Impact of High-k HfO_2 Dielectric on the Low-Frequency Noise Behaviors in Amorphous InGaZnO Thin Film Transistors

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We have investigated the impact of high-k HfO_2 gate dielectric on the low-frequency noise (LFN) behaviors of amorphous indium–gallium–zinc oxide thin-film transistors by comparing the LFNs of devices with SiO_2 and HfO_2 dielectrics. Measured LFNs are nearly $1/f$ type for both devices, but the normalized noise for the HfO_2 device is around one order of magnitude higher than that for the SiO_2 device. The bulk mobility fluctuation is considered as the dominant LFN mechanism in both devices, and the increased LFN in the HfO_2 device is attributed to the enhanced mobility fluctuation by the remote phonon scattering from the HfO_2.

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Since the first report by Nomura *et al.*,[1)] amorphous indium–gallium–zinc oxide (a-IGZO) thin-film transistors (TFTs) have attracted much attention due to their excellent electrical and optical characteristics.[2)] Recently, much effort has been made to reduce the operation voltage of a-IGZO TFTs by incorporating high-k dielectrics for the use of the device in mobile systems.[3–5)] Several groups reported promising results with high-k dielectrics in a-IGZO TFTs.[3,4)] However, high defect densities in high-k dielectrics and high-k dielectric/channel interfaces have been known to cause the adverse effects in device performances.[5)] In this paper, we investigated the impact of high-k HfO_2 dielectric on the low-frequency noise (LFN) behaviors in a-IGZO TFTs. LFN is a powerful tool for the assessment of gate dielectric quality, and it is necessary to reduce the LFN for the implementation of high-performance analog circuits. Although the LFN behaviors of metal–oxide–semiconductor field-effect transistors (MOSFETs)[6)] and amorphous silicon (a-Si) TFTs[7)] have been studied by many authors, very little is known about the LFN behaviors of a-IGZO TFTs yet.[8)] This work is the first report on the LFN behaviors of the a-IGZO TFTs with a representative high-k gate dielectric material, HfO_2 ($k \sim 25$).

Figure 1(a) shows the schematic cross-section of fabricated a-IGZO TFTs with a staggered bottom gate structure. Devices are fabricated as follows: molybdenum (Mo) as a gate metal was deposited and patterned by a conventional photolithography on a thermally grown SiO_2/silicon substrate. Then, 20-nm-thick HfO_2 was deposited by atomic layer deposition (ALD) method at 150 °C followed by plasma-enhanced chemical vapor deposition (PECVD) deposition of a SiO_2 (= 100 nm) at 300 °C. The sample with a PECVD deposited SiO_2 (= 120 nm) was prepared to fabricate a reference device. As an active layer, a-IGZO layer (= 50 nm, a-IGZO target; $Ga_2O_3 : In_2O_3 : ZnO = 2 : 2 : 1$ at. %) was deposited by radio-frequency (RF) magnetron sputtering at room temperature (RT) in a mixed Ar/O_2 (100 : 1 at sccm). For the source/drain, a 200-nm-thick Mo was sputtered at RT and then patterned by dry-etching. After N_2O plasma treatment on the channel surface of the a-IGZO active layer, a SiO_2 passivation layer was continuously deposited at 150 °C by PECVD without a vacuum break. The channel length (L), the channel width (W), and the length of the overlap region between the gate and source/drain were designed to be 10, 50, and 10 μm, respectively.

