

# Modeling and Simulation of Single-Electron Multi Tunnel Junction Memory

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## ABSTRACT

For optimization of Quantum-Dot-based Multi Tunnel Junction Memory (MTJM) [1], we propose an original compact model validated by physical simulations. We analyze the impact of physical and technological parameters (Temperature, dots density, geometries...) on writing and retention characteristics of the MTJM cell, and so we show that this concept could be an alternative for Advanced DRAM Applications (for the 50 nm node predicted around 2011 by ITRS).

**Keywords:** modeling, simulation, nanocrystal memory, double tunnel junction, quantum confinement.

## 1 INTRODUCTION

Many concepts of Nanocrystal-based-memory have recently attracted much attention. The understanding and optimization of these devices need an important work of modeling and simulation. Yet the classical device simulators can not correctly take into account single-electron phenomenon and quantum effects. This work presents a model of MTJM and demonstrates the capability of such Memories to be alternative solutions for future DRAM applications.

## 2 DEVICE DESCRIPTION

The memory cell is described in Figure 1: the principle is similar to Flash Memory, the information charge is stored on the Floating Gate of a MOSFET. The main difference concerns the writing mechanism which is ensured by a "single-electron" current between the Control Gate (CG) and the Floating Gate (FG) via nanocrystals.

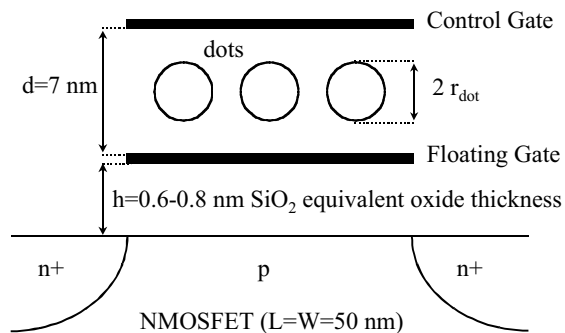


Figure 1: MTJ Memory structure.

In this paper, we assume that the dots are metallic: the tunneling of charges between CG, dots and FG shows nonlinear conduction characteristics which can be described with the "orthodox theory" of Coulomb blockade (CB).

The retention is ensured by the CB phenomenon above FG and thick High-k gate insulator.

## 3 SIMULATION TECHNOLOGY

The tunneling of charges between CG, dots and FG is described in terms of "tunnel junction" [2] characterized by two elements : a capacitance and a conduction term called "tunnel resistance" (Figure 2). We model the upper part of the MTJ Memory (above FG) with tunnel junctions.

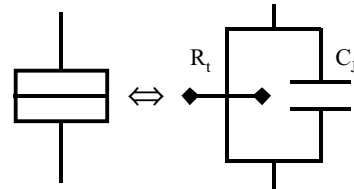


Figure 2: Parameters of a tunnel junction : a capacitance  $C_J$  and a tunnel resistance  $R_t$ .

To accurately predict the behavior of the MTJ Memory we use an efficient 3D capacitor simulator (ICARE [3]) and a reference simulator for "single-electron" devices (SIMON[4]). The circuit which model the MTJ Memory is represented in Figure 3 (with lateral interactions between dots) :

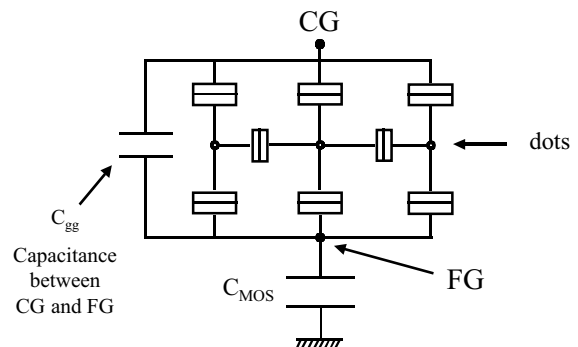


Figure 3: Electrical equivalent circuit (SIMON) for the MTJ Memory (with 3 dots).

In the following, we monitor the number of stored charges on the FG during and after the writing cycle imposed on the Control Gate (Figure 4).

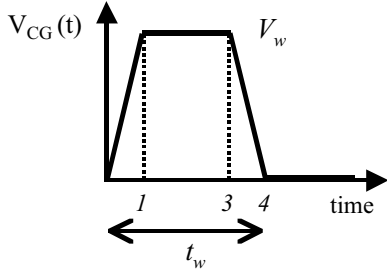


Figure 4: Writing cycle used in simulations and models.

