Two-Dimensional Simulation of Ferroelectric Nonvolatile Memory Cells

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Abstract

An approach to increase the capabilities of integrated circuit nonvolatile memory is to take advantage of the hysteresis in the polarization of ferroelectric materials. For a rigorous analysis of this and similar devices a suitable model for the ferroelectric effects has been developed. We describe this model and show the results of its implementation into a device simulator.

1. Introduction

The development of nonvolatile memory cells using ferroelectric materials leads to designs with two-dimensional hysteretic field properties like the ferroelectric field effect transistor (FEMFET), firstly described in [1]. Basically a FEMFET is an NMOS transistor modified by inserting a ferroelectric layer in the sub-gate area, as schematically outlined in Fig. 1. The simulation of the two-dimensional hysteresis curve leads to the nontrivial problem of field rotation and forces the calculation of a set of parameters for the nonlinear locus curve at each grid point. Aside from calculating the exact field distribution a simulator for ferroelectric devices has to fulfill further properties: To allow the calculation of transfer characteristics it has to be insensitive to the magnitude of the applied voltage steps. To keep pace with future developments of ferroelectric devices, the expansion of the algorithm to three-dimensions should be possible.

2. The Simulation Model

Primary focus was laid on the simulation of field rotation. This means that as described in [2] and [3] a constant rotation of a magnetic field will cause a lag angle χ of the induction. It is intuitive that the properties for ferroelectric problems will be similar. For a rigorous two-dimensional analysis, the simple approach to decrease the electric field first to zero, then to increase it to the value of the next operating point and to add the two derived polarization components cannot be employed, as it is inconsistent with the one-dimensional hysteretic properties. Even more the results strongly depend on the distance between the calculated operating steps. According to this we assume a straight trajectory between the vectors of the old and the newly applied electric field. This also assures a proper numerical behavior if the

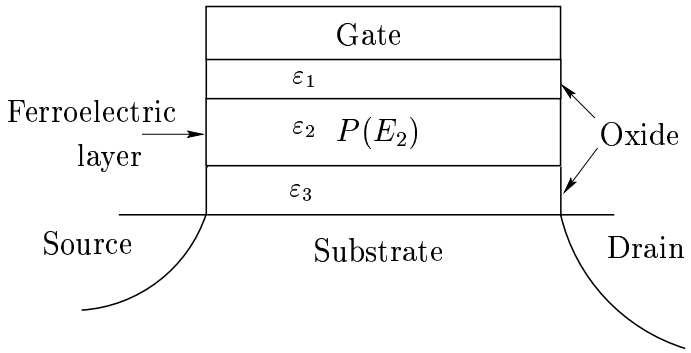

Figure 1: Ferroelectric nonvolatile memory field effect transistor.

applied voltage steps will be increased. The basic principle of our model is to split the polarization $\vec{P}_{old}$ and the electric field $\vec{E}_{old}$ of the previous operating point into the components in the direction of the next applied electric field $\vec{P}_{old,\parallel}$ and $\vec{E}_{old,\parallel}$ as well as orthogonal $\vec{P}_{old,\perp}$ and $\vec{E}_{old,\perp}$. For each of these components a locus curve is calculated. These curves lead to the polarization in direction of the electric field and the remanent polarization in the orthogonal direction, thus forming a primary guess $\vec{P}_0$ for the next polarization.

As plotted in Fig. 2 $\vec{P}_0$ is divided into a component in the direction of the electric field $\vec{P}_{\parallel}$ and into the orthogonal component $\vec{P}_{\perp}$. The scalar values of the two components are added and compared to the maximum polarization at the given magnitude of the electric field $\|\vec{E}\|$, forming an upper limit for the available number of switching electric dipoles. Due to the vanishing electric field in the normal direction making it easier to switch the dipoles in this direction than the dipoles held by the electric field, the orthogonal component $\vec{P}_{\perp}$ is reduced appropriately in respect to this limit. This is shown schematically in Fig. 3 and it leads to the actual polarization vector $\vec{P}_1$ and the lag angle χ. As a first approach to the upper limit in the available number of switching dipoles the saturation polarization $\vec{P}_{sat}$ was considered, but the simulator is already prepared to use any function of the magnitude of the applied electric field $\|\vec{E}\|$. The algorithm to handle field rotation is also capable to deal with three-dimensional problems.

For a general approach to two-dimensional hysteretic effects an inhomogeneous field distribution has to be assumed. This prevents the usage of a simple one-dimensional hysteresis model using the same locus curve for the complete ferroelectric region. According to the algorithm presented above two different locus curves have to be calculated for each grid point. Therefore, numerical methods to calculate the locus curves as described in [1] and [4] cannot be applied. In order to overcome these difficulties a model was implemented into the device simulator MINIMOS-NT which describes all hysteresis curves by *tanh* functions derived from analytical calculations. The parameters of the locus curves are calculated using the projections of the old directions of the old electric field $\vec{E}_{old,\parallel}$, $\vec{E}_{old,\perp}$ and the old polarization field $\vec{P}_{old,\parallel}$, $\vec{P}_{old,\perp}$. This hysteresis model was chosen in accordance to [5]. To adjust this model to the two-dimensional case the locus curves are not calculated due to the last turning point but to the saturation polarization, so the lancette curves will not exactly fit the-one dimensional hysteresis model. The resulting locus curves plotted in Fig. 6 are the result of a transient simulation of a capacitor with a ferroelectric dielectric.