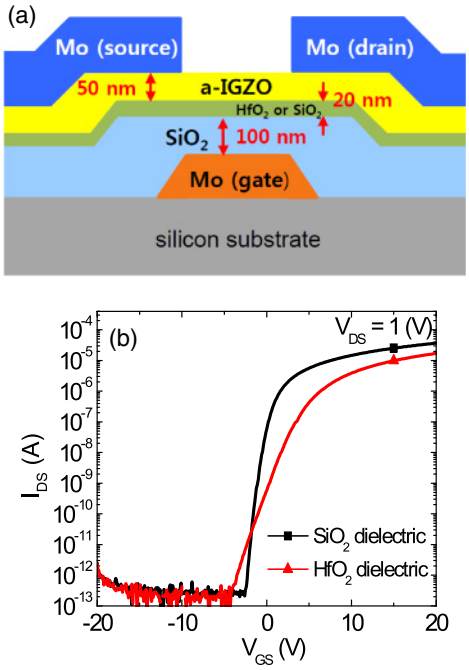

Fig. 1. (Color online) (a) Schematic cross-section of the fabricated bottom gate a-IGZO TFTs with SiO_2 and HfO_2 dielectrics. (b) Representative transfer curves of the a-IGZO TFTs with SiO_2 and HfO_2 dielectrics measured at drain-to-source voltage (V_{DS}) of 1.0 V.

Figure 1(b) shows the representative transfer curves of the a-IGZO TFTs with SiO_2 and HfO_2 interfacial dielectric layers. For the a-IGZO TFT with a SiO_2 interfacial dielectric layer, the subthreshold slope (S), field-effect mobility (μ_{FE}), turn-on voltage (V_{ON}), and threshold voltage (V_{TH}) are 0.36 V/dec, 16.2 $cm^2 V^{-1} s^{-1}$, −2.6 V, and 1.7 V, respectively. The μ_{FE} was determined by the maximum transconductance at a low drain-to-source voltage ($V_{DS} = 1.0$ V).[5)] These electrical parameters are comparable to those of the a-IGZO TFTs in recently published literature works.[2)] On the other hand, the a-IGZO TFT with a HfO_2 interfacial dielectric layer exhibits the S of 1.30 V/dec, μ_{FE} of 9.4 $cm^2 V^{-1} s^{-1}$, V_{ON} of −4.2 V, and V_{TH} of 6.4 V. It can be

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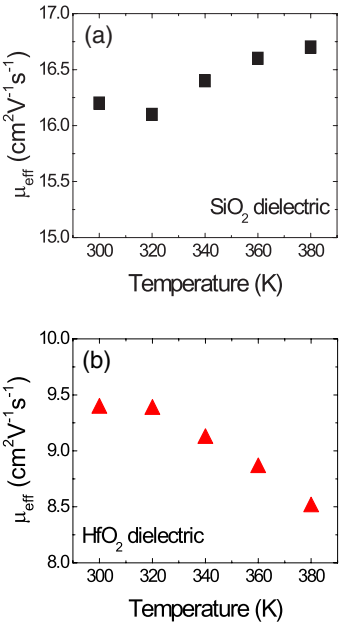

Fig. 2. (Color online) Temperature-dependent field-effect mobility (μ_{FE}) of the a-IGZO TFTs with (a) SiO_2 and (b) HfO_2 dielectrics.

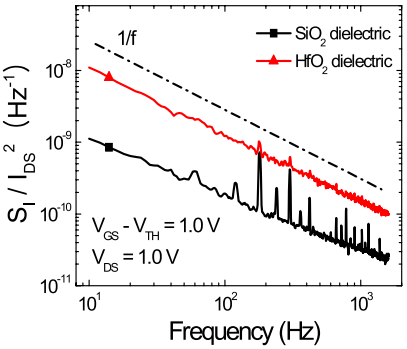

Fig. 3. (Color online) Normalized noise power spectral densities ($S_I/I_{DS}{}^2$s) for a-IGZO TFTs with SiO_2 and HfO_2 dielectrics, measured at the same gate overdrive voltage ($V_{GS} - V_{TH}$) of 1.0 V and drain-to source voltage (V_{DS}) of 1.0 V.

