Comprehensive Numerical Modeling of Filamentary RRAM Device

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Abstract

Resistive random-access memory (RRAM) is a non-volatile memory that operates via resistive switching between the insulating (OFF) and conducting (ON) states, representing the logical '0' and '1' binary states, in response to external bias. Attributes such as high memory density, fast read and write speeds, and low power consumption make RRAM a promising new technology. However, RRAM is prone to variability issues and reliability concerns and therefore understanding the underlying physics behind the device operation is essential prior to its industrial application. Here, we present a thermodynamic numerical model of resistive switching in filamentary RRAM. The equilibrium ON and OFF states of RRAM are due to formation and destruction of a conducting filament. These processes take place when the device minimizes its free energy by locally transforming material into conducting or insulating phase. Such transformations depend on the external bias polarity. The numerical model consists of four programming modules corresponding to ON and OFF states and SET (OFF→ON) and RESET (ON→OFF) switching process, which collectively simulate the current-voltage characteristics of RRAM. Each programming module is separately constructed in the COMSOL Multiphysics® modeling software package. To add programming capability and to connect the four modules, we used MATLAB® package which communicates with COMSOL® via LiveLink™ for MATLAB. We modeled a cylindrical RRAM device in COMSOL® using the 2D Axisymmetric space dimension. The Electric Currents physics interface from the AC/DC module and the Heat Transfer in Solid physics interface from the Heat Transfer module are used to compute the electric field and temperature distribution, and the current-voltage characteristics of the device. In addition, the Electrical Circuit physics interface from the AC/DC module is used to construct a circuit with a load resistor and a power source connected in series with the RRAM device. For SET and RESET process, the minimum in device free energy is calculated with respect to filament radius and gap (region of dissolved filament) size. That allowed us to obtain the stable phase configurations for various power source values, yielding the switching current-voltage characteristics. Additionally, our modeling reproduces I-V with observed voltage ramp-rate dependence and cycle-to-cycle variations, which was achieved by accounting for ramp-rate dependent activation energy of conduction and incorporating randomness of the amorphous material respectively. Incorporating the system randomness with COMSOL modeling is a unique feature of our work. Based on thermodynamic description, our model provides a much-simplified description of the switching process in comparison to the generally required kinetic approach, making our modeling accessible to broader readers and modelers. This work was supported in part by the Semiconductor Research

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Figures used in the abstract

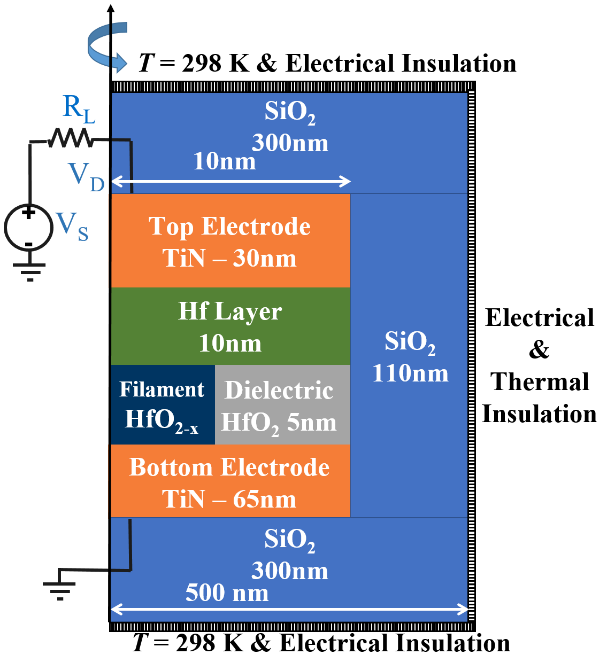

Figure 1: Schematic of a cylindrical RRAM device constructed in 2D Axisymmetric space dimension depicting the geometric parameters, utilized materials, applied boundary conditions, and circuitry.