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HAL Id: jpa-00227880
https://hal.science/jpa-00227880

Submitted on 4 Feb 2008

SPICE MODEL FOR TRANSIENT ANALYSIS OF EEPROM CELLS

R. BEZ, D. CANTARELLI, P. CAPPELLETTI and F. MAGGIONI

*SGS-Thomson Microelectronics, Via C. Olivetti 2, Agrate Brianza (MI),
Italy*

Abstract. *An equivalent model for the EEPROM cell, described on a SPICE circuit analyzer,
is used for the transient analysis of erase(E)/write(W) characteristics with ramp waveform
programming pulses. The results of the simulation are compared with the experimental data
obtained by an innovative method for measuring E/W curves. The validation of the model is
made over different variations of the cell lay-out, different programming voltages and different
rise times for the ramp of the programming pulse.*

1 Introduction

The two transistors FLOTOX cell (Fig. 1.$\mathcal{A}$) is the most widely used among the memory devices proposed
for Electrically Erasable Read Only Memories (EEPROM). The first analytical model for this type of
EEPROM cell has been proposed by Bhattacharyya in 1984 [1]. A more detailed circuit model has been
implemented by Kolodny et al.[2] in order to simulate the shift of the cell threshold voltage after step
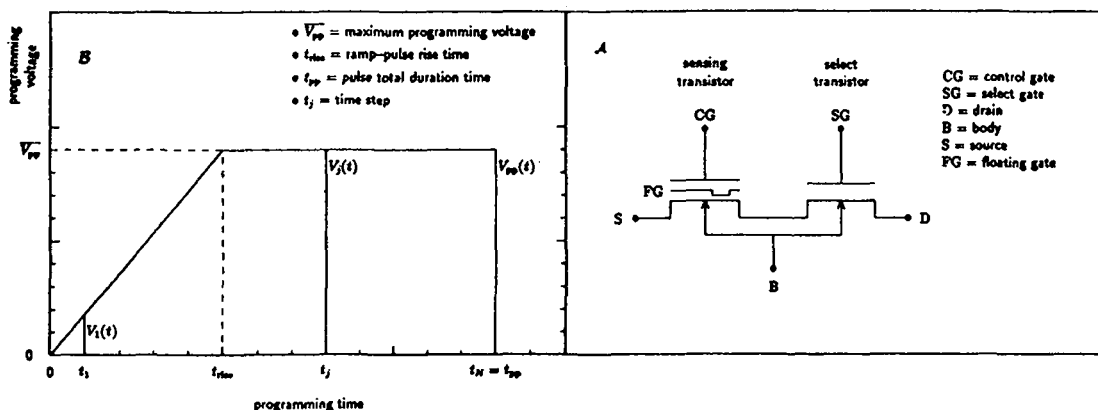programming pulses.

Figure 1. $\mathcal{A}$: two transistors FLOTOX cell scheme.
$\mathcal{B}$: a typical ramp waveform programming pulse. $V_{\text{pp}}(t)$ is the complete pulse; $V_j(t)$ is the $V_{\text{pp}}(t)$ stopped at $t = t_j$.

In actual device operation the cell is programmed with a ramp waveform pulse in order to minimize the tunnel current (the peak value of programming current is known to be proportional to the ramp speed): in this case the threshold shift is a function of both the ramp rise time and the pulse width for a fixed pulse amplitude. Therefore an accurate simulation of the transient behavior (*i.e.* threshold shift *vs.* time) of the cell during the programming cycle is desirable.

In this work an equivalent model for transient analysis of EEPROM cell is proposed. The model is described in term of SPICE [3] components in order to utilize a well proven MOSFET capacitance model. A further advantage in using SPICE is the linkability of the cell model to other circuital blocks for global simulation. An innovative experimental method, able to measure transient E/W characteristics, is used for validating and optimizing the model.

2   Experimental

E/W curves are defined as threshold voltage *vs.* time, where, for operative reasons, the threshold voltage (V_{CG}^T) is defined as the control-gate voltage measured at fixed drain current ($I_D = 10\mu A$ with $V_D = 2V$ and $V_S = V_B = 0V$). Erasing (writing) is defined as the programming operation, which sets the negative (positive) charge state on the floating-gate, *i.e.* the high (low) threshold voltage condition.

