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ELECTRICAL CONDUCTIVITY AND PHENOMENOLOGY OF SWITCHING IN THE GLASSY ALLOY $Ge_{0.09}As_{0.20}Te_{0.71}$

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The essential characteristics of the switching phenomenon, excluding memory effects, have been analyzed in the bulk chalcogenide semiconductor glass $Ge_{0.09}As_{0.20}Te_{0.71}$. A device has been designed and built to activate the samples correctly, and with which the contact pressure of the electrodes can be regulated. One of the results of this research is the constancy of the electrical power with which switching takes place. The functional dependence between the physical variables, delay time and applied voltage, is typical of bulk glasses. We have found a dependence of electrical conductivity on the applied field, which shows a deviation from the linear behaviour of the $I-V$ characteristics in the blocking state. Also, the temporal dependence of the intensity has been studied, for voltages lower and higher than V_{th}, which provides information about the evolution of the temperature of the material during electrical stimulation. The experimental results support an electrothermal model for the switching effect in the glass studied, and with the configuration of the electrodes used. The electronic contribution to the switching process is demonstrated by the dependence of electrical conductivity on the applied field.

1. Introduction

The electrical switching phenomenon has, from the beginning, attracted considerable interest [1]. Today, it still is a controversial subject, therefore all experimentation leading to its clarification is beneficial. The amorphous materials used are extremely varied, the most common being the chalcogenide semiconductors [2], organic semiconductors [3] and the oxides [4].

Basically, switching consists in a transition from a state of high resistance (OFF) to one of low resistance (ON), the transition being generated by the application of a specific voltage, named threshold voltage V_{th}. Two types of processes are found, i.e. threshold switching and memory switching. The difference lies in the fact that in the latter, once the current is suppressed, the state of low resistance remains. The explanation given for the ON state remaining when memory switching takes place, is based on the presence of a crystalline filament, which is a consequence of the Joule heating of the amorphous material [5].

Two types of mechanisms which regulate switching have been proposed. One is based on effects of an electronic nature [6], the other is founded on the

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consequences of the current flowing through the material [7]. Today there is no doubt about the mechanisms shown by each kind of sample, i.e., electronic effects dominate in thin-film structures, while the effects which influence the behaviour of bulk samples are thermic.

In this work we have carried out a systematic study of the glassy composition $Ge_{0.9}As_{0.20}Te_{0.71}$. The experimental results throw light on the dependence of electrical conductivity on the applied field. We have also studied the temporal dependence of the current in the voltage range near V_{th}. We have also measured electrical resistance and threshold voltage at room temperature. The study of the relation between delay time and switching voltage parameters has been carried out, which provides information about the kind of process that takes place in the present case. We have designed and built a device (DASEC) with which the samples can be activated correctly, and allows the contact pressure of the electrodes on the material to be controlled.

2. Experimental

The glassy ingot was prepared with materials of 99.99% purity. The desired amounts of the finely powdered raw materials were placed in a quartz tube, which was then evacuated, and subsequently filled with helium. This last operation was carried out several times. Finally, the tube was sealed. The tube was then placed in a rotatory furnace, at 900°C, for three days, to ensure the correct melt and reaction of the components. The tube was then rapidly cooled in an ice-bath. The samples thus obtained are fragile enough.

The amorphous character of the ingot was confirmed by X-ray diffraction. In our case, the diffraction pattern showed a diffuse aspect, lacking well defined peaks, which are characteristics of the presence of crystalline remains. The ingot was fragmented into pieces of approximately 1 $cm^2 \times 1$ mm, which were set in epoxy-type resin. The samples were polished, to attain a mirror-like surface.

Two wolfram point contact electrodes were placed 1.5 mm apart on the polished surface. The quality of the electrical contact was ensured with gentle pressure, by means of springs attached to the electrodes. Fig. 1 is a schematic representation of the device used (DASEC).

