A Regional Model for Threshold Switching in Phase Change Memory Based on Space Charge Effect

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ABSTRACT

In this paper, a regional model for threshold switching is presented based on the space charge effect in Phase Change Memory (PCM). In this model, the PCM unit is divided into two parts according to the electric field distribution resulted from the space charge effect. Then the field and voltage in each part are calculated separately and the total voltage is the sum of the two partial voltages. The physics of threshold switching is explained based on the field distribution under different current. This paper also provides the scaling trend with this model: the threshold voltage (V_{th}) varies directly with the thickness of phase change material (L), while the threshold current (I_{th}) changes conversely with L; which is consistent with the reported data.

Keywords: phase change memory, Ovonic Threshold Switch, space charge effect, scaling trend

1 INTRODUCTION

Phase Change Memory (PCM) has been regarded as the most promising candidate in the next generation memory technology due to its good scalability, low power, and short programming time [1]. These years, the PCM technology has sparked keen interest from IBM, Samsung and other companies. However, most of the mechanisms of PCM are still controversial; which is a barrier for the memory design. Therefore, this paper aims to explain one of the most important features of PCM--Ovonic Threshold Switch (OTS).

OTS refers to the phenomenon when the voltage of amorphous $Ge_2Sb_2Te_5$ (a-GST) reaches the threshold voltage (V_{th}), the current increases rapidly with a voltage snap-back. This effect brings down the resistance of a-GST and provides a large current to enable the crystallization. Besides, it determines the programming window and speed. Therefore, it is badly needed to understand the OTS mechanism. So far, two OTS models have been accepted by most researchers. One[2] is proposed by Adler who believes the snap-back is the result of a balance between a strong SRH recombination through trap levels and avalanche breakdown. The other one[3] is given by Daniele Ielmin. He explains the phenomenon as a ballistic tunneling between the trap state and conduction band level. Both theories are able to account for the basic characteristic of OTS, but unable to explain the scaling trend of the threshold current (I_{th})—I_{th} scales inversely with the thickness of GST.

In this paper, space charge effect is introduced to explain OTS as well as its scaling trend. This effect is generated by the injection of carriers from avalanche multiplication and also explains the similar phenomenon in p-i-n diodes[4] and metal-n-n+ diodes[5]. This paper is organized as follow: a regional model is given in Section 2; the simulation results and physical explanation for OTS and scaling trend are provided in Section 3; finally, a conclusion is offered in Section 4.

2 ANALYTICAL MODEL

Since a-GST is regarded as a defective p-semiconductor with a equivalent accepter density N_A, the structure of a PCM unit can be simplified as a semiconductor terminated with two metal contacts (Figure 1).

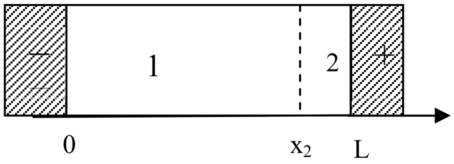

Figure 1 The simplified structure of a PCM unit with a-GST.

The assumptions used in this model are as follows:

a, Only considering the drift part of current, which is verified by detailed theories of the injected contact[6].

b, Neglecting the recombination via defects. Although a lot of defects existed in a-GST, they are not effective traps as the electron traps are above E_F and hole traps below E_F in the band structure[7]. Hence, only their contribution to low mobility is considered.

c, The field at cathode is the saturated electric field Es ,which is reasonable in [5].

d, The hole is neglected near the anode, which is accepted for a reversed metal-p semiconductor junction.

The part near the cathode is forward biased and the one near the anode reverse biased under a voltage. As a-GST is only 10~60nm thick and has a low doping density, the depletion region almost extends to the entire device with the increase of voltage. Therefore, the field increases along the units. When the field exceeds a critical field Ec, avalanche multiplication takes place. As the field near the anode is larger than other parts of the device, generation is activated first near the anode, and then expands into the bulk. Then the generated holes drifts towards the cathode and electrons accumulate near the anode, which arouses the separation of electric field. Therefore, the device is divided into two parts accordingly:

Part 1: In this part, the field is relatively small and the generation can be neglected. The basic equations are:

$$J = qVs(n_s + p_s) \tag{1}$$

$$\frac{\varepsilon}{q}\cdot\frac{dE}{dx} = n_s + \mathrm{N}_A^{-} - p_s = \frac{J + J_1}{qVs} - 2p_s \tag{2}$$

Where $J_1 = p_0 qVs = N_A^{-} qVs$.

