Monochromatic Photonic Capacitance-Voltage Technique for Donor- and Acceptor-Like Density-of-States over the Full-Energy Range in Amorphous TFTs

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Abstract

We report a novel technique for extraction of subgap donor and acceptor density-of-states (DOS) over the full energy range \((E_g < E < E_F)\) by using monochromatic photonic capacitance-voltage (MPCV) technique in n-channel a-IGZO TFTs. In the proposed method, we extract donor- and acceptor-like states \((g_D(E) \text{ and } g_A(E))\) as the subgap DOS under depletion \((V_{GS} < V_{TH})\) and accumulation \((V_{GS} > V_{TH})\) bias by employing a sub-bandgap optical source. We obtained \(g_D(E)\) and \(g_A(E)\) over the full energy range as a superposition of the exponential deep and tail states as well as shallow donor states with \(N_{DD} = 8.0 \times 10^{11} \text{ [eV}^{-1}\text{cm}^{-3}]\), \(kT_D = 0.16 \text{ [eV]}\), \(N_{TD} = 5.0 \times 10^{17} \text{ [eV}^{-1}\text{cm}^{-3}]\), \(kT_D = 0.47 \text{ [eV]}\), and \(N_{SD} = 1.5 \times 10^{17} \text{ [eV}^{-1}\text{cm}^{-3}]\), \(kT_S = 0.16 \text{ [eV]}\).

I. Introduction

Amorphous Indium-Gallium-Zinc-Oxide (a-IGZO) thin film transistors (TFTs) are known to be prospective devices for possible application to active-matrix organic light-emitting diode displays (AMOLEDs) and flexible displays due to low temperature, large uniformity, and high carrier mobility [1]. Among electrical properties, experimental modeling and characterization of the subgap density-of-states (DOS) is important to estimate the reliability and stability caused by the fabrication process, layout, and long-term performance associated with robust circuits and systems. There have been works on the analysis and extraction of subgap DOS in a-IGZO TFTs [2-3]. Especially, a qualitative analysis of the subgap DOS for instability under the negative/positive bias illumination stress (N/PBIS) has become a significant issue [4-5].

In this work, we report a technique for extraction of the full-energy range subgap DOS \((g_D(E) \text{ and } g_A(E))\) by using a capacitance-voltage data under dark and photonic states with subgap optical source \(h \nu = E_g \approx 2.6 \text{ eV} \approx E_F\) as a monochromatic photonic capacitance-voltage (MPCV) technique. Through the proposed technique, it is possible to extract the full range subgap DOS over the bandgap in the active amorphous semiconductor layer. Using only one-shot C-V measurement as a function of the gate bias \((V_{GS})\), the subgap DOS can be characterized for the dependence on material, fabrication process, and electrical stress of the active layer. We expect that the proposed method is a powerful tool for characterization of amorphous active layers in TFTs without iteration procedure and/ or complicated calculation.

II. Characterization of \(g_D(E)\) and \(g_A(E)\) over the Bandgap

Fig. 1 shows cross-sectional view and setup for the C-V measurement of n-channel a-IGZO TFTs with an inverted staggered bottom gate. Capacitive equivalent circuit with photo-responsive capacitance \((C_{photo}^D) \text{ and } C_{photo}^A)\) are include for the carriers generated from the localized traps in the amorphous active layer. In Fig. 1(a), negative/positive bias illumination stress \((V_{GS} < V_{TH})\) and \((V_{GS} > V_{TH})\) under photonic state.

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Fig. 1 shows cross-sectional view and setup for the C-V measurement of n-channel a-IGZO TFTs with an inverted staggered bottom gate. Capacitive equivalent circuit with photo-responsive capacitance \((C_{photo}^D) \text{ and } C_{photo}^A)\) are include for the carriers generated from the localized traps in the amorphous active layer. In Fig. 1(a), negative/positive bias illumination stress \((V_{GS} < V_{TH})\) and \((V_{GS} > V_{TH})\) under photonic state.
In order to obtain $g_{d}(E)$ at a specific energy level, the extracted $AC_{\text{ph},D}$ for a differential $V_{GS}$ (or $\phi_{g}$) from experimental C-V data is obtained from

$$AC_{\text{ph},D} = \frac{C_{GS}(V_{GS}) - C_{D}(V_{GS})}{W \times L_{\text{GD}}} \left[ \text{F} \cdot \text{cm}^{-1} \right].$$

Finally, we extract $g_{d}(E)$ through

$$g_{d}(E) = \frac{2eC}{q} \left[ \text{eV}^{-1} \cdot \text{cm} \right] \left( E_{c} - E_{v} \right), \quad E_{v} < E < E_{c}.$$  \hspace{1cm} (6)

We also note that the photo-responsive charges generated from acceptor-like trap states ($g_{a,D}(E)$) in the energy range $((E_{c}-E_{\text{ph}}))$ are dominant in the accumulation region ($V_{GS}>V_{TA}$) as shown in Fig. 2(b). Therefore, dark and photonic C-V data can be modeled as

$$C_{\text{int}}(V_{GS}) = C_{GD} + C_{CS} + C_{DA}.$$  \hspace{1cm} (7)

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with the additional capacitance $C_{\text{ph},A}$ for the optically generated charges from localized traps over the energy ($E_{c}-E_{\text{ph}}$). Combining Eq.(7) with Eq.(8), $C_{\text{ph},A}$ [F] can be obtained through

$$C_{\text{ph},A}(V_{GS}) = \frac{1}{C_{GD} + C_{CS} + C_{DA} + C_{\text{ph},A}}.$$  \hspace{1cm} (10)

