and optical power $P_{\mathrm{opt}}=50$ mW is illuminated to a-IGZO TFTs during C-V measurement, electrons trapped in the localized states (n_{loc}) in the energy range (E_C-E_{ph}) $\sim E_F$ are excited to E_C by the photon energy and transferred to free electrons n_{free}. These excited electrons respond to a small signal voltage and consequently contribute the variation in C-V characteristics under photonic excitation. Here, E_C and E_F are the CBM and the quasi-Fermi level, respectively. During C_{photo}-V_{G} characterization, as seen in Fig. 1, it is assumed that the charge variation ΔQ results from the optically pumped electrons only in the energy level $[E_C(V_{\mathrm{G}})-E_{\mathrm{ph}}]$ because the trapped electrons above (E_C-E_{ph}) are excited and swept out to the S/D electrodes as soon as the optical source is turned on. In other words, the absorption and relaxation of a photon energy reach the steady state by the detailed balance. Then, $C_{\mathrm{IGZO}}(V_{\mathrm{G}})$ can be extracted from Eq. (3) since C_{ox} can be calculated and the scanned (photoresponsive) energy range for $g(E)$ is controlled by both the surface potential (ϕ_s) through V_{G} and the photon energy E_{ph}. As a result of the conversion of ΔQ to the photoresponsive charge density, consequently, $g(E)$ can be extracted from

$$C'_{\mathrm{IGZO}}=\frac{C_{\mathrm{IGZO}}}{(W\times L\times T_{\mathrm{IGZO}})}, \qquad (4)$$

$$g(E)=\frac{C'_{\mathrm{IGZO}}}{q^2}. \qquad (5)$$

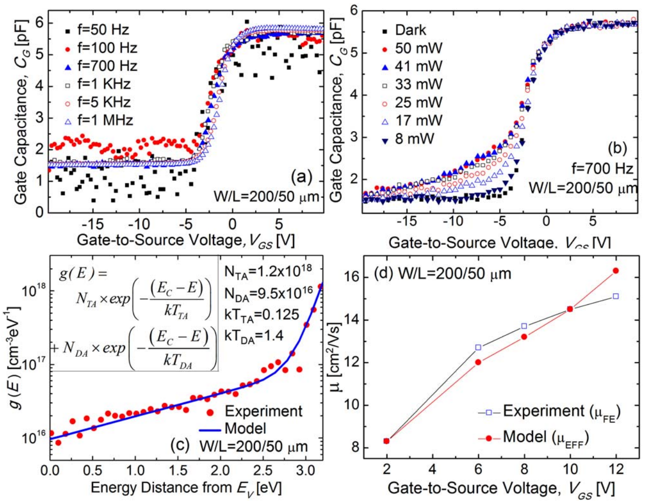

FIG. 2. (Color online) (a) The frequency f and (b) the optical power P_{opt} dependence of C-V measurement in a-IGZO TFTs. [The $g(E)$ was extracted under $P_{\mathrm{opt}}=50$ mW and $f=700$ Hz.] (c) Finally extracted $g(E)$ which is consistent with a linear superposition of two exponential functions as is the case in a-Si:H TFT and (d) the V_{G}-dependence of mobility (open:measured field-effect mobility μ_{FE}: solid:effective mobility μ_{eff} used in TCAD model).

As long as the band bending is not so steep over the region, $g(E)$ can be assumed to be uniform along the a-IGZO depth direction. Two transition points in the C-V curve correspond to E_i ($V_{\mathrm{G}}\approx$ the midgap voltage V_{midgap}) and E_C ($V_{\mathrm{G}}\approx$ the threshold voltage V_T), respectively, as shown in the inset of Fig. 1. In order to confirm a comprehensible charge pumping by the optical source, P_{opt} and f (frequency) dependences of C_{photo}-V_{G} curves should be taken into account. Figure 2(a) shows that the C_{photo}-V_{G} characteristic becomes insensitive to the frequency at $f>700$ Hz. Figure 2(b) shows that the optical response of the C_{photo}-V_G curves saturates at $P_{\mathrm{opt}}>41$ mW, and this guarantees that the trapped charges in corresponding energy levels are sufficiently excited by photons. Figure 2(c) shows the extracted $g(E)$ from optical response of C-V characteristics at $f=700$ Hz and $P_{\mathrm{opt}}=50$ mW. As is the case in amorphous hydrogenated Si (a-Si:H) TFT,[8,9] it can be modeled by a linear superposition of two exponential functions (deep states and tail states) described as