Considering the assumption a), the electric field distribution in Part 1 is obtained:

$$E(x) = Es + \frac{q}{\varepsilon}\left(\frac{J + J_1}{\mathrm{qVs}} - 2p_s\right)x \tag{3}$$

In the above equations, Vs, Es are the saturated velocity and electric field respectively; q is the magnitude of electron change; ε is the dielectric permittivity; N_A is the equivalent doping density and the average concentration for electrons n_s and holes p_s in the bulk are adopted for simplification;

Part 1 is terminated at $x=x_2$, where avalanche multiplication can't be ignored. In this model, x_2 is defined as the point where the density of generated carriers equals the charge exists in this region, which is expressed by:

$$\frac{J + J_1}{qVs} - 2p_s = 2\int_0^{x_2} g\,dx \tag{4}$$

The right side of (4) is calculated using the simplified method in reference[5] and arrives at:

$$2\int_0^{x_2} g\,dx = \frac{x_2}{E_2 - E_s}\cdot\frac{2J\alpha_\infty}{qV_s b_n} E_2{}^2 \exp\left(-\frac{b_n}{E_2}\right) \tag{5}$$

Where E_2 is the electric field at $x=x_2$.

Substitute the value of (3) at x_2 into (4)(5), one gets:

$$E_2 = \frac{b_n}{\ln(J/J_0)} \quad \left(J_0 = \varepsilon V s b_n / 2\alpha_\infty x_2^2\right) \tag{6}$$

Other parameters in equation (3) are given by combining the results of Part 1 and Part 2 at $x=x_2$.

Part 2: the field is bigger and a large number of free carriers are knocked out in this part. Owing to the electric field force, a majority of electrons are stored near the anode, which will result in a rapid change of electric field. Therefore, it is concluded that the avalanche multiplication zone is very narrow, and it wouldn't bring in too much error if the electric field is assumed to increase linearly with the slope of that at x=L.

Hence, the basic equations become:

$$J = n(L)qVs = M\cdot p_s\cdot q\cdot V_s \tag{7}$$

$$\frac{dE}{dx} = \frac{q(n(L) + N_A^{-})}{\varepsilon} \quad \frac{E_M - E_2}{L - x_2} = \frac{J + J_1}{\varepsilon Vs} \tag{8}$$

Here n(L), E_M are the electron density and field at x=L respectively; M is the multiplication factor. Similarly, the simplified method for avalanche breakdown is adopted, and obtains the following results:

$$1 - \frac{1}{M} = \frac{C}{J - J_1} E_M^2 \exp\left(-\frac{b_n}{E_M}\right) \tag{9}$$

where $C = {Vs\cdot\varepsilon\cdot\alpha_\infty}\big/{b_n}$. The solution of equation set consisted of (3) (6) (7) (8) is:

$$E_M^2 \exp\left(-\frac{b_n}{E_M}\right) = \frac{(J - J_1)^2}{2CJ}\cdot\left(1 - \frac{E_2 - E_s}{E_2 - E_M + L(J - J_1)/\varepsilon Vs}\right) \tag{10}$$

$$x_2 = L - \frac{(E_M + E_2)\cdot\varepsilon Vs}{J + J_1} \tag{11}$$

Obviously, only when $x_2<L$, Part 2 exists and the total voltage is the sum of V_1 and V_2, otherwise, it equals V_1. Therefore, the critical current I_{th} can be defined as the current in the case of $x_2=L$. It is derived by solving equation (9) and Poisson's equation:

$$\begin{aligned} J_{\mathrm{th}} &= (J_1 + b_{\mathrm{n}}\varepsilon Vs / L\ln(J_{\mathrm{th}}/J_0)) \\ I_{\mathrm{th}} &= J_{\mathrm{th}}\cdot A \end{aligned} \tag{12}$$

Where A is the area of electrodes.

Based on the calculation results, the total voltage is described as follows:

$$V_{\text{total}}=\begin{cases} V_1=E_s\cdot L+\dfrac{(E_2-E_s)\cdot L^2}{2x_2} & I<I_{\text{th}} \\ V_1+V_2=\dfrac{(E_2+E_s)\cdot x_2}{2}+\dfrac{(E_M^2-E_2^2)\cdot \varepsilon Vs}{2(J-J_1)} & I>I_{\text{th}} \end{cases} \tag{13}$$

Where E_2, E_M, x_2, I_{th} are the solution of equation (6) (10) (11) (12) respectively, and other parameters are shown in Table 1.

property	amorphous GST
V_s	5×10^4cm/s
E_s	2×10^4V/cm
α_∞	4.4×10^5/cm
b_n	0.99×10^6V·cm
ε_r	16.5
N_A	10^{16}/cm^3

Table 1: The electronic parameters of amorphous GST. Inside them, the values of N_A, Vs are extracted from [8, 9], and Es, α_∞, b_n are fitting parameters based on the corresponding values of Si.

3 RESULTS AND DISCUSSIONS

3.1 The Electric Characteristic of a PCM Unit

In order to compare with the data in [10], 75nm is taken as the diameter of the electrode. Based on the calculation in Section 2, current versus voltage and electric field distribution are presented in Figure 2, 3.

