

# A Ferroelectric DRAM Cell for High-Density NVRAM's

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**Abstract**—The operation of a ferroelectric DRAM cell for nonvolatile RAM (NVRAM) applications is described. Because polarization reversal only occurs during nonvolatile store/recall operations but not during read/write operations, ferroelectric fatigue is not a serious endurance problem. For a 3-V power supply, the worst-case effective silicon dioxide thickness of the unoptimized lead zirconate titanate film studied here is less than 17 Å. This cell can be the basis of a very high-density NVRAM with practically no read/write cycle limit and at least  $10^{10}$  nonvolatile store/recall cycles.

## I. INTRODUCTION

THE LARGE charge storage density requirement for future generations of DRAM's has generated significant interest in high dielectric constant materials such as tantalum pentoxide and yttrium oxide. However, because of the lower dielectric breakdown strengths of these materials, the net gain in charge storage density has been a factor of 2 or 3 at best. Recently, nonvolatile memory cells exploiting the large polarization and ferroelectric hysteresis loops of materials such as lead zirconate titanate ( $\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$ , commonly called PZT) have been proposed [1]. However, because these memories suffer from fatigue, a gradual loss of polarizability following repeated read/write cycling, ferroelectric materials have also been considered as a direct replacement for oxide/nitride/oxide structures in conventional volatile DRAM's [2]. In this case, the ferroelectric is not cycled between the two polarization states during read/write operation, thus possibly avoiding significant fatigue. In this letter we describe a ferroelectric nonvolatile RAM (FNVRAM) which normally operates as a conventional DRAM yet also exploits the hysteresis loop of ferroelectric materials for nonvolatile operation.

## II. MATERIAL PROPERTIES AND PREPARATION

Metal-ferroelectric-metal (MFM) capacitors were fabricated using lead zirconate titanate as the ferroelectric material. Polycrystalline 4000-Å PZT films were prepared by sol gel deposition [3] and subsequent annealing at 650°C in an oxygen ambient. Platinum was used for both top and bottom electrodes. In addition to the conventional Sawyer-Tower measurement, large-signal quasi-static capacitance (voltage

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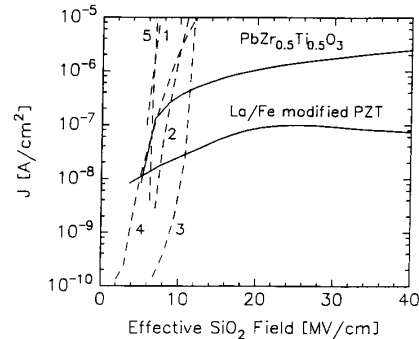


Fig. 1. The conduction characteristics of PZT films are superior to other dielectric structures (1:  $\text{SiO}_2/\text{Si}_3\text{N}_4$  [6], 2:  $\text{Ta}_2\text{O}_5/\text{Si}_3\text{N}_4$  [7], 3:  $\text{Y}_2\text{O}_3/\text{SiO}_2$  [8], 4:  $\text{Ta}_2\text{O}_5/\text{SiO}_2$  [9], 5: 60-Å  $\text{SiO}_2$ ).

ramp rate: 1 V/s) and small-signal high-frequency capacitance (1 MHz, 10 mV rms) measurements were used to obtain the ferroelectric capacitor polarization. Fig. 1 is a plot of the current density versus effective electric field [4] (defined as the equivalent silicon dioxide field needed to obtain the same capacitor polarization) for a  $\text{PbZr}_{0.5}\text{Ti}_{0.5}\text{O}_3$  film and a  $\text{PbZr}_{0.5}\text{Ti}_{0.5}\text{O}_3$  film prepared from a lanthanum-iron modified sol gel. The electrical conductivity of PZT films is influenced significantly by impurities. Adding the proper impurities compensates for the enhanced conductivity arising from oxygen and lead vacancies [5]. Because of the large polarization of the PZT films (the relative dielectric constant calculated from the large-signal capacitance is approximately 1300), a 2-V drop across a PZT film corresponds to an effective  $\text{SiO}_2$  field of 17 MV/cm. At these high fields, the PZT films exhibit superior leakage characteristics compared to other dielectric films [6]–[9] (see Fig. 1). However, the leakage current needs to be reduced further to meet the refresh time requirements for high-density DRAM's.