The measurement of the threshold voltage was obtained using voltage pulses of increasing amplitude. The pulse width was 60 s. The chosen time span was considered to be a reasonable observation time. If, during the course of excitation, switching was held off, the following voltage pulse was increased by 1 V, attending the recovery of the sample resistance. The electrical resistance of the samples was determined by measuring the current flowing through the material when a voltage of 3 V is applied. Given the clear tendency of the Ge–As–Te system to crystallize [8], the current was cut off once switching was achieved, to avoid memory effects. Delay time was measured by means of a memory oscilloscope (Trio Model MS-1650B) time base.

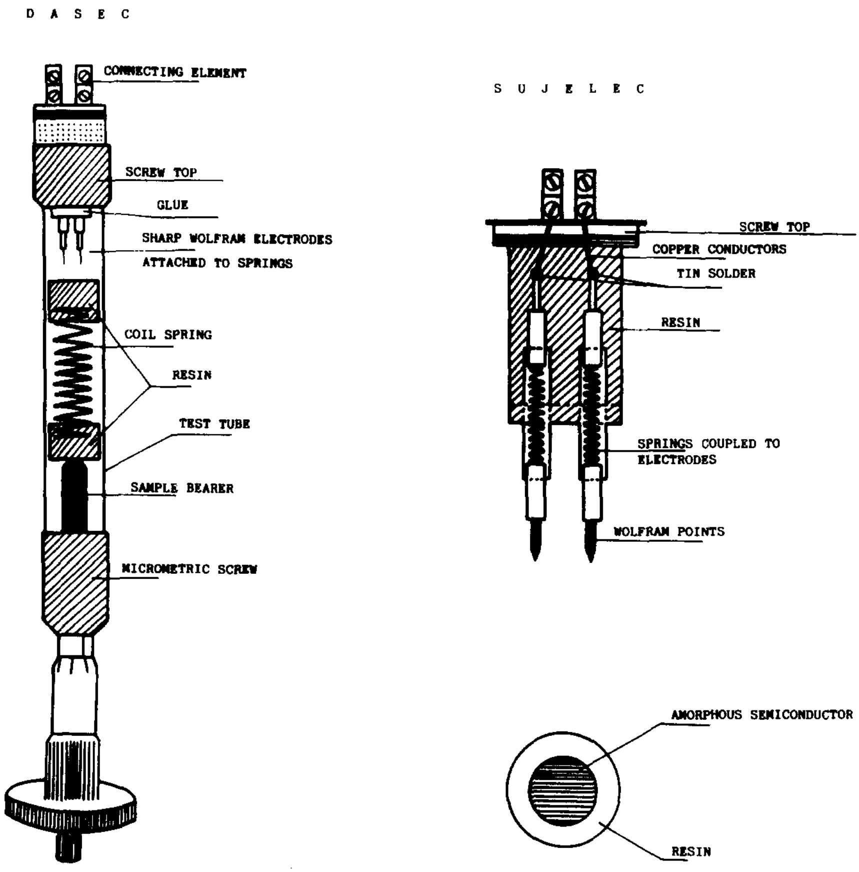

Fig. 1. (a) Device for the superficial application of switching stimuli. (DASEC); (b) electrode system and sample.

3. Results and discussion

3.1. Threshold voltage and resistance measurements

The histogram for the three physical parameters, threshold voltage, electrical resistance and electrical power, is shown in fig. 2. The mean values for the three parameters mentioned, as well as their corresponding standard deviations, are shown below:

$$\bar{V}_{\mathrm{th}} = 95\ \mathrm{V}, \quad \bar{R} = 1.19\ \mathrm{M\Omega}, \quad \bar{P} = 7.6\ \mathrm{mW},$$
$$s = 7\ \mathrm{V}, \quad s = 0.17\ \mathrm{M\Omega}, \quad s = 0.3\ \mathrm{mW}.$$

From this, one can observe that standard deviation in all cases is less than 15%. The aforementioned measurements have been carried out in different frag-

