# THE FORMATION PROCESS AND THE ELECTRICAL NATURE OF THE LOCK-ON FILAMENT IN $Ge_{0.09}As_{0.20}Te_{0.71}$ GLASS

E. MÁRQUEZ, P. VILLARES and R. JIMÉNEZ-GARAY

*Departamento de Fisica Fundamental, Facultad de Ciencias, Universidad de Cádiz, Apartado 40, Puerto Real, Spain*

Received 12 March 1985; in final form 29 July 1985

Lock-on (memory) phenomena observed in the amorphous semiconductor $Ge_{0.09}As_{0.20}Te_{0.71}$ have been investigated. The threshold voltage, $V_{th}$, and sample resistance, $R$, were measured during the formation of the filament. A relationship was obtained between the parameters $V_{th}$ and $R$ during the formation process. The electrical conductivity of the lock-on filament was deduced to be $\approx 1.1 \times 10^4\ \Omega^{-1}\ m^{-1}$. The influence of an existing lock-on filament on the formation of a new filament is also described.

## 1. Introduction

Reversible electrical switching and lock-on (memory) phenomena have been observed in several amorphous chalcogenide semiconductors [1–12]. A study of the lock-on process has been carried out [6], where a general review of the principal characteristics of the memory phenomenon is made. Research previous to the aforementioned study made clear that the memory (lock-on) and memory-off (un-locking) phenomena observed in some compositions of the Ge–As–Te system are due to thermally induced phase transformations caused by Joule heating, and that the lock-on filament formed in a glass with high As concentrations consists of degenerate crystalline $As_2Te_3$ [7]. Nevertheless, the dependence between the threshold voltage $V_{th}$ (minimum voltage at which the resistance falls to the on-state) and the resistance in the off-state $R$ during the different stages of filament formation is still not well documented. Information concerning the variation of these parameters during this growth process was provided by Steventon, who analyzed the behaviour of the thin-film structure of Ge–As–Te glasses during multiple-set pulses [8].

Additional experimental analyses by electrical and optical methods of lock-on phenomena in the $Ge_{0.09}As_{0.20}Te_{0.71}$ glassy composition are described in this paper. A relationship between threshold voltage and electrical resistance for the memory process is found. To study the electrical nature of the lock-on filament, its electrical conductivity was found. A study was also undertaken of the influence of a lock-on filament on the formation of a new filament, when the lock-on filament is close to the electrodes between which the formation of the new filament will take place.

## 2. Experimental

The samples used in these experiments were prepared as described in a previous paper [9]. The amorphous character of the samples was corroborated by X-ray diffraction. The study of the compositional homogeneity of the material was carried out with Castaing's microprobe technique. The standard deviations of the results obtained are less than 2%, which means that the degree of homogenization achieved by this method of fabrication of the material is high. These results were obtained by analyzing the composition of one sample on 20 surface sites. All samples showed electrical switching and memory effects.

Fragments of ingots of $\approx 1\ cm^2 \times 1$ mm were set in an epoxy-type resin and their surfaces were polished with 0.3 μm alumina powder. Two tungsten point

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contact electrodes were placed on the virginal polished surface, 1.5 mm apart, and good electrical contacts were ensured by gentle pressure against the samples. A dc bias voltage was applied across the electrodes with a current limiting resistor in series. Thus, the current flowing through the material during the memory (lock-on) process could be controlled by changing the value of the resistor. The process was observed by means of an Olympus inverted metallurgical microscope with camera attachment.

To study the growth process of the filament, pulses of increasing amplitude were used, with an application time of 1 min and recuperation time of 5 min. Once switch-on takes place, the voltage across the sample was maintained during a time interval of 100 ms. All measurements were carried out at room temperature.

## 3. Results and discussion

### *3.1. Relationship between $V_{th}$ and R during the growth process of the filament*

With the aim of studying the growth process of the filament, the threshold voltage and off-state resistance were measured in each switching operation, so that any possible relationship between both parameters could be found. Threshold voltage was used as a measure of the uncrystallized (low conductance) path length between the electrodes [8]. Also, the measurement of the off-state resistance of a chalcogenide sample as a function of the number of operations can provide useful information about possible structural alterations and their distribution within the material [10]. Fig. 1 shows the changes in resistance and threshold voltage during multiple-set pulses, indicating that while the filament is growing, $V_{th}$ decreases gradually and $R$ remains high, until the threshold voltage approaches zero and the resistance decreases rapidly. Fig. 1 also shows the on-resistance, which provides information about the cross-sectional area of the lock-on filament, owing to the great difference between electrical resistivity of the crystal and glass [8].

