A transient circuit model for a phase change memory element


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ABSTRACT

Non-volatile memories based on phase change materials (PCMs), also called ‘Ovonic Unified Memories’ (OUM), are promising candidates as a scalable and fast programmable alternative to existing memory concepts. We present a transient lumped element model of a phase change memory cell (PCMC). It can be used in a circuit simulator to optimize an OUM. The model is physics-based and describes typical features such as threshold voltage (V_T) switching. Also, and unlike existing circuit models [1,2], this model simulates V_T and resistance drift as found for PCMCs. All model parameters have physical meaning.

Keywords: circuit model, compact model, phase change memory cell

1 INTRODUCTION

Soon after the first publications on phase-change materials in the late 1960’s [3], it was recognized that non-volatile and electrically programmable memories could be made using such materials. Recently, PCM-materials have been integrated into IC-technologies [4,5,6]. Existing memory concepts fail to scale in the ongoing quest of downsizing the memory elements. With PCM-technology, a scalable memory concept is anticipated.

A PCMC is in either a high-ohmic amorphous (RESET) state or in a low-ohmic crystalline (SET) state. Switching between the states is achieved by joule heating: high powers lead to melting and rapid quenching preserves the amorphous state. At moderate power levels the PCMC crystallizes. In figure 1, a schematic of a ‘line-concept’ cell is shown. Current is run through the line to heat it up and change its state.

A typical feature of PCM-materials that is employed during programming, is its ‘threshold voltage switching’ behavior. In the amorphous state, the I(V)-characteristics show ‘snapback’: beyond V_T the device breaks down and snaps back to join the same I(V)-curve as the crystalline state. V_T and R_RESET vary over time and depend on the switching history. V_T reduces just after a switching event and only slowly recovers [7] (see figure 2). This effect is particularly awkward in OUM-design as it puts constraints on the readout voltage and currents.

Pirovani et al. have developed a physical model for the PCMC that explains most of its electrical features [7]. Key issue is the switching-dependent appearance and disappearance of traps, associated with structural ‘valence alternation pairs’ (VAPs), determining V_T, R_RESET and their drift. Pirovano’s model is implemented in a numerical device simulator.

To enable and optimize the design of driver circuitry for an OUM, we developed a transient circuit model for a single cell. In the next section, we will first describe the model. In section 3 we show an example simulation and a comparison with experiments, followed by conclusions in section 4.
2 MODEL DESCRIPTION

The model consists of two parts. A thermal network (figure 3) calculates the temperature distribution in the cell caused by joule heating. An electrical network (figure 4) describes the momentous resistance. We assume a simple line geometry and a growth-limited PCM (doped GeSbTe [8]). In such materials two amorphous/crystalline (a/c-) interfaces move ‘up and down’ the line during programming cycles (reflecting melting or crystallization).

The model keeps track of the location of the amorphous-crystalline interface $x_{a/c}$. The speed of $x_{a/c}$ depends on the local temperature $T(x_{a/c})$ (ref. [8] and figure 5). $T(x_{a/c})$ is determined from the thermal network. $x_{a/c}$ at the end of the programming cycle determines the PCMC-resistance and state.

2.1 Thermal network

The thermal network determines the temperature distribution inside PCMC. We solve the heat equation by using electrical equivalencies and describing the – distributed– thermal network as an electrical network. The thermal network should be dense enough to resolve the temperature profiles in the structure correctly. At each node in the model, power is generated by relating it to the joule heating in the device. In this paper, we apply the relatively simple model given in figure 3 to model the line concept cell.

$$\rho_{am} = 1/(q \mu \rho)$$

$p = p_{eq}(N_T, N_A, T) + \Delta p$

$$\tau = \frac{1}{1/\tau_0 + 1/\tau_T}$$

$$\tau_T = \frac{N_{T_0}}{N_T} \tau_{T_0}$$

$$\rho_{cr} = \rho_{cr300} \frac{(T/300)^{3/2} e^{-E_G(T/300-1)/(2kT/q)}}$$

2.2 Electrical network

The electrical network (figure 4) consists of three resistances: the crystalline and amorphous part and a constant series resistance to account for any other resistance. The heat generated in the line is input to the thermal network, the heat in the series resistance not.

The crystalline resistance $R_{cr}$ is modeled to be temperature dependent (in analogy with doped semiconductors).

Figure 4. The electrical model consists of three resistances. Also, dummy networks are used to describe the carrier and trap dynamics. Resistivity $\rho_{cr300}$, bandgap $E_G$ and breakdown parameters $\alpha_{cr}$, $E_{cr}$, and $b$, as well as $N_{T_0}$ and doping $N_A$ are considered material parameters that can be independently determined. Mobility $\mu$ and lifetimes and reaction rates $\tau_0$, $\tau_{T0}$, $\sigma_{Tr}$ and $\sigma_{Tf}$ also have physical meaning, but are to date determined by calibration of the model to cell measurement data.
To model the more complicated behavior of the amorphous resistance $R_{am}$, impact ionization and recombination effects are included. In this paper, conduction is assumed to take place primarily by holes as it is believed that the hole mobility is larger than the electron mobility. This is, however, not essential to the model. To calculate $R_{am}$, the hole concentration $p$ must be known, as we will calculate the specific resistance from $\rho = 1/(q \mu_p p)$, with $q$ being the elemental charge and $\mu_p$ the hole mobility. We assume $p$ is constant in the amorphous region. Next, we write $p = \Delta p + p_{eq}$, with $p_{eq}$ being the background hole concentration of the material at zero and low currents and $\Delta p$ the excess hole concentration due to breakdown. We keep track of $\Delta p$ and $p_{eq}$.

