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Carrier transport properties of solution processed ultra thin (4 nm) zinc-tin-oxide (ZTO) thin film transistor are investigated based on its transfer characteristics measured at the temperature ranging from 310 K to 77 K. As temperature decreases, the transfer curves show a parallel shift toward more positive voltages. The conduction mechanism of ultra-thin ZTO film and its connection to the density of band tail states have been substantiated by two approaches, including fitting logarithm to the transfer curves from 310 K to 77 K according to the two-dimensional Mott variable range hopping theory and the extraction of density of localized tail states through the energy distribution of trapped carrier density. The linear dependency of log \( I_D \) vs. \( T^{-1/3} \) indicates that the dominant carrier transport mechanism in ZTO is the variable range hopping. The extracted value of density of tail states at the conduction band minimum is \( 4.75 \times 10^{20} \) cm\(^{-3}\) eV\(^{-1}\) through the energy distribution of trapped carrier density. The high density of localized tail states in the ultra thin ZTO film is the key factor leading to the room-temperature hopping transport of carriers among localized tail states. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4973992]

Amorphous oxide semiconductor (AOS) thin film transistors (TFTs) have been extensively researched due to their advantages such as high optical transparency, relatively high electron mobility, and low temperature processing techniques so that AOS could be used as transparent and flexible backplanes. As well-known, the disordered amorphous semiconductors have a high density of states (DOS) that exist within the energy band gap, which will strongly affect the charge transport properties and mobility. Several groups have studied the carrier transport properties in indium gallium zinc oxide (IGZO) at room temperature, is dominated by trap-limited conduction as well as percolation, which are both band like transport above the mobility edges. At low temperatures, electrons are constrained to the localized states around the Fermi level \(( E_F) \) but cannot excite electrons to conduction band owing to low thermal energy. Consequently, electrons must hop among the localized states around \( E_F \) and the charge transport mechanism is variable range hopping (VRH). In recent years, advanced AOS TFT devices pursue thinner active layer thickness, which is representative of the electron transport in two-dimensional systems, and the band tail states in AOS will be more significant. Considering a disordered material with very thin thickness and high density of localized states, carriers may be conducted through the localized states. Consequently, the carrier transport process in AOS TFTs becomes complex and is worthy of in-deep investigation.

In this work, zinc-tin oxide (ZTO) is chosen as the TFT active layer owing to its low-cost competency as compared with IGZO. ZTO is deposited by a solution process to form a uniform and ultra-thin active layer. We have combined two approaches to resolve the conduction mechanism of ultra-thin ZTO film and its connection to the density of band tail states. First, it is demonstrated that the hopping conduction mechanism is dominant for carrier transport in ultra-thin ZTO TFT by the linear dependency of log \( I_D \) vs. \( T^{-1/3} \) over a temperature range \(( T = 310–77 \text{ K})\). Furthermore, based on the temperature-dependent measurement, the hopping density of localized states \( (\text{i.e., the density of band tail states}) \) is derived through two-dimensional Mott VRH theory. For the second approach, we calculated the density of trapped carriers as a function of the surface potential \((E_F-E_C)\) based on the charge induction by band bending at \( T = 310 \text{ K} \), and it can be used to extract the density of localized tail states. Our result suggests that the variable range hopping mechanism dominates the charge transport in solution process ZTO TFT from 77 K to room temperature.

A bottom gate TFT stack was fabricated on the p-Si substrate (as gate electrode) covered with a 100 nm-thick \( \text{SiO}_2 \) layer (as gate dielectric). The ZTO active layer was prepared by a solution process with tin chloride and zinc acetate precursors \( (\text{molar ratio of Zn:Sn = 1:1}) \) in the solvent of ethylene glycol monomethyl ether as described in Ref. 8. The ZTO precursor solution was spin-coated on the \( \text{SiO}_2/\text{Si} \) substrate and annealed in air at 500°C to form ZTO active layer with a thickness of 4 nm. A 300 nm-thick Al was deposited by e-beam evaporation through a shadow mask to define the source/drain electrodes as well as the channel width \((2000 \mu m)\) and length \((100 \mu m)\). High-resolution transmission electron microscopy (HRTEM) images were obtained by using a JEM 2100F field-emission transmission electron microscope.
electron microscope, and TEM samples were prepared by a focus ion beam system (SII SMI 3050). The TFT transfer curves (drain current ($I_D$) vs. gate voltage ($V_G$)) were measured by using Agilent B1500 A semiconductor parameter analyzer in a cryogenic probe station (Lakeshore TTPX) under the vacuum ambient with the temperature ranging between 77 K and 310 K.