#### 4 IMPACT OF THE SPATIAL REPARTITION OF DOTS

First of all, we checked (Figure 5) that, in the studied ranges of temperature (up to 300 K) and dots density ( $10^{11}$  to  $10^{12}$   $\text{cm}^{-2}$ ), the stored charge on the FG shows a low dependence on the repartition of dots (periodic or random).

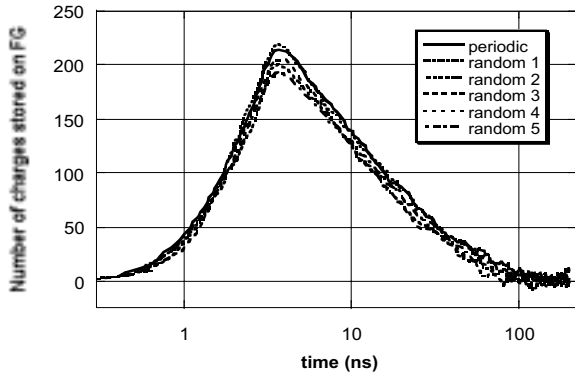


Figure 5: Monte Carlo simulations of stored charges for one periodic and five randomized dots repartitions (density :  $6.4 \cdot 10^{11}$   $\text{cm}^{-2}$ ,  $r_{\text{dot}} = 1.5$  nm,  $T = 300$  K,  $V_w = 1$  V,  $t_w = 4$  ns).

This justifies the MTJM model of Figure 6 where lateral interactions between dots are neglected. In the following, this circuit is used for modeling the electrical behavior of the memory.

#### 5 THE DOUBLE TUNNEL JUNCTION

As we consider that interactions between the dots are negligible, the central element of the memory is the double junction (Figure 7). Its current-voltage characteristics controls the writing, retention and erase of the Memory cell.

In the following, we assume that the spherical dots :

- i) have the same radius
- ii) are equidistant between CG and FG.

A good approximation for all these hypotheses is to consider that all the junctions have the same capacitance and the same tunnel resistance.

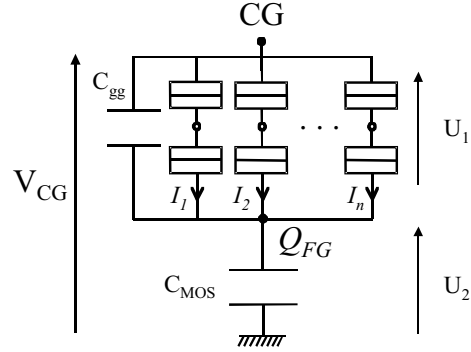


Figure 6: Electrical equivalent circuit of the MTJM cell (with no interaction between the dots).

#### 5.1 Current-voltage characteristics of a double symmetric junction

In the usual range of biases across a double tunnel junction, the excess charge  $q$  on the island of a double junction equals  $-e$ ,  $0$  or  $+e$ . Because of these charge states only 8 tunnel rates have to be taken into account [2]:

$$\tilde{\Gamma}_1(V, q=0), \tilde{\Gamma}_2(V, 0), \tilde{\Gamma}_1(V, -e), \tilde{\Gamma}_2(V, -e), \tilde{\Gamma}_1(V, q=0), \tilde{\Gamma}_2(V, 0), \tilde{\Gamma}_1(V, +e) \text{ and } \tilde{\Gamma}_2(V, +e).$$

For example,  $\tilde{\Gamma}_1(V, q=0)$  is the probability that an electron tunnels from the island through the junction 1 (with the voltage  $V$  and no charge on the island). The others tunnel rates are described in Figure 7:

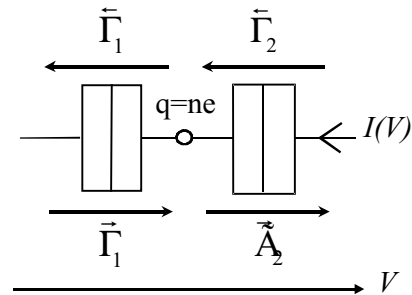


Figure 7: Notations for the tunnel rates across the junctions.

The hypotheses of the “orthodox theory” [2] for  $\tilde{A}_1(V, q=0)$  leads to equation (1):

$$\tilde{A}_1(V,0) = \frac{1}{2eR_t} \cdot \frac{V - V_C}{1 - \exp(-\frac{V - V_C}{V_0})} \quad (1)$$

with

$$V_C = \frac{e}{2C_J}, \quad V_0 = \frac{2k_B T}{e} \quad (2)$$

where  $C_J$  and  $R_t$  are respectively the capacitance and the tunnel resistance of the junctions.