seen that the S value for the HfO_2 device is much larger than that of the SiO_2 device, suggesting that the interfacial trap density of the HfO_2 device is higher than that of the SiO_2 device. Notable degradation of μ_{FE} is also observed in the HfO_2 device. Generally, the mobility degradation in high-k transistors is known to be caused from the remote phonon scattering,[9] Coulomb scattering,[10] and surface roughness scattering.[11] In this article, we made use of the classical Mathiessen's rule and the experimental temperature dependence of the scattering terms[12] to investigate the dominant scattering mechanism causing the mobility degradation in a-IGZO TFTs with HfO_2 gate dielectrics. From Mathiessen's rule

$$\frac{1}{\mu_{\text{eff}}} = \frac{1}{\mu_{\text{ph}}} + \frac{1}{\mu_{\text{sr}}} + \frac{1}{\mu_{\text{cb}}} = \beta T^{\alpha} + \gamma + \frac{\delta}{T}, \qquad (1)$$

where μ_{eff}, μ_{ph}, μ_{sr}, and μ_{cb} represents the total effective mobility and mobilities due to phonon scattering, surface roughness scattering, and Coulomb scattering, respectively. α, β, γ, and δ are all positive and temperature-independent constants. Figures 2(a) and 2(b) depict the μ_{FE}s for the SiO_2 and HfO_2 devices extracted from the transfer curves measured at various temperatures (300, 320, 340, 360, and 380 K). The data shows that the μ_{FE} slightly increases with a temperature in the SiO_2 device, but notably decreases with increasing temperature in the HfO_2 device. Considering that the scattering probability for each transverse electron with phonon is enhanced with increasing temperature, and leads to the degradation in the mobility, the results in Fig. 2 represents that the dominant mechanism of the mobility degradation in the HfO_2 device is the enhanced remote phonon scattering from the HfO_2 dielectric.

Figure 3 shows the normalized noise power spectral densities ($S_I/I_{DS}{}^2$s) of both devices for a gate overdrive voltage ($V_{GS} - V_{TH}$) of 1.0 V, where I_{DS} and V_{GS} are the drain-to-source current and the gate-to-source voltage, respectively. The noise measurements were performed in a shield chamber at RT. In both devices, predominantly $1/f^{\gamma}$-like spectra are obtained with a frequency exponent γ of 0.8–0.9. As seen in Fig. 3, the $S_I/I_{DS}{}^2$ of the HfO_2 device is around one order of magnitude higher than that of the SiO_2 device.

Generally, there are two major theories to explain the origin of the LFN in transistors. McWhorter originally proposed the carrier number fluctuation theory which considers that the LFN is attributed to the random trapping and detrapping processes of charges in the traps located near the dielectric-channel interface.[13] Due to the charge fluctuation, the surface potential fluctuates and results in the fluctuation of the channel carrier density. The bulk mobility fluctuation theory based on Hooge's hypothesis considers that the LFN is a result of the fluctuation in the bulk mobility which is induced by fluctuations in phonon popular through phonon scattering.[14,15] One method of finding the dominant mechanism causing the LFN is to investigate the $S_I/I_{DS}{}^2$ dependence on the $(V_{GS} - V_{TH})$ at fixed frequencies.[7] Figure 4(a) shows that the slope in the log–log plot of $S_I/I_{DS}{}^2$ against $(V_{GS} - V_{TH})$ is close to -1 at a fixed frequency of 40 Hz for both devices, which represents that the LFN is mainly due to the bulk mobility fluctuation in both dielectric devices.[7] The constant slope in Fig. 4(a) also suggests that the source/drain contact noise can be negligible, and the noise mainly comes from the intrinsic channel region in fabricated devices.[16] Because of the different gate bias dependence of the channel and contact noise, the slope should be ~ 2 when the contact is the dominant noise source.[16] In Fig. 4(a), the slopes are constant as ~ -1, which represents that the contact noise is negligible in both devices in all overdrive voltages.

Previous reports have shown that the HfO_2 dielectric increases the LFN in silicon-based MOSFETs, and large efforts have been devoted to find out the mechanism causing this phenomenon. One possible mechanism is the increase of carrier trapping/detrapping due to the high density of traps in the bulk or at the interface of the HfO_2 dielectric. Srinivasan *et al.* investigated the LFN behavior of the n- and p-channel MOSFETs with HfO_2 gate dielectric, and reported that the LFN characteristics behave as being predicted by a carrier number fluctuation mechanism caused by a carrier exchange with traps near the interface.[17] Another possible mechanism is the increase of the electron–phonon scattering