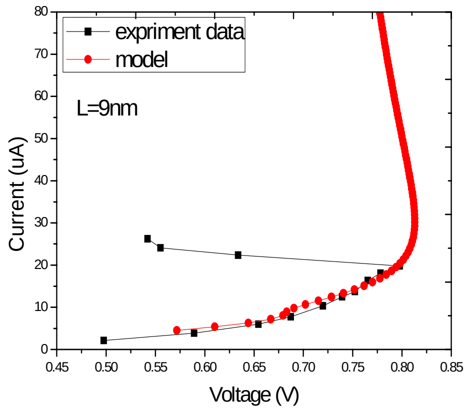

Figure 2 Current versus voltage for a PCM unit with L=9nm

The model results and the data match pretty well in Fig.2 until $I>I_{th}$. According to reference[11], data above the switching point isn't representative of the initial amorphous material owing to the parasitic capacitance in the experiment, therefore, our model is reasonable.

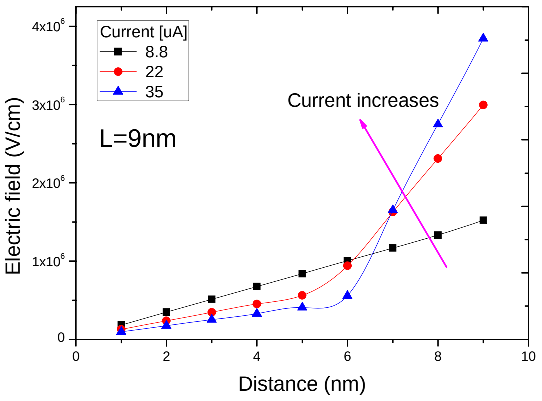

Figure 3 The electric field distribution along the unit for various current (L=9nm)

Figure 3 provides a clue for the physics of OTS: If $I<I_{th}$, only drift region exists and the slope of field increases linearly, consequently, the area below the lines—the voltage across the unit increases correspondingly (curve a). Once I exceeds I_{th} (curve b, c), both parts exist at the same time but with contrary slope trends. The slope of Part 2 increases with I, while the one of Part 1 lowers substantially; which results in V_2 and V_1 change reversely. From Figure 3, the avalanche multiplication zone is narrow. Therefore, the decrease of V_1 has more impact to V_{total} than the increase of V_2, eventually producing a voltage snap-back.

3.2 The Effects of L on the ElectricProperties of PCM Units

Figure 4 illustrates the effect of L: V_{th} is proportional to L, while I_{th} is otherwise; which is the same with the reported data [10].

In order to discover the mechanism of scaling trend, the field distribution for PCM units with L=15,19nm is plotted in Figure 5. As mentioned above, V_{th}, I_{th} are the voltage and current under which a certain number of carriers are generated by avalanche breakdown. It is accepted avalanche breakdown happens when electric field exceeds a critical field $E_c=3.3\times10^5$V/cm [8, 12] ,as the blue line denotes. From Figure 5, it is observed that avalanche generation takes place in a larger part of the device; therefore, more carriers are produced in the thicker unit. In another word, for a unit with bigger L, the carriers needed for switching can be generated with a smaller current; which is just the reported scaling trend.

Although this model makes progress in the mechanism of scaling trend, further work is still needed in the future, such as the effect of trap distribution to the avalanche breakdown and the physics of delay time.

4 CONCLUSION

This paper proposes a regional OTS model based on space charge effect. The physics of OTS is explained successfully by the change of field distribution under different currents. The dependence of threshold voltage and current on the thickness of GST is also discussed in this paper, and the results are consistent with the reported data. This model provides a reference to define the program window, and gives helpful guidance for the simulation of the PCM reliability.

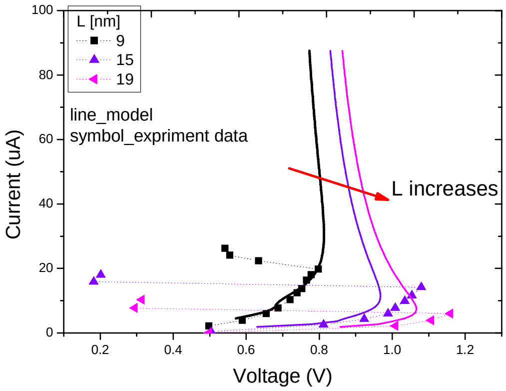

Figure 4 Current versus voltage for PCM units with different L

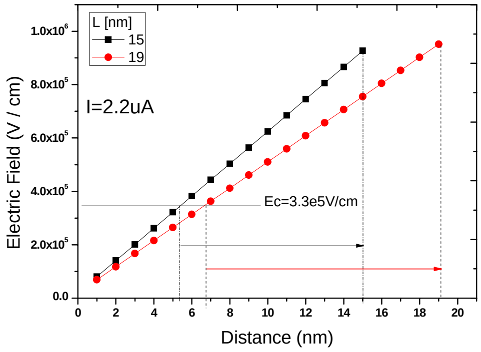

Figure 5 Field distribution for PCM units with different L

5 ACKNOWLEDGMENTS

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