RF Noise Characteristics of High-k AlTiO$_x$ and Al$_2$O$_3$

Gate Dielectrics

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We have characterized the radio frequency (RF) noise in high-k Al$_2$O$_3$ and AlTiO$_x$ gate dielectrics, which have respective effective oxide thickness (EOT) of 12.5 and 12.2 Å. The measured noise figure in gate dielectric is material dependent and sensitive to dielectric defect after stress. Although the high-k AlTiO$_x$ gate dielectric has lower EOT, it has a higher noise figure than others. From the simulation in our proposed equivalent circuit model, the dominant noise is thermal noise and the reason for increasing noise figure after stress is due to additional parallel resistance by trap-assisted tunneling.

One important direction of next generation metal-oxide semiconductor field effect transistors (MOSFETs) is the replacement of thermal oxide with high-k dielectrics. However, the scaling of complementary metal oxide semiconductors (CMOS) has resulted in a strong improvement in the radio frequency (RF) characteristics that cause Si-based CMOS devices currently to be used in RF front-end extraction system up to 6 GHz that covers the most important frequency band for wireless communication.

Results and Discussion

We have first measured the low-frequency characteristics of high-k AlTiO$_x$ and Al$_2$O$_3$. Figure 1 shows the capacitance-voltage (C-V) characteristics of different dielectric capacitors. The flat C-V characteristics with little capacitance change are due to the highly doped n$^+$-Si bottom transmission line and the large threshold voltage. The EOT of 12.5 and 12.2 Å are obtained from directly calculating the measured capacitance values without quantum correction.

The calculated k values of 15 and 9 are obtained for AlTiO$_x$ and Al$_2$O$_3$, respectively. Thus, adding Ti-O into Al-O gate dielectric can effectively increase the k value.

Figure 2a and b shows the current density vs. voltage (J-V) characteristics of various gate dielectrics and the current density change ($\Delta J$) after constant voltage stress, respectively. The leakage current of AlTiO$_x$ at the bias voltage of 1 V is about three orders of magnitude less than that of conventional SiO$_2$ at the same EOT reported in the literature. The relatively larger leakage current in AlTiO$_x$ than Al$_2$O$_3$ may be due to both smaller bandgap and weaker bond-related higher defects in Ti-O. However, the lower EOT can be obtained for AlTiO$_x$ due to the higher dielectric constant, even associated gain were measured by an ATN-NPSB noise parameter extraction system up to 6 GHz that covers the most important frequency band for wireless communication.

Experimental

High-k Al$_2$O$_3$ and AlTiO$_x$ capacitors with coplanar transmission lines fabricated on Si substrates are used for RF noise characterization. First, the n$^+$ Si bottom transmission line is formed. Then high-k Al$_2$O$_3$ or AlTiO$_x$ is formed by depositing Al or Ti/Al on HF-vapor passivated Si followed by oxidation and annealing. A more detailed fabrication process of high-k Al$_2$O$_3$ dielectric can be found elsewhere. It is found in our previous study that the self-limiting oxidation mechanism is one of the important merits of Al$_2$O$_3$ for either reproducibility or uniformity control. The advantages of adding Ti-O into Al$_2$O$_3$ is to reduce effective oxide thickness (EOT) by adding the very high-k TiO$_x$ and at the same time preserve the slow oxygen diffusion through Al-O matrix. Negligible EOT reduction is measured after 800°C annealing due to the Al-O related self-limiting oxidation mechanism like Si$_3$N$_4$. Finally, the Al top transmission line is patterned to form the high-k high-$k$ capacitor. Standard two-port S-parameters and RF noise figures are measured and de-embedded for high-$k$ capacitors and 0.18 μm MOSFETs. The noise figure and associated gain were measured by an ATN-NPSB noise parameter extraction system up to 6 GHz that covers the most important frequency band for wireless communication.

Figure 1. C-V characteristics of the Al$_2$O$_3$ and AlTiO$_x$ gate capacitors measured at 100 kHz. Conventional 23 Å SiO$_2$ is also added for comparison. The measured area is 20 × 20 μm.

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though the bandgap is smaller, and the achieved EOT is smaller than the stacked TiO$_2$-Si$_3$N$_4$ gate dielectric. The larger increasing leakage current in AlTiO$_x$ after stress also indicates the weaker bonding in Ti-O. This increase in stress-induced leakage current (SILC) is caused by the generation of defects during stress that can be further used for noise mechanism study.

To investigate the effect of stress on noise and identify the noise mechanism, we have further measured the rf noise of devices before and after stress. Figures 3a-c shows the measured noise figure as a function of frequency for AlTiO$_x$, Al$_2$O$_3$, and SiO$_2$, respectively. The noise figure in a fresh device increases as increasing $k$ from SiO$_2$ to AlTiO$_x$. The Al$_2$O$_3$ shows the lowest noise figure increase after stress and the AlTiO$_x$ is the worst. Therefore, from the rf noise point of view, the Al$_2$O$_3$ gate dielectric performs better than AlTiO$_x$. It is known that the Al-O bond energy is higher than Ti-O; thus, the origin of noise after stress may be related to defect generation and current fluctuation inside the gate dielectric.

We have further investigated the origin of noise. Since the stress effect increases the leakage current by trap-assisted tunneling, the shot noise may be responsible for the rf noise because it originates from the random carrier injection through the energy barrier of the gate dielectric. However, this is unlikely because the shot noise usually decreases rapidly as frequency increases into the gigahertz regime. We have used an equivalent circuit model to further understand the origin of noise. Figure 4 shows the proposed noise model for high-$k$ capacitors. This model contains a gate capacitor ($C$) in parallel with a resistor ($G$), which is used to simulate the leakage-current-related loss effect of the capacitor. Because the stress increases the leakage current, additional resistance ($R$) is added to model the SILC effect.

Figure 5a-c shows the simulated noise figure using the physically based equivalent circuit model for AlTiO$_x$, Al$_2$O$_3$, and SiO$_2$, respectively, where the good matching of measured and modeled results were first obtained before optimizing the noise figure in the model. We have also plotted the measured data for comparison. The good agreement between the measured and modeled noise figure suggests the excellent accuracy of this model. Therefore, the origin of rf noise in the high-$k$ capacitor is due to the loss-related thermal noise.

To understand the gate-oxide-related rf noise in MOSFETs, we have also shown the measured and simulated minimum noise figure from a multifingered 0.18 $\mu$m MOSFET in Fig. 6a and the equivalent circuit model is in Fig. 6b. The gate oxide for this device is conventional SiO$_2$ and the thickness is 30 Å. Close matching be-
tween the measured and modeled noise figure indicates the good accuracy of the noise model. However, by continuously scaling down the gate dielectric thickness or replacing by high-$k$ dielectric in the next generation CMOS technologies, significant thermal noise from gate dielectric resistance ($R_{gs}$) and resistance ($R_{stress}$) by SILC effects will result in higher noise in MOSFETs according to the transistor noise model. In the worst case, the gate dielectric noise may contribute a large portion of total noise.

Conclusions

We have characterized the rf noise of high-$k$ AlTiO$_x$ and Al$_2$O$_3$ gate dielectrics. The dominant noise source in gate capacitors is thermal noise that increases after stress due to additional leakage-related resistance by SILC effects.

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References