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Two-Dimensional Simulation of Ferroelectric Memory Cells

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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 devices, a suitable model for the ferroelectric effects has been developed. We describe this model and show the results of its implementation in a device simulator.

I. 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 Ref. 1. Basically a FEMFET is an n-channel metal oxide semiconductor field-effect transistor (NMOS) modified by inserting a ferroelectric layer in the sub-gate area, as schematically outlined in Fig. 1. A simulation of the two-dimensional hysteresis curve leads to a 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 algorithm must be capable of being expanded to three-dimensions.

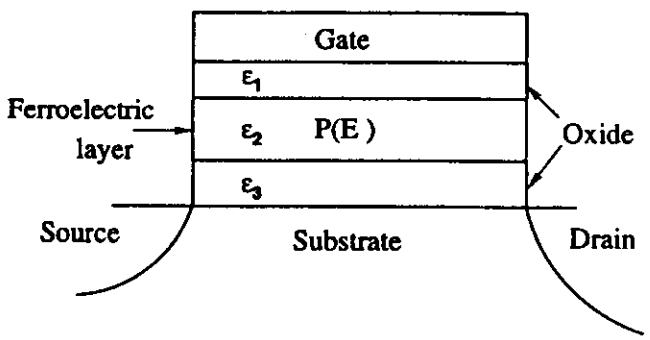

Fig. 1. Ferroelectric nonvolatile memory field-effect transistor.

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II. THE SIMULATION MODEL

The primary focus was laid on the simulation of the field rotation. This means that as described in Refs. 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 proper numerical behavior if the applied voltage steps are increased. The basic principle of our model is to split the polarization $\boldsymbol{P}_{old}$ and the electric field $\boldsymbol{E}_{old}$ of the previous operating point into components parallel to the direction of the next applied electric field $\boldsymbol{P}_{old,\parallel}$ and $\boldsymbol{E}_{old,\parallel}$ and into components orthogonal to that field $\boldsymbol{P}_{old,\perp}$ and $\boldsymbol{E}_{old,\perp}$. For each of these components, a locus curve is calculated. These curves lead to the polarization in the direction of the electric field and to the remanent polarization in the orthogonal direction, thus forming a primary guess $\boldsymbol{P}_0$ for the next polarization.

As plotted in Fig. 2 $\boldsymbol{P}_0$ is divided into a component in the direction of the electric field $\boldsymbol{P}_{\parallel}$ and into an orthogonal component $\boldsymbol{P}_{\perp}$. The scalar values of the two components are added and compared to the maximum polarization at the given magnitude of the electric field $\|\boldsymbol{E}\|$, forming an upper limit for the available number of switching electric dipoles. Because the electric field vanishes in the normal direction making it easier to switch the dipoles in this direction than it is to switch the dipoles held by the electric field, the orthogonal component $\boldsymbol{P}_{\perp}$ is reduced appropriately with respect to this limit. This is shown schematically in Fig. 3 and leads to the actual

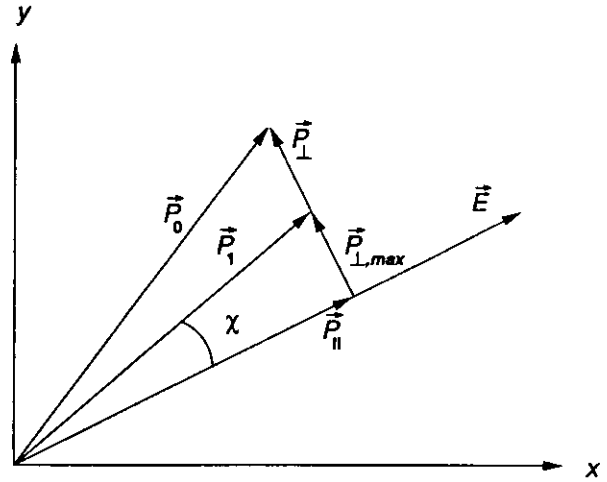

Fig. 2. Calculation of the resulting polarization.

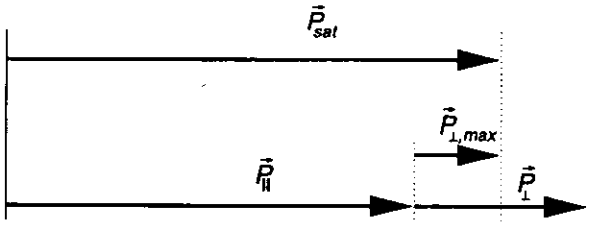

Fig. 3. Reduction of the orthogonal component.

polarization vector $\boldsymbol{P}_1$ and the lag angle χ. As a first approach to the upper limit in the available number of switching dipoles, the saturation polarization $\boldsymbol{P}_{sat}$ was considered, but the simulator was already prepared to use a function of the magnitude of the applied electric field $\|\boldsymbol{E}\|$. The algorithm to handle field rotation was also capable of dealing 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 Refs. 1 and 4 cannot be applied. In order to overcome these difficulties, we implemented a model into the device simulator MINIMOS-NT to describe all hysteresis curves by the *tanh* functions derived from the analytical calculations. The parameters of the locus curves are calculated using the projections of the old directions of the old electric field $\boldsymbol{E}_{old,\parallel}$, $\boldsymbol{E}_{old,\perp}$ and the old polarization field $\boldsymbol{P}_{old,\parallel}$, $\boldsymbol{P}_{old,\perp}$. This hysteresis model was chosen in accordance with Ref. 5. To adjust this model to the two-dimensional case, we did not calculate the locus curves due to the last turning point but calculated those due to the saturation polarization, so the lancette curves did not exactly fit the one-dimensional hysteresis model. The locus curves plotted in Fig. 6 are the result of a transient simulation of a capacitor with a ferroelectric dielectric.