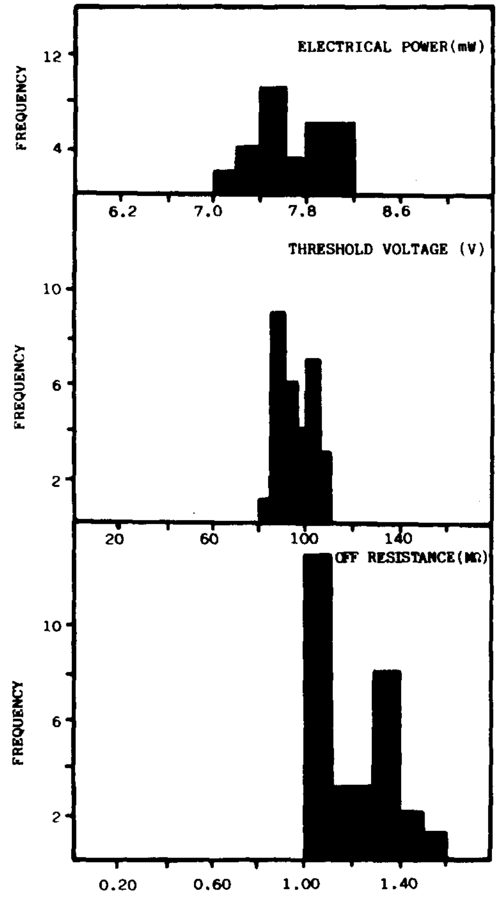

Fig. 2. Histograms of electrical characteristics: a) threshold power; b) threshold voltage; c) off resistance.

ments of the ingot, the electrodes always being in contact with virgin areas of the sample surface.

We suggest three causes for the dispersion in the results:

a) the difficulty of exactly reproducing the electrical contacts even using the DASEC device mentioned;

b) the variations in room temperature, given that threshold voltage is extremely sensitive to temperature fluctuations. More precisely, a variation of 5°C in room temperature can cause a change of 10% in threshold voltage (9);

c) the non-homogeneity of the samples, given that the parameters analyzed depend strongly on the percentages in the composition of each one of the constituting elements.

The fact that the initial electrical power is constant must be stressed. This is also found in the glassy system Al–As–Te as pointed out by Alegría et al. [10]. The values of log V_{th} vs. log R are shown in fig. 3, and the correlation present between parameters V_{th} and R is clearly seen. The experimental data obey the

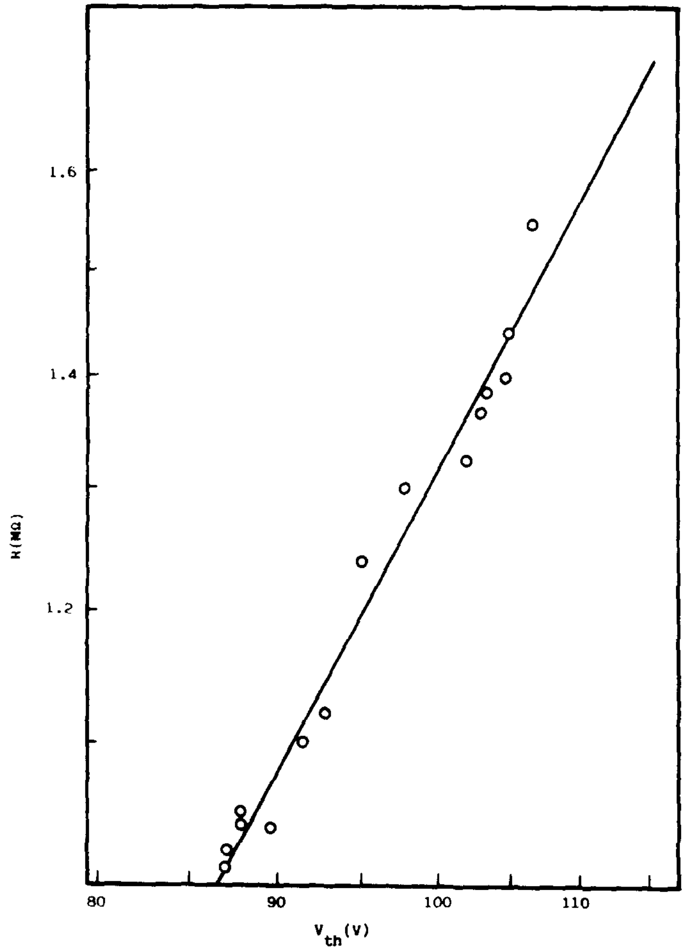

Fig. 3. Threshold voltage vs. electrical resistance.