To study the dependence between the parameters $V_{th}$ and $R$ during the growth process by stages, each resistance was associated to the arithmetic mean of the

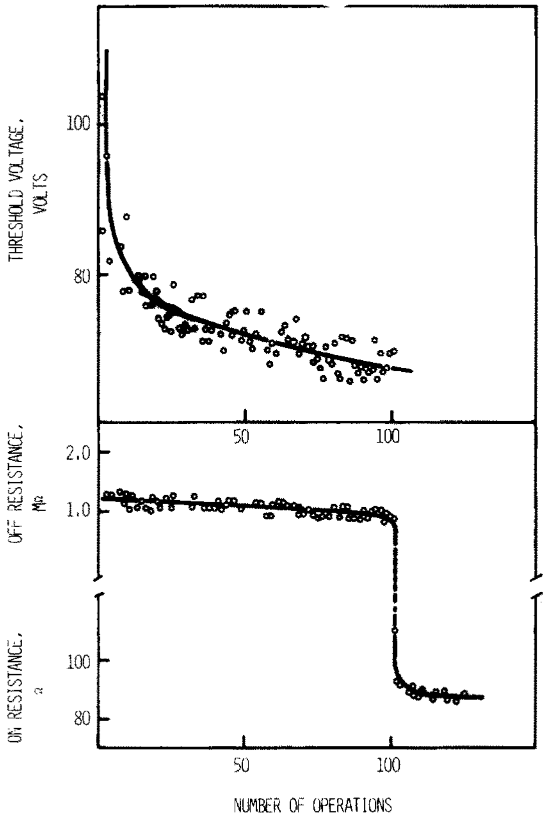

Fig. 1. Sample resistance and threshold voltage during multiple-set pulses.

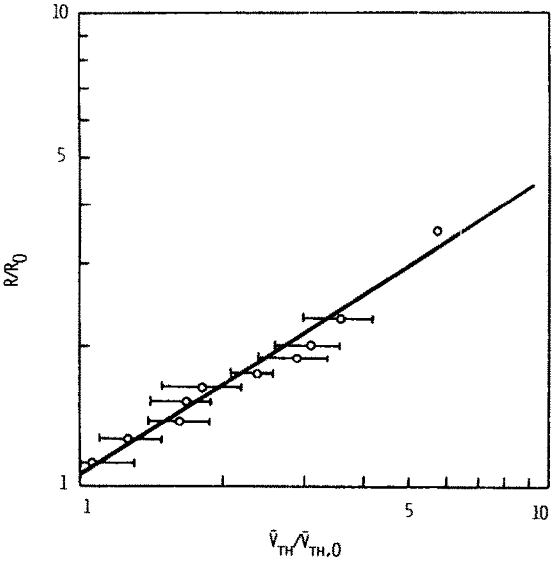

Fig. 2. Variation of mean threshold voltage with off-state resistance during growth process of the filament.

corresponding threshold voltages (for each value of $R$, different values of $V_{th}$ were found). Fig. 2 shows the mean threshold voltages, $\bar{V}_{th}$, and their respective $R$ values, both being normalized at the lowest values of $\bar{V}_{th}$ and $R$. The segments appearing in fig. 2 represent the standard deviations of the distributions, each one associated with their respective resistance. The slope of the log–log plot is 1.6. The formation of the lock-on filament gives rise to modifications in the heat generation and conduction processes in each of the stages that make up the growth process. These modifications are reflected in fig. 2. In the literature [10], similar behaviour is described in thin-film STAG glass devices, which is attributed to a phase separation within the conducting channel.

### 3.2. *The electrical nature of the lock-on filament*

To determine the electrical conductivity of the lock-on filament, a filament was formed in an uninterrupted manner. A voltage was applied which was higher than the threshold voltage [9]. In the instant where the current switched to the on-state, a fluid path (switch-on path) was seen to form between the two electrodes as a consequence of Joule heating. If the voltage was maintained after the switch-on transient had taken place, a new narrow filamentary path was formed in the molten region, the growth process of which was independent of polarity. During the formation of the filament the voltage across the two electrodes decreased gradually. When the formation process was over, the voltage reached a low constant value, thus indicating the completion of the lock-on process. After the lock-on process was performed, the $I$–$V$ characteristics were approximately ohmic, i.e. the on-state was memorized. At the lock-on state, the voltage is called lock-on voltage, $V_{LO}$, and the current, lock-on current, $I_{LO}$. Fig. 3 shows a photomicrograph of one of the filaments formed in one of the samples under study. The tracks of the molten switch-on path, wider than the lock-on filament, can also be observed in fig. 3.

The resistance of the filament decreases according to the magnitude of the lock-on current. On the other hand, the microscopic observation of the filaments formed under different lock-on conditions shows that

