THERMAL SWITCHING DUE TO A LOCAL INHOMOGENEITY EXISTING BETWEEN THE ELECTRODE AND THE AMORPHOUS SEMICONDUCTOR

by

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SYNOPSIS

Switching transients in sandwich-type amorphous switching devices with electrodes of large area were studied experimentally. The results were analyzed in terms of a modified thermal switching model: the current concentration in the inhomogeneous region existing at the electroe-semiconductor interface causes a thermal switching. The reciprocal delay time $1/t_D$ is proportional to the square of an applied voltage V_p^2, indicating that the switching is caused by a certain kind of thermal process. The slope on the characteristic, however, is much larger than the theoretical value, in spite of using the resistivity obtained from the current-voltage characteristic in the regime just before switching. These results must be attributed to a localized small region with a resistivity much lower than the bulk resistivity. Some examples of asymmetric switching characteristic due to a local inhomogeneity are also shown.

1. Introduction

The electrical switching phenomena in amorphous semiconductors1) have been known more than a decade and investigated by many workers.2)-5) The various model proposed to explain the switching process may be categorized into two types. (1) Homogeneous model: a thermistor-type switching caused by internal Joule-heating, an electro-thermal switching and a pure electronic switching are included in these models, which assume that the amorphous film does not suffer any structural change during switching. H. Fritzsche and S. R. Ovshinsky6) have shown that thick amorphous layer shows a thermistor-type switching while thin amorphous layer shows an electronic swithcing. (2) Heterogeneous model: a heterogeneous structure change, e.g. phase separation, in the filamentary region of the amorphous material plays a dominant role in the non-destructive and repetitive switching.

We have no notion of denying or neglecting these various switching models proposed by many workers. However, we consider that it is of interest to study the switching behaviour of a sandwich-type device because when we want to realize a number of devices on a plate we must make use of such a device instead of a point-contact device which is mechanically weak and unstable as the history of semiconductor device tells us. In the case of sandwich-type devices, we often experience the fluctuation of the value of threshold voltage, particularly in large area devices, even if we prepared such samples as carefully as possible. Also we often observe an asymmetric switching even when we use the symmetrical electrode system. We consider that these must be attributed to a certain kind of inhomogeneity at the electrode-semiconductor interface, e.g. an inhomogeneity due to a local potential fluctuation.

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It is the purpose of the present paper to show experimentally and theoretically that, in the case of sandwich-type devices with electrodes of large area on an insulating glass substrate, a certain kind of thermal switching may be caused by a local inhomogeneity existing at the interface of electrode and amorphous semiconductor.

2. Sample preparation and experimental procedure

The sandwich-type amorphous switching devices having a system of $As_{30}Te_{48}Ge_{10}Si_{12}$ were prepared by evaporation on glass substrates in a vacuum of 10^{-5} Torr. The schematic outline of the device is shown in Fig. 1. The bottom electrodes are prepared so thick as not to be destructed during switching. Also, the top electrodes are made thick and/or coated with silver paste. For comparison a point metal electrode covered with gold is used as the top electrode on the other active part shown as (6) in Fig. 1. The film thickness ranges from 0.4 to 1.6 μm. The active area ranges from 0.4 to 1.8 mm^2. Voltage pulses of width 30 μs and of interval 1.6 ms were applied to samples. All measurements were carried out on virgin samples in air at room temperature unless otherwise stated.

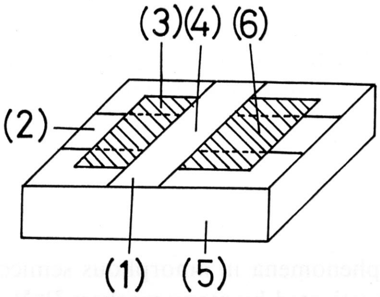


Fig. 1 **The geometry of the sample. (1) top electrode (gold) (2) bottom electode (gold) (3) amorphous film (4) active area (5) glass substrate (6) active part touched by a point contact.**

3. Experimental results and discussions

It has been known that a finite time t_D is necessary before switching as shown in Fig. 2. The OFF-state current I_{OFF} and the applied voltage V_p are constant during the "delay