following law:

$$2 \log V_{\mathrm{th}} = \log R - 2.11, \tag{1}$$

which is converted to

$$\frac{V_{\mathrm{th}}^2}{R} = 7.8 \times 10^{-3}\ \mathrm{W}, \tag{2}$$

which means that the initial power capable of producing switching is the same in all cases, and its value is of 7.8 mW approximately.

3.2. Delay time measurements

We have undertaken the study of delay time, considered to be the period elapsing between the application of a voltage high enough to provoke switch-

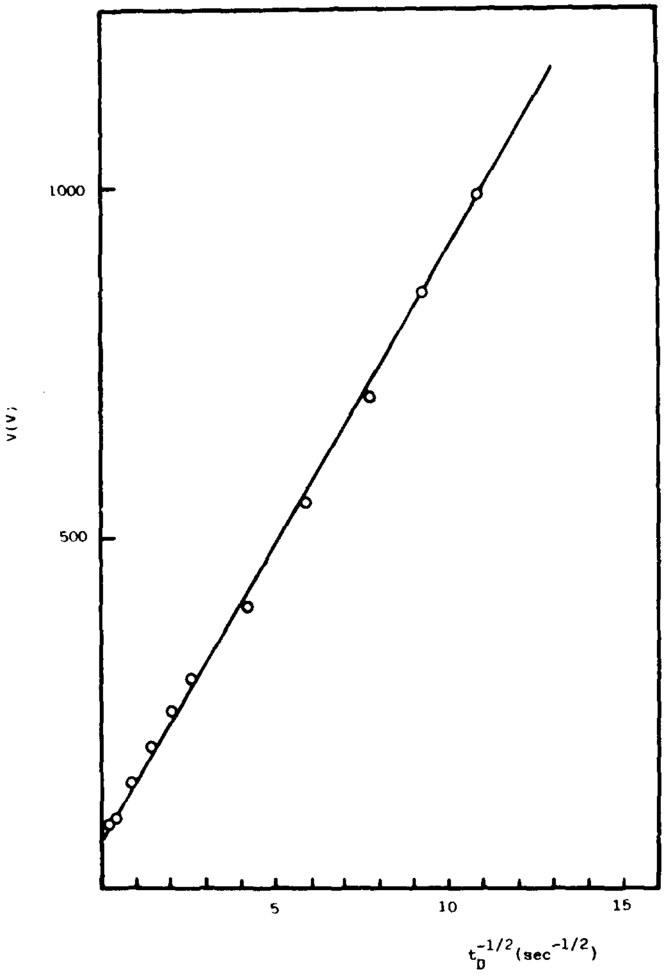

Fig. 4. Variations in delay time with applied voltage.

ing, and when this occurs, with the aim of finding the kind of dependence between the aforementioned parameters and the switching voltage.

Many studies have been carried out with the object of finding the correlation between delay time and the corresponding switching voltage. Different kinds of functional dependences have been found [11,12]. Fig. 4 shows the experimental results, indicating that a linear relation exists between $t_D^{-1/2}$ and V. The mathematical expression of the straight line is as follows:

$$t_D^{1/2} = \frac{84}{V - 76}. \tag{3}$$

This expression is the one normally proposed for bulk samples. By extrapolating the previous equation, the voltage associated with infinite time is deduced to be 76 V. This is interpreted as the minimum voltage which can generate switching. It should be pointed out that when the over-voltages are small, statistical fluctuations appear in the delay time, which agrees with what has been reported in the literature [13]. This reduces the validity of the minimum switching voltage already mentioned.

