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Reversible non-linear electrical switching in CdTeS-doped glass

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The electrical switching behaviour of $CdTe_xS_{1-x}$-doped borosilicate glass was studied by determining the d.c. current–voltage characteristics using a current source. The *I–V* characteristic is non-linear for high current density, leading to deviation from Ohm's law. The experimental data have been analysed assuming that the increase in the glass conductivity is dominated by the Joule effect. The theoretical model used is in good agreement with the experimental results.

1. Introduction

Semiconductor-doped glasses have attracted considerable attention during the past few years [1, 2]. These glasses are attractive for fabrication of non-linear optical waveguide devices. In recent years, a great effort has been made to understand the electrical properties of these glasses.

Ovshinsky [3] was the first to show that some amorphous semiconducting systems exhibit electrical switching in chalcogenide glass alloys. Oxide glasses containing transition metal ions also exhibit semiconducting properties and switching behaviour [4, 5]. Since then, a number of researchers have tackled the problem of understanding the origin of the non-linear threshold switching.

A characteristic of electrical switching is the strong deviation from Ohm's law for high applied voltage. When the field across the sample reaches a certain value, the conductivity increases by several orders of magnitude and the material passes from a resistive to a conducting state.

These switching devices, in general, could be classified into two categories: monostable (threshold) and bistable (memory) devices. In the first case, Fig. 1a, the glass has two different conductivity states. In the first state, the system is in a high-resistance situation; above a threshold voltage the material goes to a high conduction state with the voltage decreasing in value (Fig. 1a). For certain classes of glasses, the hysteresis is not present.

In the memory device behaviour (Fig. 1b) the system goes to the conduction state and stays there indefinitely, even if the current is reduced to zero. This irreversible behaviour is associated with the formation of crystalline filaments by local devitrification of the glass under the action of the intense current. The reverse change to the initial state is obtained by heat treatment of the glass sample, to obtain a remelting of the crystalline filaments.

Some theoretical models are available in the literature: the thermal model [6], the electrothermal model [7] and the electronic model [8]. In the first model, the switching between an insulating to a conducting state is associated with the Joule heating effect which increases the temperature leading to a reversible phase transition. For a glass system, this model is not appropriate, because no reversible phase transition occurs. The electrothermal mechanism is associated with conductive channels in the material and space charge at the electrodes. The electronic mechanism assumes no heating of the sample and results from space charges at the electrodes.

In the present work, we studied the switching behaviour of CdTeS-doped glass around room temperature with a view to establishing the mechanism of the observed reversible threshold switching.

2. Experimental procedure

Experimental glasses were prepared by melting a batch containing 38.25 SiO_2, 13.28 B_2O_3, 41.93 Na_2O_3 and 6.54 ZnO (wt %) mixed with cadmium, tellurium and sulphur in the $CdTe_{0.9}S_{0.1}$ stoichiometry. The melting of the batch in an alumina crucible was achieved by using an induction furnace (10 kHz, 30 kW) at 1400 °C for 1 h. The batch was then poured into a stainless steel mould and pressed between two stainless steel plates, in order to inhibit the process of nucleation and growth of quantum dots. The resulting glass was completely colourless. All samples were submitted to an annealing at 450 °C for 3 h in order to obtain a stress-free optical quality glass. These samples were cut and polished into 1 mm thick plates. Silver and nickel paste were used alternatively to form