For good numerical behavior, whether or not the electric field will be incremented is determined before starting the actual solving process because for each of these 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.

III. SIMULATION OF THE FEMFET

The FEMFET is a device based on the hysteretic properties of the polarization and the displacement of a fer-

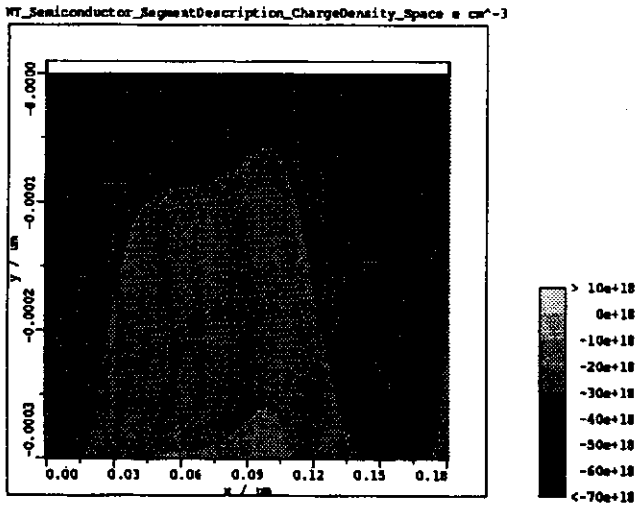

Fig. 4. Space-charge density of the NMOS.

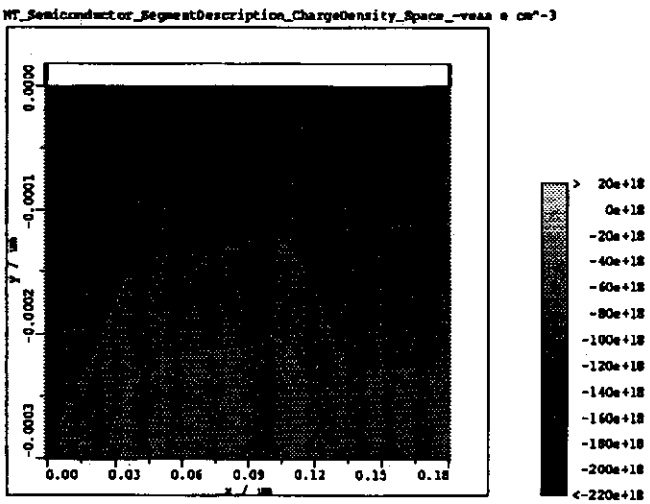

Fig. 5. Space-charge density of the FEMFET.

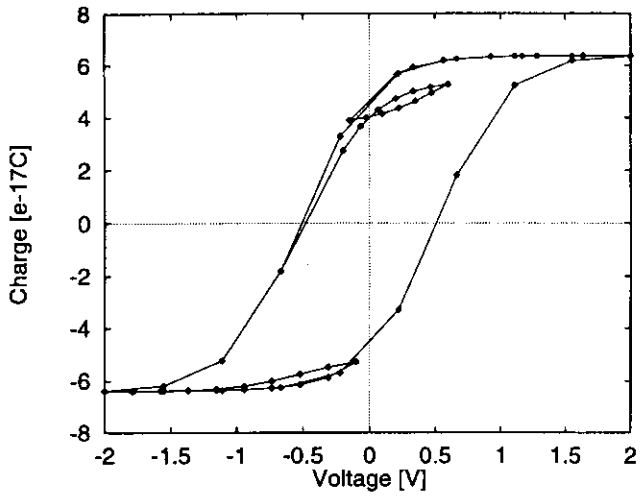

Fig. 6. Simulated hysteresis curve.

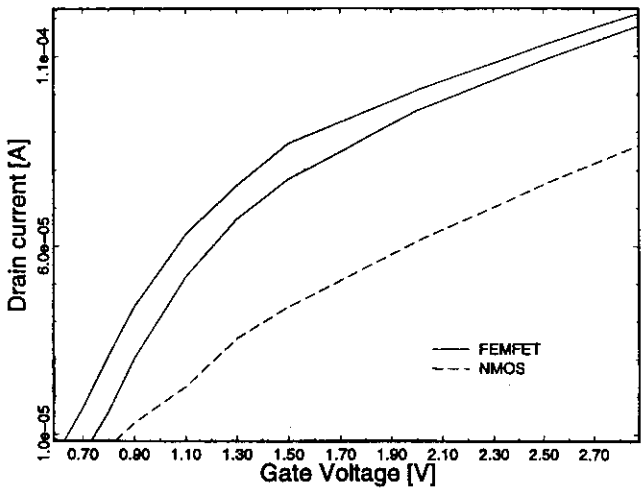

Fig. 7. Simulated I-V characteristics of the FEMFET and the NMOS.

roelectric 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.

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 that of the FEMFET was 0.6 V. 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 significantly 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 hysteretic behavior of the polarization, the drain current of the device not only depends on the gate voltage but also on the history of the gate voltage. Thus, I-V characteristics of the transistor also show a hysteresis, which allows the use of the device as a nonvolatile memory. Figure 7 shows the simulated I-V characteristics received for the NMOS and the FEMFET by sweeping the gate voltage from zero to saturation and vice versa. The bulk voltage was set to 0.5 V, and the drain voltage to 0.1 V. With a flat hysteresis curve, we received a voltage shift of 0.1 V.

IV. CONCLUSIONS

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

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