Three-Dimensional Simulations of RESET Operation in Phase-Change Random Access Memory with Blade-Type Like Phase Change Layer by Finite Element Modeling *

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An optimized device structure for reducing the RESET current of phase-change random access memory (PCRAM) with blade-type like (BTL) phase change layer is proposed. The electrical thermal analysis of the BTL cell and the blade heater contactor structure by three-dimensional finite element modeling are compared with each other during RESET operation. The simulation results show that the programming region of the phase change layer in the BTL cell is much smaller, and thermal electrical distributions of the BTL cell are more concentrated on the TiN/GST interface. The results indicate that the BTL cell has the superiorities of increasing the heating efficiency, decreasing the power consumption and reducing the RESET current from 0.67 mA to 0.32 mA. Therefore, the BTL cell will be appropriate for high performance PCRAM device with lower power consumption and lower RESET current.

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In recent years, phase-change random access memory (PCRAM) has been considered to be a promising candidate for next generation memory technology characterized by its nonvolatility, low power consumption, high speed, simple cell structure and favorable fabrication compatibility with complementary metal-oxide-semiconductor (CMOS) process.[1–3] By applying electrical pulses to PCRAM cells, phase change material can achieve reversible switching between the crystal (SET) and amorphous (RESET) states. Digital information will be stored by the feature of resistance contrasts between the crystal and amorphous states (two or three orders of magnitude).[4–6]

The RESET current is one of the most important parameters for commercial production of PCRAM. Low RESET current is in favor of reducing the loss of power and increasing the integration density of PCRAM cells. There are two major ways to reduce the RESET current, including seeking for high performance materials and optimizing the device structure.[7,8] In this work, an optimized device structure for reducing the RESET current of PCRAM with blade-type like (BTL) phase change layer was proposed, and we analyzed the electrical and thermal distributions during RESET operation by three-dimensional finite element modeling. Compared with the blade heater contactor (BHC) structure, the BTL cell had smaller programming region of $Ge_2Sb_2Te_5$ (GST) layer, lower RESET current and higher switching speed.

Figure 1 shows the three-dimensional diagrams of PCRAM cells investigated. In the BHC cell, as shown in Fig. 1(a), the titanium nitride (TiN) heater contactor is blade-type. In the BTL cell, as shown in Fig. 1(b), the TiN heater contactor and the GST layer are both blade-type and their contact surfaces are cross-shaped. The thickness of the blade-type layers are all 10 nm and the shapes of the bottom of other layers are square.

The cross section view of the BTL cell is shown in Fig. 2, which is the same as that of the BHC cell, including tungsten (W) bottom electrode contactor, TiN heater contactor, GST, TiN contactor and top electron contactor W. SiN is selected as the dielectric material and surrounds PCRAM cells.

Finite-element model has been established by the COMSOL Multiphysics software. The finite element model of PCRAM consists of an electrical model coupled with a thermal model by Joule heating. Heat transfer by conduction is modeled utilizing the tran-

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sient heat equation

$$\frac{\partial \rho CT}{\partial t} = Q + \nabla \cdot (k \nabla T), \tag{1}$$

where ρ is the density, C is the heat capacity, T is the temperature, t is the time, k is the thermal conductivity, and Q is the heat flux which can be expressed as

$$Q = J \cdot E = \sigma E^2 = \sigma |\nabla V|^2, \tag{2}$$

where J is the current density, σ is the electric conductivity, and V is the electric potential.

Table 1 lists the electrical and thermal parameters of the materials used in the three-dimensional finite element model. In this study, we only consider the temporal and spatial dependence of the thermal and electrical conductivities of materials in the phase-change layer. The room temperature (300 K) is set as the exterior boundary temperature in PCRAM cells and continuity is applied to interior boundaries in PCRAM cells. Appropriate meshes could help obtain more accurate simulation results, therefore we refine meshes in the programmable GST region. The current pulses for the RESET operation are applied to the initial crystalline model and the temperature in GST is heated above the melting temperature, forming a molten region. Then the molten region is quenched rapidly for amorphization, and to avoid possible recrystallization, achieving switching from the crystal phase to the amorphous phase.[16]

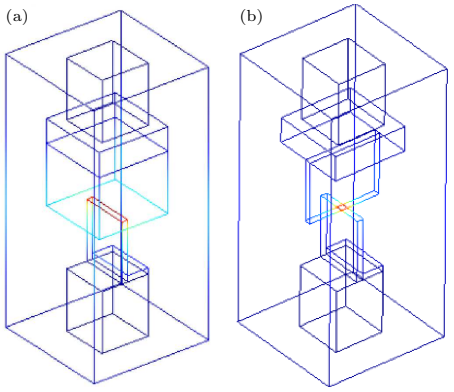

Fig. 1. Three-dimensional diagrams of (a) PCRAM cell with BHC structure and (b) PCRAM cell with BTL structure.

