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Studies of Ferroelectric HfO_2 Materials before Memory and Logic Applications

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Abstract

HfO_2 ferroelectrics are compatible with the advanced semiconductor processes, and are promising for memory and logic applications. However, electrical performances of HfO_2 ferroelectrics are still immature. This work investigates the status of HfO_2 ferroelectrics from the viewpoint of endurance performances.

1. Characteristics of HfO_2 Ferroelectrics

Since the first reports of ferroelectricity in HfO_2-based crystalline films in 2011 [1-2], many attractive characteristics of this material have been demonstrated. The metastable orthorhombic crystal structure is probable to be the origin of ferroelectricity [1, 3]. Many kinds of elements are useful develop ferroelectric films [4, 5]. Aggressive scaling of the film thickness as thin as 3 nm has been studied [6]. Superior ferroelectric capacitors could be prepared by annealing at 400 ^{o}C and less [7-9]. The polarization switching speeds faster than 10 ns have been reported [10, 11]. These characteristics promise the application of ferroelectric HfO_2 thin films in memory and logic applications.

2. Potential applications of HfO_2 ferroelectrics

Developments of electronic devices integrated with HfO_2 ferroelectrics are in progress. Ferroelectric materials such as $Pb(Zr,Ti)O_3$ (PZT) with 80 nm thickness have already been utilized as the FeRAM with 130 nm technology node [12]. An advantage of ferroelectric HfO_2 films is the thickness, around 10 nm. Because of its extremely thin structure, FeRAMs with ferroelectric HfO_2 can be integrated with the state-of-art DRAM process [13]. HfO_2 is thus expected to increase the capacity of FeRAM drastically. Application of HfO_2 ferroelectrics in one-transistor-type memory (FeFET) is also investigated at advanced technology nodes [13-16]. A study to replace the 3D-NAND by vertical FeFETs is also reported [17]. Ferroelectric tunnel junction (FTJ) is a two-terminal memory, and is expected as a new type non-volatile memory [18, 19]. In addition to these memory devices, investigation of steep subthreshold swing logic devices using FeFETs is stimulated [20]. Although its device physics is still controversial [21], many challenges are ongoing.

Device technologies utilizing ferroelectric HfO_2 contribute to realize many kinds of useful circuits. In combination with the SRAM, the ferroelectric HfO_2 contributes to reduce the power consumption [22, 23]. Scalability of ferroelectric HfO2 is compatible to develop in-memory computing systems [24, 25]. A random switching behavior of multi-domains in ferroelectric capacitors is useful to emulate the human brain and to develop neuromorphic circuits [26-31]. Expectations of HfO_2 ferroelectrics for next generation LSI are increasing.

3. Status of Ferroelectric HfO_2 Performances

An important property of memory materials for LSI application is the tough endurance. Stability of memory property during the large number of bias cycle is the essential. HfO_2 ferroelectrics are no exception.

We fabricated $Hf_{0.5}Zr_{0.5}O_2$ capacitors by sputter deposition and annealing, and examined their electrical properties [32, 33]. Ferroelectric properties are summarized in Fig. 1. Remnant polarization larger than 20 $\mu C/cm^2$ is attained when the applied electrical field is larger than 2 MV/cm. However, a hard breakdown occurs when the electrical field reaches 4 MV/cm. Endurance performance is correlated with the applied electrical fields. A smaller electrical field is preferable for the better endurance.

Endurance performances of HfO_2 ferroelectrics were reported by many groups [34-46]. Relationship between the endurance and the electrical field is summarized in Fig. 2. Irrespective of the deposition methods, the dopants, the electrodes, and the annealing conditions, the endurance performance is correlated with the electrical field. An important point it that the number of endurance cycle in HfO2 ferroelectrics even the best endurance cycle 10^{10} is still far below the performance of commercial FeRAM using PZT [12]. In order to utilize HfO_2 ferroelectrics in FeRAM, endurance cycles as large as 10^{12} is necessary. For the logic applications, endurance cycles of 10^{15} is mandatory. Thus, material property of ferroelectric HfO_2 is in the development stage.

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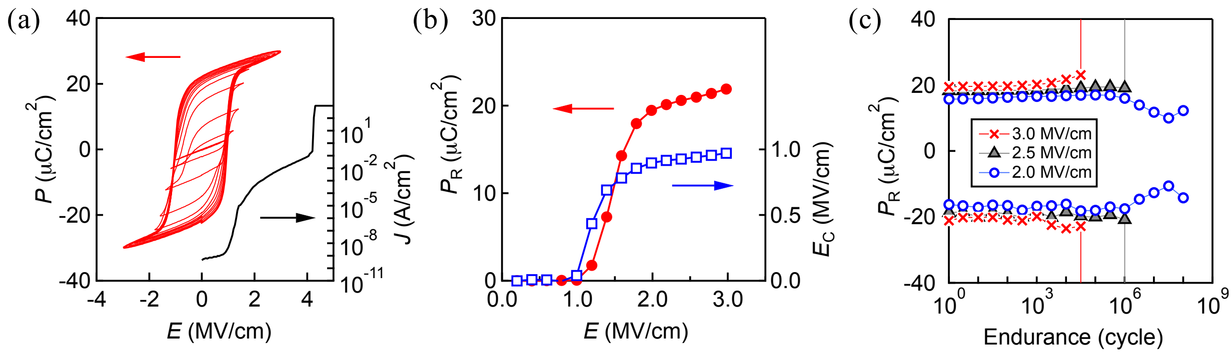

Fig. 1. (a) *P-E* and *J-E* curves of the 10-nm-thick $Hf_{0.5}Zr_{0.5}O_2$ film capacitor with the increment of sweep bias. (b) Applied electrical field dependence of the remnant polarization P_R and the coercive field E_C. (c) Endurance performances with the applied electrical fields.

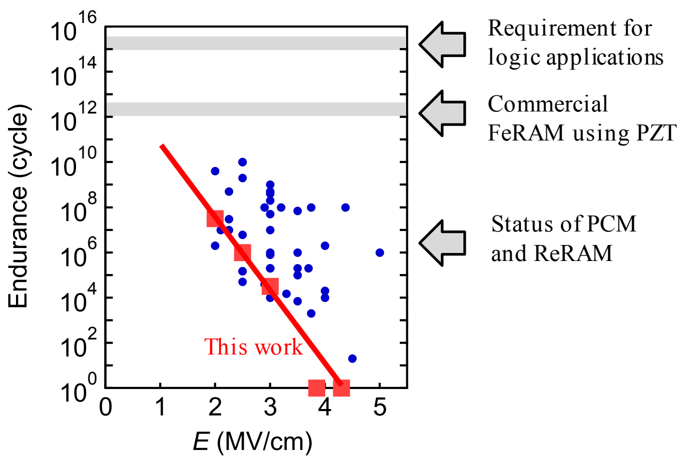

Fig. 2. Endurance of HfO_2-based ferroelectric capacitors with applied electrical fields. The red squares show our results in this work, and the blue circles are the data reported in the references prepared by many dopants, various deposition methods, various electrodes, and various annealing conditions. Lower electrical fields are preferable to achieve a larger endurance cycles. Performances of HfO_2 ferroelectrics are still far below the commercial FeRAM.