$$g(E)=N_{\mathrm{TA}}\exp\left[-\frac{(E_C-E)}{kT_{\mathrm{TA}}}\right]+N_{\mathrm{DA}}\exp\left[-\frac{(E_C-E)}{kT_{\mathrm{DA}}}\right], \qquad (6)$$

with extracted model parameters as $N_{\mathrm{TA}}=1.2\times 10^{18}$ cm^{-3} V^{-1}, $N_{\mathrm{DA}}=9.5\times 10^{16}$ cm^{-3} V^{-1}, $kT_{\mathrm{TA}}=0.125$ eV, and $kT_{\mathrm{DA}}=1.4$ eV. These characteristic model parameters are consistent with those based on a numerical simulation and fitting with respect to the order of magnitude.[5] In addition, Fig. 2(d) shows an effective mobility $\mu_{\mathrm{eff}}(V_{\mathrm{G}})$ used in our model compared with the measured field-effect mobility $\mu_{\mathrm{FE}}(V_{\mathrm{G}})$. The V_{G}-dependent mobility in a-IGZO TFTs is originated from the incremental portion of filled localized states among total states (consequently the percentage of the injected channel electrons is free to drift) modulated by V_{G}.[10,11] The discrepancy at higher V_{G} shows that an amorphous oxide semiconductor TFT mobility model should be developed with a full consideration of $g(E)$ and the V_{G}-dependent trap filling.

Finally, Fig. 3 shows the measured output [drain current (I_{DS})-drain-source voltage (V_{DS})] and transfer

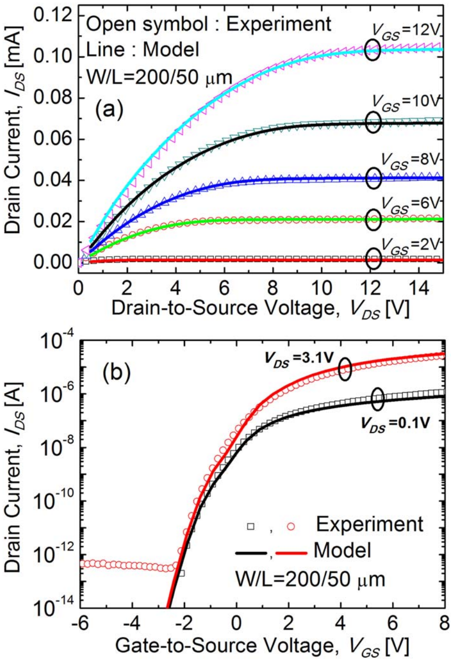

FIG. 3. (Color online) (a) Measured output characteristics and (b) transfer characteristics of *a*-IGZO TFTs. The model characteristics are obtained from TCAD simulation incorporated by the extracted $g(E)$ with the equilibrium $n_{\mathrm{free}}=1.35\times10^{17}$ cm^{-3} and $\phi_B=0.36$ eV. The model agrees very well with measured characteristics.

[I_{DS}-gate-source voltage (V_{GS})] characteristics of *a*-IGZO TFTs compared with the model obtained from TCAD simulation incorporating the extracted $g(E)$.[12] In the simulation, the equilibrium $n_{\mathrm{free}}=1.35\times10^{17}$ cm^{-3} and Schottky barrier height $\phi_B=0.36$ eV (between *a*-IGZO and S/D Mo electrodes) were used. Note that the $g(E)$-based model reproduces measured characteristics very well for a wide range of V_{GS} and V_{DS} by considering only a single process-controlled parameter set without employing any fitting parameter.

In conclusion, the modeling of *n*-channel *a*-IGZO TFTs based on the $g(E)$ extracted from optical response of *C*-*V* characteristics was reported. In addition, the validity of the extracted $g(E)$ was verified by its incorporation into TCAD model and comparison with the measured current-voltage characteristics of *a*-IGZO TFTs. Our results show that the proposed model is very useful for a simple and fast extraction of the acceptorlike DOS $g(E)$ near the CBM of *n*-channel multicomponent oxide semiconductor-based TFTs.

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