For the differential gate bias $AV_{GS}$ (or $\phi_{g}$) as a measurement step, we obtain $AC_{\text{ph},D}$ and $g_{a}(E)$ through

$$AC_{\text{ph},D} = \frac{C_{GS}(V_{GS}) - C_{D}(V_{GS})}{W \times L_{\text{GD}}} \left[ \text{F} \cdot \text{cm}^{-1} \right]$$

$$g_{a}(E) = \frac{2eC}{q} \left[ \text{eV}^{-1} \cdot \text{cm} \right] \left( E_{c} - E_{v} \right), \quad E_{v} < E < E_{c}.$$  \hspace{1cm} (11)

$$g_{a}(E) = \frac{2eC}{q} \left[ \text{eV}^{-1} \cdot \text{cm} \right] \left( E_{c} - E_{v} \right), \quad E_{v} < E < E_{c}.$$  \hspace{1cm} (12)

III. Experimental Results and Discussion

For the full-energy range subgap DOS by the proposed technique, we measured the capacitance between the gate and source/drain (connected) for n-channel TFTs with an inverted staggered bottom gate. It was measured by the HP4284A Precision LCR meter at f=40 kHz for a robust data. The TFT employed for the characterization has the gate dielectric (SiO$_{2}$) $T_{GD}$=200 nm, the active layer IGZO=50 nm, the gate length L=12 $\mu$m, the gate width W=24 $\mu$m, and the gate-to-S/D overlap length ($L_{\text{GD}}$)=4 $\mu$m. Fig. 3 shows that measured $C_{GD}$ characteristics under dark and sub-bandgap photonic states ($E_{ph}$= 2.6 eV).

We note that the overlap capacitance for the gate-source/drain metal contact region is eliminated and the threshold voltage shift caused by the photovoltaic effect under photonic C-V measurement is also compensated for the proposed technique [7]. Therefore, we can extract the intrinsic subgap DOS only for the active layer. For the energy distribution of $g_{d}(E)$ and $g_{a}(E)$, the nonlinear relation between the surface potential $\psi_{s}$ for the energy level can be obtained from the gate bias-dependent C-V data through

$$\psi_{s} = \frac{1}{C_{GS}} \left[ 1 + \frac{C_{GD}}{C_{GS}} \right] V_{GS}, \quad \psi_{s} = \frac{1}{C_{GS}} \left[ 1 + \frac{C_{GD}}{C_{GS}} \right] V_{GS} \left[ \text{eV} \right].$$

Fig. 4 shows extracted $g_{d}(E)$ and $g_{a}(E)$ from the MPCV can be modeled as a superposition of deep, tail, and shallow states in exponential relations as

$$g_{d}(E) = N_{\text{sh}} \times \exp \left[ \frac{E_{c} - E}{k_{B}T_{\text{sh}}} \right] + N_{\text{tail}} \times \exp \left[ \frac{E_{c} - E}{k_{B}T_{\text{tail}}} \right] + N_{\text{sh}} \times \exp \left[ \frac{E_{c} - E}{k_{B}T_{\text{sh}}} \right].$$

$$g_{a}(E) = N_{\text{sh}} \times \exp \left[ \frac{E_{c} - E}{k_{B}T_{\text{sh}}} \right] + N_{\text{tail}} \times \exp \left[ \frac{E_{c} - E}{k_{B}T_{\text{tail}}} \right] + N_{\text{sh}} \times \exp \left[ \frac{E_{c} - E}{k_{B}T_{\text{sh}}} \right].$$

We obtained characteristic parameters for $g_{d}(E)$ and $g_{a}(E)$ over the bandgap as $N_{\text{sh}}=1.0 \times 10^{17} \left[ \text{eV}^{-1} \cdot \text{cm}^{-1} \right], k_{B}T_{\text{sh}}=0.16 \left[ \text{eV} \right], N_{\text{sh}}=8.0 \times 10^{16} \left[ \text{eV}^{-1} \cdot \text{cm}^{-1} \right], k_{B}T_{\text{sh}}=0.47 \left[ \text{eV} \right], N_{\text{sh}}=5.0 \times 10^{17} \left[ \text{eV}^{-1} \cdot \text{cm}^{-1} \right], k_{B}T_{\text{sh}}=0.01 \left[ \text{eV} \right], N_{\text{sh}}=8.0 \times 10^{16} \left[ \text{eV}^{-1} \cdot \text{cm}^{-1} \right], k_{B}T_{\text{sh}}=0.15 \left[ \text{eV} \right], N_{\text{sh}}=1.5 \times 10^{17} \left[ \text{eV}^{-1} \cdot \text{cm}^{-1} \right], k_{B}T_{\text{sh}}=0.16 \left[ \text{eV} \right].$

IV. Conclusion

We reported MPCV technique for extraction of the subgap DOS over the full-energy range through the sub-bandgap photo-responsive C-V characteristics of n-channel a-IGZO TFTs. The extracted subgap DOS is fully separated into donor- and acceptor-like states ($g_{d}(E)$ and $g_{a}(E)$) by using one-shot C-V measurement. The proposed method can be a powerful tool for a robust characterization of structure-, process-, and stress-dependent variation of the subgap DOS in amorphous semiconductor TFTs without simulation and complicated equations.

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References