Characterization of Free Electron-Deembedded Subgab Density-of-States in a-IGZO TFTs from the Sub-Bandgap Optical Subthreshold Characteristics

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Abstract

An optical differential ideality factor technique (ODIFT) is proposed for extraction of free electron-compensated subgap (E_V<E<E_C) density-of-states (DOS) over the bandgap in amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs). In the technique, the differential ideality factors $d\eta(V_{GS})/dV_{GS}$ under dark and photo-illumination under subthreshold bias (V_{GS}<V_T) is combined with the sub-bandgap photons ($h\nu$<E_g) to confine photonic excitation of electrons only from the subgap localized states over the bandgap in a-IGZO TFTs. We applied the ODIFT to a-IGZO TFTs with $W\times L$=50×25 μm^2 and extracted the energy distribution of DOS for the localized states over the bandgap.

1. Introduction

Extraction of the subgap density of states (DOS) $g(E)$ over the bandgap (E_V<E<E_C) in amorphous semiconductors is very important in the characterization and modeling of TFTs [1,2] by using capacitance-voltage (C-V), current-voltage (I-V), and other techniques [3,4,5]. They require complicated calculations or cause a drift of inherent properties by the thermal and/or electrical stress during characterization [6].

In this letter, we report an optical differential ideality factor technique (ODIFT) for extraction of $g(E)$ by employing the differential ideality factor $d\eta(V_{GS})/dV_{GS}$ under sub-bandgap optical illumination with photon energy less than the energy bandgap(E_{ph}=$h\nu$<E_g). By employing differential ideality factors under dark and under sub-bandgap photonic excitation, the intrinsic DOS for the localized states is fully separated from the contribution of free electrons especially for the gate bias close to the threshold voltage (V_T).

2. Device fabrication

The fabrication procedure for the a-IGZO TFTs is as follows: On a glass substrate, the first sputtered deposition at RT and patterning of the Mo gate are followed by PECVD of SiN_x and SiO_2 at 370 ℃ as a gate dielectric thickness (T_{ox} = 258 nm). The a-IGZO layer (T_{IGZO} = 50 nm) is sputtered at RT in a mixed atmosphere of Ar/O_2 and wet etched with a diluted HF. An etch stopper SiO_x layer is deposited by PECVD at 150 ℃ and patterned by wet etching. For the formation of the source/drain (S/D) electrodes, Mo is sputtered at RT and patterned by dry etching. A passivation layer (SiO_x and SiN_x ; thickness = 100 nm each) is followed by deposition, and finally, the devices are annealed at 250 ℃ for 1 hr in the furnace. The employed a-IGZO TFTs has W = 50 μm, L = 25 μm and L_{ov} = 10 μm.

3. Results and Discussion

In order to extract the distribution of DOS $g(E)$, ODIFT employs the differential of the difference in the ideality factor under dark and sub-bandgap photo-illuminated condition based on the subthreshold drain ($I_{D,sub}$) under the gate bias V_{on}<V_{GS}<V_T is described [7] by

$$I_{D,sub} \cong \mu_{eff} C_{ox}\left(\frac{W}{L}\right)(\eta-1)V_{th}^{2}\exp\left(\frac{V_{GS}-V_T}{\eta V_{th}}\right) \tag{1}$$

with V_{on} as the turn-on voltage, V_T as the threshold voltage, η as the ideality factor, and V_{th} as the thermal voltage, μ_{eff} as the effective mobility, C_{ox}(=ε_{ox}/T_{ox}) as the oxide capacitance per unit area, and W/L as the gate width/length ratio.

In a-IGZO TFTs, the total substrate capacitance (C_S) in the active channel region consists of the capacitance (C_{FREE}) for free electrons in the conduction band, the DOS-induced capacitance (C_{LOC}) for the localized electrons in the subgap states (including both interface and bulk traps), and the photo-induced capacitance ($C_{LOC,ph}$) for the photo-generated electrons pumped from the sub-bandgap photo-responsive energy range in the bandgap as shown in Fig. 1(b).

We note that previous method [8] are does not consider the free electron-induced capacitance (C_{FREE}) in subthreshold region (V_{GS} < V_T). Therefore, we now propose the ODIFT, which employs sub-bandgap photons combined with differential ideality factor for separate extraction of the subgap DOS $g(E)$ excluding the contribution from free electrons in a-IGZO TFTs. We note that the ideality factor $\eta(V_{GS})$ is described by [7]

$$\eta_{dark}(V_{GS}) = 1+\frac{C_{LOC}(V_{GS})+C_{FREE}(V_{GS})}{C_{ox}} \tag{2}$$

$$\eta_{ph}(V_{GS}) = 1+\frac{C_{LOC}(V_{GS})+C_{FREE}(V_{GS})}{C_{ox}}+\frac{C_{LOC,ph}(V_{GS})}{C_{ox}}. \tag{3}$$

V_T-independent but V_{GS}-dependent ideality factor $\eta(V_{GS})$ can be experimentally obtained from the subthreshold drain current of a-IGZO TFTs through

$$\eta(V_{GS}) = \left(\frac{(V_{GS}+\Delta V_{GS})-V_{GS}}{V_{th}}\right)\Bigg/\ln\left(\frac{I_{D,sub}(V_{GS}+\Delta V_{GS})}{I_{D,sub}(V_{GS})}\right). \tag{4}$$

