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Low-Frequency Noise in Amorphous Indium Zinc Oxide Thin Film Transistors with Aluminum Oxide Gate Insulator *

Ya-Yi Chen(陈雅怡)[1,2], Yuan Liu(刘远)[2**], Zhao-Hui Wu(吴朝晖)[1**], Li Wang(王黎)[1], Bin Li(李斌)[1], Yun-Fei En(恩云飞)[2], Yi-Qiang Chen(陈义强)[2]

[1]*School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510640*
[2]*Science and Technology on Reliability Physics and Application of Electronic Component Laboratory, China Electronic Produce Reliability and Environmental Testing Research Institute, Guangzhou 510610*

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Low-frequency noise (LFN) in all operation regions of amorphous indium zinc oxide (a-IZO) thin film transistors (TFTs) with an aluminum oxide gate insulator is investigated. Based on the LFN measured results, we extract the distribution of localized states in the band gap and the spatial distribution of border traps in the gate dielectric, and study the dependence of measured noise on the characteristic temperature of localized states for a-IZO TFTs with Al_2O_3 gate dielectric. Further study on the LFN measured results shows that the gate voltage dependent noise data closely obey the mobility fluctuation model, and the average Hooge's parameter is about 1.18×10^{-3}. Considering the relationship between the free carrier number and the field effect mobility, we simulate the LFN using the ΔN–$\Delta\mu$ model, and the total trap density near the IZO/oxide interface is about 1.23×10^{18} $cm^{-3}eV^{-1}$.

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Amorphous indium-zinc oxide thin film transistors (a-IZO TFTs) have drawn a great deal of interest owing to their excellent electrical characteristics and good stability. Therefore, the devices can be applied in next-generation displays and flexible integrated circuits.[1]

As the active switch devices are for addressing the panel electrode circuit, the low-frequency noise (LFN) is a key parameter, which sets the minimum level of signal detected and processes in the following circuit.[2] Therefore, the noise performances of a-IZO TFTs need to be analyzed and minimized carefully.

As a new material of gate dielectric, aluminum oxide (Al_2O_3) is excellent with a low leakage current and good compatibility with the transparent oxide semiconductor.[3] Thus it can improve the performance of the TFTs. LFN behaviors of IZO TFTs with the gate dielectric layers of SiO_2 and SiN_x have been reported by many groups.[4–6] However, few studies have discussed LFN characteristics in a-IZO TFTs with a gate oxide of Al_2O_3. As reported, the magnitude and main features of LFN may strongly depend on the quality of channel and gate insulator. Thus the LFN performance in devices with the Al_2O_3 gate dielectric should be investigated before it can be pushed into the custom market.

We measure and discuss the LFN in all operational regions of a-IZO TFTs with an Al_2O_3 gate insulator. Based on the LFN measured results, we especially focus on investigating the dependence of noise on the characteristic temperature of localized states and on extracting the total trap density near the IZO/Al_2O_3 interface, which are closely related to the I–V characteristics of a-IZO TFTs.

The devices under test are a-InZnO TFTs with a bottom gate structure.[3] The Al gate electrode layer in thickness of 300 nm was deposited on a glass substrate. A 140-nm-thick insulation of Al_2O_3 was anodized in the electrolyte consisting of ammonium tartrate solution and ethylene glycol. Then a 40-nm-thick IZO active layer was deposited on Al_2O_3. Finally, the Mo/ITO drain/source electrodes were sputtered on the active layer. The channel length L is 10 μm, and the widths W are 20 μm and 50 μm, respectively.

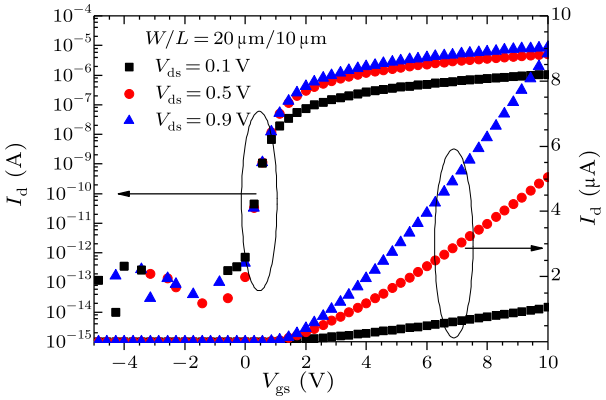

Fig. 1. Transfer characteristics in a-IZO TFTs.

