Experimental Evidence of Energy-Controlled Switching in Amorphous Semiconductors

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The switching delay time and transition time, and threshold voltage for the onset of switching in the amorphous semiconductor Si_{12} Ge_{10} As_{30} Te_{48} have been measured under various conditions using rectangular voltage pulses. The results show that both the threshold voltage and the delay time decrease, but the transition time increases with increasing temperature; and that these switching properties are strongly dependent on the width and the repetition rate of applied voltage pulses. It is proposed that the delay time is associated with the time required for the formation of a filament to cause switching, and that the transition time is associated with the transit time of a carrier across the switching filament. All the experimental phenomena indicate clearly that the switching process is energy-contolled.

1. Introduction

Threshold switching phenomena in noncrystalline chalcogenide semicondutors have been extensively studied in the past few years1). So far, it is generally believed that in the bulk devices the switching phenomena are initiated by a current-aided thermal process or an energy-controlled process,2-5) while in the thin film devices they are caused by a charge-controlled process.6)7) It should be noted that switching phenomena involve filament formation, high-field effect and transient transition; and the process is so complex that a complete theoretical analysis for either energy-controlled process or charge-controlled process has not yet been achieved. To distinguish these two processes, more experimental results are required. It is therefore the purpose of this paper to present some new experimental results to further support the energy-controlled process for the threshold switching in Si_{12} Ge_{10} As_{30} Te_{48}.

2. Experimental

The material used for this investigation was Si_{12} Ge_{10} As_{30} Te_{48} chalcogenide glass semiconductor supplied by Royal Radar Establishment in England, and the sample preparation techniques were the same as those described earlier.5) All the devices were fabricated in a sandwich configuration with molybdenum electrodes; the thickness of the samples being about 100 μm, the top and the bottom electrodes being, respectively, 0.8 mm^2 and 20 mm^2 in area, and about 1 μm in thickness. Normally a slice of 6×6 mm^2 contains 5-16 devices, the nearest distance between any top electrode and the edge of the slice being kept as large as possible to avoid surface leakage or discharge.

The switching time can be divided into two parts: namely, (a) the delay time τ_d which is defined as the time required for the switching forming process to be completed and measures the interval between the instant of application of a voltage pulse V_p and the instant just before the transition from the "off" state to the "on" state; and (b) the transition time τ_s (or called "the switching time, we think it is better to call τ_s the transition time and $\tau_d+\tau_s$ the switching time to avoid confusion), which is de-

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fined as the time required for the device to switch from its "off" state to its "on" state. Both τ_d and τ_s were measured with a Tektronix type 549 storage oscilloscope using rectangular voltage pulses to cause switching. The pulse generator provides pulses of pulse amplitudes ranging from 0 to 1600 V, pulse widths ranging from 0.1 msec to 10 msec, and the repetition rates ranging from 0.1 pulse/sec to 3×10^3 pulses/sec, both the rise time and the fall time being less than 10 μsec. The maximum current passing through the device in the "on" state was adjusted by varying the current-limiting resistance connected in series with the device. The typical waveform of the volage cross the device (with switching action) and that of the current passing through the device are shown fig. 1.

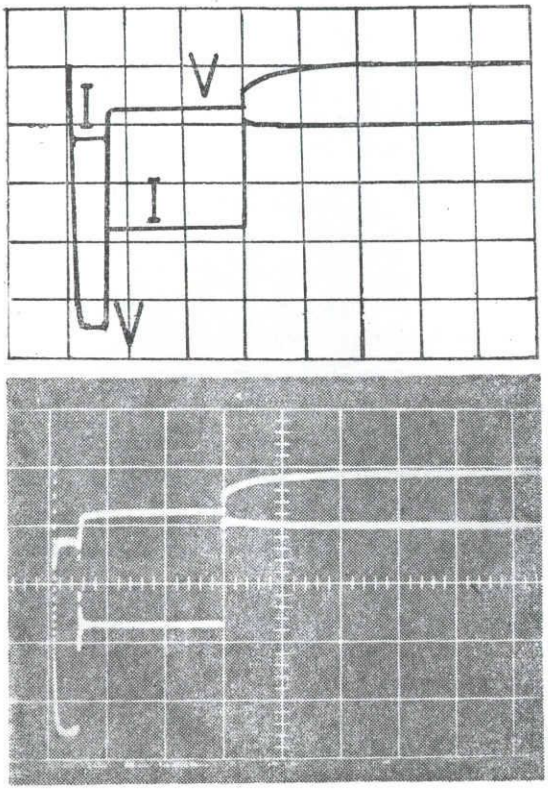

Fig. 1. Oscillograms illustrating the typical waveform of the voltage a voltage across the device (upper trace) and that of the current passing through the device (lower trace). Horizontal; 1 msec/div., vertical; 100 V/div. (upper trace), 2 mA/div. (lower trace).

