ADVANCED SPICE-LIKE MODELING OF E²PROM CELLS *.

M.Lanzoni, J. Suñé, C.Riva (†), P. Ghezzi (†), P.Olivo and B. Riccò

DEIS University of Bologna, (†) SGS-Thomson,Italy

One of the main issues in the design of Electrically Erasable PROMs (E²PROM) is the capability to correctly simulate at circuit level the behavior of the memory cell during programming. As far as FLOTOX [1] cells are concerned, an accurate and effective SPICE model has to account for various phenomena taking place within the injector area, i.e. the thin oxide separating the floating gate (FG) from the drain and the interfaces with the surrounding semiconductor.

This work is intended to present an advanced SPICE-like model of FLOTOX cells that considerably improves the state of the art, because it considers quantum effects that have been completely overlooked in existing works [2], in spite of their playing a significant role in determining the tunneling current used in cell programming.

The equivalent circuit of the cell used so far is shown in Fig. 1. An ideal MOS transistor (representing the cell sense transistor driven by the floating gate) is part of a complex capacitive network modeling the couplings between the FG and the other regions of the cell. A controlled voltage source (V_{si}) is connected in series to the tunnel capacitor (C_t) to model the sum of the voltage drops into the semiconductor (φ_s) and the polysilicon (φ_p). A tunnel diode (D_{fn}) is connected in parallel to C_t to model the current flowing through the thin oxide during programming that is expressed by the well known Fowler-Nordheim equation. This latter contains two parameters, often adjusted to fit experimental results, that depend on a few physical quantities, among which the $Si - SiO_2$ barrier height (Φ_0) plays a dominant role.

Unfortunately, the simplest type of modeling making use of constant values of Φ_0 and V_{si} (as done in [2]) leads to significant differences between simulations and measurements, mainly because the dependence of Φ_0, φ_p and φ_s on the field into the oxide (E_{ox}) is not considered. A first improvement can be obtained using classical expressions for φ_s and φ_p. In this case, however, important quantum effects into the accumulation layer near the oxide interface are neglected. The most important consequences of such effects are: a) an effective barrier height (Φ_{eff}) depending on E_{ox} must be considered; b) the classical expression of the (field dependent) band bending within the injecting semiconductor, significantly underestimates the voltage drop V_{si} in series with C_t, hence it must be replaced by a "quantum" one.

Recently, both these effects have been studied exactly with a complex numerical procedure described in [4] (of course, unsuitable for SPICE modeling). In the present paper, simplified analytical expressions approximating such a theory are implemented in a SPICE model for FLOTOX cells, that has been compared with accurate simulations of cell programming.

The model used in this work is represented in the flow diagram of Fig. 2. After the potential V_{fg} between FG and drain has been calculated, the field into the oxide is obtained by solving the second order equation expressing V_{fg} as a function of φ_s, φ_p and the MOSFET flat-band voltage (V_{FB}). In this equation, the quantum potential drop into the accumulated injecting layer(φ_{acc}) is expressed by

$$\varphi_{acc} = a_0 + a_1 E_{ox} + a_2 E_{ox}^2 \qquad (1)$$

where a_0, a_1 and a_2 are constants, while band bending into the depleted layer is calculated by means of the classical expression. The effective "quantum" barrier height Φ_{eff} is given by the following expression

$$\Phi_{eff} = \Phi_0 - (c_0 + c_1 E_{ox} + c_2 E_{ox}^2). \qquad (2)$$

The as and cs parameters of equations (1) and (2) are determined once and for all in the development of the simplified version of the "quantum" theory of accumulated layers of ref. [4]. Finally, the tunneling current is evaluated by means of the usual Fowler-Nordheim expression using Φ_{eff} instead of Φ_0. The whole procedure is then repeated until self-consistency between the current and the charge on the FG (Q_{fg}) is obtained.

In order to compare the model with experiments, measurements of the cell main parameters have been performed on test structures (essentially arrays of cells connected in parallel with the FG made accessible). Program characteristics have been obtained multiplying the derivative of the cell threshold voltage as a function of time by the capacitance (C_{pp}) between the floating- and the control-gate as described in [3]. Fig. 3 shows results of simulations performed using both the model of ref. [2] and the quantum model, as well as to measurements of cell erase current obtained for various values of the maximum program pulse voltage (V_{pmax}). As can be seen, only the quantum model gives good agreement with experiments in all cases. In particular, with the simple model of ref. [2] parameter values that optimize the agreement at $V_{pmax} = 14V$ produce significant errors in the other cases. The model of this work provides very good agreement with experiments, also in the case of cell writing and of different values of the programming pulse characteristics (leading edge duration, V_{pmax},..).

* Work partially supported by EEC under the project ESPRIT-APBB.

The model presented in this paper has been found in good agreement with measurements in all cases. Furthermore it is suitable for implementation in SPICE, since the closed form by which J_t can be expressed as a function of V_{fg} and technological parameters allows to reduce part of the equivalent circuit (V_{si} and D_{fn}) to a simpler module (D_q)representing the whole injector area (Fig. 4).

References

[1] J. Lee et al., IEDM 83 Tech. Dig., p. 589, 1983.

[2] R. Bez et al., Journal de Physique, Vol. 49, Suppl. No 9, p. C4-677, 1988.

