SIMULATION OF FERROELECTRIC NONVOLATILE MEMORY CELLS WITH MINIMOS-NT

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Abstract

The basic goal of our approach is to set up a tool which is able to reproduce the macroscopic behavior of a ferroelectric device by calculating current, voltage and charge at the contacts correctly. To reach this several models were included into our simulator MINIMOS-NT, which allow a general transient two-dimensional simulation of arbitrary device structures.

1 Introduction

During recent years ferroelectric materials became more and more attractive for usage in nonvolatile memory cells. Increasing clock frequencies lead into a regime where the frequency dependence of basic material parameters like coercive field and remanent polarization can no longer be neglected. At high frequencies, the hysteresis widens and the coercive field increases, which is of fundamental interest for the extraction of parameters for write and read cycles like applied voltage or pulse length.

2 Hysteresis Model

MINIMOS-NT offers a rigorous approach to treat the static hysteresis properties [1][2] of ferroelectric materials, which was recently extended to the exact calculation of subcycles.

Using the box integration method, the third Maxwell equation

$$\mathrm{div}\vec{D} = \rho \tag{1}$$

is solved. To bring in hysteresis, we separate the electric displacement into a linear and a nonlinear part

$$\vec{D} = \varepsilon \cdot \vec{E} + \vec{P}. \tag{2}$$

The nonlinear part $\vec{P}$ holds the hysteresis and is modeled by

$$P = k \cdot f(E \pm E_c, k) + P_{\mathrm{off}}. \tag{3}$$

The parameters k and P_{off} are necessary for the simulation of the subcycles of the hysteresis, the function f is the shape function for the subcycles, E_c is the coercive field.

By now two different types of shape functions are implemented in the simulator, the $\tanh$ and the $\arctan$ function. The implementation for the $\tanh$ shaped function is

$$P = k \cdot P_{\mathrm{sat}} \cdot \tanh(w \cdot (E \pm E_c)) + P_{\mathrm{off}}. \tag{4}$$

P_{sat} is the saturation polarization. w is a shape parameter and the same for each locus curve. This function is a good approach for the material properties of PZT($\mathrm{Pb(Zr,Ti)O_3}$).

$$P = \frac{2}{\pi} \cdot k \cdot P_{\mathrm{sat}} \cdot \arctan(2 \cdot (E \pm E_c) \cdot \frac{k}{w}) + P_{\mathrm{off}}. \tag{5}$$

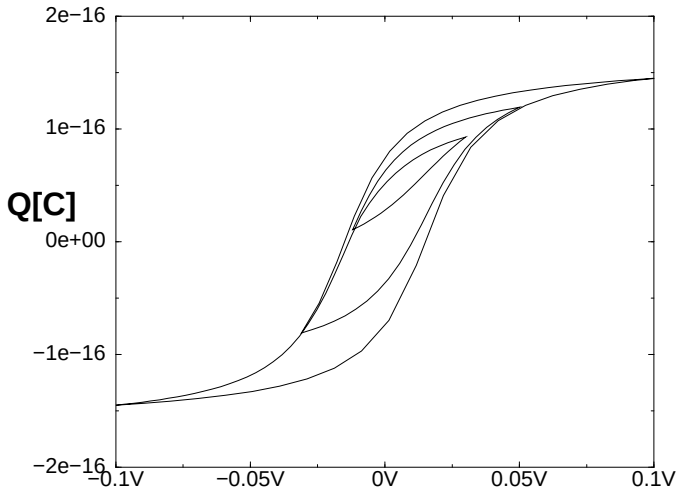

Fig. 1: Simulated hysteresis including multiple subcycles

is the implementation for the arctan shape function. Again, w is the shape parameter. The arctan function covers the physical properties of SBT($SrBi_2Ta_2O_9$) in a very accurate way. A drawback of this method is that the parameters of the locus curves have to be calculated numerically. This leads to a slight increase of the numerical afford and accordingly of the computation time.

Using these subcycles the whole history of the ferroelectric material is simulated. The necessary parameters are calculated according to Preisach hysteresis [3][4]. This allows the simulation of the following effects:

- Locus curves hit last turning point: Closed subcycles can be simulated
- Memory wipe out: A turning point erases all information of previous smaller turning points

A complete set of subcycles is plotted in Fig. 1, showing the simulation results for a planar capacitor.

3 Two-Dimensional Model

Expansion of hysteresis into two dimensions leads to a drastic increase of the complexity in the numerical and physical properties. However the effects concerning field rotation demand the development of a two-dimensional algorithm. It has to take into account the remanent polarization components orthogonal to the electric field, respecting the fact that there is an upper limit to the number of dipoles as well.

The generic method implemented in our device simulator MINIMOS-NT can handle both isotropic and anisotropic materials, respectively. Due to our generic approach, our algorithm is capable to deal with materials with one, two or three anisotropy axes with arbitrary orientations.

