Peculiarities of the memory state formation in thin Ge$_2$Sb$_2$Te$_5$ films

S A Fefelov$^1$, I P Kazakova$^2$, N A Bogoslovskiy$^1$, A O Yakubov$^3$ and A B Bylev$^2$

$^1$Ioffe Institute, Politekhnicheskaya 26, St Petersburg 194021, Russia
$^2$Saint Petersburg State Forest Technical Academy, Institutskiy per. 5, St. Petersburg 190999, Russia
$^3$National Research University of Electronic Technology, ld. 1, Shokin Square, Zelenograd, Moscow 124498, Russia

e-mail: s.fefelov@list.ru

Abstract. The current-voltage characteristics of Ge$_2$Sb$_2$Te$_5$ thin films were measured by a sequence of triangular current pulses with an increasing maximum current. Each current pulse forms in the sample a conducting filament with an area proportional to the maximum current in the recording pulse.

1. Introduction
Chalcogenide glassy semiconductors of the GeSbTe system are promising and are already used in phase-change memory (PCM) based on the glass-crystal phase transition [1]. Particularly attractive for the non-volatile memory elements with electrical information recording are high write speed, significant difference in the resistances of the crystalline and amorphous phases, and a large number of rewriting cycles. Despite the recent significant advances in the PCM technology, the physics of the processes occurring during electrical recording of information is still a subject of discussion [2]. Incomplete understanding of the processes accompanying the transition to the crystalline state makes it difficult to improve the PCM technology [1-4]. In this paper we study the current-voltage (I-V) characteristics of Ge$_2$Sb$_2$Te$_5$ thin films in order to study the processes occurring during the formation of the memory state.

2. Materials and methods
The studies were carried out on thin-film "sandwich" type samples. On thermally oxidized silicon substrates with a 1 μm thick SiOx oxide film was deposited Au conductive coating which was used as the bottom electrode. Amorphous Ge$_2$Sb$_2$Te$_5$ film with thickness 130 nm was deposited by the magnetron sputtering of polycrystalline target. The top electrode was a gold clamping probe with a contact area of about $10^{-4}$ cm$^2$. The measurements were made using the previously proposed and well proven method with a current generator [6]. A series of triangular current pulses was applied to the sample with a maximum current ($I_{\text{max}}$) sequentially increasing from 0.1 mA to 8.2 mA. And a voltage drop on the sample was measured. The pulse duration was 2 ms, the time interval between the pulses was on the order of several seconds.
3. Results

For each point of the sample, the initial resistance was measured at a low current of 6.5 μA. For as-deposited samples, the initial resistance at various points varied over a wide range from approximately 40 to 120 kΩ. For the annealed samples, the initial resistance was higher, and the spread of values was sufficiently lower, approximately from 240 to 300 kΩ.

When current flows through an amorphous GeSbTe sample, a strongly nonlinear I-V curve is observed; after the voltage across the sample reaches the maximum value, called the threshold voltage $V_{th}$, the resistance of the sample sharply decreases, which is called the switching effect. In our measurements, the threshold voltage for as-deposited samples varied in the range from 1.5 to 5 V. We found that for points with a lower initial resistance the value of the threshold voltage $V_{th}$ was also lower. For annealed samples, $V_{th}$ was varied in the range from 4 to 8 V.

It is known that, for structures with an S-shaped I-V curve, a uniform current distribution is unstable against formation of a high current filament [7]. The characteristic size of the filament in GST thin film samples is about 1 μm [2]. Therefore, we believe that in our samples with a top contact size of about 100 μm, a high current filament is formed during switching. This conclusion is confirmed by the fact that after switching the voltage on the sample remains constant even if the current through the sample significantly increases. Significant heating occurs inside the current filament due to the release of Joule heat. Thus, inside the filament arise the conditions for crystallization.

Figure 1 shows the I-V curves obtained on an as-deposited sample by applying a series of four current pulses with $I_{max}$ 100 μA, 1900 μA, 3700 μA and 8200 μA. As can be seen from the figure, when a current pulse is applied, the sample turns into a low-resistance state and memorizes this state. As the current decreases, the sample remains in the low-resistance state. When the next pulse is applied, the sample resistance does not change as long as the current does not exceed the maximum current of the previous pulse. With a subsequent increase in current, the voltage across the sample remains constant, approximately 0.4 V. The sample turns into a state with a lower resistance. In our opinion a high current filament is formed in the sample; inside the filament arise the conditions for crystallization. The current density in the filament is determined by the parameters of the sample; with an increase of current, the cross-section of the filament increases proportionally to the total current through the sample.

![Figure 1. I-V curves of an as-deposited sample obtained by four current pulses with increasing $I_{max}$.](image-url)
Figure 2 shows the I-V curves obtained by applying a repeated pulse with the same maximum current value. This data show that a current pulse forms a conductive filament with a resistance depending on the recording current – maximum current \( I_{\text{max}} \). If the current does not exceed the recording current, the I-V curve is linear. A small deviation from linearity at high currents is associated with sample heating. Probably the crystalline phase in the filament has a limited carrier concentration; therefore, when the current exceeds the recording current, the excess current flows through the amorphous region. This leads to the heating of the amorphous periphery of the filament, crystallization and increase of the filament cross section.