The excess hole concentration $\Delta p$ is calculated in a dummy network (figure 4) where a capacitor is charged by the current sources representing the competing mechanisms of impact ionization and recombination through traps. The rate of recombination is determined by the trap concentration $N_T$ and associated lifetime $\tau_T$. A complication arises from the fact that the traps disappear quite suddenly when the device breaks down. The traps return only slowly to their equilibrium concentration $N_{T0}$, which is assumed to be equal to twice the concentration of VAPs. To model the dis- and reappearance of traps, the trap dynamics are included in the model. Similar to $\Delta p$, $N_T$ is calculated using a dummy network where the charge on a capacitor is a measure for $N_T$. At breakdown, the VAPs reconfigure, forced by an abundance of holes and electrons, from a donor and acceptor trap $C_3^+$ and $C_3^-$ into two non-trapping states $C_3^\theta$, see Adler [9] and Pirovano [7]. The implemented reaction is therefore:

$$h^+ + e^- + C_3^+ + C_3^- \leftrightarrow 2C_3^\theta$$

(1)

If we further assume that $C_3^+$ and $C_3^-$ cannot live separate lives (being a VAP), we may assume $[C_3^+]/[C_3^-] = N_t$. Next realizing that $[C_3^+]/[N_{T0}/N_t]$ we arrive at:

$$\frac{dN_T}{dt} = \sigma_f p n N_T^2 - \sigma_r (N_{T0} - N_T)^2$$

(2)

where $\sigma_f$ and $\sigma_r$ are the forward and reverse reaction rates. In breakdown, $p = n = \Delta p$ and we may rewrite this to:

$$\frac{dN_T}{dt} = \sigma_f (\Delta p N_T)^2 - \sigma_r (N_{T0} - N_T)^2$$

(3)

The equilibrium hole concentration $p_{eq}$, as well as electron concentration $n_{eq}$, are calculated using Boltzmann statistics including the contribution of doping and traps. Using standard text-book formulae for solid state semiconductors we write:

$$n_{eq} = N_c e^{E_F/U_T}$$

$$p_{eq} = N_v e^{-(E_G + E_F)/U_T}$$

$$N_A^- = N_A \frac{1}{1 + 4e^{(E_A - E_F)/U_T}}$$

$$N_{TA}^- = N_T \frac{1}{1 + 4e^{(E_{TA} - E_F)/U_T}}$$

where $N_c$ and $N_v$ are the effective density of states, $U_T$ the thermal voltage $kT/q$, $N_A$ the hole doping level and $N_{TA}^-$ the charged trap concentrations. In this paper, the acceptor level $E_A$ is chosen to be very close to the valence band so that in practice $N_A^- \approx N_A$. The trap energies $E_{TD}$ and $E_{TA}^- \approx N_T$ are set to the same midgap state. The Fermi level $E_F$ is solved within the model by applying the ‘charge neutral’ condition:

$$n_{eq} + N_A^- + N_{TA}^- = p_{eq} + N_{TD}^+$$

(5)

$p_{eq}$ is thus known. Through $N_{TA}^-$ and $N_{TD}^+$ it is obvious that the trap concentration plays a role in determining $p_{eq}$ and hence $R_{RESET}$. $N_T$ also determines $V_T$ through its effect on the carrier lifetime $\tau_T$. Drift of both $R_{RESET}$ and $V_T$ is thus quite naturally modeled by keeping track of the momentous trap concentration. When the device breaks down, all traps disappear and the lifetime becomes high: $V_T$ is low. Also, $N_{TD}^+$ and $N_{TA}^-$ become low and the Fermi level moves to $E_A$ and thus near the valence band. This
results in a higher $p_{eq}$, i.e. lower $R_{\text{RESET}}$. When the traps reappear over time, the lifetime will decrease again and $V_T$ will recover. Also, $E_F$ moves back towards the trap level, which means a lower $p_{eq}$ and increasing $R_{\text{RESET}}$. A ‘residual’ lifetime $\tau_0$ is included in the model, not related to valence alternation pairs, to avoid the lifetime becoming infinite. $\tau_0$ sets the apparent holding voltage of the device.

### 3 SIMULATION RESULTS

Simulation results are given in figures 6 and 7. In figure 6, we show the drift of $V_T$ and $R_{\text{RESET}}$ after a breakdown event. A device with $L\times W=80\times 20\text{nm}^2$ is measured and simulated. Measurements are done with 6V triangular, 100ns wide pulses with a series resistance of 1kΩ. The measured $V_T$s are taken from dynamic IV-curves with an accuracy of $\pm 0.1-0.2$ V. Figure 7 shows the programming curve for the same device. Each data point is measured in a sequence of three pulses: first a large pulse to completely amorphize the line, followed immediately by a square programming pulse of 100ns wide, followed finally by a small read pulse to determine $R_{\text{RESET}}$. As in figure 6, the programming is done with 1kΩ series resistance. The second pulse was increased to determine each data point. The actual voltage $V_{\text{cell}}$ across the cell is measured. A transient simulation to determine one data point in figure 7 involved ~2500 time steps and took 5-15 seconds to calculate in a circuit simulator on a linux-based state-of-the-art pc.

The model is able to capture all features in the measurements.

### 4 CONCLUSION

In conclusion, we have developed a physics based transient circuit model for a phase change memory cell. It captures all relevant features, including threshold switching and drift of the threshold voltage and resistance. The model is fast and can be used in a circuit simulator.

### REFERENCES