The I–V characteristics of the devices were measured by an Agilent B1500. Low-frequency noises (LFN) were measured by a Keysight E4727A.

The transfer characteristics are shown in Fig. 1. The threshold voltage is extracted as 1.44 V, and the subthreshold swing is 0.19 V/dec. The effective-field

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**Corresponding author. Email: liuyuan@ceprei.com; phzhwu@scut.edu.cn

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mobility is calculated to be 21.94 cm^2/Vs.

The measured LFN characteristics of the a-IZO TFTs are presented in Fig. 2. According to Fig. 2, the drain-current noise power spectral density (S_{id}) follows a $1/f^{\gamma}$ rule with $\gamma = 0.95$, which illustrates that the flicker noise ($1/f$ noise) is the main component of LFN in a-IZO TFTs.[7] The deviation from $\gamma = 1$ reveals that the defect distribution is not uniform in the gate insulator,[8] and $\gamma < 1$ indicates that the density of defects is larger at the IZO/Al_2O_3 interface.[9] In addition, $\gamma < 1$ may also be related to the characteristic temperature of the tail states existing in the channel.

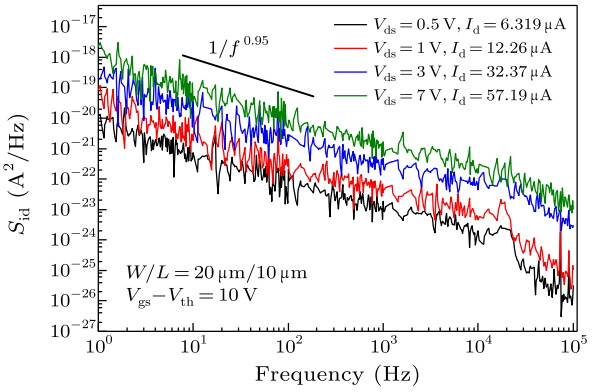

Fig. 2. Low-frequency noise in a-IZO TFTs.

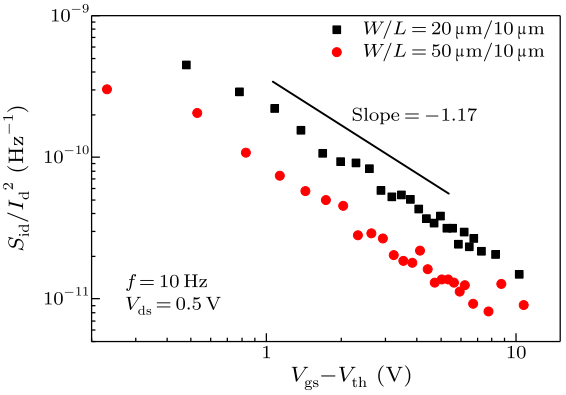

Fig. 3. The value of S_{id}/I_d^2 versus $V_{gs} - V_{th}$ in a-IZO TFTs.

To find the origin of $1/f$ noise, the dependence of the normalized noise power spectral density (S_{id}/I_d^2) on the effective gate voltage ($V_{gs} - V_{th}$) is plotted in Fig. 3 for two channel widths. The behaviors of the $1/f$ noise in the a-IZO TFTs can be explained by two models: the carrier number fluctuation (ΔN) model and the mobility fluctuation ($\Delta\mu$) model.[10,11] The $1/f$ noise is dominated by the ΔN theory if the slope of S_{id}/I_d^2 approaches -2, while it is dominated by the $\Delta\mu$ theory if the slope of S_{id}/I_d^2 approaches -1. The slope fitted in the low gate voltages is -1.17 in Fig. 3, which is close to the predictions of the mobility fluctuation theory.