E/W curves are measured for programming pulses $V_{pp}(t)$ with a ramp waveform (Fig. 1*B*). A block-scheme of the experimental setup is shown in figure 2*A*. The programming pulses are generated by an *HP 8160A* programmable pulse generator. The threshold detector is a current–voltage converter, which forces on the control-gate the voltage needed to sustain a $10\mu A$ drain current; this *ad hoc* designed circuit allows a faster measurement of the threshold voltage, which is measured by a *Keithley 192 DMM* voltmeter. All instruments are controlled by an *HP 300* computer.
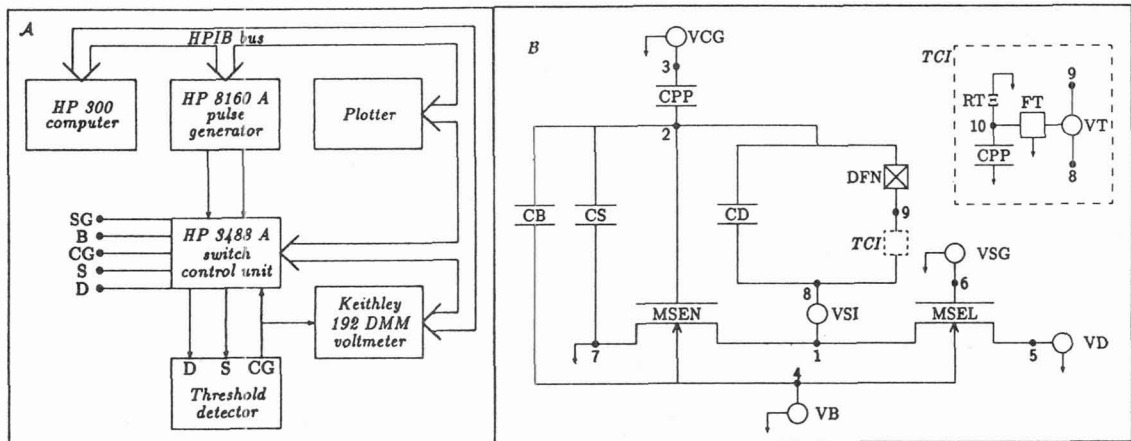

Figure 2. *A*: block-scheme of experimental setup.
B: SPICE equivalent model for the FLOTOX cell. Element description: MSEN=sensing transistor; MSEL=select transistor; CPP=CG-FG capacitance; CX=FG-X capacitance (X=D,S and B); VY=voltage source (Y=CG,SG,D and B); VSI=voltage source simulating voltage drop in silicon; DFN=Fowler-Nordheim diode; *TCI*=tunnel current integrator. Node description: 1=sensing transistor drain; 2=FG; 3=CG; 4=B; 5=D; 6=SG; 7=S; 8=silicon surface underneath tunnel oxide; 9,10=unreal nodes added for simulation purposes.

In order to clarify how the E/W characteristics are obtained let us refer to the writing curve. The programming pulse timebase is divided into N time steps $t_1..t_j..t_N = t_{pp}$. After cycling the cell few tens of

times in order to stabilize the threshold shift, N values of the threshold voltage (V_{CGj}^T) are measured after stopping the writing pulse at each time step; before each $V_j(t)$ writing pulse, complete (i.e $V_{pp}(t)$) E/W pulses are applied to reset the cell to the initial erased state. The writing curve is obtained by plotting the N values $V_{CGj}^T = V_{CG}^T(t_j)$ vs. the programming time.

3   Simulation

The equivalent circuit shown in figure 2B is described in terms of SPICE components to simulate the EEPROM cell; the description of each component of the circuit is made in the figure caption. The "tunnel diode" (DFN) model can be easily introduced in SPICE using the well known Fowler-Nordheim (FN) equation [4]: external parameters are the pre-exponential and the exponential constants (usually called A and B), the tunnel oxide thickness and the tunnel oxide area. The Ward-Dutton [5] charge model is used for simulating the gate-to-channel capacitance of the sensing transistor. A voltage source (VSI) is introduced to take into account the voltage drop in the n^+ depleted region underneath the tunnel oxide during the writing cycle. A Tunnel Current Integrator TCI is added to the circuit to determine at the node 10 a voltage value equivalent to the threshold shift.

The DFN parameters are fixed, using theoretical values for A and B (A$= 1.67 \times 10^{-6}$AV^{-2}, B$= 224$MVcm^{-1}) and the measured ones for the tunnel oxide thickness and area. The capacitance values are chosen as fitting parameters of the model, because they can hardly be determined from experimental data. Anyway the fitting values are within a 15% variation from the lay-out capacitances.

In order to compare simulations and experimental data is useful to put an initial condition on node 10 to obtain the threshold voltage instead of the threshold shift. Moreover an initial condition can be put also on node 2 to simulate the charge on the floating-gate due to a programmed state.
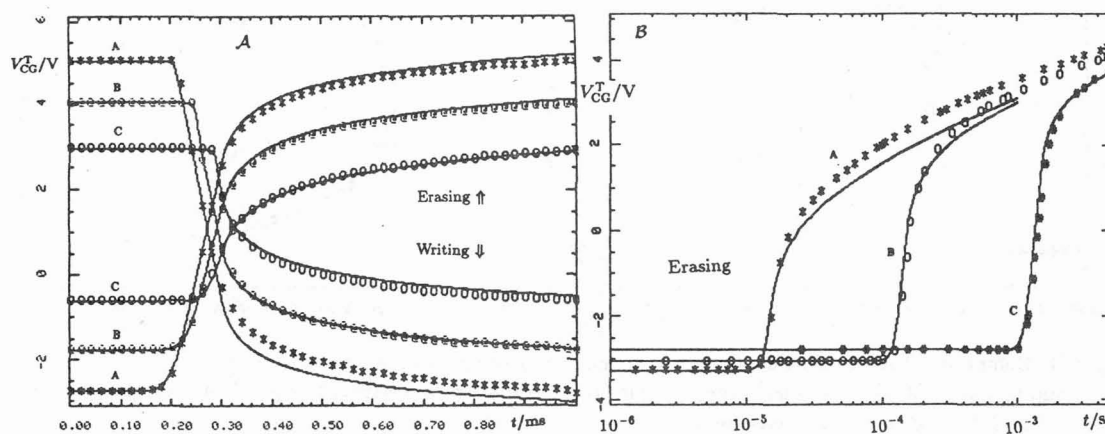

