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Magnetic tunnel junction model in Verilog-A for use in CAD environments for integrated circuits

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Electrical model of a magnetic tunnel junction is developed in Verilog-A language, which can use in CAD systems to design an integrated circuit of spintronics devices. In order to check the correct operation of the model verification tests were created and carried out in Cadence ADE. Each test corresponds to the operating mode of the magnetic tunnel junction: switching, generation, rectification. Thus, the developed model can be used to simulate hybrid circuits comprising CMOS elements and magnetic tunnel junctions.

Keywords: magnetic tunnel junction, MTJ, spintronics, spintronics devices, magnetic tunnel junction model in Verilog-A, MTJ model development, MTJ operating modes.

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1. Introduction

Spintronics or spin electronics is a rapidly growing promising field of micro and nanoelectronics. The information carrier in the spintronic components is not only the electron charge, but also its spin [1]. Spintronic devices such as magnetoresistive sensors, magnetoresistive random access memory (MRAM) [2–4], comprise a combination of a CMOS circuit (complementary metal-oxide-semiconductor structure) and a spintronic part, where magnetic tunnel junctions (MTJ) are the main elements. In the simplest case, a magnetic tunnel junction consists of two ferromagnetic layers separated by a dielectric. The lower ferromagnetic layer with a fixed magnetization orientation is called the reference or polarizer, while the upper ferromagnetic layer has a variable magnetization orientation and is called free (Fig. 1). If the magnetizations of the free and the reference layers are in the same direction, the MTJ has minimum resistance, and its state is called parallel (P), while a state in which the magnetizations are in opposite directions is called anti-parallel (AP), and is characterized by maximum resistance.

Much research in the last decade has been related to the spin-transfer effect [5], driven by the prospect of commercial introduction of radio frequency (RF) spintronics devices. Technologies for spintronic microwave devices such as nanogenerators [6], spin-torque diodes [7], radio frequency detectors, harvesters [1] are being actively developed. This necessitates the modelling of their electronic circuits, which are CMOS elements working in conjunction with spintronic ones, and which take into account the microwave properties of magnetic tunnel junctions. It is relevant to create a compact MTJ model that allows the calculation of the electrical characteristics of a component and the application of this data in common computer-aided design (CAD) environments for integrated circuits.

We present a compact model of magnetic tunnel transition, written in the high-level language Verilog-A/AMS, for predictive modelling of MTJ behavior in spintronic devices. In order to qualitatively verify the model in Cadence ADE CAD, we developed and performed tests corresponding to the main modes of operation of the MTJ, namely switching, generation and rectification.

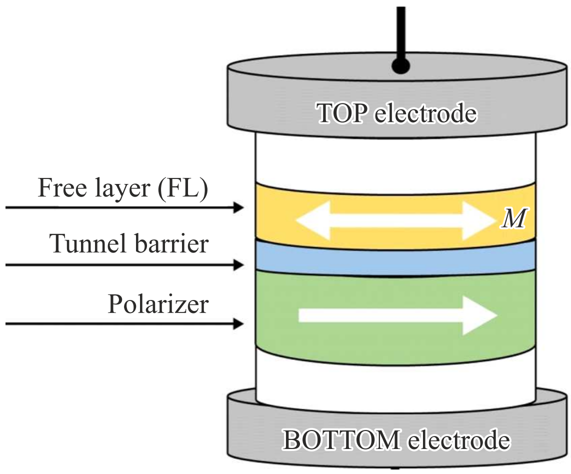

Figure 1. Magnetic tunnel junction stack.

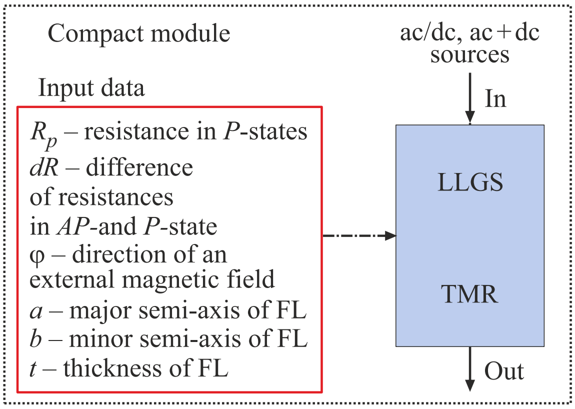

Figure 2. Block diagram of the MTJ model.

