Ferroelectric Properties of an Innovative FeFET with 3.3V Writing, 10^9 Endurance, and Long Retention

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Recently we reported 3.3 V write-voltage ferroelectric-gate field-effect transistors (FeFETs) with 10^9 endurances and stable retentions measured for 10^5 s.[1)] The FeFETs had an Ir/$Ca_{0.2}Sr_{0.8}Bi_2Ta_2O_9$ (CSBT)/HfO_2/Si metal/ferroelectric/insulator/Si (M/F/I/S) gate stack. For developing the FeFETs, a novel polycrystallization-annealing process in N_2 dominant ambient was introduced, whereas a conventional ambient was pure O_2. The optimum ambient at 780 ºC was 1000-sccm-N_2 mixed with 0.5-sccm O_2. The FeFET showed a 0.59 V memory window (V_w) in the drain-current *vs.* gate-voltage (I_d-V_g) hysteresis curve scanned by $V_g = \pm 3.3$ V. The M/F/I thicknesses of the Ir, CSBT, and HfO_2 layers were 75, 135, and 5 nm, respectively. A conventional O_2-annealed Pt/CSBT/$(HfO_2)_{0.75}$ $(Al_2O_3)_{0.25}$/Si FeFET with a 160 nm-thick CSBT showed only $V_w = 0.31$ V at $V_g = \pm 3.3$ V despite the thicker CSBT than that of the novel FeFET.

In comparison with the conventional O_2 annealing process, the novel N_2-dominant annealing effectively enlarged ferroelectric V_w by two factors.[3)] One was a suppressed interfacial-layer (IL) growth. The IL was SiO_2 inevitably grown between the HfO_2 layer and the Si substrate during the annealing at about 800 ºC. The optimum N_2-dominant annealing resulted in a 2.6 nm-thick IL which was 0.8 nm thinner than the conventional by an O_2 annealing.[2)] The other factor for the enlarged V_w was an improved CSBT ferroelectricity in the FeFETs. It was revealed using our new analysis method of FeFETs.[3)] In the method, a relationship of V_w *vs.* maximum P (P_{max}) was derived from two experimental relations of P-V_g (Fig. 1(a)) and V_w *vs.* $V_{g,max}$. The P is the ferroelectric polarization which is equivalent to a surface-charge density common to the F/I/S. The $V_{g,max}$ is the scanned V_g amplitude. P-V_g was measured using Radiant RT6000S. V_w-$V_{g,max}$ is extracted not only from I_d-V_g measured using Agilent 4156C but also from the P-V_g (Fig. 1(a)). In the all the measurements, applicable V_g was restricted to satisfy the condition of $P_{max} < 2.5$ μC/cm^2. The $P_{max} < 2.5$ μC/cm^2 is our rule in operating Si-based FeFETs. Otherwise, charge injection into the IL starts, which may degrade the endurance and retention of the FeFETs. Coercive field E_c of the CSBT was evaluated as $2E_c = V_w/d_{CSBT}$, where d_{CSBT} was the CSBT thickness. We successfully extracted an important ferroelectric property $2E_c$-P_{max} (Fig. 1(b)) from the FeFET which is not directly measurable in the M/F/I/S. As shown in Fig. 1(b), we found that the CSBT had $2E_c = 68.3$ kV/cm at $P_{max} = 2.36$ μC/cm^2 in the FeFET annealed in the optimum N_2-dominant gas. On the other hand, in a conventional FeFET annealed in pure O_2, the CSBT had only $2E_c = 33.9$ kV/cm at the $P_{max} = 2.36$ μC/cm^2.

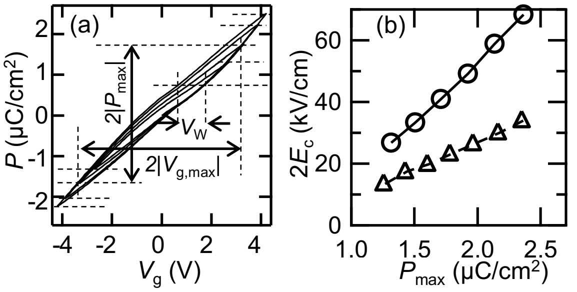

Fig. 1 (a) Measured P-V_g at various $V_{g,max}$. (b) Analyzed $2E_c$-P_{max} of this work (○) and the conventional (△).

In conclusion, 3.3 V write-voltage high-quality FeFETs were achieved by the optimum N_2-dominant gas annealing process. The novel process had two effects on enlarging the V_w: the IL thickness reduction and the ferroelectricity improvement of the CSBT in the FeFETs.

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3) W.Zhang *et al.*, accepted for Jpn. J. Appl. Phys.