Fig. 1 shows the cross-sectional TEM micrograph of solution processed ZTO film. Note that the TEM specimen was prepared by spin-coating the ZTO precursor solution onto a thin 10 nm SiO$_2$ grown on Si substrate and covered with an Al protection layer. As measured from the micrograph, the thickness of ZTO film is about 4 nm and the image contrast suggests that ZTO is amorphous-like. In addition, the grazing incidence X-ray diffraction data for 4 nm ZTO film do not show diffraction peak at two-theta angles of 20°–80°, indicating that the solution processed ZTO thin film is essentially amorphous (see Section S1 in supplementary material). The thin ZTO and long channel length (100 µm) possibly leads to a relatively high channel resistance as compared to the contact resistance (the Al/ZTO junction is an Ohmic contact according to their work function difference, see Section S2 in supplementary material). Therefore, the channel resistance shall be dominant in our electrical analysis, and the influence of contact resistance may be ignored.

To determine the conduction mechanism of the ZTO active layer, the drain current of ZTO TFT measured at 310 K to 77 K is analyzed. Fig. 2(a) shows the hysteresis $I_D$-$V_G$ curves of the ZTO TFT measured at 310 K and 77 K. The device was characterized in high vacuum ($3 \times 10^{-3}$ Torr) in order to avoid any influences in the atmosphere. The clockwise hysteresis $I_D$-$V_G$ curve is obtained by sweeping $V_G$ in the forward ($-20 \text{ V}$ to $+40 \text{ V}$)-to-reverse ($+40 \text{ V}$ to $-20 \text{ V}$) voltage direction. The hysteresis window is very small ($<1 \text{ V}$), which suggests no interface trap states between SiO$_2$ and ZTO. In addition, the narrow hysteresis window indicates that the $V_G$ sweep range will not influence the TFT operation process. Fig. 2(b) shows the $I_D$-$V_G$ curves of the ZTO TFT under operating temperatures from 310 K to 77 K. The threshold voltages are shifted to more positive values with decreasing operating temperature while the electron mobility decreases slightly (see Sec. S3 in supplementary material). It can be explained by the reduction of thermally excited carriers at lower temperatures. Consequently, the threshold voltage needed for carrier accumulation in the ZTO active layer at low temperature increases.

In two-dimensional (2D) systems, the temperature dependence of the 2D VRH conduction by Mott is given by

$$I_D = I_{D0} \exp \left( -\frac{B}{T^{1/3}} \right),$$

where $I_{D0}$ is the drain current prefactor, and $B$ is a material constant (see discussion later). Figs. 3(a) and 3(b) depict the log $I_D$ vs. $T^{-1/3}$ curves at the above-threshold ($V_G$ above $V_{TH} = -1.35 \text{ V}$) and sub-threshold ($V_G = -10.72 \text{ V}$ to $-1.35 \text{ V}$) regions of ZTO TFT, respectively. All log $I_D$ vs. $T^{-1/3}$ curves exhibit a linear dependency, indicating that the variable range hopping should be the dominant electrical transport mechanism in ZTO for both above-threshold and sub-threshold regions.

The transport mechanisms of channel electrons are discussed based on the distribution of conducting carriers within the energy band gap of ZTO. From the distribution of conducting carriers, we can further determine the density of tail states. The carrier concentration in ZTO semiconductor can be calculated by following Lee and Nathan’s derivation. As a first step, the conduction carrier density ($n_{\text{cond}}$) in ZTO TFT should be defined. The conduction carrier density as a function of gate voltage ($n_{\text{cond}}(V_G)$) is extracted from the measured $I_D$-$V_D$ characteristics

$$n_{\text{cond}}(V_G) = \frac{1}{\varepsilon_S k T} \left( \frac{L I_D(V_G)}{n W V_D} \right)^2,$$