3. Results and discussion

The threshold switching phenomena depend on the voltage amplitude, the width and the repetition rate of the applied rectangular pulses and the ambient temperature. In the following, we shall present and discuss the results separately according to the dependence of different parameters.

A. The effect of temperature on the switching threshold voltage and delay time.

Figure 2 shows that both the threshold voltage (V_{th}) and the delay time (τ_d) decrease with increasing temperature, but the threshold input power (P_{th}) to set on switching is practically independent of temperature. The latter phenomenon is similar to that observed under dc voltages and indicates that the formation of a switching filament depends only on the input thermal energy.[5] By assuming that the Jonle heat is generated by the current flow, and then conducted away to the surroundings, the energy balance equation is given by;

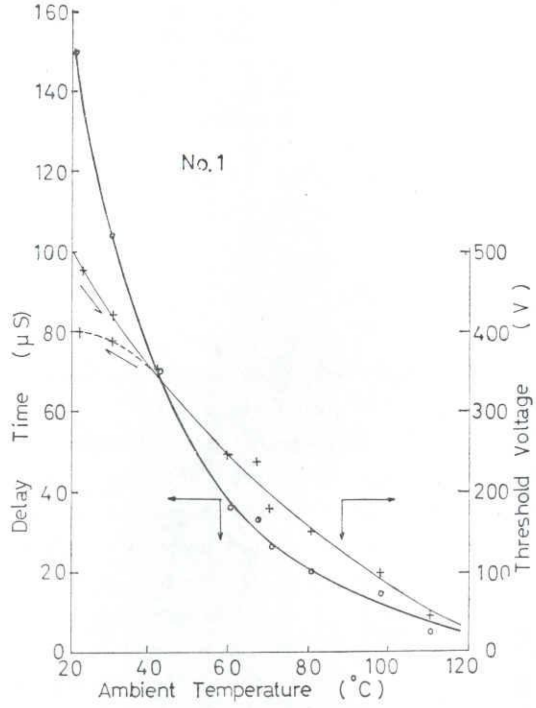

Fig. 2. The variation of threshold voltage and delay time with temperature.

$$P_{th}\tau_d = C_v\, g\, V_f(T_f - T) + KS\,(T_f - T)\tau_d \qquad (1)$$

where

$$P_{th}=I_{th}\ V_{th}, \tag{2}$$

I_{th} is the current corresponding to V_{th} at the switching threshold point; C_v and k are, respectively, the specific heat per unit volume and the thermal conductivity of the amorphous semiconductor; g and V_f are, respectively, the density and the volume of the switching filament; S is the area of the interface between the filament and its surroundings; T and T_f are, respectively, the ambient temperature and the temperature of the filament in the "switching-on" state. Rearranging eq. (1), we obtain

$$\tau_d=\frac{C_v g V_f/P_{th}}{(T_f-T)^{-1}-k\ S/P_{th}} \tag{3}$$

using the following values

$C_v=340$ Joules/kg deg.[2]
$k=10^5$ W/m^{2}deg.[2]
$g=5.5\times10^3$ kg/m^3 [2]
$T_f=573$ K [8]
$P_{th}=100$ mW
$d=100$ μm (sample thickness)

and assuming $S=2\pi rd$ and $V_f=\pi r^2d$, where r is the radius of the filament; we have computed τ_d as a function of T based on eq. (3), to fit the experimental data by adjusting the value of r as shown in fig. 2. From this curve fitting, r has been estimated to be 1-2μm which is close to that estimated by Coward.[9]