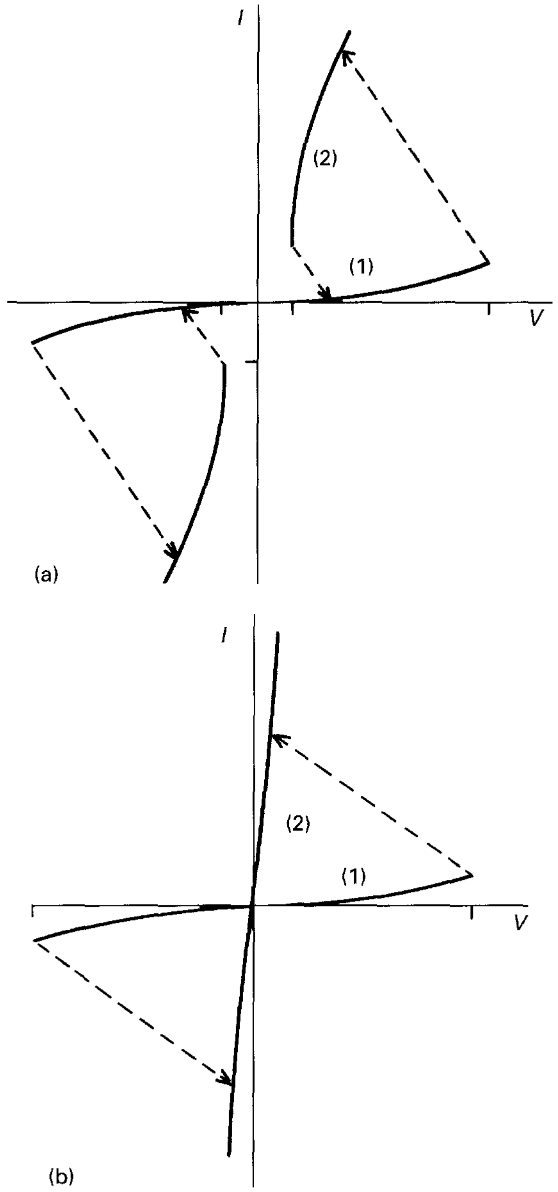

Figure 1 Electrical switching in semiconductor-doped glass: (a) monostable device, (b) bistable device.

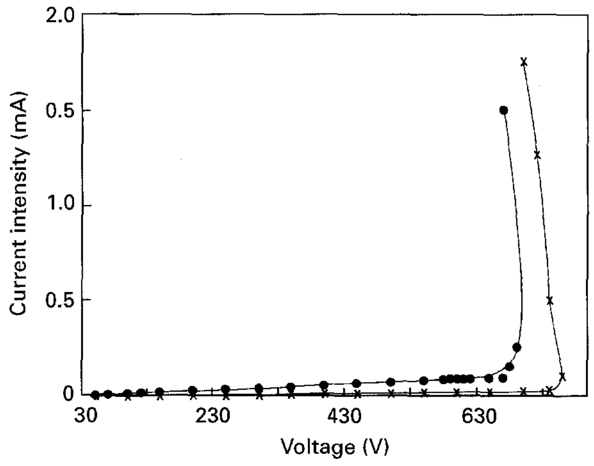

Figure 2 Experimental variation of the voltage as a function of the applied current (I–V representation), T = (○) 296 K (×) 230 K, (——) a guide to the eye.

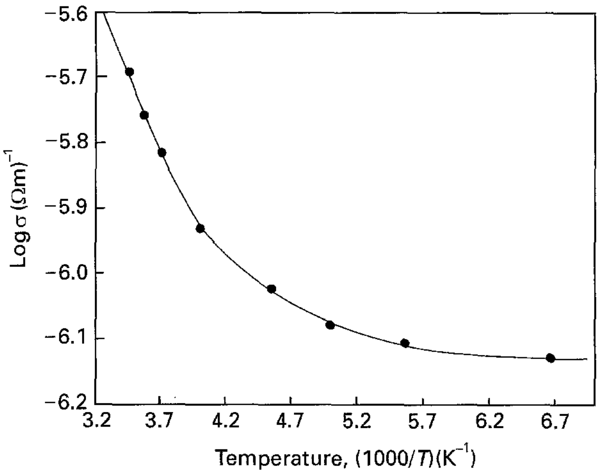

Figure 3 Conductivity versus T^{-1} for CdTeS-doped glass; (——) a guide to the eye.

the electrodes. A thermocouple was maintained on the sample holder, close to the sample surface in order to measure the temperature variations of the apparatus. The I–V characteristics were measured using a constant current source.

For measurement of the conductivity versus temperature, a capacitance bridge (General Radio model 1615-A) in conjunction with a lock-in amplifier operating at 100 kHz (EG&G model 5208) were used. Low-temperature measurements were done in a Supervaritemp (JANIS) cryostat system with a temperature controller in which the temperature could be maintained constant within 0.1 K.