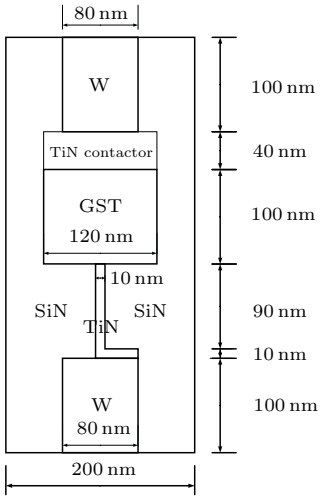

Fig. 2. Schematic cross-section view of the BTL cell.

Table 1. The thermal and electrical parameters of the related materials.

	Electrical Conductivity σ (Ω/m)	Density ρ (kg/m^3)	Thermal conductivity K (W/m·K)	Specific heat capacity C_p (J/kg·K)
W	1.75×10^7	19300	178	132
TiN contactor	10^6 (Ref. [9])	5400 (Ref. [10])	13 (Ref. [10])	784 (Ref. [12])
TiN	10^5 (Ref. [9])	5400 (Ref. [10])	0.44 (Ref. [11])	784 (Ref. [12])
GST (Liquid &Cryst.)	100800 (Ref. [13])	6200 (Ref. [14])	0.5 (Ref. [15])	202 (Ref. [12])
GST (Amorph.)	3 (Ref. [13])	6200 (Ref. [14])	0.2 (Ref. [15])	202 (Ref. [12])
SiN	10^{-15}	2220	1.45	700

When the temperature in the GST region is higher than the melting temperature ($T = 893$ K), GST materials will be in the liquid state. There is a fast quenching at the falling edge of current pulse, thus we consider the melting region as the amorphous region marked by the isothermal contours of melting temperature (893 K), as shown in Fig. 3. The bottom electrode, TiN heater contactor, amorphous GST, crystalline GST, and the top electrode will form a series of resistance, when the amorphous region fully covers the bottom electrode contactor. The value of PCRAM cell resistance surges by 10^2–10^4 times, which means that the RESET operation has finished, the related current pulse is called the RESET current pulse.[17,18] Figures 3(a) and 3(b) are obtained by applying RESET current pulses of 0.67 mA to the BHC cell and 0.32 mA to the BTL cell, respectively. It is obvious that the melting region of the GST layer in the BTL cell is smaller than that in the BHC cell, and the programming current in the BTL cell is lower than that in the BHC cell.

Figure 4 illustrates the temperature distributions of PCRAM cells at the RESET current, which is obtained by performing transient simulations. The cor-

responding surface temperature of the model can be determined from the gray level bar on the right of the figure. Compared with the BHC cell, the area of the temperature distribution in the BTL cell is smaller and more concentrated on the TiN/GST interface. Hence, the BTL cell has higher heating efficiency and lower RESET current.

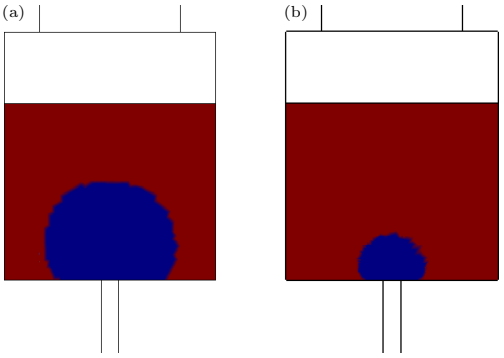

Fig. 3. Melted regions at electrical current pulses of (a) 0.67 mA in the BHC cell and (b) 0.32 mA in the BTL cell.

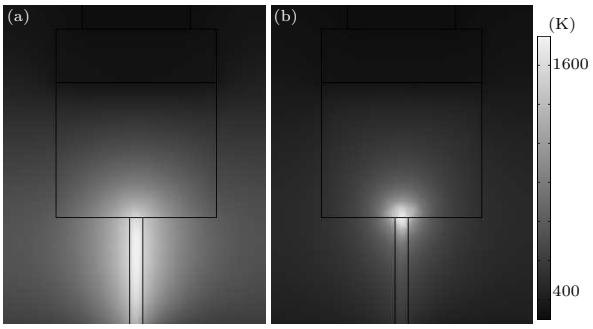

Fig. 4. Temperature distributions at electrical current pulses of (a) 0.67 mA in the BHC cell and (b) 0.32 mA in the BTL cell.

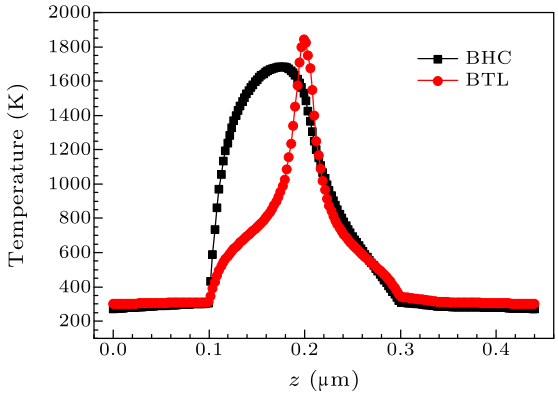

Fig. 5. Temperature profiles along vertical direction (z-axis) in the middle of BHC and BTL cells.