It is obvious that as temperature increases, I_{th} increases; so V_{th} must decrease to maintain a constant P_{th}. At 120°C the device is easily changed from its "switching-on" state to a "memory" state. Once it is in its memory state, it is difficult to erase it at the same temperature. Normally, it requires a sharp pulse of amplitude higher than V_{th} and of polarity opposite to that causing switching, to erase it. After erasing, the V_{th}—T curve when lowering the temperature follows closely that when increasing temperature except for temperatures lower than 40°C as shown in fig. 2. The lowering of the V_{th} (see the dash curve in fig. 2) at $T<40°$C may be caused by the fact that the ratio of the concentration of crystalline domains to that of amorphous domains, because of previous switching cycles at higher temperature, is much larger than that before the device had been subjected to 120°C.

B. The effect of pulse repetition rate on the switching threshould voltage and delay time.

Figure 3 shows the threshold voltage as a function of pulse repetition rate for various pulse widths. At low repetition rates, such as those lower than 100 pulses/sec, V_{th} is practically independent of repetition rate, but decreases with increasing pulse width. At repetition rates higher than 100 pulses/sec, V_{th} decreases with increasing repetition rate and tends to approach its dc value, if the repetition rate continues to increase. Furthermore, with pulse widths larger than 2 msec the value of V_{th} is very close to its dc

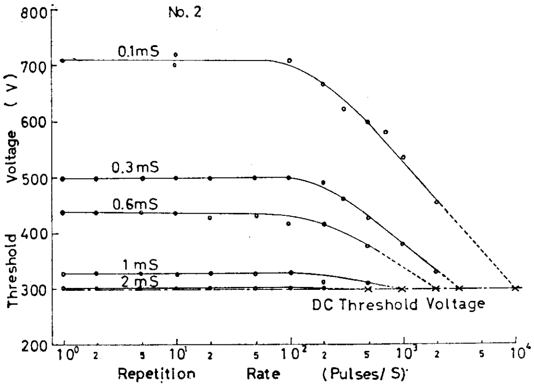

Fig. 3. The variation of threshold voltage with pulse repetition rate at 20°C.
(pulse widths (a): 0.1 msec, (b): 0.3 msec, (c): 0.6 msec, (d): 1.0 msec, (e): 2.0 msec)

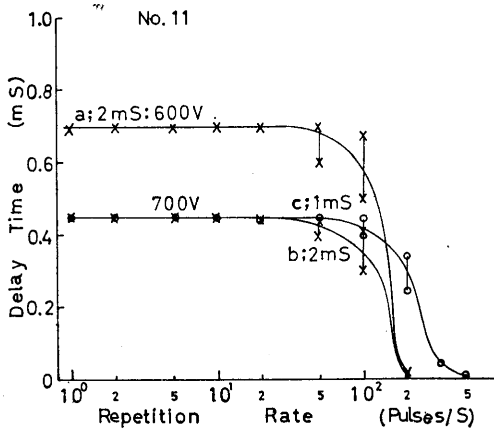

Fig. 4. The variation of delay time with pulse repetition rate at 20°C. (a) pulse width: 2 msec, pulse amplitude: 600V, (b) pulse width: 2 msec, pulse amplitude: 700V, (c) pulse width: 1 msec, pulse amplitude: 700V.

value, irrespective of the repetition rate. The delay time is strongly dependent on the amplitude and the width of applied pulses. At low repetition rates, such as those lower than 50 pulses/sec, τ_d is practically independent of repetition rate; while at repetition rates higher than 50 pulses/sec, τ_d gradually decreases with increasing repetition rate as shown in fig. 4.

By assuming that the current is space-charge limited and proportional to the square of applied voltage,5) the input power would then be proportional to the cube of applied voltage. If the first term is much larger than the second term in eq. (1), we can write

$$V_{th} \propto \tau_d^{-1/3} \qquad (4)$$

When the applied voltage is much larger than the dc value of V_{th}, the experimental results are in good agreement with eq. (4), but when the applied voltage is close to the dc value of V_{th}, τ_d becomes scattering as shown in fig. 5 indicating that the thermal process depends greatly on the pre-history of switching operations.

