EPROM DESIGN USING DEVICE SIMULATION

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ABSTRACT

The energy transport (ET) method has been used for the simulation of EPROM programming. After the appropriate non-Maxwellian energy distribution is calculated based on an average energy determined using the ET method, an expression for injected gate current is integrated to find total gate charge, and hence threshold voltage shift, as a function of time. Comparison of theoretical and experimental results for actual EPROM programming validates the method. The effects of varying doping profile on EPROM performance are also demonstrated. ET simulation is shown to be a useful and efficient means of aiding the design of EPROM devices.

I. Introduction

EPROM programming is sensitive to many device parameters, such as channel length and width, thicknesses of the oxides between control and floating gates and below the floating gate; drain and control gate voltages; substrate impurity concentration and distribution; etc. Because of the complicated nature of this sensitivity, particularly in submicron-scale devices, simple design rules may be deceptive. Simulation based on correct physics can be very useful in reducing design time and costs for these devices.

II. Approach

For simulation purposes, we represent an EPROM device as a MOSFET whose gate takes the place of the floating storage gate of the EPROM. The charge injected into the floating gate determines the threshold voltage of the device. In order to perform a simulation, the effective value of the voltage on the floating gate during programming must be known. The value of this voltage is taken as the gate voltage that must be applied to the equivalent MOSFET in order to produce the specified value of drain current at the specified value of drain voltage during programming. Given these parameters, a two-dimensional ET simulation can be performed to obtain average electron energy at each point in the device.[1] If the *form* of the distribution function is known, the quantified distribution function can then be obtained on the basis of this average energy.

The first two terms of the Legendre polynomial expansion can be used to represent the form of the distribution function, and appropriate methods for determining the details of the polynomial expansion on the basis of the average energy have been described elsewhere.[2] The two-dimensional simulation gives the density of electrons at each point; the distribution function tells us what the energy of these electrons is; and the charge injected into the gate can be obtained by using a suitable description of charge injected into the gate as a function of these parameters. Time dependence of the charge injected into the gate--and hence of shift of threshold voltage, or how much programming has been achieved, can be calculated as a function of time by stepping the simulation, adjusting the equivalent floating-gate voltage at each time step according to the charge that has reached it and its capacitances. It is important to use for this purpose a formulation for the injected current that is correct for the actual energy distribution, which is not Maxwellian. The expression for injection that we use is an exponential one that reduces to Richardson's equation for a Maxwellian distribution function.[3]

III. Calculation

A. Control Gate Voltage

EPROM programming simulation begins with a solution using our program UMDFET[4] of the two-dimensional energy transport and Poisson equations for the equivalent MOSFET, to determine the equivalent EPROM floating gate voltage required to produce the specified programming drain current at the programming drain voltage. This is

an iterative process; since gate voltage is usually an independent input variable and drain current a dependent variable, UMDFET had to be "turned around" to determine gate voltage for an input drain current, by trial-and-error. In EPROM programming the control (second) gate voltage is adjusted to regulate programming. The control gate voltage required to produce the determined equivalent EPROM floating-gate voltage was calculated using the equivalent capacitances between floating and control gates and between these gates and the substrate. Simple parallel-plate capacitance values were used for each of these gates, although the situation in the actual EPROM, where the surfaces of these gates are not planar, is more complicated.

B. Programming Currents

Our method for the calculation of hot-electron-induced gate currents, on the basis of the real non-Maxwellian distribution function, has also been described elsewhere.[5] UMDFET provides values of average electron energy at all points of its two-dimensional mesh. Electron injection from the entire device volume should be calculated, but for the calculations to be illustrated here we simplified the problem by considering that only those electrons flowing within the first few hundred Angstroms of the oxide/silicon interface contribute to gate current, and used the one-dimensional equation for average energy.

$$\frac{dw}{dx} = \frac{21}{20}\epsilon E - \frac{9}{20}\left(\frac{40}{9}\frac{m^*}{\tau_p \tau_w}(w - w_0) + \epsilon^2 E^2\right)^{1/2} \qquad (1)$$

In (1), w = average electron energy, E = electric field at the surface, t_p = energy-dependent momentum relaxation time, t_w = energy-dependent energy relaxation time, and w_0 = equilibrium electron energy.