Figure 3. Comparison between simulated (solid line) and measured (symbols) E/W characteristics (i.e. threshold voltage V_{CG}^T vs. time t) of the standard cell (SC). $\mathcal{A}$: the ramp waveform programming pulse $V_{pp}(t)$ is used with the same t_{rise} ($t_{rise} = 300\mu$s) and the same t_{pp} ($t_{pp}=1$ms) but with different V_{pp} (A: $V_{pp}=16$V;   B: $V_{pp}=15$V;   C: $\overline{V_{pp}}=14$V). $\mathcal{B}$: the $V_{pp}(t)$ is used with the same $\overline{V_{pp}}$ ($\overline{V_{pp}}=15$V) and the same t_{pp} ($t_{pp}=5$ms) but with different t_{rise} (A: $t_{rise} = 15\mu$s; B: $t_{rise} = 150\mu$s; C: $t_{rise} = 1.5$ms).

4 Discussion

First the analysis are centralized on a standard cell (SC) operating with $\overline{V_{pp}}$ at different values with the same t_{rise} (Fig. 3$\mathcal{A}$): a good agreement (an error of 3% in the worst case) between simulation and experimental data is found for the complete E/W curve and in particular for the final threshold shift.

Secondly, the model is validated on different cells, each of one having a single lay-out variation with respect to the SC, e.g. the tunnel oxide area or the active area are increased; modifying only those physical parameters in the SPICE EEPROM model that are interested in the lay-out variation, the experimental data are again fitted with a good accuracy (Fig. 4).

Finally different t_{rise} and different t_{pp} with the same $\overline{V_{pp}}$ are considered, operating on the SC. In this case the same fitting parameters are not able to give an acceptable fitting, if t_{rise} and/or t_{pp} are changed over wide ranges (Fig. 3B). These discrepancies are attributed to the inaccuracy of the theoretical FN equation to model the actual tunnel current, which is known to deviate from the FN equation at high electric fields [6,7]. In conclusion:

1. the SPICE EEPROM model is able to simulate correctly the transient behavior of the cell (and indeed the physical E/W mechanism), but using fitting parameters;

2. the parameters, found by fitting, are able to take into account cell lay-out variation and/or different $\overline{V_{pp}}$ values, but they are not for different ramp speed;

3. to obtain a self consistent EEPROM model, able to simulate any programming condition, the exact form of the tunnel current in the high electric field range or, at least, different experimental A and B values for different electric field ranges, should be used in the DFN model.
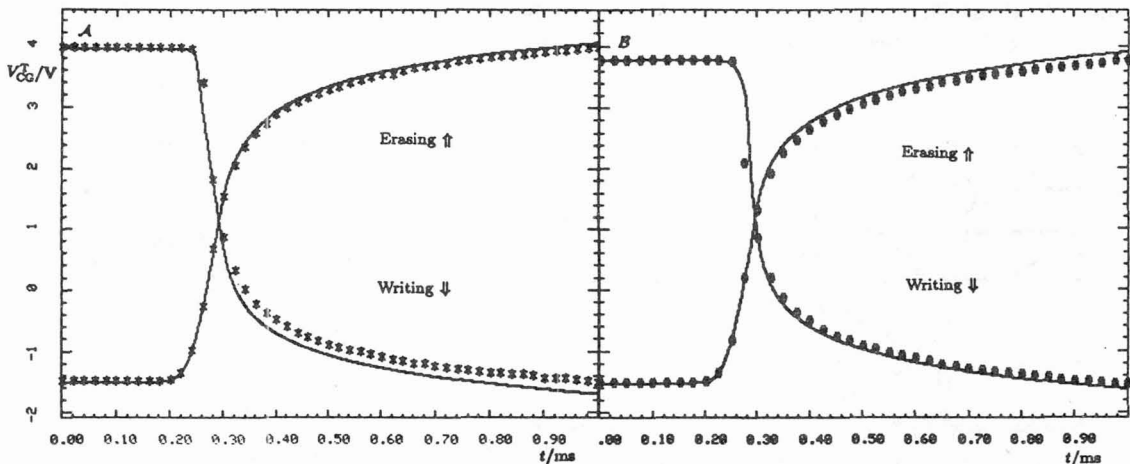

Figure 4. Comparison between simulated (solid line) and measured (symbols) E/W characteristics ($\overline{V_{pp}}$=15V, t_{rise} = 300μs and t_{pp}=1ms) of different cells, having a single lay-out variation with respect to the SC. $\mathcal{A}$: tunnel oxide area increased by 40%; B: active area increased by 7%.

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