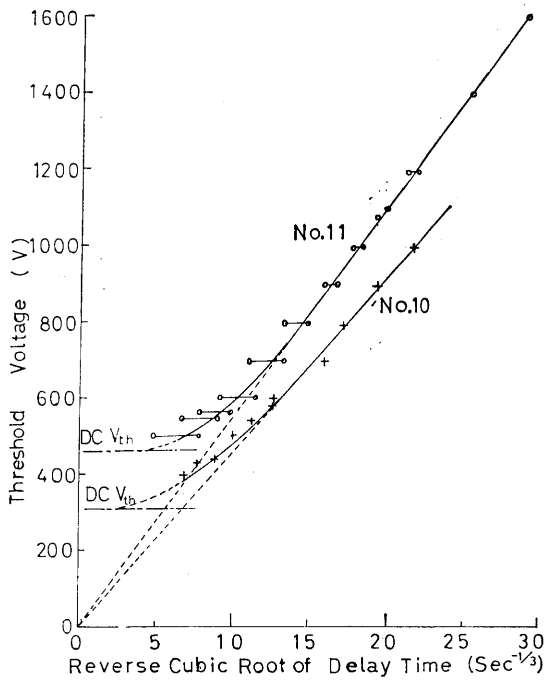

Fig. 5. Threshold voltage as a function of delay time.

For the device configuration used in the present investigation, the time constant of power dissipation is of the order of 1 msec at the threshold input power level. When the input power and hence the amplitude of applied pulses increase, the time constant of power dissipation increases, thus causing a decrease in τ_d. It is also posible that the heat-energy piled-up effect becomes very important when the mark-to-space ratio (or the pulse repetition rate) become large. This explains why both the threshold voltage and the delay time decrease with increasing repetition rate for repetition rates higher than a certain critical value as shown in fig. 3 and 4.

C. The effect of dc bias on the pulse switching threshold voltage

The dc bias voltage causes a decrease in pulse switching threshold voltage if both are in the same polarity, and vice versa as shown in fig. 6. For the dc bias voltage larger than 200 V in negative polarity (same polarity as that of the applied pulses), the pulse threshold voltage drops very rapidly with increasing dc bias voltage. A similar phenomenon also occurs when the dc bias voltage are in positive polarity (opposite to that of the applied pulses) and sufficiently high, and in this case the pulse threshold voltage drops much more abruptly. The dc values of V_{th} are, respectively, 420 V and 440 V for devices No. 22 and No. 24. This experiment shows clearly

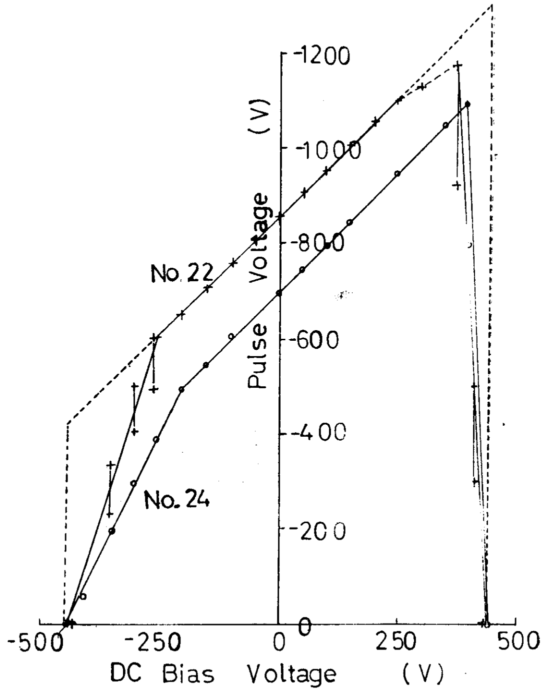

Fig. 6. The effect of dc bias voltage on the pulse switching threshold voltage.

that the heating effect due to dc bias becomes significant only when the dc voltage are higher than a certain critical value at which sufficient heat can be produced to affect the subsequent formation of the switching filament.