In a-IZO TFTs, the effective mobility is related to the number of free carriers in the channel. Therefore, the fluctuation of effective mobility may be induced by the fluctuation of carriers numbers in the channel. Thus a carrier number fluctuation with correlated mobility fluctuation ($\Delta N - \Delta\mu$) model[12] is used to analyze the $1/f$ noise characteristics. As was reported, S_{id}/I_d^2 can be expressed as[12]

$$\frac{S_{id}}{I_d^2} = \left(1 \pm \alpha_c \mu_{eff} C_{ox} \frac{I_d}{g_m}\right)^2 \left(\frac{g_m}{I_d}\right)^2 S_{vfb}, \quad (1)$$

where α_c is the Coulomb scattering coefficient, g_m is the transconductance of the devices, and S_{vfb} is the flat-band voltage noise spectral density, which is related to the trap state density near the IZO/Al_2O_3 interface,

$$S_{vfb} = \frac{q^2 KT\lambda N_t}{WLC_{ox}^2 f^{\gamma}}, \quad (2)$$

where λ is the tunneling attenuation distance (about 0.11 nm in Al_2O_3), and N_t is the trap state density near the interface. The values of α_c and S_{vfb} can be extracted from the relationship between the gate voltage noise spectral density (S_{vg}) and the effective gate bias ($V_{gs} - V_{th}$), which can be expressed as[12]

$$S_{vg} = S_{vfb}[1 \pm \alpha_c \mu_{eff} C_{ox}(V_{gs} - V_{th})]^2. \quad (3)$$

The changes of S_{vg} versus $V_{gs} - V_{th}$ with two channel widths have been plotted in Fig. 4. As shown in Fig. 4, S_{vg} increases nonlinearly with $V_{gs} - V_{th}$ when V_{gs} is higher than V_{th}. However, S_{vg} is reduced when V_{gs} is below V_{th}, which may be induced by the exponential variation of free carriers with V_{gs} in the subthreshold region.[12]

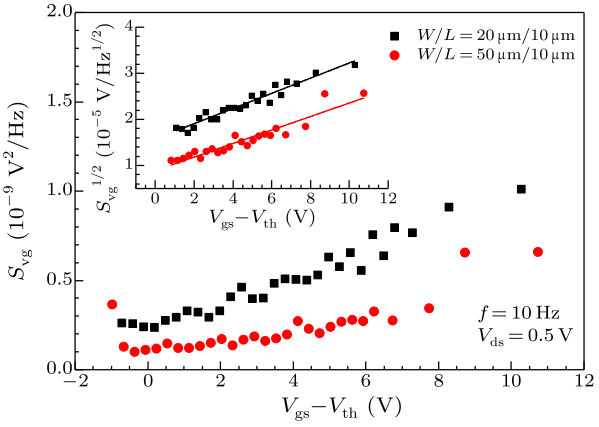

Fig. 4. The value of S_{vg} versus $V_{gs} - V_{th}$ in a-IZO TFTs.

The value of $S_{vg}^{1/2}$ versus $V_{gs} - V_{th}$ is also displayed in Fig. 4, from which α_c and S_{vfb} can be extracted. Here $\alpha_c \sim 1.31 \times 10^5$, and S_{vfb} are 2.8×10^{-10} and 1.3×10^{-10} of devices with 20 μm and 50 μm channel widths, respectively. The value of S_{vfb} is inversely proportional to WL, which is consistent with the prediction of Eq. (2).

The total trap state density N_t near the IZO/Al_2O_3 interface can be calculated by Eq. (2), and the values are about $1.23 \times 10^{18}\,\mathrm{cm^{-3}\cdot eV^{-1}}$ in these devices. Finally, the measured results and fitting results with the $\Delta N - \Delta\mu$ theory are plotted in Fig. 5. It presents that the measured results can be well modeled under low drain current intensities. The deviation of fitting results with measurements under high current intensities may be caused by the contact resistance.[13,14]

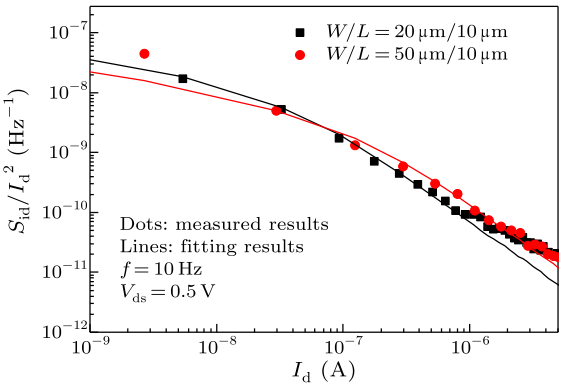

Fig. 5. The value of S_{id}/I_d^2 versus I_d in the linear region.