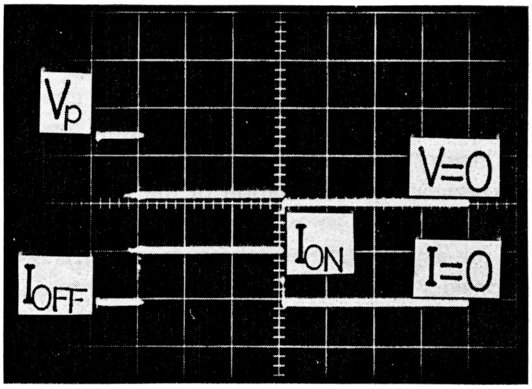


Fig. 2 **Wave form of an applied voltage and a current response. V_p is an applied voltage. I_{OFF} is an OFF-state current and I_{ON} is an ON-state current.**

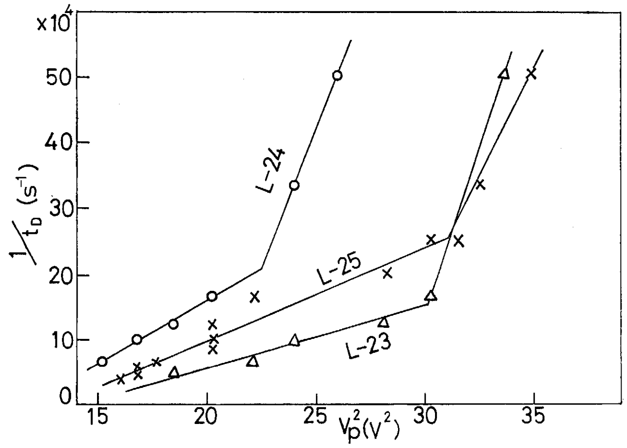


Fig. 3 Delay time t_D as a function of an applied voltage V_p for different samples.

time'' t_D. Also the delay time has been known to depend on the applied voltage. Figure 3 shows the delay time variations with applied voltage for different samples prepared by the authors.

According to the approximate solution of the thermal balance equation, the relation between t_D and V_p in the case of a square wave voltage pulse is given as follows$^{6)}$

$$1/t_D = A_t \cdot V_p^2, \qquad A_t = \Delta E/2kT_0^2\rho(T_0)CL^2. \tag{1}$$

ΔE corresponding to a band gap (a mobility gap) of amorphous semiconductor, k being the Boltzmann's factor, T_0 ambient temperature, $\rho(T_0)$ resistivity at the ambient temperature, C specific heat per volume, L electrode separation. Equation (1) indicates that $1/t_D$ is expected to be proportional to V_p^2. The linearity of the graph is observed over the all ranges of the applied voltage except for a ''kink-point'' as shown in Fig. 3.

At first, the characteristics below the kink-voltage is discussed, where the duration time of ON-state is short enough for the sample to be cooled before the next voltage pulse is applied. The fact that the delay time t_D is inversely proportional to V_p^2 implies that switching may be caused by some sort of thermal process. However, the experimental value of the slope(A_e) of the curve is much larger than the proportional factor A_t calculated from eq. (1). For example, A_e of the curve L–25 is about 1.4×10^4, while A_t is about 10 obtained by substituting $\Delta E = 1$ eV, $\rho(T_0) = 10^6$ ohm·cm, $C = 1$ J/cm^{3}deg$^{(6)}$, $L = 0.65$ μm and $T_0 = 296$°K. Since the switching phenomena are reversible and the sample resistance remains unchanged before and after switching, the physical coefficients in eq. (1) are not changed. However, if a very small localized inhomogeneity exists inevitably between the electrode and amorphous material, it may possibly trigger a switching as shown below.

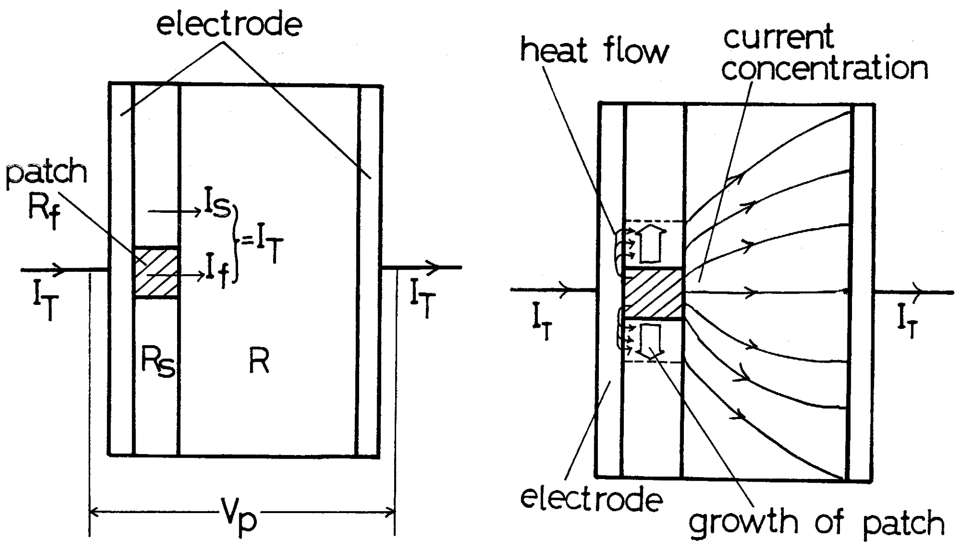
Here, we show that the thermistor-type switching is possible if the ''inhomogeneity'' (hereafter refered to as ''patch'') is assumed, even when the sample thickness is small (below 5 μm) in which the switching is believed to be caused by an electronic process. Figure 4 (a) shows the current distribution in the sample having a small patch region whose resistance R_f (and resistivity also) is assumed to be much smaller than the resistance of the rest region, i.e. $R_f \ll R_s$, R. From a simple circuit theory, we obtain the following equations