A typical implementation of a nonvolatile memory cell are integrated capacitors with common ground plate (= finger structure). The resulting hysteresis is outlined in Fig. 2.

4 Transient Model

According to the concept of our device simulator MINIMOS-NT we tried to find an analytic model based on differential equations instead of an approach based on statistical physics [5] in order to model the transient properties.

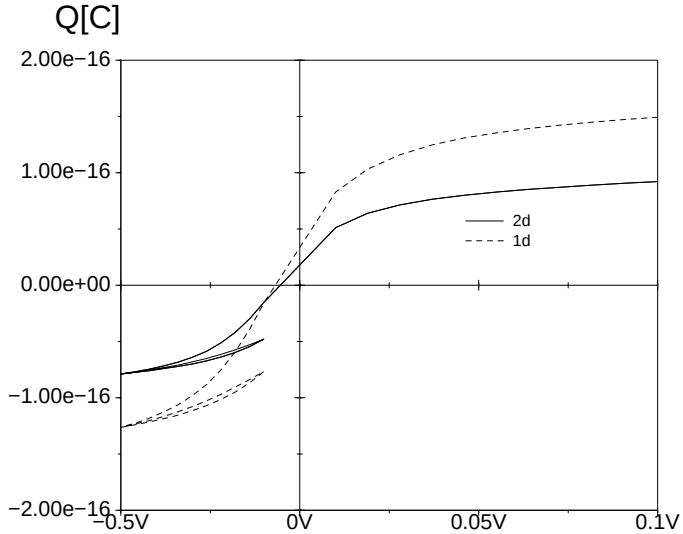

Fig. 2: 'One-dimensional' capacitor versus finger structure

We extended a common approach [6] for the frequency dependence of linear dielectric materials. We start with the static, nonlinear equation

$$P = f(E(t)). \tag{6}$$

Following our approach we add a transient term to the electric field

$$E(t) = E_{\text{stat}} + \tau_{ef} \cdot \frac{dE}{dt} \tag{7}$$

where E_{stat} is the static component of the electric field and τ a material dependent time constant. The actual electric field is calculated and can be entered into (6), thus forming the first term for the transient equation

$$P_{\text{ef}} = f(E(t)). \tag{8}$$

Basically, this terms shifts the hysteresis curves and increases the coercive field. Still following the approach for linear materials, we add a transient term stemming from the change of the polarization

$$P_{\text{pol}} = -\tau_{\text{pol}} \cdot \frac{dP}{dt}. \tag{9}$$

Again τ_{pol} is a time constant. Aside from increasing the coercive field as well, this term flattens the hysteresis. Experimental data shows that these two terms can be fitted into the physical properties in a limited range of frequencies only. In order to improve this,

$$P = P_{\text{pol}} + P_{\text{nonlin}} \tag{10}$$

a third term, representing the nonlinearity of the material, was added,

$$P_{\text{nonlin}} = c \cdot k_{\text{nonlin}} \cdot (P - P_{\text{ef}}) \cdot \frac{dE(t)}{dt}. \tag{11}$$

This term allows also a physical interpretation as it increases with the offset between the polarization component stemming from the electric field and the actual polarization. k_{nonlin} is a material dependent constant.

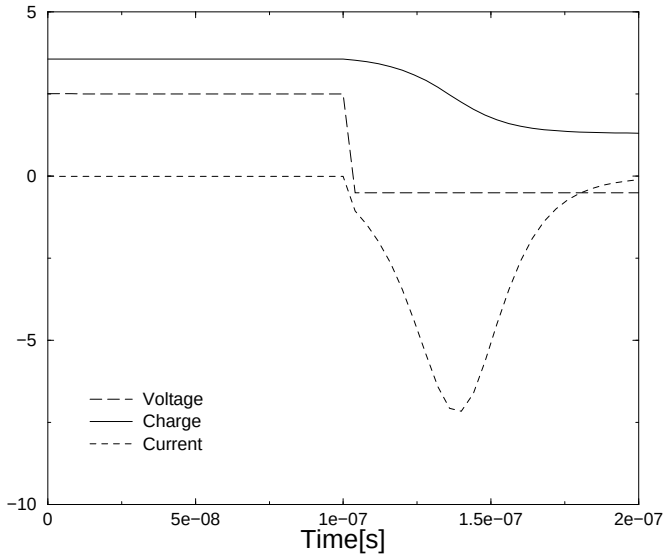

Fig. 3: Charge and current response of a voltage jump

Both transient equations (7) and (10) are discretized with a forward Euler scheme, which offers a reasonable stability.

With our model, the analysis of ferroelectric memory cells for arbitrary variation of the contact voltage is now possible. Fig. 3 shows the time depending current and charge when a voltage jump is applied to a capacitor.

Conclusion

The application of the new simulation tool to circuit simulation is very promising. It can immediately be used for the extraction of specifications for the read and write cycles of ferroelectric memory cells.

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