[3] R. Bez et al., IEEE Trans. on Electron Dev., Vol. 37, p. 1081, 1990.

[4] J. Suñé et al., submitted to J. of Appl. Phys.

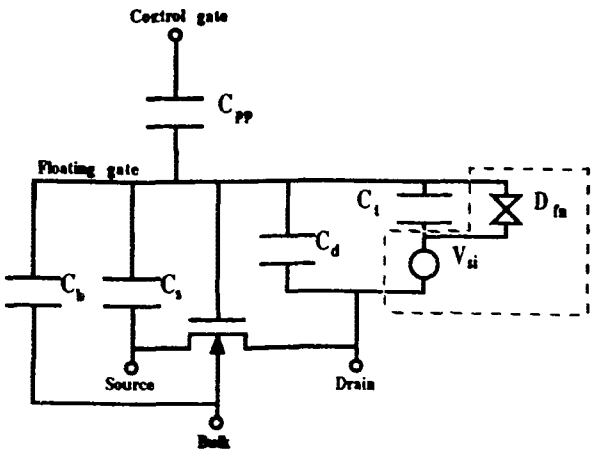

Fig. 1 Equivalent circuit of E²PROM cells used in simulations. C_s, C_d and C_b are the capacitances between the floating gate (FG) and source, FG and drain, FG and bulk, respectively; C_{pp}, instead, denotes the capacitance between FG and the control gate of the cell sense transistor. V_{si} represents the total voltage drop in the semiconductor regions. The tunnel diode D_{fn} provides a current described by the well known Fowler-Nordheim expression. The present work provided advanced models for the part enclosed within dotted line.

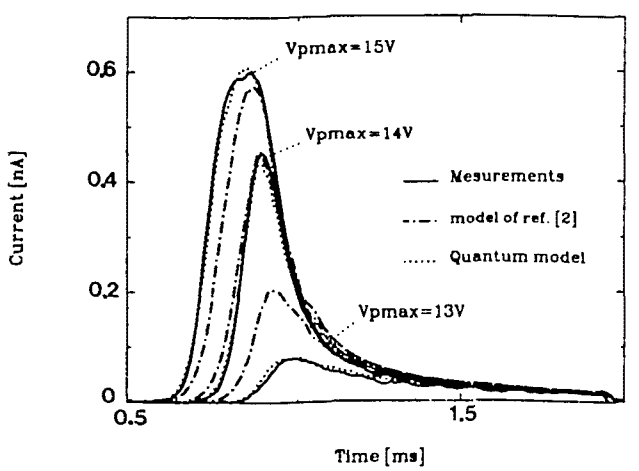

Fig. 3 Comparison between measurements (solid lines) and simulations of cell erasing. The maximum amplitude of program pulse (V_{pmax}) has been varied while the leading edge and width were always 1 and 2 ms, respectively. As can be seen, simulations using the model of ref [2] (dash-dotted lines) do not fit measurements at various values of V_{pmax}. On the contrary the quantum model (dotted lines) allows to obtain good agreement in all cases.

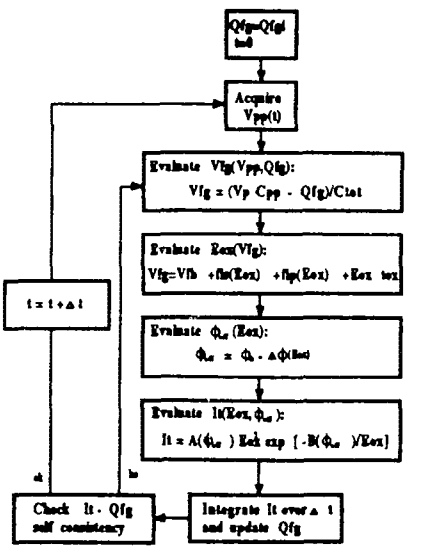

Fig. 2 Flow diagram of the simulator using the "quantum" model of E²PROM cells. Particular care has been taken to guarantee the self-consistency between the charge into the floating gate and the tunnel current. This allows to perform simulations with a wide time step (saving computing time) without numerical drawbacks.

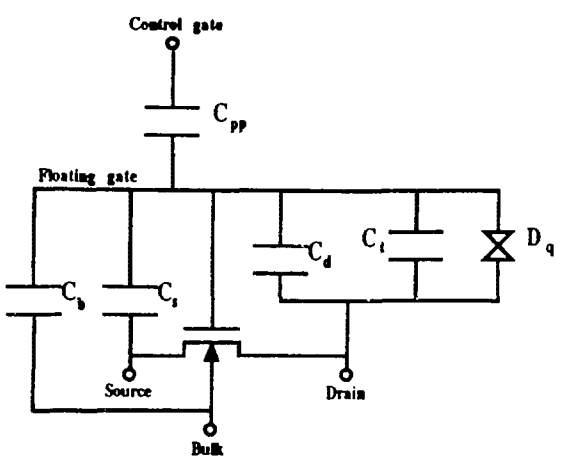

Fig. 4 Equivalent circuit of E²PROM cells of the present work. The main difference with that of Fig. 1 is due to the replacement of the block D_{fn} and V_{si} with a single "quantum" element (D_q).