where $\mu$ is the mobility of the ZTO layer, $\varepsilon_S$ the permittivity of semiconductor (the $\varepsilon_S$ of a-IGZO is put in since $\varepsilon_S$ of ZTO is not available), $k$ is the Boltzmann constant, $T$ is the
absolute temperature, W and L are the channel width and the channel length, \( I_D(V_G) \) is the drain at given \( V_G \), and \( V_D \) is the drain voltage. Next, the \( V_G \) and \( E_F \) (the Fermi level of ZTO) can be a correlation by a mapping function \(^{13,14}\)

\[
E_F - E_C = 2kT \ln \left( \frac{I_D(V_G)}{\sqrt{N_{ES}kT \mu(W/L)V_D}} \right),
\]

(3)

where \( E_C \) is the conduction band minimum at ZTO/dielectrics interface, \( N_C \) is the effective density of states for free carriers which is about \( 5 \times 10^{18} \text{ cm}^{-3} \). Based on these parameters and Equation (3), we analytically compute the correspondence of \( V_G \) with \( E_F - E_C \) of ZTO TFT at off-state, sub-threshold, and above-threshold at 310 K, where the lowest \( E_F - E_C \) point represents the TFT in the flat band condition (see Section S4 in supplementary material). Since the minimum \( E_F - E_C \) is \(-0.88 \text{ eV}\), it indicates that the Fermi level lies 0.88 eV below the conduction band minimum.

Next, we should define the density of trapped carriers (\( n_{\text{trap}} \)) at localized states. The \( n_{\text{trap}} \) and \( n_{\text{cond}} \) can be related to the electric potential of the semiconductor (i.e., the channel), which can be derived with Poisson’s equation \(^{13,14}\)

\[
\frac{d^2 \varphi}{dx^2} = \frac{q}{\varepsilon_S} \left( n_{\text{cond}} + n_{\text{trap}} \right),
\]

(4)

\[
E = -\frac{d\varphi}{dx},
\]

(5)

where \( x \) is the distance from the semiconductor/dielectric interface along the channel depth, and \( \varphi \) is the semiconductor potential along \( x \), \( E \) is the electric field. The carrier densities can be connected to gate voltage using a charge balance equation:

\[
Q_{\text{ind}} = C_{OX}(V_G - V_{TH}).
\]

Here, \( Q_{\text{ind}} \) is the total induced charge density at semiconductor/dielectric interface; \( C_{OX} \) is the gate-insulator capacitance, where \( V_{TH} \) is a threshold voltage. This yields the following:\(^{13,14}\)

\[
E(x = 0) = \sqrt{\frac{2q}{\varepsilon_S} \int_0^{\varphi_S} (n_{\text{cond}} + n_{\text{trap}})d\varphi} \approx \frac{C_{OX}(V_G - V_{TH})}{\varepsilon_S}.
\]

(6)

Squaring Equation (6) and taking its first derivative with respect to the surface potential \( \varphi(x = 0) = \varphi_S \), and \( q\varphi_S = E_F - E_{\text{Eb}} \), where \( E_F \) is the Fermi level position at surface, \( E_{\text{Eb}} \) is an equilibrium Fermi level. Therefore, \( n_{\text{trap}} \) can be computed as:\(^{13,14}\)

\[
n_{\text{trap}} = \frac{\varepsilon_S}{2q} \frac{dE^2}{d\varphi} - n_{\text{cond}}.
\]

(7)

Fig. 4 exhibits the density of the conduction carriers and density of the trapped carriers as a function of \( E_F - E_C \) at the ZTO/dielectrics interface. The band gap of ZTO is 3.7 eV, as evaluated from the absorption edge of the UV-Vis spectrum (see Sec. S5 in supplementary material). The carrier densities are extracted from the transfer curve measured at \( T = 310 \text{ K} \).