2. Compact MTJ model structure

The magnetic tunnel junction model is a single module (Fig. 2) including:

• the numerical solution of the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) [5] equation which describes the magnetization dynamics **M** of a free MTJ layer under the action of an external magnetic field and takes into account shape anisotropy and spin transfer effect

$$\dot{\mathbf{M}} = -\gamma[\mathbf{M}\times\mathbf{H}_{eff}] + \alpha/M_s[\mathbf{M}\times\dot{\mathbf{M}}] + \mathbf{T}_{STT}, \qquad (1)$$

where γ — gyromagnetic ratio, $\mathbf{H}_{eff}$ — effective magnetic field, α — Hilbert attenuation coefficient, M_s — saturation magnetization. $\mathbf{T}_{STT}$ — torque consisting of two components: Slonczewski torque $T_{ST} = (a_j\gamma/M_s)\mathbf{M}\times[\mathbf{p}\times\mathbf{M}]$ and field torque $T_{FLT} = \gamma b_j[\mathbf{M}\times\mathbf{p}]$, where $\mathbf{p}$ – normalized vector of magnetization of the reference layer, j — current density calculated by the formula $j = I_{in}(t)/S$, I_{in} — current flowing through the MTJ, S — free layer area of MTJ. Values $b_j \approx 0.4a_j$, $a_j = \hbar P/(2teM_s)$, where P — degree of current polarization, t — free layer thickness, and e — electron charge. An elliptical base MTJ with geometric dimensions a (the larger half-axis of the ellipse) and b (the smaller half-axis of the ellipse) was taken for modelling.

• calculation of the tunnel magnetoresistance (TMR) of the MTJ and consequently its output voltage

$$V_{out} = I_{in}\big(R_p + (1-\mathbf{m}\cdot\mathbf{p})dR/2\big), \qquad (2)$$

where $dR = R_{ap} - R_p$, and R_{ap}, R_p — the MTJ resistance in AP- and P-state, respectively.

The effective magnetic field $\mathbf{H}_{eff}$ is the variation derivative of the free energy in magnetization and includes contributions of different nature: anisotropy, magnetostatic, exchange, Zeeman energy fields. We assume that the magnetization distribution is homogeneous over the sample volume, then for an MTJ with in-plane free layer magnetization the total energy is the sum of the Zeeman energy and the anisotropic energy of shape

$$E = E_z + E_{anis} = M_xH\cos(\varphi) + M_yH\sin(\varphi) + \frac{1}{2}\left(N_xM_x^2 + N_yM_y^2 + N_zM_z^2\right),$$

where demagnetizing factors $N_x + N_y + N_z = 4\pi$, H — value of external magnetic field, φ — direction of external magnetic field relative to the major axis of the ellipse.

The syntax of the Verilog-A [8] language allows to solve equations like (1) using integration schemes *idt/idtmod* with configurable tolerances in the time domain.

To verify the magnetic tunnel transition model on Verilog-A, tests were developed and carried out in Cadence ADE CAD. Each test represents the initial simulation conditions under which the MTJ enters switching, generation, and rectification modes.

3. MTJ switching mode

In spintronic MRAM devices and TMR sensors, MTJ is switched from P to AP state and vice versa under the action of an external magnetic field directed along the light magnetization axis of the free layer. To simulate the switching mode in the Spectre integrated circuit simulator, a typical MRAM magnetic tunnel junction design with free layer dimensions $350\times160\times5$ nm and a tunnel magnetoresistance of 120%, corresponding to a good quality sample, with a resistance in P-state (AP state) 560 Ω (1225 Ω). Continuously varying the magnitude of the