## III. MEMORY CELL OPERATION

### A. Nonvolatile Mode

The FNVRAM cell is a simple one-transistor DRAM cell with a ferroelectric capacitor as shown in Fig. 2. A conductive diffusion barrier is required as the storage node contact to prevent interdiffusion of silicon with the ferroelectric material during high-temperature annealing. Two different bias schemes for the operation of the FNVRAM cell are described. In the first scheme, the cell plate is always held at half of the supply voltage ( $V_{DD}/2$ ). During DRAM operation, the storage node is at either  $V_{DD}/2$  or  $V_{DD}$  such that

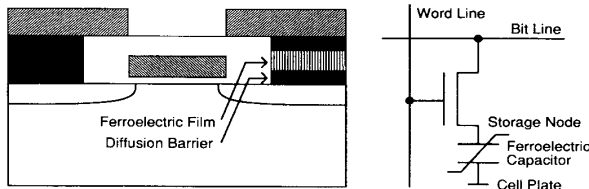


Fig. 2. The FNVRAM cell is a conventional DRAM cell with a ferroelectric capacitor dielectric. Since the ferroelectric material has a very large polarization, it is possible to incorporate the capacitor in the contact hole of the select transistor.

the ferroelectric capacitor is not cycled between opposite polarization states. In the second scheme, the cell plate is held at  $V_{DD}$  during DRAM operation and the storage node is at either 0 V or  $V_{DD}$ . Upon command or power failure, a nonvolatile store operation is executed: the state of the cell is read and written back as one of the two permanent polarization states of the ferroelectric film. In the first scheme, if the DRAM datum is ZERO, i.e., the storage node is at  $V_{DD}/2$ , the word line is selected and the bit line is grounded. The ferroelectric is now polarized in one direction (nonvolatile ZERO). In the second scheme, a DRAM ZERO (storage node at  $V_{DD}$ ) is stored as a nonvolatile ZERO by selecting the word line, driving the bit line to  $V_{DD}$ , and grounding the cell plate. The recall operation [1] is performed similarly to a DRAM read: the remanent polarization of the ferroelectric film is sensed and restored as one of the two DRAM states.

In this manner, the ferroelectric film is only cycled between opposite polarization states during nonvolatile store/recall operations, not during DRAM read/write operations. Even after  $10^{10}$  store/recall cycles (corresponding to 10 store/recall cycles per second for 30 years), there is sufficient detectable ferroelectric polarization. Therefore, fatigue from store/recall cycling is not a serious limitation to the nonvolatile operation of this cell. Since the ferroelectric polarization is not reversed during DRAM read/write operation, there is almost no loss in nonvolatile polarization even after  $10^{10}$  read/write cycles. At this rate, the FNVRAM cell is expected to tolerate orders of magnitude higher nonswitching read/write cycles than the  $10^{12}$  switching cycles demonstrated for PZT films [10].

### B. DRAM Mode

DRAM read/write cycling still causes degradation in the DRAM capacitor polarization. This degradation is observed in the measured large-signal capacitance and can be attributed to the effect of space-charge accumulation in the PZT film on the detectable ferroelectric polarization. Very little degradation is observed in the small-signal capacitance after  $10^{10}$  read/write cycles (see Fig. 3(a)) since the small-signal capacitance is attributed primarily to nonferroelectric ionic and electronic polarizability. Even if there is no detectable ferroelectric polarization, the nonferroelectric polarization, characterized by a small-signal capacitance, is available for DRAM capacitor polarization. In this worst case, the DRAM capacitor polarization for a 3-V supply is effectively a 17-Å silicon dioxide film subjected to a 3-V voltage swing (see Fig. 3(a)).