The temperature profiles along the vertical direction (z-axis) in the middle of the BHC cell and the BTL cell are shown in Fig. 5. As shown in Fig. 5, the temperature distribution in the BTL cell is more focused on the TiN/GST interface and the highest temperature is in the BTL cell. In the BHC cell, the temperature distribution is in a wide range, and there is numerous unnecessary energy loss. The electric-field sections along the vertical direction (z-axis) in the middle of the BTL cell and the BHC cell are shown in Fig. 6. The result is similar with that in Fig. 5. The electric-field values of the BHC cell, compared with those in the BTL cell, are higher in the TiN heater layer, while the values in GST layer are much lower. Therefore, the BTL cell increases the heating efficiency and reduces the power consumption.

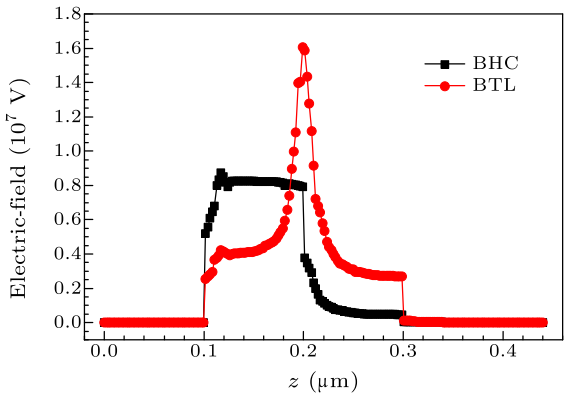

Fig. 6. The electric-field sections along the vertical direction (z-axis) in the middle of the BTL cell and the BHC cell.

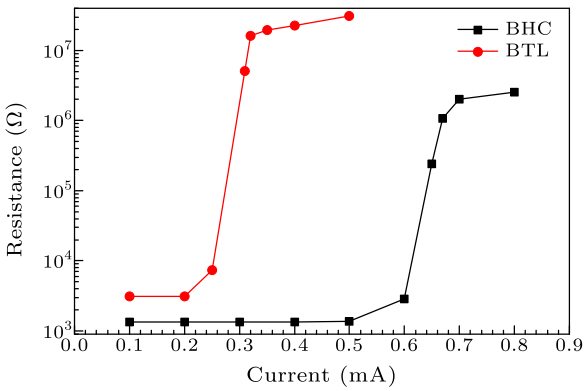

Fig. 7. Relationships between cell resistance and the current pulse of BHC and BTL cells in the RESET operation.

In the RESET operation, when the value of the resistance has a dramatic change, which is increased by two or three orders of magnitude, the RESET operation succeeds. The current pulses of 50 ns width with different amplitudes are applied to the PCRAM cell in finite-element simulations.[19] Figure 7 shows the relationships between the cell resistance and the current pulse of both the BHC cell and the BTL cell during the RESET operation. The value of high resistances is 100 times higher than that of the low resistances. The RESET current of the BHC cell is about 0.67 mA, while that of the BTL cell is only 0.32 mA, indicating a large gap between the two values. That is, the BTL cell shows better performance.

When the RESET current is invariant in PCRAM cells, an appropriate pulse width can effectively reduce power consumption. The RESET current varies with the pulse width in the BTL cell, as shown in Fig. 8. The RESET current of the BTL cell is optimized when the pulse width is approximately 18 ns. The change of the RESET current in the cell is very small when the pulse width is larger than 18 ns. The current pulses of 30 ns width with 0.32 mA are applied to the BTL cell, which could achieve the RESET operation.

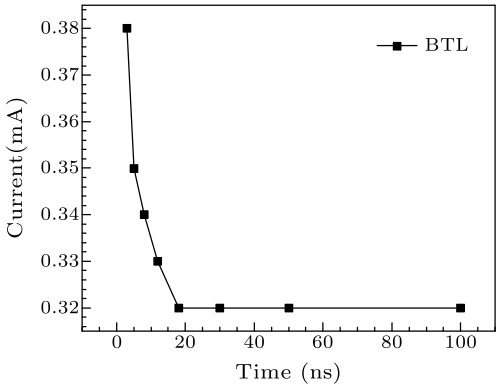

Fig. 8. Variations of the RESET current with the pulse time of the BTL cell.

In summary, a new PCRAM cell structure with BTL structure has been proposed. The electrical thermal behaviors of BTL and BHC cells during RESET operation have been simulated and analyzed by three-dimensional finite element modeling. Compared with the BHC cell, the programming region of the GST layer in the BTL cell is much smaller, and thermal electrical distributions of the BTL cell are more concentrated on the TiN/GST interface. The BTL cell has the superiorities of increasing the heating efficiency, decreasing the power consumption and reducing the RESET current from 0.67 mA to 0.32 mA. Therefore, the BTL cell is appropriate for next-generation PCRAM devices with lower power consumption and lower RESET currents.

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