Analytic Model forAmorphous GST OTS in Phase Change Memory Cell with Hopping Transport

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ABSTRACT

This paper presents an analytic model for amorphous GST OTS in phase-change-memory cell with the hopping transport mechanism, which is widely used in the organic semiconductor device simulation. In this work an equivalent hopping probability model is presented according to the Abrahams-Miller formula, and then an equivalent capacitor model is develped to depict the charge distribution in the amorphous GST. By coupling the hopping probability model and the capacitor model, the OTS I-V characteristic for OTS effect with different geometry and trap density are achieved, and the results agree with those from the reported measurements data.

Keywords: chalcogenide glasses, Monte Carlo, charge transport

1 INTRODUCTION

Thanks to high operation speed, low power consumption, high density and compatibility with the CMOS technology, phase-change memory becomes the most promising competitor for the next generation NVM [1]. The set and reset operations of PCM rely upon the transition between the amorphous state and the crystalline state in some chalcogenide materials (Ge2Sb2Te5, namely GST is the most widely used). The typical current-voltage characteristic of amorphous chalcogenide material is as shown in Figure 1 [6]. The reset process is an electro-thermal driven process, whereas the set process is divided into the OMS and the OTS processes. The OMS process is an electro-thermal driven nucleation process. However, the mechanism of the OTS process is an open issue [2], which needs more discussion. There have been some OTS models based on the G-R theory [2], and the hot filament theory [4] respectively. This article presents a model based on the hopping transport process, which is used widely in the amorphous/organic semiconductor devices modeling. Because of the existence of large amount of the defects in the amorphous materials, the carriers transport process is a phonon-assisted transport process. As a result of the transport characteristic, the hopping transport mechanism is suitable for modeling the OTS effect in the amorphous chalcogenide.

2 MODEL DESCRIPTION

In term of the former study, the amorphous GST is difficult to be modeled with the traditional D-D model. As a kind of amorphous semiconductor material, there are many defects in the energy band, so it is more reasonable to model the transport characteristic of the amorphous GST with the hopping transport theory [3]. Based on the hopping transport characteristic of the GST material, we develop a model which is fit for depict the threshold switch effects.

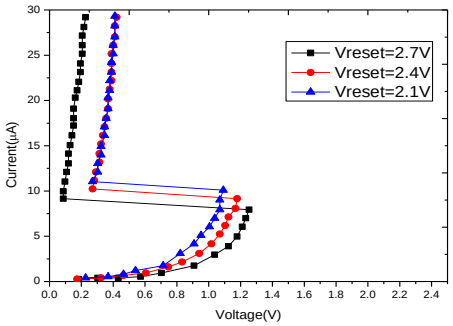

Figure 1: The basic transport characteristic of amorphous state

According to the Abrahams-Miller rate expression, the approximation of the hopping rate between two different defect sites is the following formula [3].

$$SS = \begin{cases} \upsilon_0 \exp(-2\alpha R) & if \quad \Delta\varepsilon > 0 \\ \upsilon_0 \exp(-2\alpha R)\exp(-\Delta\varepsilon / k_b T) & if \quad \Delta\varepsilon \le 0 \end{cases} \quad (1)$$

Where υ_0 denotes the attempt-to-escape frequency, $\Delta\varepsilon$ stands for the potential difference of the different sites, R is the distance of the different sites, α is a function related to the lattice constant and wave-function's special decay[5].

In this article, the energy band plot is assumed as Figure2, whose defects' distribution is assumed to be uniform around the middle of the band gap.

As a current is passing the material, according to the hopping transport mechanism, the ratio of Current and boundary hopping rate I/S_0, i.e. the charge is injected into

one contact region. Because of the charge's accumulation, the inner potential plot is shown in Figure 3 (a).In the process of our simulation, it is shown in Figure 3 that as the current flow through the material, charges inject to the cathode (left side) and dissipate from the anode (right side), which is caused by the hopping process stem from the electrical potential change.

According to the simulation, in this model, the charge's effect is simplified into two pair of individual electrodes. One pair is derived from the metal electrodes Figure 3(b), which stands for the metal electrode charge (Q1). The other pair is the part origin from the inner defects filling profile (Q2). For both of these electrodes can be modeled as a plate capacitor, the whole material voltage profile is simplified into charge-induced voltage from the two pairs of electrodes; a model for OTS is established.

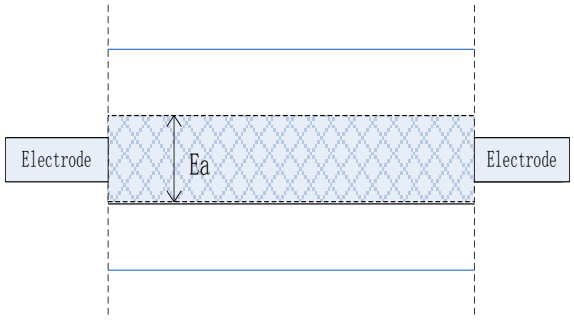

Figure 2: The schematic diagram of the defect state in amorphous GST materials.