So, the behavior of a double tunnel junction is governed by the Master Equation [2] which links the probabilities of the different charge states to the tunnel rates:

$$\begin{aligned} \dot{p}_{-1} &= \tilde{A}_{1,0} p_0 - \tilde{A}_{0,-1} p_{-1} \\ \dot{p}_0 &= \tilde{A}_{0,1} p_1 + \tilde{A}_{0,-1} p_{-1} - (\tilde{A}_{1,0} + \tilde{A}_{-1,0}) p_0 \\ \dot{p}_1 &= \tilde{A}_{1,0} p_0 - \tilde{A}_{0,1} p_1 \end{aligned} \quad (4)$$

where  $p_n(t)$  is the probability to find the island with the charge  $q=ne$  and  $\Gamma_{m,n}$  is the rate for a transition from state  $n$  to state  $m$ .

$$\tilde{A}_{n+1,n} = \tilde{A}_1(V, ne) + \tilde{A}_2(V, ne) \quad (5)$$

$$\tilde{A}_{n-1,n} = \tilde{A}_1(V, ne) + \tilde{A}_2(V, ne) \quad (6)$$

The current which depends on the tunnel rates and the island charge is given by equation (7) :

$$\frac{I(V)}{e} = p_0 (\tilde{A}_1(V,0) - \tilde{A}_1(V,0)) - p_1 \tilde{A}_1(V,-e) + p_{-1} \tilde{A}_1(V,e) \quad (7)$$

## 5.2 Quasi-stationary regime

If we consider that the probabilities  $p_n$  do not depend on time, the equations (4) to (7) leads to a simple formula of the current-voltage characteristics of the double symmetric junction (8).

This (quasi-stationary) current model has been validated by comparison with Monte Carlo simulations (as we did,

otherwise, for the transient case). An example is given on Figures 8-a.

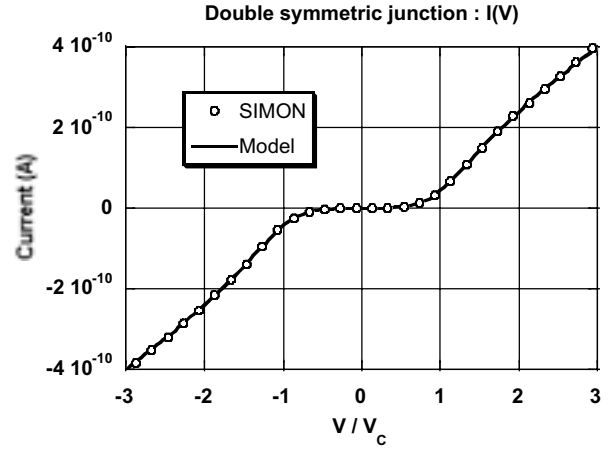


Figure 8-a: Comparison between formula (8) and SIMON simulation (linear scale):  $C_J = 0.1 \text{ aF}$ ,  $R_t = 10^9 \Omega$ ,  $T = 300 \text{ K}$ .

Moreover, Figure 8-b shows the perfect agreement between the two sets of data in the blockade regime :

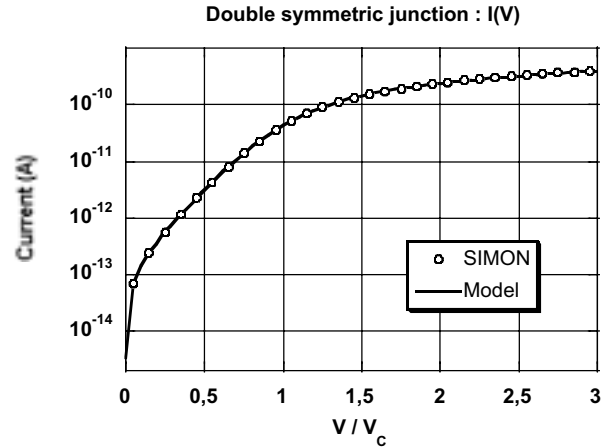


Figure 8-b: Comparison between formula (8) and SIMON simulation (log scale):  $C_J = 0.1 \text{ aF}$ ,  $R_t = 10^9 \Omega$ ,  $T = 300 \text{ K}$ .

$$I(V) = \frac{\frac{(V - V_C) \cdot (V + V_C)}{R_t} \cdot \left[ 1 - \exp(-\frac{2V}{V_0}) \right]}{(V - V_C) \cdot \left[ 2 + \exp(-\frac{V - V_C}{V_0}) \right] \cdot \left[ 1 - \exp(-\frac{V + V_C}{V_0}) \right] + (V + V_C) \cdot \left[ 1 + 2 \cdot \exp(-\frac{V + V_C}{V_0}) \right] \cdot \left[ 1 - \exp(-\frac{V - V_C}{V_0}) \right]} \quad (8)$$