3. Results and discussion

The I–V characteristics of the sample of CdTeS doped glass at 296 and 230 K are shown in Fig. 2. The voltage across the device first increases with increasing current; after a threshold voltage, there is a slight decrease in the voltage with increasing current giving a differential negative resistance. In all the experiments, the switching process is completely reversible without hysteresis and depends on the sample temperature. This is a characteristic of the reversible threshold switching (Fig. 1a).

During these experiments, carried out under higher current densities, temperature variations $\leqslant 10\,^{\circ}\mathrm{C}$ have been found. Furthermore, this temperature increase remains relatively limited below the maximum voltage. This temperature variation should be responsible for the increase in the conductivity, because the sample temperature is certainly higher than that measured on the sample holder surface.

The electrical conductivity of the sample using the complex impedance method was also measured (Fig. 3). The measured activation energy, $E_a = 0.086$ eV, and conductivity, $\sigma \approx 10^{-6}\,\Omega^{-1}\,\mathrm{m}^{-1}$, at room temperature is characteristic of switching in semiconducting glasses [9]. The increase in conductivity with increasing temperature is clear in Fig. 3.

We assume that the I–V relationship in the glass is described by

$$V = R(T)I \qquad (1)$$

where T is the temperature of the entire sample. We will assume that the temperature is a function of the dissipated power according to the model given by Marquez *et al.* [10] by

$$T = T_0 + \alpha VI \tag{2}$$

where α is the heat dissipation factor and T_0 is the sample temperature for zero current. We will assume a simple exponential dependence of the conductivity on temperature as

$$\sigma = \sigma_\infty \exp(-E_a/kT) \tag{3}$$

where σ_∞ is the conductivity at infinite temperature, and E_a the electrical activation energy. Taking into account Equations 2 and 3, Equation 1 can be expressed as

$$V = R_\infty I \exp\left[\frac{E_a}{k(T_0 + \alpha VI)}\right] \tag{4a}$$

then

$$\ln\left(\frac{V}{R_\infty I}\right) = \frac{E_a}{k(T_0 + \alpha VI)} \tag{4b}$$

which leads to

$$VI = \frac{E_a}{\alpha k}\left[\ln\left(\frac{V}{R_\infty I}\right)\right]^{-1} - \frac{T_0}{\alpha} \tag{5}$$

In Fig. 4 we have plotted the variations of the electrical power, VI, as a function of $[\ln(V/R_\infty I)]^{-1}$ using the experimental results reported in Fig. 2 for $T_0 = 230$ K. From Equation 5, we should expect a linear behaviour. The linearity is observed for low values of voltage, but it is non-linear for high intensities (Fig. 4). In the same figure, the continuous line is the theoretical calculation from Equation 5 (see figure caption). This behaviour suggests that the proposed model may be applicable at low voltages but needs modification for high intensities above switching.

In Fig. 5 we report the same experimental measurements in an I–V curve. The switching at 730 V is quite clear. For high voltages, we have a negative differential resistance regime. In the same figure, the theoretical curve corresponding to the experimental data using Equation 4 is also reported. The activation energy, E_a, and the resistance extrapolated to infinite temperature, R_∞, is obtained from the temperature dependence of the conductivity. From the slope $E_a/k\alpha$ and the interception at T_0/α in Fig. 4, we can calculate the heat dissipation factor, α.