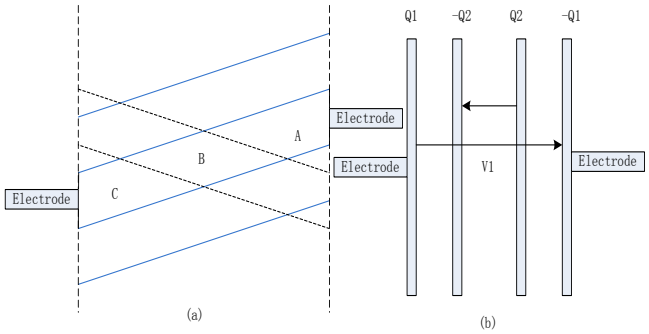

Figure 3: The schematic diagram of energy band structure under a bias voltage.(a is the shematic potential plot, b depicts the two pair of electrodes in this model)

According to the hopping rate expression(1) and the energy band shape Figure 3 (a), the effective hopping rate of electrons in the device adopts the average of the two parts (A-C and B-C, as shown in Figure 3 (a)). In the C region, all the potential will be lower that in the A region, it is acceptable to assume a single value S_0 stand for the hopping rate. In the B region, it is shown that the hopping rate is lower than that of A-C because of partly overlap. So it can be modeled as another value S_1 , which is much smaller than S_0 . Average the value according to their geometry area, the effective hopping rate of charge is shown as:

$$S_{eff} = \begin{cases} \dfrac{S_0 Vq + S_1(2E_a - Vq)}{2E_a} & if\ V \le E_a / q \\ S_0(1 - \dfrac{E_a}{2Vq}) + S_1 \dfrac{E_a}{2Vq} & if\ V > E_a / q \end{cases} \quad (2)$$

Where Ea stands for the defect energy's distribution range. V specifies to the injected charge induced energy band configuration.

Comparing the potential of A and C region and the hopping formula, it is meaningful to assumed them to be fully filled and empty. The inner charge distribution will be a consequence from the geometry method. In this article, we adopt this simple model to depict the inner charge value.

$$Q_2 = \begin{cases} \dfrac{VDN_t q^2}{4} & if\ V \le E_a / q \\ \dfrac{VDN_t q^2}{4} - \dfrac{(Vq - E_a)^2 DN_t}{4V} & if\ V > E_a / q \end{cases} \quad (3)$$

Where N_t is the defects number related to the material geometry. D is the material's length.

For the outer electrode contact plate, the related capacitor distance is the material length. For the inner plate, according to the geometry shape, its capacitor distance d should between 2*D/3 and D/2. The exact value is judged by the energy band shape.

Combined with previous findings, the whole model of current-voltage relationship is shown as:

$$V = \frac{aI}{S(aI/S_0)} - bQ_2(\frac{aI}{S_0}) \quad (4)$$

Where a=D/A/ and b=d/A/ stand for the capacitor factor. S and Q2 individually are the (2) and (3).

3 RESULTS AND DISCUSSION

For the hopping characteristic of the transport process, we compare our model's results to Monte Carlo (MC) simulation results. The basic transport characteristic plot is shown in Figure 4.

From the Figure 4, it shows the snapback phenomenon of model is consistent with the simulation. Comparing with the numerical simulation, our model is correct to depict the potential file in the device.

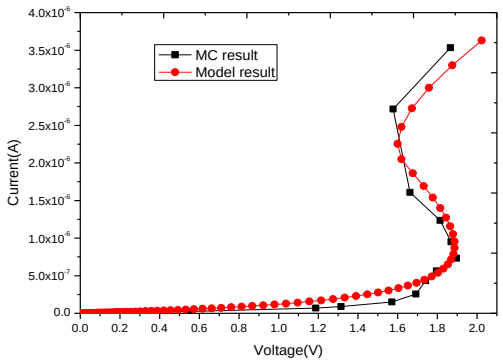

Figure 4: I-V characteristic of model results compared with simulation results

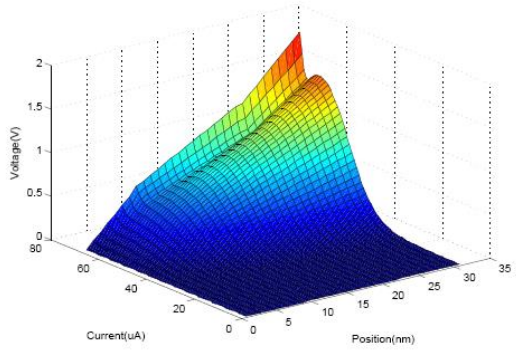

Figure 5: Inner electrical potential of material under different current values.(the left axis is the current value, the right axis is the position of material, the height is the potential value)

Extracting the inner electrical potential distribution under different current values situation, the overall potential plot of different current is shown in Figure 5.