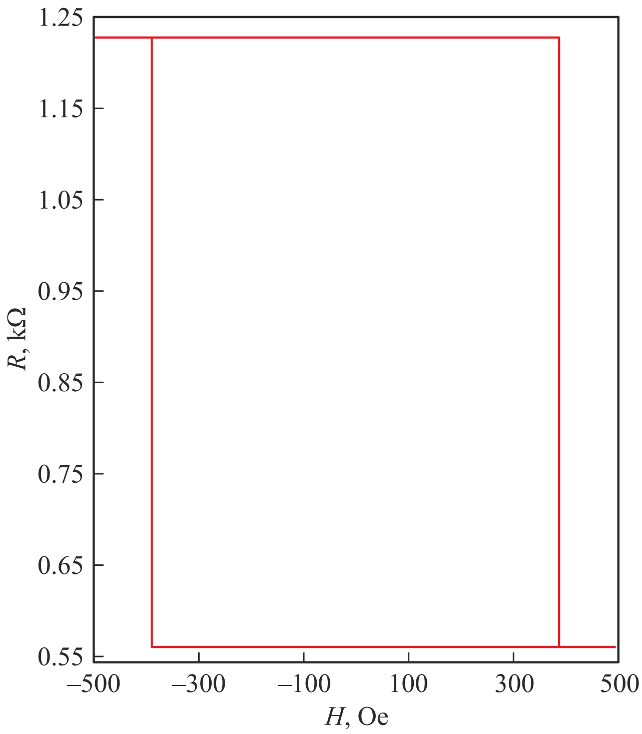

Figure 3. Block diagram of the MTJ model.

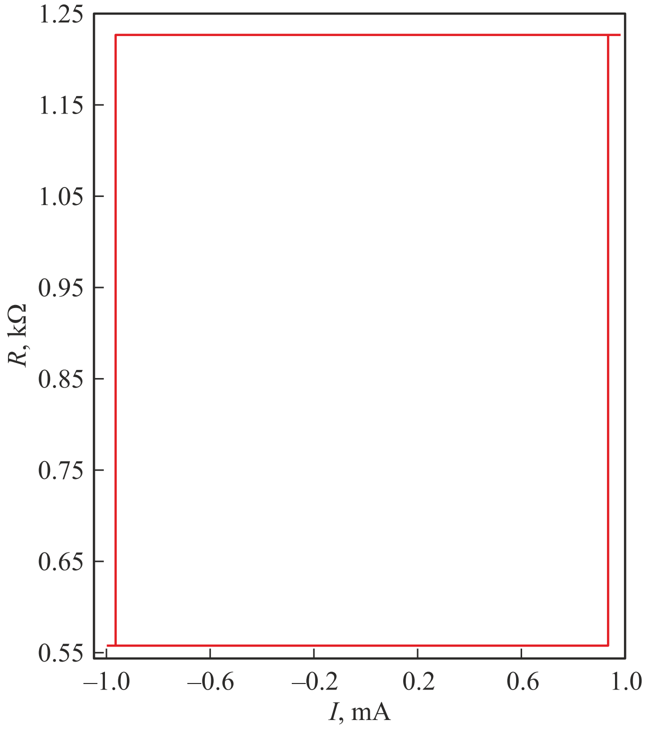

Figure 4. MTJ resistance dependence on direct current value.

external magnetic field H from -500 to 500 Oe, we calculated the MTJ resistance at each time step (Fig. 3). MTJ switching MTJ switching from AP-(P-) state to P-(AP-) state was observed in the 400 Oe field (-400 Oe).

The new generation of STT-MRAM magnetic memory uses a different recording scheme to MRAM, i.e. using DC current to remagnetize the MTJ via a spin transfer effect. A magnetic tunnel junction with geometrical dimensions of the free layer $240 \times 120 \times 2$ nm and resistance in P-state (AP state) 560 Ω (1225 Ω). In zero external magnetic field, by varying the constant current I from -1.1 to 1.1 mA, which corresponds to a current density j ranging from -4.86 to 4.86 MA/cm^2, the structure magnetoresistance was calculated (Fig. 4). Current densities below 10 MA/cm^2 ensure the device temperature stability and do not destroy the MTJ structure, as verified experimentally [9].

4. MTJ generation mode

There is increasing research interest in nanooscillators based on MTJ because of their potential application for generating gigahertz microwaves. In such devices, the direct current flowing through the MTJ causes precession of the magnetization of the free layer, resulting in resistance fluctuations. To test the generation mode, an MTJ design with free layer dimensions $350 \times 160 \times 5$ nm and resistance in P-state (AP-state) 560 Ω(1225 Ω) is selected. At constant current through the MTJ of 1−2 mA 2.25−4.5 MA/cm^2 (Fig. 5), resistance fluctuations are observed at 1.5 mA and 2 mA.

