Enhanced fatigue resistance of ferroelectric Al<sub>0.65</sub>Sc<sub>0.35</sub>N deposited by physical vapor deposition

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Aluminum scandium nitride (AlScN), a III-V ternary semiconductor, has been recognized as an innovative and promising ferroelectric material in emerging research. Among the characteristics of ferroelectric material, fatigue resistance is a critical measure of the endurance of ferroelectric films and represents an inherent challenge in the pursuit of practical applications. For instance, ferroelectric random-access memory (FeRAM) is a non-volatile memory technology capable of reliable data reading, erasing, and rewriting over prolonged periods without failure [1,2]. Accordingly, the fatigue resistance of ferroelectric materials directly influences the lifetime of FeRAM devices. However, the current maximum operational cycles observed in AlScN reach only up to 3 × 10<sup>5</sup> [3], significantly falling short of commercial requirements [4]. To address this issue, various attempts have been made using different material preparation methods [5].

In this study, we fabricated a robust ferroelectric AlScN film using the PVD method. The pure c-axis oriented ferroelectric phase was confirmed through x-ray diffraction rocking curve scans, even at a high scandium (Sc) concentration. The test results revealed that the fabricated AlScN ferroelectric capacitors can exhibit excellent polarization switching and retention capabilities. More importantly, the endurance of AlScN ferroelectric film was significantly improved to cross the milestone of ten million cycles for the first time.

Figure 1(a) presents the key process steps for fabricating AlScN ferroelectric capacitor. The process begins with an AlN/Si template. Initially, a 150 nm thick Pt bottom electrode (BE) is sputtered onto the substrate. A 450 nm thick AlScN film is then deposited using custom-built sputter deposition equipment. Subsequently, after the deposition of the AlScN film, a top electrode (TE) consisting of a 45 nm thick Ti layer followed by a 95 nm thick Au layer is formed using electron beam evaporation (EBE). A shadow mask is used during the evaporation process to define the square capacitors with dimensions of 200 µm × 200 µm and 90 µm × 90 µm. Finally, the fabricated capacitors are ready for comprehensive testing and characterization. Figure 1(b) shows the schematic representation of a prepared ferroelectric capacitor.

Figure 1(c) shows a cross-sectional scanning electron microscope (SEM) view of the capacitor device. Figure 1(d) displays the high-resolution X-ray diffraction high resolution X-ray diffraction (HRXRD) 2θ-θ scan curve, and the (0002) reflection peak of AlScN is observed at 35.8° in 2θ. The inset in Figure 1(d) shows the rocking scan of the AlScN (0002) peak, which exhibits a full width at half maximum (FWHM) value of 2.28°. The presence of a c-axis preferred orientation, indicated by the absence of additional wurtzite peaks associated with other orientations, ensures the ferroelectric characteristics of the AlScN film. In the XPS results shown in Figure 1(e), the presence of Sc is detected through Sc 2p peaks at 406.5 eV. The Sc concentration, indicated by the Sc/(Al+Sc) ratio, is estimated to be approximately 35%, revealing a relatively high concentration of Sc.

Figure 1(f) shows the P-E loops obtained using a standard method. To mitigate interference from non-ferroelectric charge, a positive-up-negative-down (PUND) measurement pulse sequence is employed, which consists of four monopolar triangle voltage pulses. This pulse sequence is specifically designed to separate the contributions from both ferroelectric switching and non-ferroelectric switching components. The P-E and J-E loops of the Al<sub>0.65</sub>Sc<sub>0.35</sub>N capacitors using the PUND method are then collected, as shown in Figures 1(g) and (h). The remnant polarization starts to saturate when the voltage exceeds 160 V, and the maximum remnant polarization is 143 µC/cm<sup>2</sup>.

To investigate the frequency response of polarization switching, the ferroelectric capacitors with a small footprint of 90 µm × 90 µm were selected. These capacitors are anticipated to have a short RC delay time, making them more suitable for fast response. Figure 1(i) illustrates the measured frequency-dependent J-E loops, demonstrating that polarization switching can persist up to 15 kHz (τ<sub>RC</sub> ≈ 33 µs). Figure 1(j) illustrates the retention behavior of the capacitor. The test results indicate minimal or no decay in remnant polarization in both positive and negative directions.
As illustrated in Figure 1, Figure 2, and Figure 3, the devices were subjected to pulses with fixed \( f_{\text{T}} = 50 \mu\text{s} \), \( V_{\text{p}} = 150 \text{ V} \) for fatigue treatment. To monitor the degradation of the ferroelectric properties, measuring voltage pulses with \( f = 1 \text{ kHz} \), \( V_{\text{p}} = 150 \text{ V} \), but a longer \( t_{\text{R}} = 5 \text{ ms} \) were introduced during the fatigue process. As illustrated in Figure 1(k), the fatigue tests conducted on ferroelectric capacitors with dimensions of 90 \( \mu\text{m} \times 90 \mu\text{m} \), demonstrate endurance beyond \( 10^7 \) cycles. Different colors represented samples from the same wafer, tested with frequencies increasing from 2 to 10 kHz with a step of 1 kHz. To explore the limits of endurance properties, fatigue training pulses with \( f = 10 \text{ kHz} \), \( t_{\text{R}} = 50 \mu\text{s} \), and \( V_{\text{p}} = 150 \text{ V} \) were continuously applied until degeneration occurred, reaching a final endurance of up to \( 5 \times 10^7 \). Figures 1(l) and (m) show the measured P-E and J-E loops during the fatigue tests. At \( 10^7 \) cycles, remnant polarization and current density abruptly drop, indicating the almost complete disappearance of ferroelectric polarization. In fact, the degradation of AlScN capacitors involves the degradation of the ferroelectric phase, an increase in resistance, and then a breakdown. In our case, the enhancement of AlScN capacitors with dimension of 90 \( \mu\text{m} \times 90 \mu\text{m} \), (l) measured P-E loops after fatigue treatments; and (m) the corresponding J-E loops.

**Conclusion.** In summary, our study has achieved successful growth of a ferroelectric Al\(_{65}\)Sc\(_{35}\)N film using the PVD method. The fabricated capacitors have demonstrated a coercive field of 2.70 MV/cm as well as an impressively large remnant polarization of 143 \( \mu\text{C/cm}^2 \). Significantly, we have set a benchmark by achieving a remarkable \( 5 \times 10^7 \) switching cycle without observable substantial degradation. This advancement represents a promising way to enhance fatigue resistance, which could push forward the practical applications of this technology in non-volatile, low-power, intelligent, and reconfigurable electronics.

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**References**