From the inner potential distribution's change characteristic, it is directly shown that the inner electrical field decreases the whole voltage drop, which is the reason to explain the threshold switching effect in the material. In the subthreshold region, as the current increase, more defects are filled and empty in the cathode and anode part of material. When the current value is still low, the defects charges still devote few to the overall potential file. As the current increases, the induced part of defects charge counter more ratio of the outer electrode file, at the threshold current value, the increase speed of inner potential exceeds that of outer electrode potential, the threshold switch phenomenon arises.

Based on our above model, we talk about the effects of different parameters on the transport characteristics. The transport characteristics under different defect densities (1×10^{19}cm-3, 1.1×10^{19}cm-3, 9×10^{18}cm-3) are shown in Figure 6.

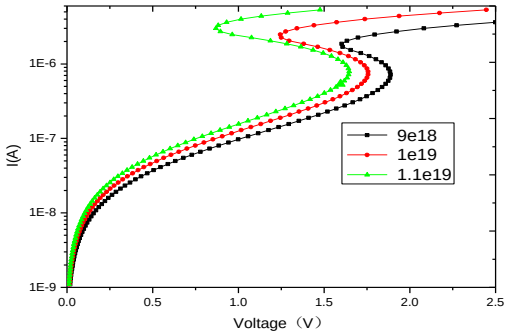

Figure 6: Transport characteristic of different defects densities

In the above three sequence results, there show the different I-V characteristics VS different defects densities. From the trend of the I-V characteristics, it shows that as the defects density increases, the threshold voltage decreases. Under the same energy band configuration, the effective hopping rate according to (2) does not change, but in the case of higher defect density, the inner part backward field increases because of the increase of Q2, so under the same current density, the voltage value is smaller under higher defect density.

Then the I-V characteristics VS different lengths are discussed, as shown in Figure 7. In this analysis, three values of the material length (30nm, 40nm and 50nm) are chosen.

Form the overall picture it is found that as the length of the amorphous area increases, the threshold voltage increases accordingly and the threshold current decreases. The tendency is the same as the reported experiment data [6]. This agrees with our model's analysis in the former. As length increases, in the subthreshold region, according to the voltage formula of the capacitor, voltage increases accordingly under the same current density. However, from (1), it is shown that the hopping rates of both regions decreases from the hopping rate formula, so the current decrease with length.

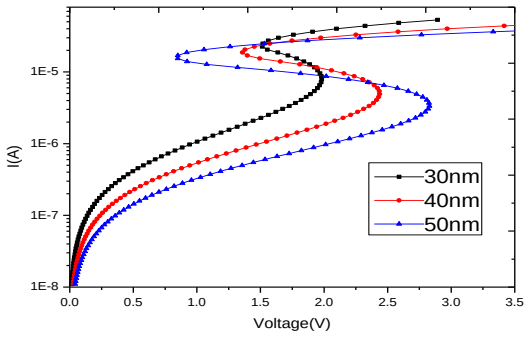

Figure 7: Transport characteristic of different material lengths

When the current is large enough, the transport process is not hopping dominant any more, some other effects like band transport become the dominant factor [2]，so the model in the whole range are not acceptable. For this region further work is to be achieved in the future.

4 SUMMARY

This article develops a new model to depict the threshold switching effect of PCM amorphous state. The results of the model are consistent with the MC simulation results and experimental data, so it is proper to predict the charge transport characteristic of amorphous state of device. As the inner states and device size change, the transport characteristic of the device changes a lot according to the model, this model provide a sound explanation in the application of memory cell of different reality situation.

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REFERENCES

[1] A. L. Lacaita. “Phase change memories: State-of-the-art, challenges and perspectives” Solid-State Electronics 50 24-31 (2006)

[2] Daniele Ielmini, Yuegang Zhang. “Analytical model for subthreshold conduction and threshold switching in chalcogenide-based memory devices” J. Appl. Phys. 102, 054517 (2007)

[3] Fabrizio Buscemi, et al. “Monte Carlo simulation of charge transport in amorphous chalcogenides” J. Appl. Phys. 106, 103706 (2009)

[4] C. Popescu, “The effect of local nonuniformities on thermal switching and high field behavior of structures with chalcogenide glasses,” Solid State Electron., vol. 18, no. 7/8, pp. 671–681, (1975).

[5] H. Houili, E. Tutis, I. Batistic. “Investigation of the charge transport through disordered organic molecular heterojunctions” J. Appl. Phys 100, 033702 (2006）.

[6] Byoung-Jae Bae, et al. “1D Thickness Scaling Study of Phase Change Material (Ge2Sb2Te5) using a Pseudo 3-Terminal Device” IEDM 2009 pp 93-96.