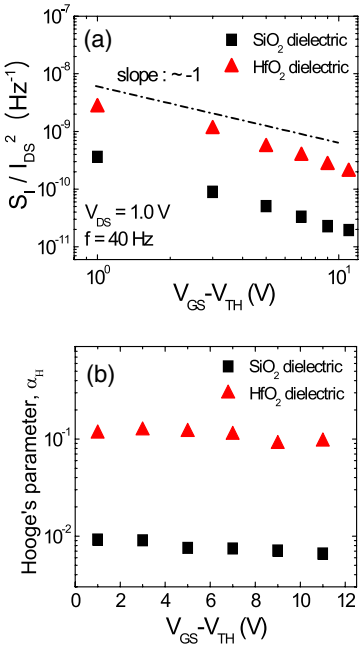

Fig. 4. (Color online) (a) Normalized noise power spectral density (S_I/I_{DS}^2) versus the gate overdrive voltage ($V_{GS} - V_{TH}$) at a fixed frequency of 40 Hz in a-IGZO TFTs with SiO_2 and HfO_2 dielectrics in the ohmic regime ($V_{DS} = 1.0$ V). (b) Extracted Hooge's parameters (α_Hs) versus ($V_{GS} - V_{TH}$) for both dielectric devices.

that originates from remote phonon modes in the high-k. Haartman *et al.* examined the LFN characteristics of the p-channel MOSFETs with HfO_2 gate dielectric, and reported that the LFN characteristics behave as being expected by a bulk mobility fluctuation mechanism caused by a remote phonon scattering from the HfO_2 dielectric.[18] Considering that the dominant mechanism of the LFN is the bulk mobility fluctuation in both dielectric devices, the increased LFN of the HfO_2-dielectric a-IGZO TFT are better explained by the enhanced electron–phonon scattering that originates from the remote phonon modes of the HfO_2. This is also consistent with our previous conclusion in Fig. 2 that the dominant mechanism of the mobility degradation in the HfO_2 device is the enhanced remote phonon scattering from the HfO_2 dielectric.

When the LFN is primarily due to the bulk mobility fluctuation, the Hooge empirical relation can be applied to analyze the LFNs of the transistors in the ohmic regime:[14]

$$\frac{S_I}{I^2} = \frac{\alpha_H}{fN}, \tag{2}$$

where f is the frequency, α_H is the Hooge's parameter, and N is the total number of carriers which can be calculated by

$$N = \frac{C_{die}WL}{q}(V_{GS} - V_{TH}), \tag{3}$$

where C_{die} is the gate dielectric capacitance per unit area and q is the elementary charge. α_H is the measure of the LFN magnitude between different devices and can be extracted from eqs. (2) and (3). Figure 4(b) depicts the extracted α_Hs versus ($V_{GS} - V_{TH}$) for both dielectric devices. The extracted α_Hs in the SiO_2 device (6.4×10^{-3}–9.1×10^{-3}) are comparable with that of the a-Si TFTs,[7] and are around one order of lower than that of the polycrystalline silicon TFTs with a same gate dielectric.[19] The α_Hs in the HfO_2 device (8.7×10^{-2}–1.2×10^{-1}) exhibit around one order of higher values than that of the SiO_2 device.

In summary, we have investigated the effect of high-k HfO_2 gate dielectric on the electrical characteristics and LFN behaviors of a-IGZO TFTs. Compared to the SiO_2 reference device, substantial degradation of S and μ_{FE} is observed in the HfO_2 device, which is attributed to the higher interface trap density and enhanced remote phonon scattering from the HfO_2 dielectric, respectively. Measured LFNs fit well to a $1/f^{\gamma}$ power law with $\gamma = 0.8$–0.9 in devices with both dielectrics, but S_I/I_{DS}^2 in the HfO_2 device is around one order of magnitude higher than that of the SiO_2 reference device. The ($V_{GS} - V_{TH}$) dependence of S_I/I_{DS}^2 shows that the LFN is mainly attributed to the bulk mobility fluctuation in the intrinsic channel region for both dielectric devices. The main mechanism causing the increase of LFN in the HfO_2 device is ascribed to the enhanced mobility fluctuation noise stemming from remote phonon modes in the high-k HfO_2.

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