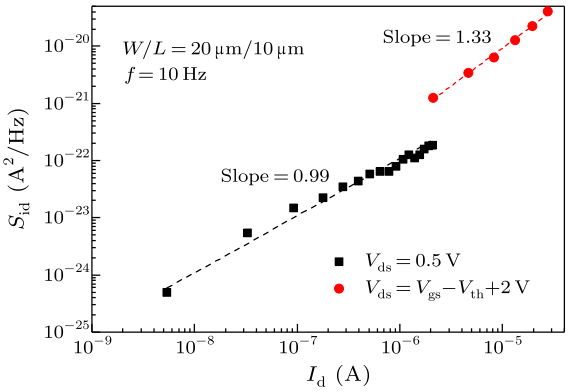

Fig. 6. The value of S_{id} versus I_d in all operation regions.

As reported in Ref. [15], $1/f$ noise may depend on the distribution of localized states in the channel. When the a-IZO TFTs are operated in the linear and saturation regions, the variations of S_{id} versus I_d are plotted in Fig. 6. As shown in Fig. 6, the slopes are 0.99 and 1.33 in linear and saturation regions, respectively.

As was reported, S_{id} in the linear and the saturation regions can be expressed as[15]

$$S_{id} = (1+\alpha)^2 M V_d^{\frac{2}{1+\alpha}} S_{vfb} I_d^{\frac{2\alpha}{1+\alpha}}, \tag{4}$$

$$S_{id} = (2+\alpha)^{\frac{2+2\alpha}{2+\alpha}} M^{\frac{2}{2+\alpha}} S_{vfb} I_d^{\frac{2+2\alpha}{2+\alpha}}, \tag{5}$$

where M and α are fitting parameters related to the localized states.[15] According to Eqs. (4) and (5), α is ~0.99 in both the regions. The value of α is a strong function of the characteristic temperature (T_t) in localized tail states, which can be expressed as $\alpha = 2T_t/T - 2$. The value of T_t is calculated to be 448.5 K.

In addition, the distribution of the localized states (N_T) in the band gap can also be extracted from the measurements of the $1/f$ noise by[16–18]

$$N_T(E) = \frac{4\lambda}{WLT_{ox}^2 KTf}\frac{I_d^2}{S_{id}}. \tag{6}$$

The surface potential $E - E_c$ with gate voltage V_{gs} can be extracted from the transfer characteristic curves,[19,20] and N_T versus S_{id}/I_d^2 can be obtained from Eq. (6). Thus the distribution of localized states ($N_T(E)$) along the band gap can be illustrated in Fig. 7. The localized states include tail and deep states, and both of them are exponentially distributed with $E - E_c$. Thus $N_T(E)$ can be expressed as

$$N_T(E) = N_{TT} \times \exp\left(\frac{E-E_c}{KT_{TT}}\right) + N_{TD} \times \exp\left(\frac{E-E_c}{KT_{TD}}\right), \tag{7}$$

where T_{TT} and T_{TD} are the characteristic temperatures of tail and deep states, while N_{TT} and N_{TD} are the density of tail and deep states at the conduction band edge, respectively. In the a-IZO TFTs, $T_{TT} = 250$ K, $N_{TT} = 8 \times 10^{21}\,\mathrm{cm^{-3}\,eV^{-1}}$, $T_{TD} = 445$ K, and $N_{TD} = 4 \times 10^{19}\,\mathrm{cm^{-3}eV^{-1}}$. The value of T_{TD} is consistent with the characteristic temperature extracted from α, which shows that the flicker noise may be dominated by the temperature of the deep states.

