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A Novel SPICE Model of Ferroelectric Capacitors Using Schmitt Trigger Circuit

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1. Introduction

Recently, ferroelectric random access memory (FeRAM) attracts a great deal of interest because it is high speed and low power consumption memories with the nonvolatile feature. In order to simulate the circuit behavior of FeRAM, it is necessary to prepare a model which represents the electrical responses of ferroelectric capacitors. Particularly, in analysis of modern large-scale integrated circuits, it is essential that the model is composed of real and ideal circuit components, so that it can be introduced in SPICE simulator.

So far, several models have been proposed and they are classified in two categories. One is the macroscopic model in which the polarization characteristics of the film are determined based on the saturated P-E hysteresis loop[1-3], and the other is the parallel-element model in which the polarization characteristics are determined by the total contribution of dipoles connected in parallel[4-6]. Some of them [3,6] can be used in SPICE simulator and give reasonable results under symmetric input condition. However, the models are not completely established so far. In this paper, we propose a novel parallel-element model of ferroelectric capacitors, in which Schmitt trigger circuit is used as a source of a micro dipole and the time-dependent behavior of polarization reversal can be taken into account.

2. Problems in the macroscopic models

A major problem in macroscopic models is inaccuracy in drawing minor loops under an asymmetric input condition, which often appears in operation of ferroelectric-gate FETs. Figure 1(a) shows hysteresis loops of ferroelectric capacitors calculated using a SPICE macroscopic model [3] under a symmetric input condition. As can be seen from the figure, the saturated loop agrees well with the measured data, because the parameters are extracted from the measured data. The minor loops are also acceptable, although details of their shape are different from the experimental data. However, when voltages with small amplitude are asymmetrically applied to the capacitor, the problem is emphasized as shown in Fig. 1(b). The initial state of curve α is on the saturated hysteresis loop and the polarization direction is upward. Then positive voltage pulses of 0.4V are repeatedly applied to the capacitor. As shown in this figure, the polarization of the film decreases by this operation, which is inconsistent with intuition as well as experimental results[7]. Similarly, the curve β shows extraordinary increase of the polarization. This failure is considered due to the procedure to determine the polarization value along a minor loop from the saturated polarization curve.

3. Parallel-element model and implementation

The problem of the above model can be solved by considering parallel connection of dipoles which have various values of coercive voltage. The idea of this parallel-element model is straightforward, but actual calculation is rather complicated[4,5]. More recently, the model was represented using circuit elements so that it could be introduced in SPICE simulator [6]. The elements used in the model were voltage-controlled resistors and voltage-controlled capacitors. In this model, however, it is anticipated that simulation time becomes longer when the higher accuracy is requested and the number of elements is increased. In such a case, it is more desirable to fabricate LSI chips to speed up simulation. From this point of view, use of real devices is essential in future application.

In this paper, we propose to use a combination of a Schmitt trigger circuit and a normal capacitor as an element in the parallel-element model, so that an LSI chip can be fabricated easily. Furthermore, since a normal capacitor is used, the time dependence of the polarization reversal can be implemented easily, as discussed in chapter 4.

Figure 2 shows a circuit diagram of the used Schmitt trigger circuit and the parallel-element model. As shown in Fig. (b), each element has different threshold values of polarization reversal and they can be controlled by the circuit parameters V_S and R_1. Since the output voltage of the circuit is ±1V, the total capacitance in Fig. 2(c) is equal to P_S (saturation polarization), where C_0 is the dielectric component of the ferroelectric capacitor. Whenever V_{in} passes the threshold value, the total polarization is changed by $\pm 2C_i$. A general method to derive the C_i values from experimental data is discussed in Ref. 6. More simply, the C_i values can be determined approximately using two sets of Schmitt trigger circuits, that is one set of V_S=0 and the other set of R_1=const.

Figure 3 shows simulated results for symmetric and asymmetric input conditions. Numbers of the elements used in the calculation are 413 and 1681 for (a) and (b), respectively. In actual calculation, a small resistor ($10^{-3}\Omega$) is connected in series to capacitors so that the transient current is suppressed within the calculation limit. As can be seen from Fig. (b), the polarization value is kept constant, even when voltages with small amplitudes are asymmetrically applied. We conclude from these results that this model can draw accurate hysteresis curves.

4. Time-dependent parallel-element model

In the model shown in Fig. 2, the polarization charges appear on the electrode immediately after the input voltage reaches the threshold voltage of a Schmitt trigger circuit. However, in the actual polarization reversal phenomenon, there is a finite delay time known as the polarization reversal time, which is a function of electric field applied to the ferroelectric film. The time dependence of polarization reversal is known to obey Avrami equation. Thus, in this model the time-dependent polarization can be represented by changing the capacitance $C_i(t)$ in the form of Avrami equation. However, since Avrami equation is not a simple function of time, it is necessary in actual calculation to divide each capacitor into smaller pieces, as shown in Fig. 4(a). The figure corresponds to i-th element in fig. 2(c). As shown in the figure, the clock frequency is changes in real time with V_{in} and the switches are sequentially turned on, after Schmitt trigger circuit is inverted. The resultant capacitance change is schematically shown in Fig. 4(b). SPICE simulation of Fig. 4 is now being conducted.

