Reliability modeling and analysis of flicker noise for pore structure in amorphous chalcogenide-based phase-change memory devices

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1. Introduction

As the scaling of flash memory is progressed to the limit, many alternative memories have been emerging recently. Phase-change memory (PCM) is also one of the strong candidates to replace the flash memory in terms of both scalability and performances because it distinguishes the set/reset states by the phase of chalcogenide material [1,2]. However, PCM has the problems which typically have high programming current and device reliability [3]. Therefore, the effort to reduce the set/reset current of the device has been actively investigated by changing the composition of Ge–Sb–Te (GST) material, contact area and structure of device [1,2]. The reason why the structure is important in reducing the set/reset current is that the principle of program/erase operation of PCM is joule heating of GST material. Thus, PCM is very sensitive to the device structure which determines the flow of the heat in the GST. However, reliability is also one of the most important characteristics of memory. In PCM, the drift and noise are the main problems to degrade the device reliability characteristic [4–6].

In this paper, we analyze the pore structure PCM device which makes the programming current small in the view of reliability characteristic enhancement. Flicker noise affects the operation and reliability of device significantly because the noise induces error at the readout operation, which generates read disturbance of the device. Here, the flicker noise is used as a diagnostic tool of reliability by extracting from the device using TCAD simulation based on Hooge’s law [7]. As a result, we provide the correlation between the reset current and reliability for the pore structure of the PCM device.

2. Modeling and simulations

We analyze the reliability characteristic for two different structures extracting the flicker noise at the read condition (Vread = 0.4 V) using Silvaco 2D ATLAS simulation [8]. The prepared structures are pore structure and mushroom structure which are general structures as shown in Fig. 1. We deposit the TiN to a bottom electrode and top electrode, deposit W to a heater, and deposit amorphous GST according to each structure with Si3N4 insulating layer. The contact area between heater and GST is 1.5 × 10−9 cm2 for both structures. The reason why we only analyze the reliability characteristic in the amorphous condition is that the noise in PCM is mostly generated in the condition of amorphous state [9]. The modeling parameters of the amorphous GST are referred from the work of Pirovano et al. [10]. The density of states (DOS) of conduction bands, the DOS of valence bands, the lone-pairs, the donor-like traps, and the acceptor-like traps are 2.5 × 1020 (/cm3), 1020 (/cm3), 1021 (/cm3), 1017–1020 (/cm3), and 1017–1020 (/cm3), respectively.

3. Results and discussion

The methods to reduce the reset current are changing the composition of GST, controlling the contact area and varying the structure of device [1,2]. Here, we analyze the reliability of device in the read situation when the contact area is reduced and the structure is changed from the mushroom to the pore structure.
The pore structure of PCM is known to be effective for the reduction of reset current by confining the switching volume of GST [11]. It reduces the reset current of device by half of mushroom structure [11] and the reset current is reduced by 53% in our simulation. It is a significant improvement for reset current. Fig. 2 shows the lattice temperature of amorphous GST when the reset operation is applied to both structures. However, in the perspective of reliability, the flicker noise spectral density is worse than the mushroom structure as shown in Fig. 3 even if there is peak and variation of the value since it has the random characteristic of noise by the fluctuations in the instantaneous electron density and drift velocity generated by TCAD simulation [8]. In other words, although the power dissipation of device decreases, the error rate for read operation is critically degraded in the pore structure. The error of PCM device at the operation is usually generated by the peak value of current. The current of PCM is comprised of two parts. One is the drift current and the other is noise current [6], and the noise current makes many peaks and variations of PCM current in time domain. In addition, induced peak of current above the switching current can be a critical trigger to change the state of GST to another state even if it is not the signal changing the state of GST. Therefore, as the noise spectral density increases, the probability to make errors is also increased and it makes the error rate for read operation degraded.

In the simulation result, we found that the ratio of the region over the specific temperature which is fully changed from crystal to amorphous in the pore structure is larger than in the mushroom structure with as much as 23% through the current path between the top and the bottom electrode even if the reset operation is equally applied to both structures. As the pore structure is effective for confining the volume through the path and reaching the melting temperature with low power, the transition of phase from crystal to amorphous is more actively generated at the path by joule heating. As a result, the pore structure has more defect centers on the current path because amorphous GST has more defect states than crystal GST. In addition, as shown in Fig. 4, the resistance of the pore structure is larger than
the mushroom structure due to the wider amorphous region [4]. It causes the increase of noise spectral density [9]. Furthermore, these defect centers are also recombined with free carriers at the read operation. Thus, the decrease of the number of free carriers is induced in GST like Table 1, and the noise becomes large according to the equation of Hooge’s law [12]. The equation is as follows:

\[
\frac{S_f}{f^2} = \frac{\alpha}{f \times N}
\]

where \(S_f\) is the noise spectral density, \(\alpha\) is the Hooge’s constant, \(f\) is the frequency and \(N\) is the number of free charge carriers.

Fig. 5 shows the effect of the contact area to the reliability in the pore structure. As the area is decreased, the flicker noise spectral density is increased. Thus, the method to reduce the contact area is beneficial to the reduction of the reset current but the device reliability is degraded by the noise effect.

\[
I = \frac{\Delta T}{V_{th}R_{th}}
\]

where \(\Delta T\) is needed to reach the melting temperature, and \(V_{th}\) is the voltage drop across the GST. These two parameters are constant here because it is always equal at the same structure and material.

The relationship between the contact area and the reset current is proportional to each other because the main reason of decreasing the reset current is the increase of the thermal resistance \((R_{th})\) of a heater due to the reduction of the contact area according to Eq. (2) [13]. However, there is only a small variation of GST characteristics. The noise generated in GST is related with the characteristic of GST and it is not related with the interface of heater/GST and the varied \(R_{th}\) of a heater [7]. Therefore, the right side of Eq. (1) is nearly the same even if the contact area is changed because it is related with the material characteristic of GST, but the current term at the left side of Eq. (1) is changed according to the thermal resistance of each contact area using Eq. (2). As a result, the normalized noise spectral density increases as the contact area is decreased since the current term is decreased by the effect of \(R_{th}\).

4. Conclusion

In this paper, we analyzed the effect of the method reducing the reset current of PCM in the aspect of device reliability. We investigated two methods by controlling the contact area and varying the device structure. It was found that the trade-off effect between reset current and reliability was observed. The method reducing contact area was beneficial to reset current reduction but the device reliability was degraded since the increased thermal resistance caused the current reduction and the normalized noise spectral density was aggravated. The method varying the device from mushroom to pore structure was also beneficial to reset current reduction since the pore structure was highly efficient in switching volume resulting in the reduction of reset current, but the device reliability was degraded. The superior efficiency of switching volume in the pore structure induced larger resistance and decrease of free carriers at the read operation. Eventually, the degradation of PCM device reliability was induced in pore structure in contrast with the improvement of reset current. Therefore, it can be concluded that methods to reduce the reset current by controlling the contact area and the switching volume can be considered at the same time for the device reliability.

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References


Fig. 5. Flicker noise spectral density for different contact areas at read operation in pore structure.

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