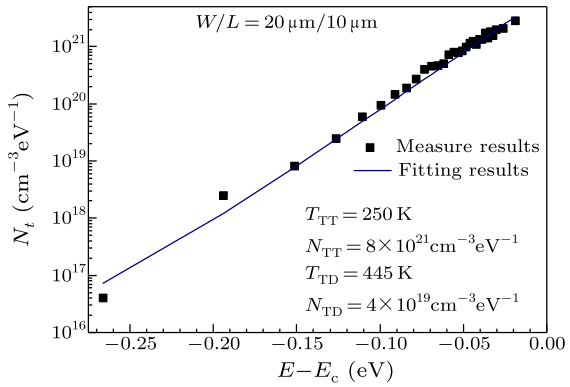

Fig. 7. Extracted density of tail states in the band gap.

The spacial distribution of the border trap density in the gate dielectric layer can be applied to evaluate the quality of the gate insulator. As was reported,[18] it can be extracted from the measurements of $1/f$ noise. The fluctuation of carrier numbers in the channel may be caused by the tunneling process of carriers between the insulator and the channel. The tunneling distance is related to the time constant $\tau = 1/2\pi f$. The frequency can be transformed to the tunneling distance[21]

$$1/2\pi f = \tau_0 \exp(\alpha_t x), \tag{8}$$

where τ_0 is the time constant (~10^{-10} s for traps distributed up to 5 nm) at the IZO/Al_2O_3 interface, and

x is the distance into the gate dielectric layers from the interface.[21] The distribution of border trap density N_t versus distance x can be calculated by Eq. (8), as plotted in Fig. 8. The values of N_t are between 10^{18} and 10^{22}, similar to that reported in a-IGZO TFTs with SiO_2 gate oxide.[22] The result indicates the great quality of gate dielectric layers in our devices.

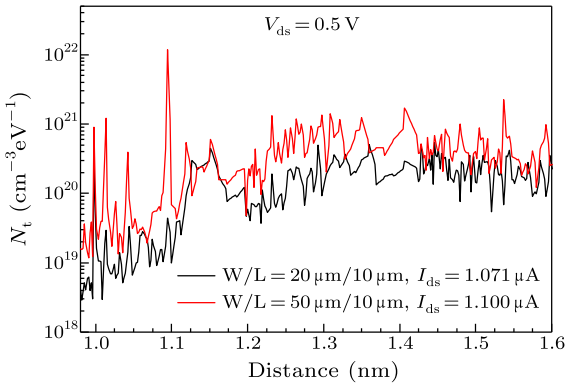

Fig. 8. Extracted spacial distribution of border traps in the gate dielectric.

The quality of channel material can be evaluated by the Hooge parameters, which is given by[11]

$$\alpha_H = \left(\frac{S_{id}}{I_d^2}\right)\frac{f^\gamma WLC_{ox}}{q}(V_{gs} - V_{th}). \quad (9)$$

The Hooge parameter is usually lower for a higher quality material. The extracted average α_H is about 1.18×10^{-3} in this work, which may link to the concentration of conduction band tail and/or deep gap states. For comparison, the reported α_H in the IGZO TFTs with the Al_2O_3 gate insulator[23] is 1.41, which is formed by the atomic layer deposition method. In addition, α_H in IGZO TFTs with the Al_2O_3/SiN_x gate dielectric[24] is $\sim 6 \times 10^{-3}$. The technology of our devices has been optimized by anodization and the interfacial states have been reduced. Thus the quality of the IZO/Al_2O_3 interface has been improved. Therefore, the value of α_H is decreased in our a-IZO TFTs based on the anodic Al_2O_3.

In summary, low-frequency noise in all operational regions of a-IZO TFTs with an Al_2O_3 gate insulator has been investigated. The measured drain current noises follow the classical $1/f^\gamma$ noise theory, which indicates that the $1/f$ noise is the dominant noise source in our devices. The $1/f$ noise is mainly induced by the mobility fluctuation and the average Hooge parameter is about 1.18×10^{-3}. Due to the relationship between the free carrier number and the field effect mobility, the $1/f$ noise can be well simulated by the $\Delta N - \Delta\mu$ model, and the total trap density near the IZO/Oxide interface is about 1.23×10^{18} cm$^{-3}\times$eV^{-1}. Furthermore, the dependence of noise on the characteristic temperature of localized states has been discussed in the whole operating region, and T_t is calculated to be 448.5 K. The distribution of the localized states in the band gap has also been calculated. Finally, the spatial distribution of border traps in the gate oxide is extracted.

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