## 6 MTJ MEMORY MODELING

Thanks to the previous analysis, the electrical behavior of a memory cell with  $n$  identical dots (Figure 6) is described by equations (4) to (7) (where  $V$  is replaced by  $U_2$ ) and the following relations:

$$V_{CG} = U_1 + U_2 \quad (9)$$

$$V_{FG} = U_1 = \frac{(C_{gg} + n C_J/2) V_{CG} + Q_{FG}}{C_{MOS} + C_{gg} + n C_J/2} \quad (10)$$

$$I = \sum_{k=1}^n I_k = \frac{d Q_{FG}}{d t} \quad (11)$$

This system is solved numerically with any CG voltage. We validate the modeling of the whole cell by comparison with Monte Carlo simulations on a set of benchmarks. An example is given in the case of the voltage signal of Figure 4:

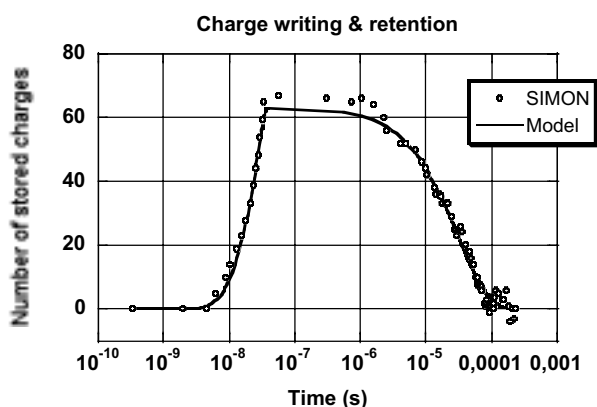


Figure 9: Comparison between our model and Monte Carlo simulation ( $r_{dot} = 1.5$  nm,  $h = 0.8$  nm,  $t_w = 40$  ns).

## 7 IMPACT OF QUANTUM CONFINEMENT ON RETENTION

A crucial physical effect (not taken into account up to now) is the quantum confinement in the dot [4]. Because of the nanometer size of the dots, it has to be taken into account in the calculation of the “threshold” of the double junction:

$$V_C = \frac{e}{2 C_J} + \frac{2 E_{conf}}{e} \quad [2] \quad (12)$$

with

$$E_{conf} \approx \frac{3 \hbar^2 \partial^2}{8 m_o r_{dot}^2} \quad (13)$$

Figure 10 shows that it significantly improves the data retention, because it directly increases the magnitude  $2V_C$  of the “blockade” region and so decreases the double junction leakage current.

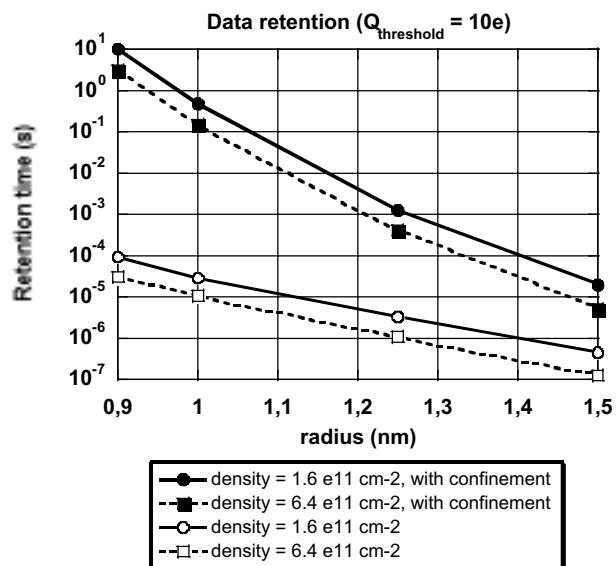


Figure 10: Memory retention time vs. dot radius and density with and without quantum confinement hypothesis ( $h = 0.6$  nm,  $t_w = 10$  ns,  $V_w = 2.5$  V).

Thanks to this effect, a technological optimization is possible for DRAM applications ( $t_{write} < 10$  ns,  $t_{retention} > 1$  s) as we show in Figure 10. This is a real challenge because it requires low densities, small dots with extremely well controlled sizes from device to device.

## 8 CONCLUSIONS

We have derived a compact model (taking into account quantum confinement) dedicated to MTJ Memory cells optimization and validated it by comparisons with physical simulations. The systematic use of this model allowed us to show that 50 nm DRAM characteristics can be reached by optimizing technological parameters.

## REFERENCES

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