$$I_T = I_f + I_s \tag{2}$$

$$V_p - I_T \cdot R = I_s \cdot R_s = I_f \cdot R_f \tag{3}$$

$$I_s = (R_f/R_s) \cdot (1 - R_f/R_s) \cdot I_T \tag{4}$$

$$I_f = (1 - R_f/R_s) \cdot I_T \tag{5}$$



(a) (b)

Fig. 4 (a) Hatched region shows a small patch at the interface. V_p=applied voltage, I_T=total current, I_f and R_f=current and resistance of the patch region respectively, I_s and R_s=current and resistance of the rest region respectively, R=bulk resistance. (b) A schematic representation for the redistribution of current and the current filament formation caused by a patch.

where

$$I_T = V_p \Big/ \left(R + \frac{R_f R_s}{R_f + R_s} \right) \simeq \frac{V_p}{R} \tag{6}$$

Bulk resistance R serves as constant current source with large output resistance. Namely, the total current I_T is nearly constant throughout the OFF-state. The current density J_s in the patch region is given by

$$J_f = (R_s/R_f)(A/a)J_s \gg J_s \tag{7}$$

where J_s is the current density in the rest region, a and A are the cross-sectional area of the patch region and the other region respectively. Evidently J_f is much larger than J_s. Namely, Joule heating is more pronounced in R_f than in R_s. As will be shown later, resistance decreases exponentially with time due to Joule heating so that R_f/R_s decreases exponentially with time since R_f is a more rapidly decreasing (exponentially) function of time than R_s. Equations (4) and (5) imply that I_f increases with time and saturates to I_T, while I_s decreases with time due to some sort of feedback effect: low-resistance patch region allows large current flow which accelerates the Joule heating and then allows larger current flow than before. Current flow (constant current I_T) gradually concentrates into the patch region. Initially the area of the patch region is expected to be qute small (about a few hundreds of angstrom) from the nature of the patch formed. Heated patch region acts as heat source. The patch region grows laterally as a result of heat flow presumably via electrode, thermal conductivity of which is quite large (Fig. 4(b)). The patch region will grow to a certain size until the current filament is to be formed. Moreover, current concentration into the patch region yields a new current distribution near the electrode-semiconductor interface. Heated, low-resistance patch region acts as "electrode" penetrating into the sample as shown in Fig. 4(b), resulting in the formation of the filamentary current path. Thus a patch-induced thermistor-type switching is performed.

Now the relation between t_D and V_p is derived. The resistance at temperature T is given as

$$R(T)=R_0 \exp(\Delta E/2kT) \tag{8}$$

$$\simeq R(T_0)\exp\{(\Delta E/2kT_0^2)(T_0-T)\} \tag{9}$$

where T_0 is the ambient temperature. Heat transport equation is given as

$$C\frac{dT}{dt}=\sigma E^2+\nabla\cdot(\kappa\nabla T) \tag{10}$$

where σ is the electrical conductivity, E electric field, κ heat conductivity. Since the phenomenon in the present case is supposed to be adiabatic, we have the following equation from eqs. (9) and (10)

$$\int_0^t dt=\int_{T_0}^T (C/\sigma E^2)dT=(CAL/V_p^2)\int_{T_0}^T R(T)dT \tag{11}$$