A Legendre polynomial form was used for the energy distribution function $f_0(E)$ at each point, and the gate current density $J_g(x)$ was then calculated using:

$$J_g(x) = \frac{qN_o(x)}{A(x)} \int_{q\phi_b}^{\infty} < V_x > f_o(\epsilon) d\epsilon \qquad (2)$$

$N_o(x)$: carrier density $(/cm)$

$f_o(\epsilon)$: distribution function

ϕ_b : oxide barrier height

$\epsilon = w + \beta w^2 \quad (\beta = 0.5)$

$$A(x) = \int_0^{\infty} f_o(\epsilon) d\epsilon$$

$$< v_x > = \frac{1}{\hbar} \cdot \frac{\partial w}{\partial \beta_x}$$

Not all electrons with enough nominal energy to overcome the potential barrier at the surface will escape into the oxide and eventually into the floating gate, because of collisions they may suffer before reaching the oxide/Si interface. This phenomenon has been taken into account by use of an oxide scattering factor, which we call P_{os}.[6]

$$P_{os} = \exp\left(-\frac{x_o}{\lambda_{ox}}\right)$$

λ_{ox} : electron MFP in the oxide

$$x_o = \sqrt{\frac{q}{16\pi\epsilon_{ox}E_{ox}}} \qquad (3)$$

$q = 1.602E - 19$ (Coulomb)

E_{ox} : oxide field (V/cm)

$\epsilon_{ox} = 3.9 \times 8.854\ 10^{-14} (F/cm)$

We used the value of 3.4nm for the electron mean free path in the oxide.

C. Enhancing Convergence

Convergence of our simulation at the high fields that occur during EPROM programming was facilitated by two-dimensional extrapolation of potential and electron density to find new trial solutions from iteration to iteration, and verified by testing of both current continuity and voltage convergence.[7] As charge builds up on the floating gate, the effective potential of this gate, and the electric field configuration, change. Charge injected into the gate was taken to be uniformly distributed on it, for the calculation of electric fields. Threshold voltage was calculated on the basis of the amount of charge on the gate, and its capacitance relative to the substrate. The calculation was then stepped in time to determine threshold voltage shifts. A flow chart of the entire EPROM programming simulation is shown in Figure 1.

IV. Results

We simulated EPROM devices with one~two micron channels and drain/gate voltages up to 17/13V on a Sun 3/60, using the methods described above. Calculation results are compared with experimental data for the programming of 1.25 micron channel EPROMs in Figure 2, for programming (control gate) voltages of 7, 8, and 9V. The calculated threshold voltage shifts agree

very well with the experimental results, even though only one adjustable parameter (optical phonon scattering probability in the energy transport simulation) was available for the energy calculation.

In order to show the usefulness of simulation in analyzing the effects of, e.g., doping profile on programming, we also simulated somewhat larger devices, deriving electric fields from a drift-diffusion program, and determining electron temperatures along the surface using a one-dimensional approximation.[8] The doping profiles in the channel which were to be compared are shown in Figure 3; gate injection current at the beginning of the programming cycle (no charge initially on the floating gate) is shown in Figure 4. It is clear that the highest concentration will yield the fastest start to programming, but further simulation is needed to reveal whether this speed advantage can be maintained, and what tradeoffs in, e.g., breakdown voltage, must be suffered.

V. Conclusions

The method we have demonstrated here is simple enough to be made available to design engineers at individual work stations, and can be applied to the efficient determination of the effects of varying design parameters on EPROM programming times. Alternative methods, such as those based on "lucky electron" models or those that use the Monte Carlo method, are respectively either much too approximate or much too expensive for this purpose.

REFERENCES

Much of the work summarized here was presented by T. Urai and J. Frey in "Simulation of EPROM Programming Characteristics" at the NUPAD 90 Conference, Honolulu, HI, June 10, 1990.

1. R. Stratton, "Diffusion of Hot and Cold Electrons in Semiconductor Barriers", *Physical Rev. 126*, 2002 (1962)

2. N. Goldsman and J. Frey, "Electron Energy Distribution for Calculation of Gate Leakage current in MOSFETs", Solid State Electron. 31, 1089 (1988)

3. N. Goldsman and J. Frey, "Prediction of Hot Electron Induced Gate Currents", presented at Device Research Conference, Amherst, MA, June 25, 1986

4. Peng, Z.Z., "UMDFET-A Two-Dimensional Device Simulator and its Application in EPROM Device Analysis", M.Sc. thesis, University of Maryland, 1989

5. N. Goldsman and J. Frey, "Efficient and Accurate Use of the Energy Transport Method in Device Simulation", IEEE Trans. ED-35, 1524 (1988)