5. Conclusions

We proposed a novel parallel-element SPICE model using Schmitt trigger circuits. It was found that the novel model represented the electrical behavior of ferroelectric capacitors accurately, even when voltages were applied asymmetrically to the capacitor. Extension to the time-dependent model was also discussed.

Acknowledgments

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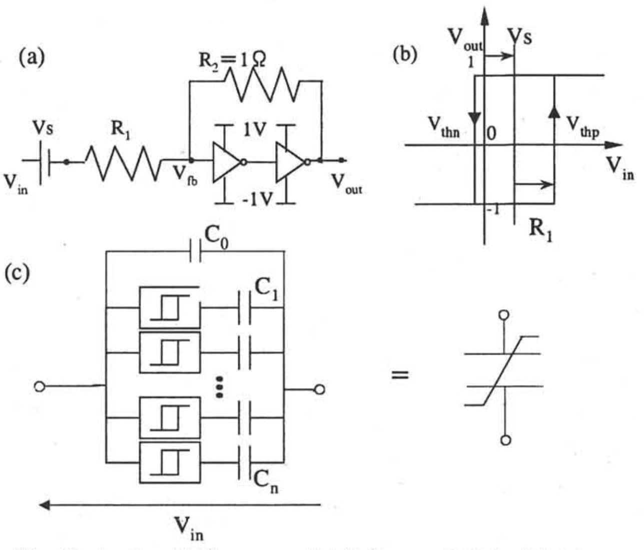

Fig. 2. A circuit diagram of (a) the used Schmitt trigger circuit and (c) the parallel-element model. (b) A characteristic of the Schmitt trigger circuit.

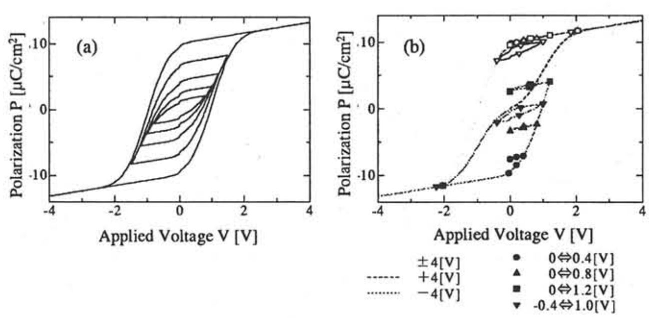

Fig.3. P-V hysteresis curves of a parallel-element model using Schmidt trigger circuit for (a) symmetric and (b) asymmetric inputs.

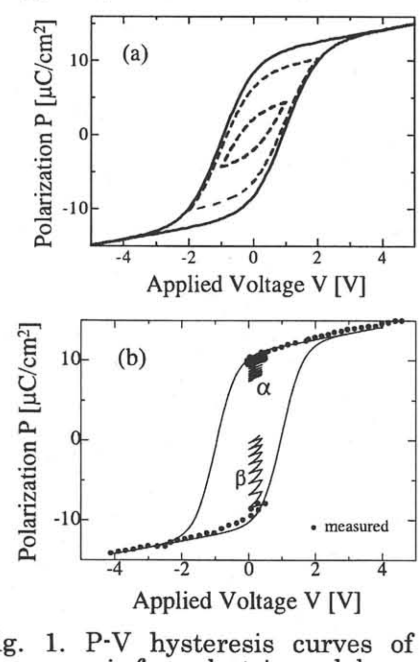

Fig. 1. P-V hysteresis curves of a macroscopic ferroelectric model.

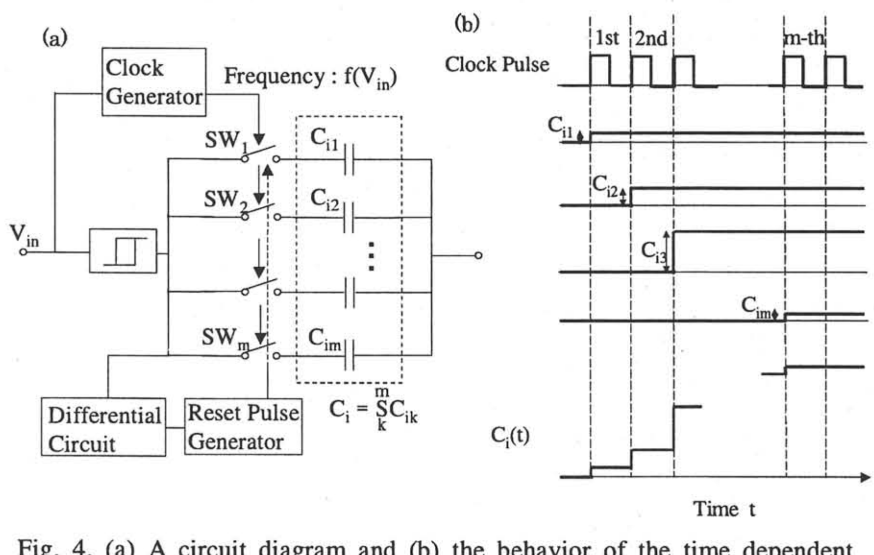

Fig. 4. (a) A circuit diagram and (b) the behavior of the time dependent parallel-element model.