For the ODIFT, we employ V_T-independent but V_{GS}-dependent differential ideality factor ($d\eta(V_{GS})/d(V_{GS})$) from experimental data [8]. The subgap DOS-induced capacitance $C_{LOC}(V_{GS})$, governed by V_{GS}-dependent localized charges $Q_{LOC}(V_{GS})$, is described by

$$\frac{d(\eta_{ph}(V_{GS})-\eta_{dark}(V_{GS}))}{dV_{GS}}=\frac{1}{C_{ox}}\left(\frac{dC_{LOC,ph}(V_{GS})}{d\psi_S}\cdot\frac{d\psi_S}{dV_{GS}}\right)[\mathrm{V}^{-1}] \tag{5}$$

$$\frac{dC_{LOC,ph}(V_{GS})}{d\psi_S}=C_{ox}\frac{d(\eta_{ph}(V_{GS})-\eta_{dark}(V_{GS}))}{dV_{GS}}\Bigg/\frac{d\psi_S}{dV_{GS}}\ [\mathrm{F/V\cdot cm^2}] \tag{6}$$

$$C_{LOC,ph}(V_{GS})=C_{ox}\int_{\psi_S(V_{GS}=V_{on})}^{\psi_S(V_{GS})}\frac{d(\eta_{ph}(V_{GS})-\eta_{dark}(V_{GS}))}{dV_{GS}}\Bigg/\frac{d\psi_S}{dV_{GS}}\,d\psi_S\ [\mathrm{F/cm^2}]. \tag{7}$$

For a non-linear mapping of the gate voltage to the energy level over the bandgap, the surface potential ψ_S is converted from the experimental C_G-V_{GS} characteristics through [3,4] and $g(E)$ can be extracted

$$\psi_S(V_{GS})=\int_{V_{FB}}^{V_{GS}}\left(1-\frac{C_G(V_{GS})}{C_{ox}\cdot W\cdot L}\right)dV_{GS}\ [\mathrm{V}] \tag{8}$$

$$g(E)=\frac{\Delta C_{LOC}(V_{GS})}{q^2T_{IGZO}}\ [\mathrm{eV^{-1}cm^{-3}}]. \tag{9}$$

The optical source (red, green) is guided over the a-IGZO active layer of the device under characterization through a multimode fiber with a diameter=50 μm and photon energy ($E_{ph,R} = 1.89$, $E_{ph,G} = 2.33$ eV < $E_{g,IGZO} = 3.2$ eV, and maximum optical power $P_{opt,R} = 9$ mW, $P_{opt,G} = 12$ mW).

Fig. 2(a) shows V_T shift and increased drain current under sub-bandgap photo-illumination compared with dark condition and Fig. 2(b) comparatively shows the I_D-V_{GS} under photo-illumination with I_D-V_{GS} and C_G-V_{GS} characteristics at f=10 kHz under dark. V_{GS}-dependent experimental ideality factors ($\eta_{dark}(V_{GS})$ under dark and $\eta_{ph}(V_{GS})$ under sub-bandgap photo-illumination) are shown in Fig. 3(a) and extracted subgap DOS $g(E)$ over the photo-responsive range in the bandgap through the proposed ODIFT is shown in Fig. 3(b) for a-IGZO TFTs. Extracted subgap DOS through the ODIFT with red and green lights are comparatively shown. $g(E)$ from the ODIFT are also compared with those from the multi-frequency C-V method (MFM) [4] and DIFT [8].

4. Summary

We proposed the optical differential ideality factor technique for extraction of subgap DOS $g(E)$ in a-IGZO TFTs. By combining the differential ideality factors under dark and sub-bandgap optical illumination, any possible contribution from free carriers in the conduction band is completely removed. The proposed ODIFT is confirmed by applition to a-IGZO TFTs with $W\times L=50\times 25\ \mu\mathrm{m}^2$ and extracted the energy distribution of DOS over the bandgap. We note that the ODIFT is advantageous over the C-V techniques for TFTs with small geometrical size suppressing any contribution from the overlapped regions.

References

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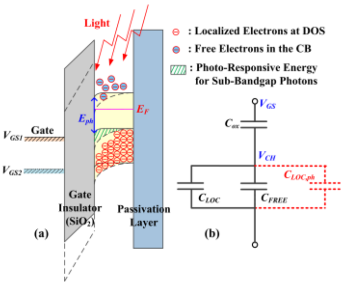

Fig. 1. (a) Energy band diagram for extraction of subgap DOS $g(E)$ in a-IGZO. (b) Capacitance model for the a-IGZO TFT in the subthreshold region.

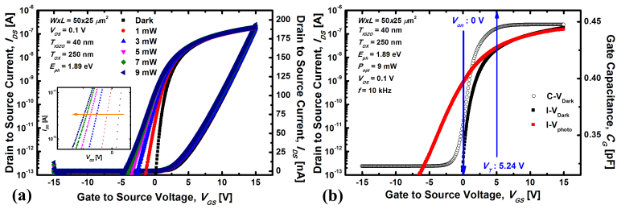

Fig. 2. (a) Optical power(P_{opt})-dependent I_D-V_{GS} characteristics a-IGZO TFTs. (b) Optically saturated I_D-V_{GS} curves under photo-illumination compared with I_D-V_{GS} under dark and C_G-V_{GS} characteristics at f = 10 kHz under dark.

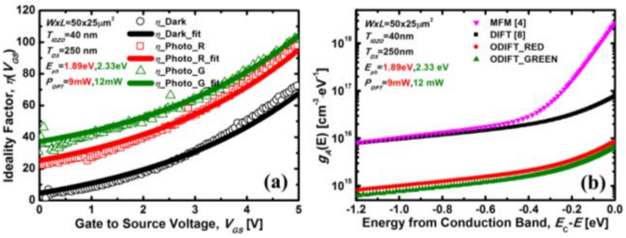

Fig. 3. (a) V_{GS}-dependent ideality factors under dark $\eta_{dark}(V_{GS})$ and photo-illuminated $\eta_{ph}(V_{GS})$. (b) Subgap DOS $g(E)$ extracted through the ODIFT are compared with those from the DIFT and MFM for the same device on the wafer.