6. Berglund, C.N., and Powell, R.J., "Photoinjection into SiO_2: Electron Scattering in the Image Force Potential Well", J. Appl. Phys. 42, 573-579 (1971)

7. Z.Z.Peng and Jeffrey Frey, "Facilitating Convergence in EPROM Device simulation", presented at NASECODE VI, Dublin, Ireland, June, 1989

8. Jeffrey Frey and N. Goldsman, "Tradeoffs and Electron Temperature Calculations in Lightly Doped Drain Devices", *IEEE Electron Dev. Lett. EDL-6*, 28 (1985)

FIGURES

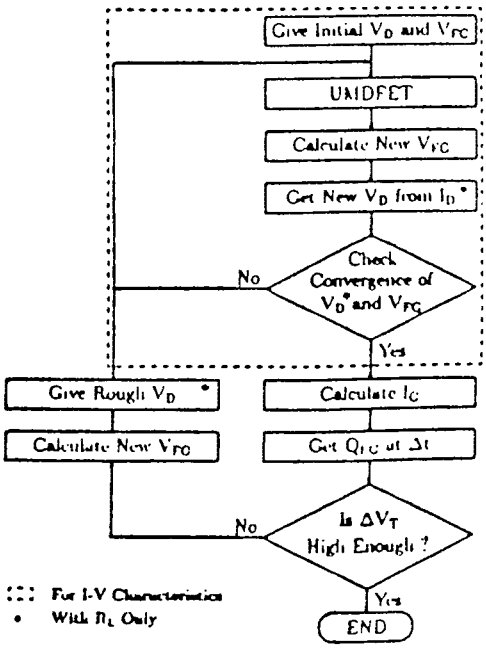

Figure 1. Flow chart for EPROM programming simulation.

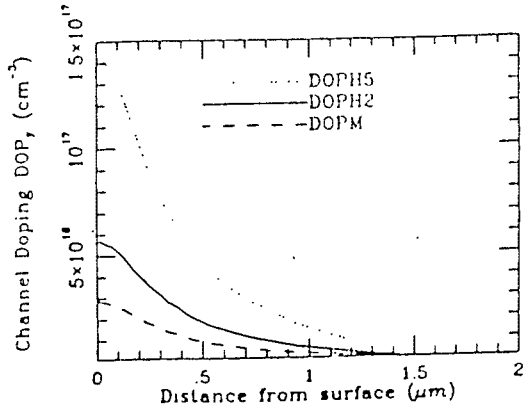

Figure 3. Channel doping profiles for three simulated EPROM cells.

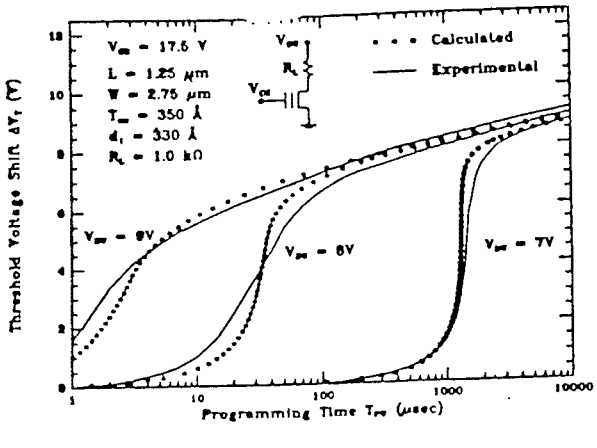

Figure 2 Change of threshold voltage with programming time as a function of control gate voltage.

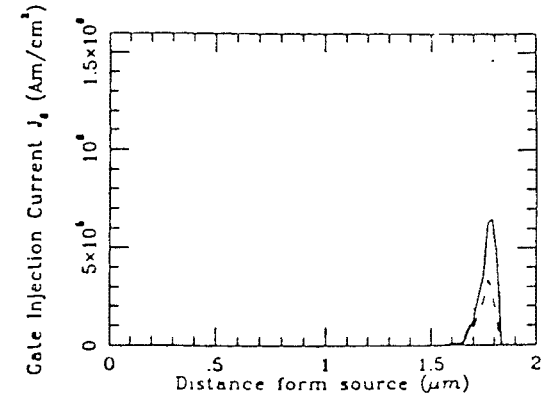

Figure 4 Current density injected into the gate along the channel for the three simulated EPROM cells.