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Study of the Density of States of a-InGaZnO Using Field-Effect Technique

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Amorphous In-Ga-Zn-O thin film transistor (a-IGZO TFT) is viewed as important new device that could be used for future flexible flat panel displays. Besides visible light transparency and the ability to be deposited uniformly over a large area at low temperatures, a-IGZO TFT has high field-effect mobility, high current on-off ratio and low subthreshold swing [1]. All these device parameters are highly dependent on density-of- localized gap states (DOS) of a-IGZO. Knowledge of these states is essential for fundamental understanding and improving the material's electronic properties. So far such DOS was not disclosed for a-IGZO. In this paper, for the first time, we report on DOS for RF sputter a-IGZO as determined from temperature dependent study of the a-IGZO TFT electrical properties. Measurements were performed on inverted-staggered RF sputter a-IGZO TFTs. We measured the drain current (I_D) versus the gate-to-source voltage (V_{GS}) at different temperatures from 30℃ up to 90℃.

We observed that the drain current is thermally activated and can be described by $I_D = I_{D0}\exp(-Ea / kT)$ for both regimes of device operation, where I_{D0} is the prefactor, Ea is the activation energy, both are V_{GS} dependent. I_{D0} can also be written as a function of Ea: $I_{D0} = I_{D00}\exp(A_{app} \cdot Ea)$, where A_{app} is the apparently observed Meyer -Neldel parameter [2]. For RF sputter a-IGZO TFTs, A_{app} is observed to be a constant (~30 eV^{-1}) over a broad range of activation energies between 0.2 and 1.4 eV, which corresponds to the subthreshold régime.

The approach of calculating the DOS is briefly described. We first express the TFT drain current by:

$$I_d(V_g) = \frac{I_{FB}}{d_s} \cdot \int_0^{d_s} \exp[(\beta - A) \cdot y(x)]dx,$$

where I_{FB} is the flat band current, d_s is the thickness of active layer, $\beta = 1/kT$, A is the Meyer-Neldel parameter, x is the distance measured from the insulator interface and y(x) is the band bending parameter. The internal potential in the semiconductor is determined by the Poisson equation together with the boundary conditions:

$$\frac{d^2y(x)}{dx^2} = \frac{e \cdot n[y(x)]}{k_s' \cdot \varepsilon_o}, \quad \frac{dy(d_s)}{dx} = y(d_s) = 0, \quad \frac{dy(0)}{dx} = -\frac{k_{ins}}{k_s} \cdot \frac{V_F}{d_{ins}}$$

where k_s (k_{ins}) is the dielectric constant of the a-IGZO (insulator), n[y(x)] is the density of localized charge, d_{ins} is the thickness of the insulator and $V_F = Vgs - V_{FB}$. Now, the drain current can be written as:

$$I_d(V_g) = I_{FB} + \frac{I_{FB}}{d_s} \cdot \left(\frac{k_s \cdot \varepsilon_o}{e}\right)^{0.5} \cdot \int_0^{y_s(V_F)} \frac{\exp[(\beta - A) \cdot y] - 1}{\sqrt{2 \cdot \int_0^{y} n(y')dy'}} dy$$

where $y_s(V_F)$ is the band-bending at the semiconductor/insulator interface, and is related to measured $Id(V_F)$ by:

$$\exp[(\beta - A) \cdot y_S(V_F)] - (\beta - A) \cdot y_S(V_F) - 1 = \frac{\beta - A}{I_{FB}} \cdot \frac{d_s}{d_{ins}} \cdot \frac{k_{ins}}{k_s} \cdot [V_F \cdot I_d(V_F) - \int_0^{V_F} I_d(V_F')dV_F']$$

We then can calculate the charge density $n(y_s)$ from:

$$n(y_S) = \frac{k_{ins} \cdot \varepsilon_o}{e \cdot d_{ins} \cdot d_s} \cdot \frac{I_{FB} \cdot \{\exp[(\beta - A) \cdot y_S(V_F)] - 1\}}{dI_d(V_F)/dV_F}$$

Finally, the DOS function is obtained from $N(E) = |dn(y_s)/dy_s|_{ys = E}$. Here, we assume that most induced charge is localized and 0 K Fermi statistics is applicable for the occupancy of the localized states. Similar approach was used for a-Si:H TFTs [3]. It should be said that the calculation procedure described above requires knowledge of the flat band voltage (V_{FB}) and Meyer-Neldel parameter (A). Proper V_F and A values were obtained by matching the theoretically calculated Ea with the Ea extracted from temperature dependent field effect measurements. Calculated a-IGZO DOS from the subthreshold regime appears to be low ($<10^{18}$ $eV^{-1}cm^{-3}$) with a characteristic energy of about 110meV; similar value (125meV) was extracted from a-IGZO TFTs SPICE simulations [4]. We also calculated DOS from the on regime using A = 0 eV^{-1}. The DOS is larger and has a steeper slope with a characteristic energy of about 30meV. The influence of the free charge was not considered in this calculation at this time.