From Equation (3), we have realized that the \( E_C - E_F \) is determined from the magnitude of the gate bias, which indicates the extent of band bending. According to Fig. 4, density of the trap carriers is higher than the conduction carrier density, suggesting that huge localized tail states below \( E_C \) and the only few electrons could be excited by thermal energy to the upper conduction band minimum. \(^{13}\)

Based on Equations (6) and (7), the density of localized tail states (\( N_{\text{tail,trap}}(E) \)) can be given as Equation (8)\(^{13,14}\)

\[
N_{\text{tail,trap}}(E) = \frac{dn_{\text{trap}}}{dq},
\]

(8)

Fig. 5 shows the distribution of the density of localized tail states vs. \( E - E_C \), in which the solid square curve is derived from Equation (8). By fitting \( N_{\text{tail,trap}}(E) \) to an exponential function of \( E - E_C \), the tail state density at conduction band minimum, \( N_{\text{tc,trap}} \), is retrieved, which follows:\(^{13,14}\)

\[
N_{\text{tail}}(E) = N_{\varepsilon} \exp \left( \frac{E - E_C}{kT_t} \right),
\]

(9)

where \( kT_t \) is the characteristic tail state energy. In this work, the retrieved values of \( N_{\text{tc,trap}} \) and \( kT_t \) are \( 4.75 \times 10^{20} \text{ cm}^{-3} \text{ eV}^{-1} \) and 78.8 meV, respectively, for ZTO TFT. In particular, the extracted \( kT_t \) is much higher than the \( kT \) (25.9 mV) at 310 K; therefore, the free carrier becomes negligible.\(^{14}\)
From the above analyses, we can find out that at the ZTO/dielectric interface, trapped carriers occupy the localized tail states below the Fermi level at $T = 310 K$. This implies the good opportunity of carriers transport through unoccupied localized tail states above the Fermi level. This result echoes the linear dependency of $\log I_D$ vs. $T^{-1/3}$ curves, indicating that the variable range hopping should be the dominant electrical transport mechanism in ZTO. The slope of $\log I_D$ vs. $T^{-1/3}$ curve is related to the constant $B$ in Equation (1), and $B$ is given by \[ B = \left( \frac{2 \alpha^2}{k N_{\text{tail}} \text{VRH}(E)} \right)^{1/3}, \] where $\alpha$ is the inverse of the Bohr radius ($a$), $k$ is the Boltzmann’s constant, and $N_{\text{tail}} \text{VRH}(E)$ is the density of localized tail states. The Bohr radius ($a$) is calculated from: \[ a = \frac{\hbar^2}{m_e e^2}, \] where $\hbar$ is the Bohr radius of hydrogen atom (0.53 Å), $e$ is the permittivity of semiconductor, $m_e^*$ is the electron effective mass ($m_e^* = 0.34 m_0$, which is the value for a-IGZO), and $m_0$ is the free electron mass. Fig. 5 also shows the distribution of the localized tail states extracted from the Mott VRH theory, $N_{\text{tail}} \text{VRH}(E)$, in the solid circle curve. The $N_{\text{tail}} \text{VRH}(E)$ can also be fitted to Equation (9), yielding $N_{\text{VRH}}$ and $kT_1$, are $2.9 \times 10^{18} \text{cm}^{-3} \text{eV}^{-1}$ and 84.6 meV, respectively. In the basic device theory, the transistor’s operation is based on the accumulation of electrons at the oxide-semiconductor interface. The high $N_{\text{VRH}}$ value leads to hopping conduction of electrons in two dimensional accumulation channel.

In a study on different types of transport mechanisms in IGZO layers, the authors demonstrated the contribution of the VRH conduction that becomes greater than band-like conduction if the Fermi level $E_F$ lies within the exponential tail states with a characteristic temperature $T_e$ around 800 K (equivalent to $kT_2 = 69$ meV) and a tail state density at conduction band minimum in the order of $3.4 \times 10^{19} \text{cm}^{-3} \text{eV}^{-1}$. Our extracting values of $N_{\text{VRH}}$ and $T_e$ are higher than the numbers reported in the previous study. Therefore, in our case, VRH mechanism seems to be the predominant mechanism in ZTO. This result is confirmed by the linear dependence of the logarithm of $I_D$ vs. $T^{-1/3}$ observed in Fig. 3. In this work, the ZTO thin film is coated by a solution processed ZTO thin film, which is also evidenced by the inferior charge-carrier mobility as compared to crystalline semiconductors.

See supplementary material for discussion of contact resistance, ZTO band gap, and additional data analysis.

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