3.3. Dependence between electrical conductivity and the applied field

In the literature [14], the relation between electrical conductivity, the field and the temperature is expressed as

$$\sigma(E, T) = \sigma_0 \exp\left(-\frac{E}{KT}\right) \exp\left(\frac{E}{E_0}\right) \tag{4}$$

and from this, a functional dependence can be found between the variables I and V. For this purpose, using the definition of electrical resistance

$$R = \frac{dV}{dI}, \tag{5}$$

and given that from eq. (4) it is possible to obtain an equation in the $R(V)$ form, the following can be deduced:

$$I = I_0\left(\exp\left(\frac{V}{V_0}\right) - 1\right). \tag{6}$$

In the previous expression, the consequences of Joule heating are not present.

The use of voltage pulses of growing amplitude and stimulation time of 20 s, with an appropriate recuperation time is necessary to obtain the I–V characteristics. The use of such pulses permits the study of temporal dependence of the intensity with which the current can be determined before the material is affected by Joule heating.

In our experience, the temporal dependence of the current, for a given voltage less than V_{th}, was

$$I(V, t) = I(V) + \Delta I\left(1 - \exp\left(-\frac{t}{c}\right)\right). \tag{7}$$

To exclude Joule heating, represented by the last addend of the second member the functional model best suited to the experimental values is extrapoled at the instant $t = 0$. The reason behind such extrapolation is that it is not possible to measure with certainty the intensity in the initial instant, given the limitations of the recorder. Using the procedure described, the I–V characteristics were found in the OFF state. Fig. 5 shows these characteristics, as well as the experimental points. The values obtained for the parameters I_0 and V_0 were

$$I_0 = 56.6\ \mu A, \quad V_0 = 63.8\ V.$$

The cited experimental points fit closely to the functional model, its mean quadratic deviation being 0.99.

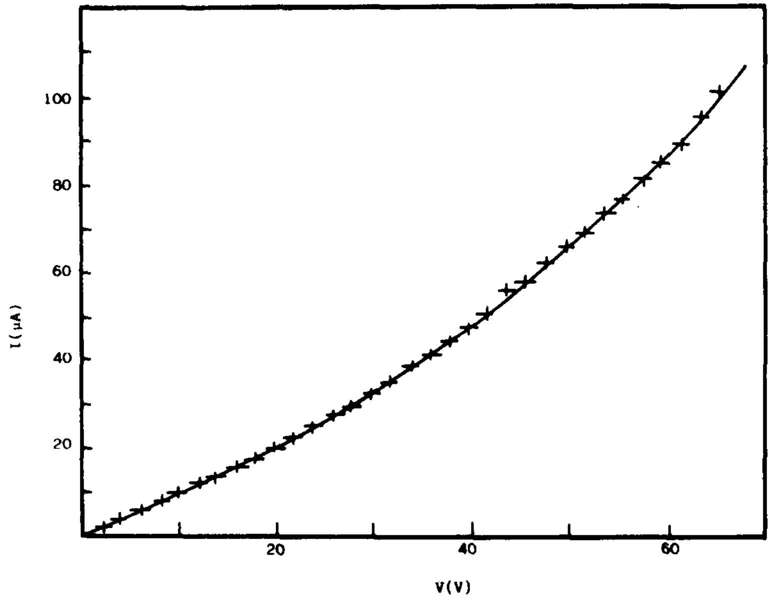

Fig. 5. $I-V$ characteristics in the blocking state at 292 K.

In ref. 15, a general relation has proposed between the variables I and V:

$$I = I_0 \exp\left(\frac{V}{V_0}\right). \tag{8}$$

However, in our case, such in dependence will only be valid for voltage values much higher than those represented in fig. 5. All of which confirms that the relation between conductivity and the applied field is

$$\sigma = \sigma_0 \exp\left(\frac{V}{V_0}\right). \tag{9}$$

3.4. Temporal dependence of the current intensity for voltages near V_{th}

Fig. 6 shows current intensity vs. time curves, for voltage values higher and lower than threshold voltage. It is observed that for voltages lower than that of the breakdown, a thermal equilibrium is reached. When the breakdown voltage is exceeded, the current undergoes a notable increase, after an attempt to stabilize, which ends on reaching the ON state.