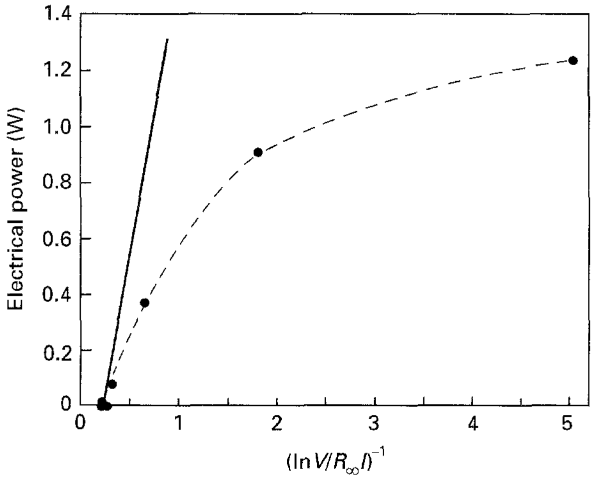

Figure 4 Variation of the input power as a function of $[\ln(V/R_\infty I)]^{-1}$ (○) $T_0 = 230$ K. The theoretical simulation obtained from Equation 5 with $T_0 = 230$ K, $E_a = 0.086$ eV, $\alpha = 500$ K W^{-1}, $R_\infty = 140$ KΩ (---) a guide to the eye.

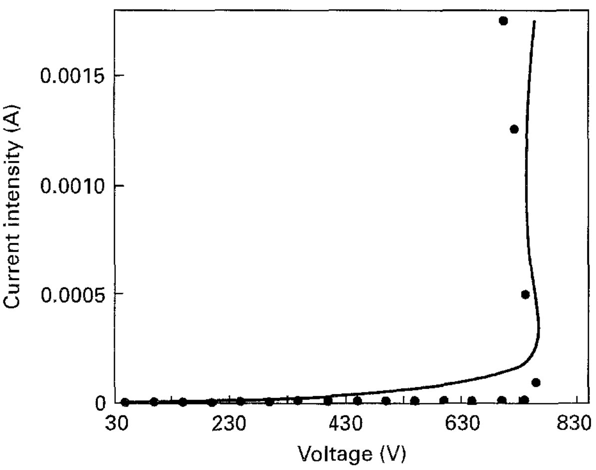

Figure 5 (○) Experimental variation of the voltage as a function of the applied current at 230 K. (——) The theoretical simulation of Equation 4 with $T_0 = 230$ K, $R_\infty = 140$ kΩ, $E_a = 0.086$ eV, $\alpha = 500$ K W^{-1}.

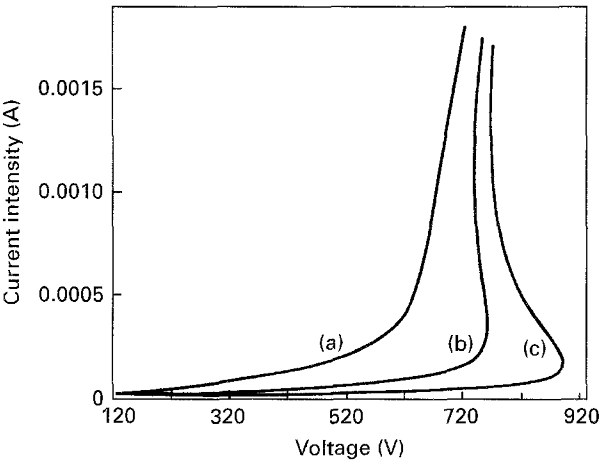

Figure 6 Theoretical simulation of the I–V curves (Equation 4) for various temperatures: T_0 = (a) 296 K, (b) 230 K, (c) 200 K, using the experimental values $R_\infty = 140$ kΩ, $\alpha = 500$ K W^{-1}, and $E_a = 0.086$ eV.

In Fig. 6 we show a family of theoretical I–V curves calculated from Equation 4 taking into account the values of α, R_∞ and E_a deduced from experimental results. The increase in the switching voltage with decreasing temperatures is in agreement with the experimental results (Fig. 6). This effect is associated with the decrease in the conductivity at low temperatures. From the same figure it is quite clear that the switching behaviour with a bistable function of the I–V characteristics is much clearer at low temperatures [11]. In all the experiments, the temperature of the glass was below the glass transition temperature, T_g, and no irreversible behaviour is expected. All the experimental I–V curves were reversible in the range of applied voltages. The thermal model used can reasonably explain all the features in this range of intensities.

4. Conclusion

The electrical threshold switching of CdTeS-doped glass is explained by taking into account the Joule effect which leads to a strong increase of the sample conductivity. We assume that the sample temperature is proportional to the injected electrical power in the sample. This theoretical model gives a good explanation of the non-linear reversible behaviour observed in the I–V curves measured in this material.

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