![Figure 2. I-V curves of an as-deposited sample obtained by second pulse with the same maximum current value.](image)

For the annealed samples, we observed a similar behavior; upon sequential application of current pulses with increasing amplitude, states with different resistances were formed. The resistance value was approximately inversely proportional to the amplitude of the current in the pulse. Also, for approximately 60% of the studied points on annealed samples, we observed the oscillations of the voltage on the sample during switching. We previously reported about voltage oscillations on other samples [8] and believe that this effect is associated with the current-limited measurement scheme. However, the detailed mechanism of the oscillations is currently not clear. For as-deposited samples, no voltage oscillations were observed.

4. Discussion
The electronic-thermal model was used to qualitatively describe the behavior of amorphous Ge\(_2\)Sb\(_2\)Te\(_5\) in a strong electric field and to explain the data obtained. According to this model, before switching a high-temperature current filament arises in the sample, wherein there are conditions for crystallization and the formation of a low-resistance state (or memory state).

From the obtained experimental data, it follows that after the transition of the sample to a low resistance state, this state is maintained, the forward branch of the I–V curve for a next pulse always follows the reverse branch of the previous I–V curve. When the current value exceeds \( I_{\text{max}} \) of the previous pulse, a formation of a new state with a lower resistance starts. It is important to note that this process occurs at a constant voltage across the sample. According to the electronic-thermal model [2] at this voltage arise the conditions for heating of the sample in the region of the current filament and increasing the area of the crystalline filament due to thermo-induced crystallization [9].
In our previous work, similar measurements were made on samples with a multilayer bottom electrode made of TiN and W [10]. On these samples, the contact between the bottom electrode and the GeSbTe film was not ohmic; therefore, observed I–V curves were more complicated. Thus, in samples with a lower TiN electrode, a small voltage jump was observed at each subsequent current pulse, which is apparently associated with the nonlinear conduction on the interface between TiN and GeSbTe [11]. This conclusion is consistent with the fact that the voltage across the sample also changed with a change in the voltage polarity. In the present work, such effects were not observed for samples with Au bottom electrode, which made it possible to separate the effects of contacts and demonstrate the constancy of the sample resistance on the reverse branch of the I–V curve and the constancy of the voltage during the formation of a state with a lower resistance.

The resistance of the formed crystalline filament was calculated from the reverse branch of the I–V curve. Assuming that in the crystalline GeSbTe filament has a cubic phase with a resistance of the order of 0.5 Ω·cm [5], we estimated that the radius of the filament is approximately 2 μm for the maximum current 8.2 mA.

5. Conclusion
A study of the I-V characteristics of thin Ge2Sb2Te5 films has been carried out in the regime of a given current with a sequence of triangular current pulses with an increasing maximum current. When a pulse with a high current is applied to the sample, its resistance decreases significantly. When the current through the sample is reduced, the sample remains in a low-resistance state. This indicates that a crystalline filament is formed with an area proportional to the value of the maximum current in the pulse. For the samples annealed at 100°C the spread of the initial resistance and threshold voltage is sufficiently lower, which indicates that annealed samples are more homogeneous. The observed dependence of the resistance of the memory state on the maximum value of current in the recording pulse can be used in memristors.

References
[1] Burr G W et al. 2010 J. Vac. Sci. Technol. B 28(2) 223
[2] Bogoslovskiy N and Tsendin K 2012 Semiconductors 46 559
[3] Athmanathan A, Stanisavljevic M, Papandreou N, Pozidis H and Eleftheriou E 2016 IEEE J. Emerg. Sel. Top. Circuits Syst. 6 87
[4] Nirschl T et al. 2007 Proc. Int. Electron Device Meeting 461
[5] Kato T and Tanaka K 2005 Jpn. J. Appl. Phys 44(10) 7340
[6] Fefelov S A, Kazakova L P, Tsendin K D, Arsova D, Pamukchieva V and Kozyukhin S A 2014 Technical Physics 59 546
[7] Ridley B K 1963 Proc. Phys. Soc. 82 1
[8] Fefelov S A, Kazakova L P, Bogoslovskiy N A and Tsendin K D 2018 Semiconductors 52(12) 1607
[9] Bogoslovskiy N and Tsendin K 2017 Solid-State Electronics 129 10
[10] Fefelov S A, Kazakova L P, Bogoslovskiy N A, Bylev A B and Yakubov A O 2020 Semiconductors 54 450
[11] Bryja H, Grüner C, Gerlach J W, Behrens M, Ehrhardt M, Rauschenbach B and Lotnyk A 2020 J. Phys. D: Appl. Phys 53 184002