If a quantitative solution is desired to the different physical parameters present in thermal breakdown (the fundamental basis of the explanation we propose for the switching phenomenon), the resolution of the differential

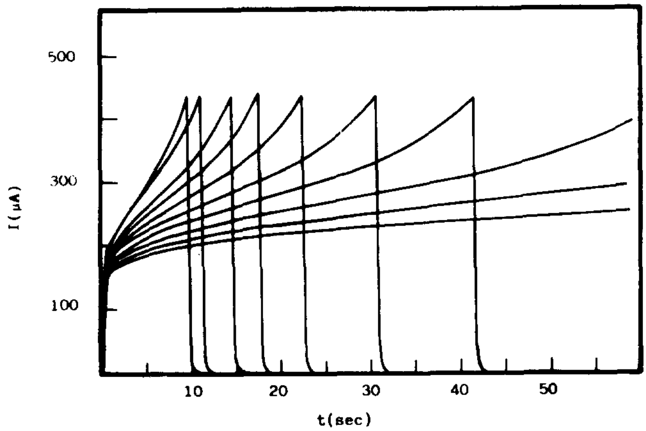

Fig. 6. Current intensity as a function of time for different applied voltages.

equation below is necessary:

$$C\frac{\partial T}{\partial t} = \sigma E^2 - \nabla \cdot (K \nabla T), \tag{10}$$

where temperature, T, is a function of position and time, C represents the specific heat per unit volume, and K is the thermal conductivity.

If the approximative hypothesis which consists in assuming that thermal breakdown occurs through a steady state is used, the temporal derivative of the temperature is cancelled. Therefore, eq. (10) can be expressed as follows:

$$\Delta T = R_T V I, \tag{11}$$

which means that heat conduction is balanced by Joule heating. This equation [11] shows that for a constant applied voltage, the rise of the temperature is proportional to the intensity of the current through it, given that R_T (thermal resistance of the material) can be considered constant in a first approximation.

Finally, the ΔT vs. t curves in the OFF state found in the literature [16] coincide with those found in this study from the intensity vs time curves. Therefore, as the curves found in the bibliography correspond to a thermal model for switching, we are faced with new experimental evidence which provides more information about the phenomenon.

4. Conclusions

The electrical parameters are subject to the same statistical variations that are found in any other fabrication and characterization process. The role of electrical power in the phenomenon under study suggests that effects of thermal origin dominate in the observed switching effect. We must also point out that the power needed for switching, of approximately 8 mW, coincides with that found for the glassy system Al–As–Te.

Another interesting observation was that after switching, when the current was suppressed, the resistance of the material underwent a slow increase, which lasted a few seconds, to finally recover the initial value. This is interpreted to be a hot conduction state. All this indicates that the mechanism which regulates the switching phenomenon analyzed, bears a strong resemblance with the electrothermal process analyzed in the literature [13,17].

The physical process is basically as follows. The temperature of the semiconductor is raised by Joule heating. The resulting increase in conductivity allows a higher current intensity to flow through the heated region, which causes the increase in Joule heating and current concentration in this region. A new steady state is established when heat conduction from the current filament balances the generated heat. This process occurs as a result of the low thermal conductivities of chalcogenide glasses, and is also due to the notable increase in their electrical conductivities, when the temperature of the material is increased. The behaviour of delay time, proportional to $(V-V_{th})^{-2}$, reaffirms the mechanism which has been proposed.

To conclude, the fact that the electrical conductivity depends on the applied field according to the relation $\sigma = \sigma_0 \exp(E/E_0)$, implies that the switching phenomenon studied, although fundamentally of a thermal nature, i.e., being a typical breakdown, can be considered a form of "electronically-aided" thermal runaway [18]. Therefore, all which has been described shows that the electrothermal theory allows us to explain a great combination of experimental facts related to switching.

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