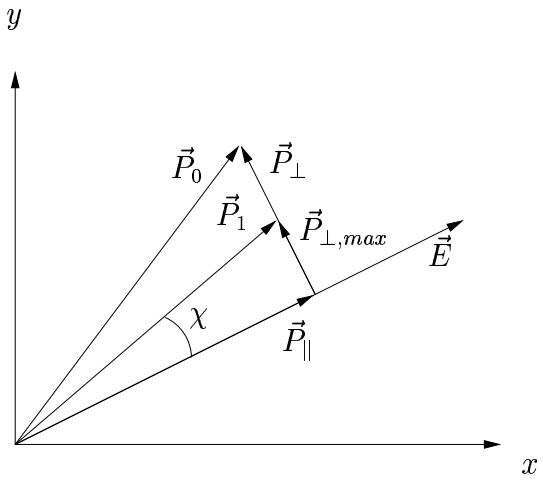

Figure 2: Calculation of the resulting polarization.

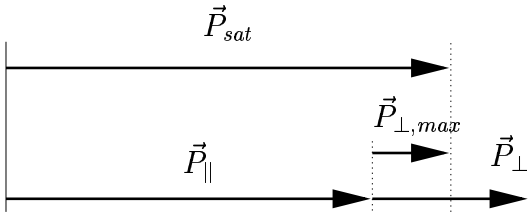

Figure 3: Reduction of orthogonal component.

For a good numerical behavior it is calculated whether the electric field will be incremented or not before starting the actual solving process, because for each of this two cases a different set of parameters has to be calculated, thus leading to different locus curves and derivatives. This assures that the correct derivatives will be used in the Jacobian matrix. A suitable approach to receive this direction information is to vary only the linear part of the electric displacement and to keep the polarization constant.

3. Simulation of the FEMFET

The FEMFET is a device based on the hysteretic properties of the polarization and the displacement of a ferroelectric material. According to Poisson's equation the displacement influences the charge at the surface of the substrate. The different contributions of the space charge density of a usual NMOS transistor and a FEMFET were calculated with MINIMOS-NT and are plotted in Fig. 4 and Fig. 5.

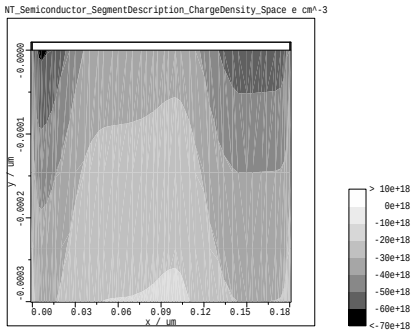

Figure 4: Space charge density of the NMOS.

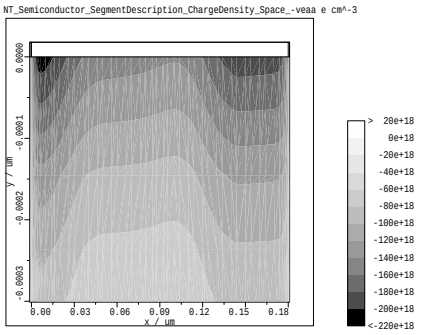

Figure 5: Space charge density of the FEMFET.

The FEMFET was constructed by inserting a ferroelectric segment in the sub-gate area of the NMOS, as outlined in Fig. 1. The threshold voltage of the NMOS was 0.7 V and 0.6 V for the FEMFET. The operating point of the ferroelectric material

was chosen on the initial polarization curve. In this case the ferroelectric polarization increases the displacement and as shown in the figures leads to a significant higher space charge density in the channel area. This will cause a higher drain current of the FEMFET for the same gate voltage. As a result of the the hysteretic behavior of the polarization the drain current of the device does not only depend on the gate voltage but also on the history of the gate voltage. So the I–V characteristics of the transistor show also a hysteresis, which allows the use of the device as a nonvolatile memory. Fig. 7 shows the simulated I–V characteristics for NMOS and FEMFET received by sweeping the gate voltage from zero to saturation and vice versa. The bulk voltage was set to 0.5 V, the drain voltage to 0.1 V. With a flat hysteresis curve we received a voltage shift of 0.1 V.

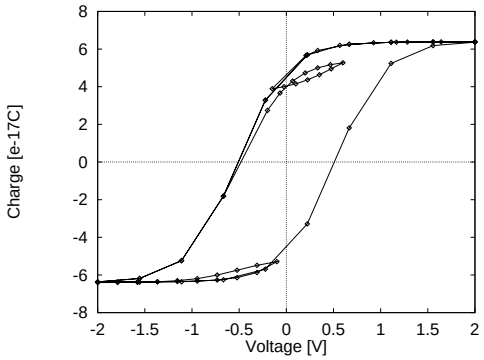

Figure 6: Simulated hysteresis curve.

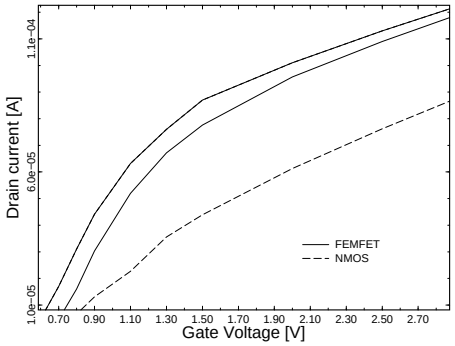

Figure 7: Simulated I-V characteristics of FEMFET and NMOS.

4. Conclusion

A general two-dimensional model for devices including at least one ferroelectric segment has been developed and was implemented into the simulator MINIMOS-NT. It is shown that it is possible to simulate materials with hysteretic properties even if they included in complex structures like a FEMFET. With calibration of simulations to measurements it is now possible to find effective material parameters for the new ferroelectric device technology.

References

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