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[3] R.E.I. Schropp et al., J. Non-Cryst. Solids, 77&78, p. 511 (1985) [4] C. Chen at al. (unpublished results)

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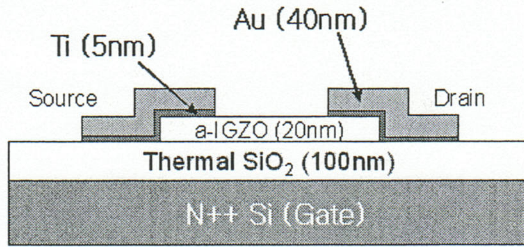


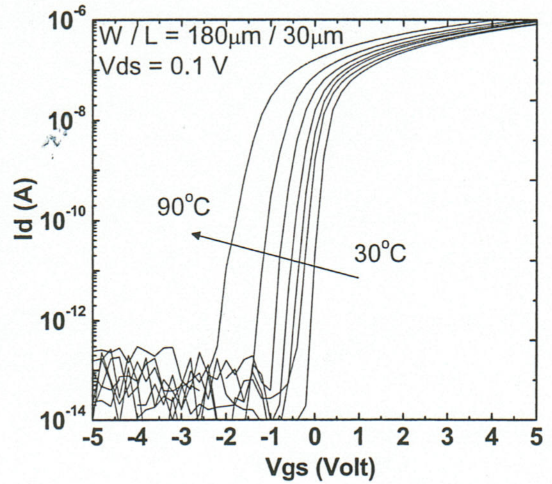
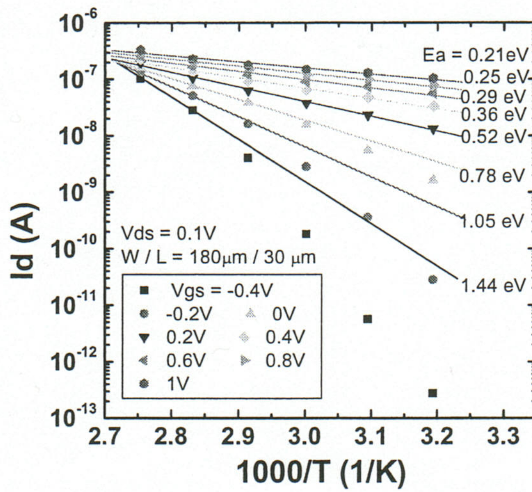


Fig. 1: Schematic cross section of an inverted -staggered RF sputter a-IGZO TFT measured in this study (top), and its transfer characteristics (I_D-V_{GS}) at different temperatures (right).



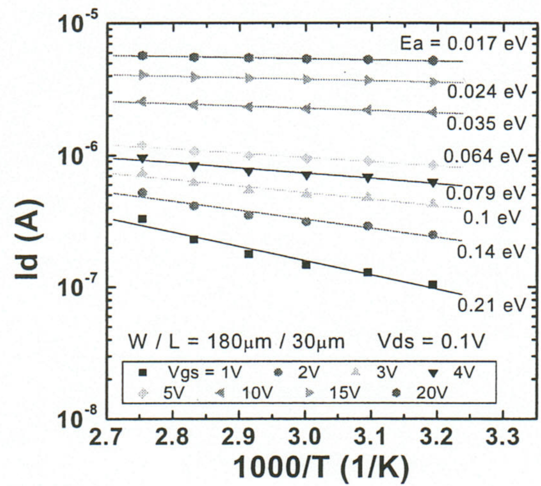
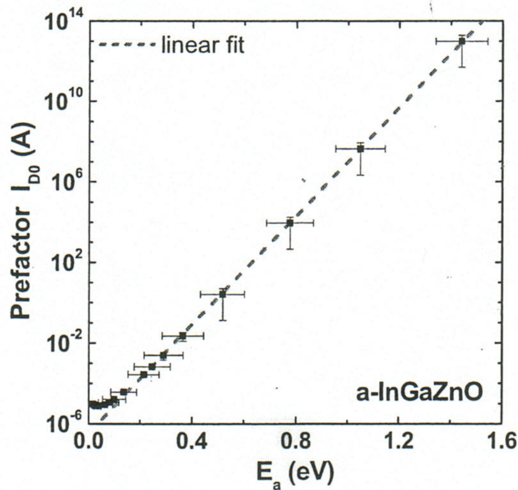


Fig. 2: Temperature dependence of the drain current in the subthreshold regime (Vgs < 1V) (left), and the on regime (Vgs > 1V) (right). Scatter dots represent the measured data; lines are used to extract Ea.



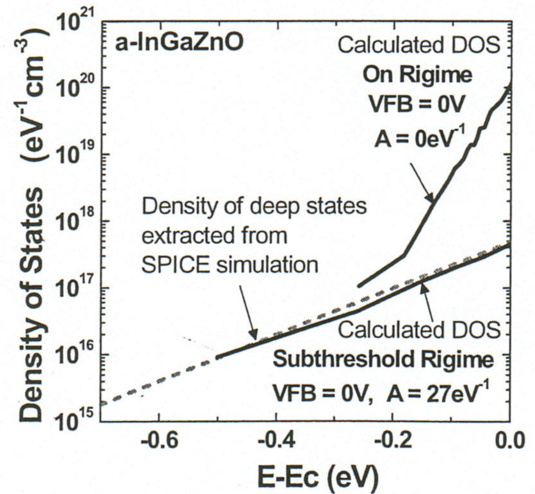


Fig. 3: Prefactor (I_{D0}) vs Activation energy (Ea) (left). Calculated Density of States as function of E-Ec (right).

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