D. The effect of temperature on the switching transition time.

In contrast to the delay time, the transition time, τ_s increases with increasing temperature as shown in fig. 7. τ_s is practically independent of the width and the repetition rate of applied pulses provided that these pulse parameters do not produce a serious heat-energy piled-up effect. It is found that when the heat-energy piled-up effect becomes important, such as that caused by the excess high pulse amplitude or the high pulse repetition rate, τ_s may also be increased possibly due to the excess high temperature in the switching filament. At the ambient temperature of 22°C, τ_s is of the order of 10^{-7}—10^{-8} sec for the sample thickness of 100 μm. This value agrees well with the experimental value of 10^{-10} sec for 1 μm thin films,[10)11)] and with the theoretical value of the time lag for thermal breakdown in amorphous semiconductors.[2)] As τ_s increases with increasing sample thickness and with increasing ambient temperature (because V_{th} decreases with increasing temperature), it is likely that τ_s is associated with the transit time of a carrier across the switching filament and may thus be related to the carrier mobility. On the basis of this model the carrier mobility has been estimated to be about 1 cm^2/V sec.

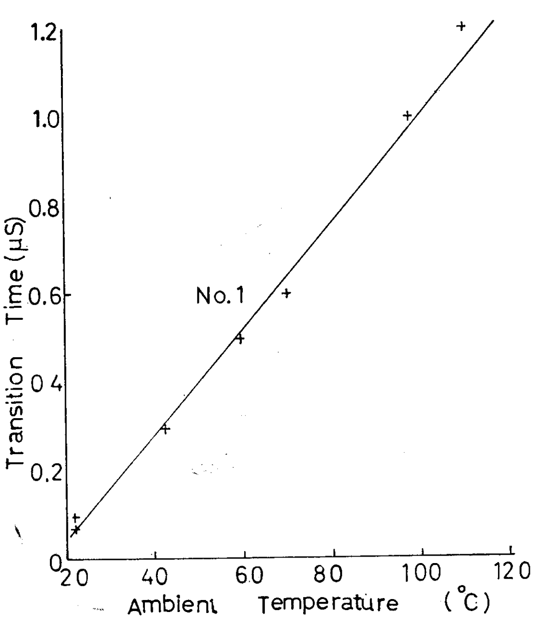

Fig. 7. Temperature dependence of transition time.

E. The effect of pulse width on the input energy for the transfer from the "switching-on" state to the "memory" state.

After the device has been switched on, a further increase in input energy will cause many clusters containing a high concentration of Te to devitrify to crystalline domains. [5)] Such crystalline domains may then join together to form a new high conductivity polycrystalline filament, and the memory state sets in. Figure 8 shows that the input energy for such a transfer process depends on the applied pulse width. It can be seen that for short pulse widths, such as those shorter than 3 msec, the Joule heating depends on the input power, while for long pulse widths, such as those longer than 3 msec, the Joule heating depends on the input energy because of the heat-energy piled-up effect. This phnomenon is a clear indication of the energy-controlled process.[12)]

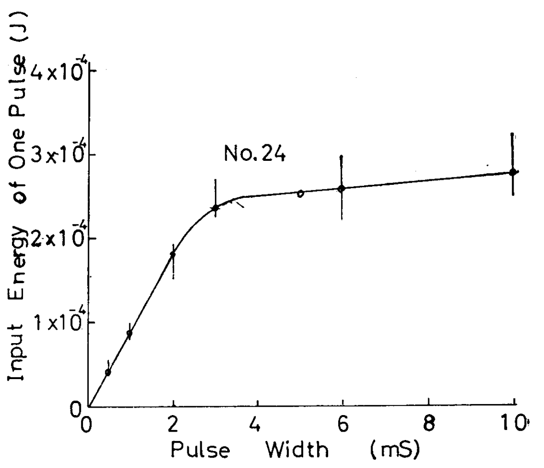

Fig. 8. Minimum input energy for the transfer from "switching-on" state to "memory" state as a function of pulse width.

4. Conclusions

On the basis of the above expermental results we can draw the following conclusions.

(a) The pulse threshold voltage depends on temperature, dc bias, the width and the repetition rate of applied rectangular pulses.

(b) The switching delay time decreases with increaisng temperature and depends on the amplitude, the width and the repetition rate of applied rectangular pulses. This delay time is associated with the time required for the formation of a filament to cause switching.

(c) The switching transition time increases with increasing temperature and is practically independent of the width and the repetition rate of applied rectangular pulses. This transition time is associted with the transit time of a carrier across the switching filament.

(d) All the observed phenomena in our experiment support the theory that the switching process is energy-controlled.

Acknowledgements

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