5. Rectification mode

A new dynamic effect, the rectification effect [10], occurs when alternating current is transmitted through the MTJ structure. When the AC frequency f coincides with the free-layer ferromagnetic resonance (FMR) frequency, the MTJ resistance oscillates. Thus, according to Ohm's law, the structure output has variable and constant voltage components. The characteristic curves of the rectified

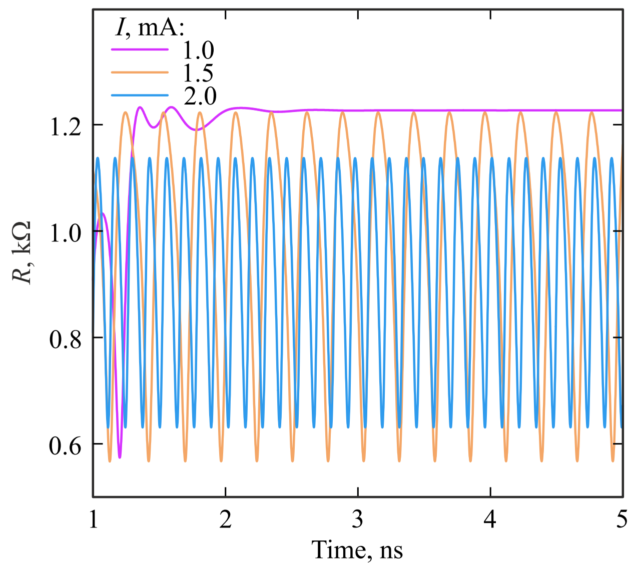

Figure 5. Time dependence of MTJ resistance at bias currents $I = 1{-}2$ mA.

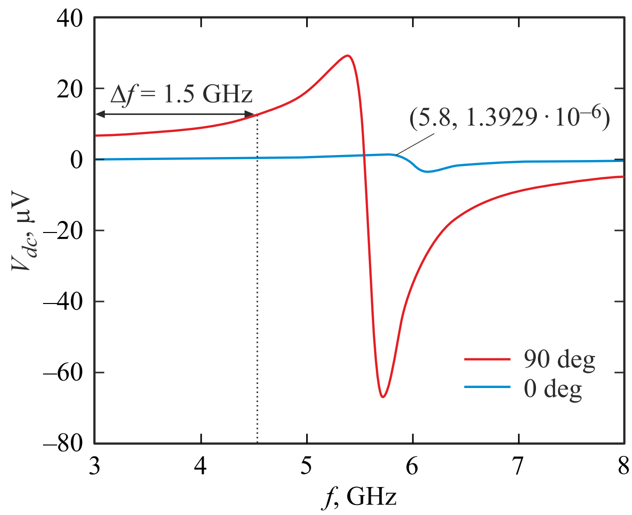

Figure 6. Dependence of the rectified voltage of the MTJ on the frequency of the alternating current amplitude 100 μA when the external magnetic field is relative to the principal axis of the ellipse 0° and 90°.

voltage versus AC frequency are shown in Fig. 6 and are called ferromagnetic resonance (FMR) curves. To test the rectification mode, an MTJ design with free layer dimensions $350 \times 160 \times 5$ nm, and resistance in P-state (AP-state) $560\,\Omega$ ($1225\,\Omega$) is taken. In an external magnetic field $H = 50$ Oe, directed along the major axis of the ellipse, when AC current is transmitted through the MTJ with amplitude $100\,\mu$A and frequency $3-8$ GHz the most effective rectification was achieved at frequency 5.8 GHz, corresponding to the FMR peak. When the field direction is reversed to 90°, there is an increase in DC voltage at the MTJ output and also the appearance of wideband rectification at frequencies $3-4.5$ GHz. This broadband rectification mode has promising applications in spintronic IoT devices [1].

6. Conclusion

The electrical model of the magnetic tunnel junction is written in Verilog-A and verified in Cadence ADE CAD. The parameterized cell of MTJ is scalable to different technological nodes and can be used to simulate the spintronic devices: TMR-sensors, MRAM, spin-torque diodes and nanogenerators.

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Conflict of interest

The authors declare that they have no conflict of interest.

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