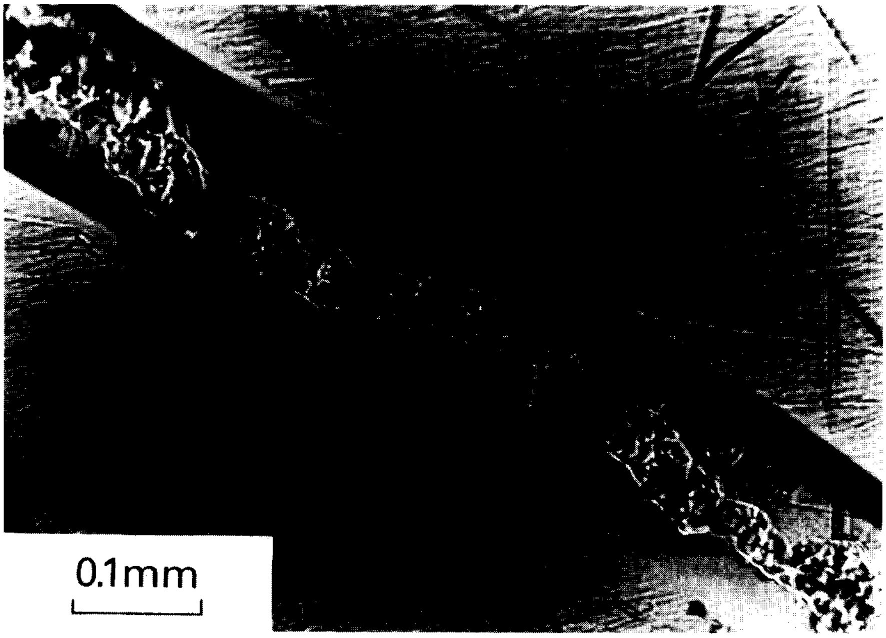

Fig. 3. Photomicrograph of the surface of glassy semiconductor after lock-on. Filament formed between two electrodes is the lock-on filament.

the filament becomes wider with increasing $I_{LO}$. Assuming a semicircular cross section, the conductivity of the filament can be estimated as follows:

$$\sigma \approx 2\,(I_{LO}/V_{LO})\,L\pi^{-1}(D/2)^{-2}\,, \qquad (1)$$

$L$ and $D$ being the length and width of the filament, respectively. The values obtained for the parameters $L$, $D$, $V_{LO}$ and $I_{LO}$ are 1.5 mm, 47 μm, 2.6 V and 15.8 mA. The conductivity value of the filaments formed in the glass under study is $\approx 1.1 \times 10^4\ \Omega^{-1}\ \mathrm{m}^{-1}$. The value obtained is high, indicating the metallic, rather than semiconductive, nature of the filament.

The electrical conductivity value of the conductive filaments formed in the composition analyzed, belonging to the area of compositions of low As concentration in the glass-forming region of the Ge–As–Te system, is very similar to that found in the literature [11] for compositions of high As concentrations. Given that glasses of low As present similar conductive filament growth [6], giving place to equally similar electrical properties, it seems probable that the filaments which appear in these compositions have an analogous electrical conductivity value. Generally speaking, the electrical conductivity of lock-on filaments appearing on the surfaces of Ge–As–Te system glasses can be considered approximately equal.

### *3.3. The influence of lock-on filament in the new formation process*

The effect of an existing lock-on filament on the formation of a new filament has been studied. It was observed that the shifting of an electrode B to the position B′ (after a lock-on filament is formed between A and B and was not erased) makes the sample to go to the off-state. To lock the sample again to the memory state, it was observed that a lower value of $V_{th}$ was required, and the new filament joined the existing filament AB at B″ to form a filament B′B″ (fig. 4). This new filament between the electrode positions AB′ is not formed along the line joining AB′, but along the AB″B′ path. Similar behaviour was observed when A is moved to A′, keeping the position of B′ unchanged (fig. 4).

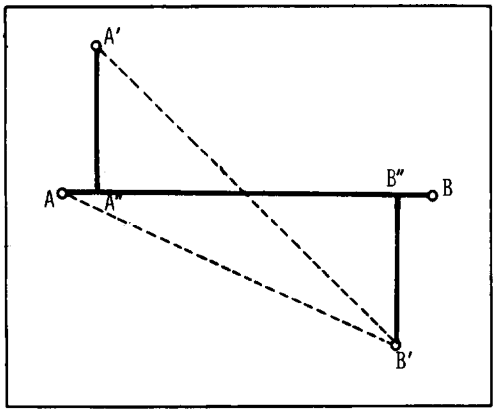

Fig. 4. The effect of the presence of a lock-on filament on the new filament formation.

It was observed that if both electrodes A and B were moved to new positions, near an existing filament, then the new filament always joined the previous filament provided the new filament was shorter than the direct path between the two electrodes. The presence of a lock-on filament next to the electrodes offers a low-resistance path, and the new filament is formed through the path of minimum resistance between the two electrodes. This shows that $V_{th}$, for a given geometry and electrode configuration and for small electrode separations, depends mainly on the sample resistance. This agrees well with the relation found between threshold voltage and the sample resistance, when virginal contacts are used, which indicates that the electrical power needed to cause switching is approximately constant [9].

In the literature [12] similar behaviour is described for glasses belonging to the high As concentration region of the Ge–As–Te system. Therefore, this effect of the lock-on filament close to the electrodes on the growth process of a new filament could be generalized to the whole glassy system.

## 4. Conclusion

Microscopic observations show that the growth process of the conductive filament does not depend on the polarity, in agreement with what has been described in the literature [6] on low As glasses of the Ge–As–Te system. Therefore, it seems reasonable to consider that crystallization takes place before ionized elements start migrating, since the crystallization rate in this type of glasses, with a low As concentration, is very high. From the experimental results obtained in this work, it is deduced that the lock-on process can be interpreted as a thermally induced glassy–crystallization phase transformation. Consequently, all the observations are consistent with the kinetic model of growth of the conductive filament proposed by Tanaka et al. [6].

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