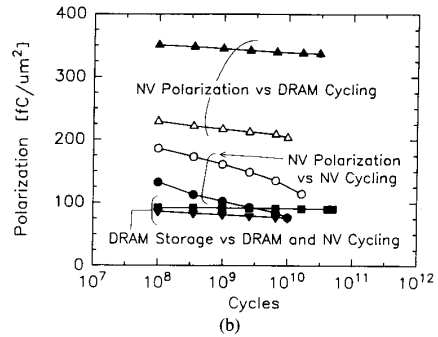
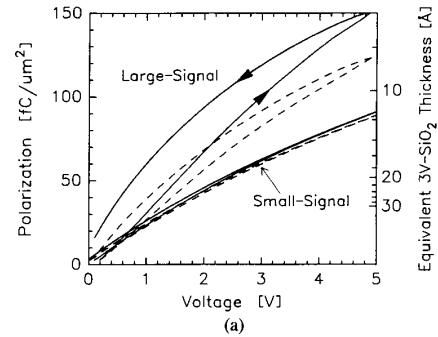


Fig. 3. (a) DRAM read/write cycling causes a significant loss in detectable polarization during DRAM operation (large-signal capacitance). However, the small-signal capacitance provides a lower limit for the available polarization. This limit is approximately  $60 \text{ fC}/\mu\text{m}^2$  for a 3-V swing across the ferroelectric capacitor. (Fresh curves: solid lines; polarization after  $10^{10}$  read/write cycles: dashed lines.) (b) Endurance characteristics of  $\text{PbZr}_{0.5}\text{Ti}_{0.5}\text{O}_3$  (closed symbols) and lanthanum-iron modified films (open symbols). Capacitance measurements from  $-5$  to  $5$  V and  $0$  to  $5$  V are used to determine the nonvolatile polarization and DRAM storage capacity, respectively.

The endurance properties of the FNVRAM cell are summarized in Fig. 3(b). The top two curves show that the nonvolatile polarization is virtually unaffected by DRAM read/write cycling ( $0$  to  $5$  V) but fatigues significantly after nonvolatile store/recall cycling ( $-5$  to  $5$  V) (see the two curves in the middle). The two curves on the bottom represent the worst-case polarization (small-signal capacitance limit) available for DRAM operation following read/write cycling (square symbol) and store/recall cycling (triangular symbol).

The characteristics presented above represent an unoptimized  $4000\text{-}\text{\AA}$   $\text{PbZr}_{0.5}\text{Ti}_{0.5}\text{O}_3$  film. Improved performance and reliability are possible by modifying the composition of the film: a lanthanum-iron modified PZT film has comparable storage capacity but much higher resistivity than  $\text{PbZr}_{0.5}\text{Ti}_{0.5}\text{O}_3$  and exhibits less fatigue as shown in Figs. 1 and 3(b), respectively. Further increase in DRAM storage density is possible by scaling the ferroelectric film thickness: for a 1.5-V power supply, a  $2000\text{-}\text{\AA}$  film has an equivalent  $\text{SiO}_2$  thickness of less than  $9 \text{ \AA}$  [11].

### IV. SUMMARY AND CONCLUSIONS

The operation and endurance of the FNVRAM cell are discussed. Ferroelectric fatigue does not pose a serious endurance problem for this cell since polarization reversal only

occurs for nonvolatile operation but not for DRAM operation. A loss in the detectable polarization is observed even during DRAM operation. However, a lower limit for the available polarization can be obtained from the small-signal capacitance of the ferroelectric film. For the unoptimized 4000-Å PZT films studied here, this lower limit is  $60 \text{ fC}/\mu\text{m}^2$  for a 3-V power supply equivalent to a 17-Å silicon dioxide film. The resistivity and endurance properties of ferroelectric films can be optimized by modifying the composition of the film. This cell can be the basis of a very high-density NVRAM with practically no read/write cycle limit and at least  $10^{10}$  nonvolatile store/recall cycles.

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