solving for t, we have

$$t=t_0[1-\exp\{(\Delta E/2kT_0^2)(T_0-T)\}] \tag{12}$$

where

$$t_0=2kT_0^2R(T_0)CAL/\Delta EV_p^2$$

$$=2kT_0^2\rho(T_0)CL^2/\Delta EV_p^2. \tag{13}$$

From eq. (12) we obtain the following equation

$$T=T_0(1+\gamma t)\simeq T_0\exp(\gamma t) \tag{14}$$

where

$$\gamma=2kT_0/\Delta Et_0\ll 1$$

is assumed. Derivation from eq. (8) to eq. (13) is quite standard.⁶⁾ Equation (14) is an approximation as well as eqs. (9) and (12). H. Fritzsche and S. R. Ovshinsky⁶⁾ have also shown that T approximately increases exponentially with time just after the application of voltage pulse. The time dependence of resistance R just after the application of voltage pulse is derived from eqs. (9) and (12)

$$R(T)=R(T_0)(1-t/t_0)\simeq R(T_0)\exp(-t/t_0). \tag{15}$$

In the case of homogeneous model, t_0 corresponds to the delay time t_D as given in eq. (1) based on the conventional thermal model.⁶⁾ However, as shown before, the experimental results disagree with the prediction of eq. (1). Such deviations from the theoretical prediction must be attributed to $\rho(T_0)$. As discussed before, the small projection of low resistivity, which was grown at the patch by Joule heating and current concentration, extends from one electrode to the other, resulting in the formation of the filamentary path prior to switching. Thus the value of $\rho(T_0)$ in eq. (13) must be interpreted as the average resistivity of growing patch which may presumably be much lower than the bulk resistivity. Based on this interpretation, the value of A_t in eq. (1) becomes much large as observed in experiment. The time t_0 is thus interpreted as the time required for the patch to grow large enough to initiate or trigger the formation of the current filament. Although the delay time t_D is the sum of the time t_0 and the time required for the filament formation bridging two electrodes, t_D is expected to be nearly equal to t_0 since the filament formation will occur accelerately due to enhanced current concentration just as avalanche breakdown. The experimental value of A_t(i.e. A_e) is $4\times10^2\sim1\times10^3$ times larger than the value A_t

obtained by substituting the bulk resistivity for $\rho(T_0)$. Also A_e is about 10^2 times larger than A_t obtained by substituting for $\rho(T_0)$ the resistivity which is simply calculated from the I–V characteristics in the regime just before switching. These results may support the validity of patch-induced thermal switching model.

As for the characteristics in the regime above the kink-voltage as shown in Fig. 3, no comments are given except such a linearity and a large value of A_e may possibly be obtained when a long duration of ON-state is repeated in the filamentary region (hence a hot channel remains without being cooled), whether the switching process is due to the patch-induced thermal mechanism or the conventional one.

Furthermore two investigations were carried out. First, Fig. 5 shows the contact-area dependence of A_e/A_t. It is an increasing function of the contact area A. When the graph is extrapolated to the longitudinal axis ($A \to 0$), the extrapolated value $(A_e/A_t)_{A\to 0}$ is in agreement with the data obtained by using point contact. These results indicate that the larger the contact-area is, the larger the current concentrating into the patch. From eq. (5), the current I_f approaches to I_T with time (i.e. current concentration), while I_T is proportional to the contact-area A, and then the average resistivity of the growing patch $\rho(T_0)$ will decrease with increasing the contact-area.

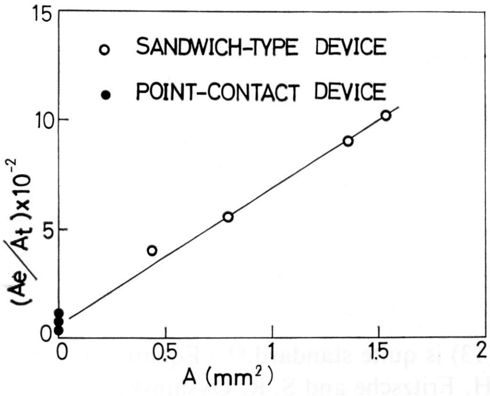
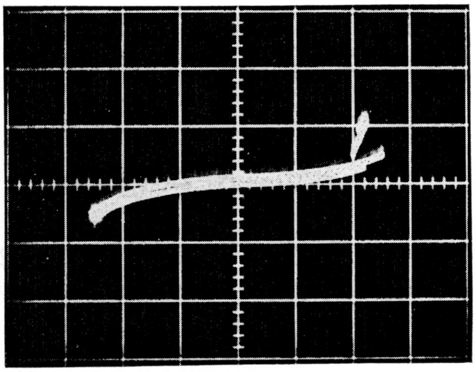
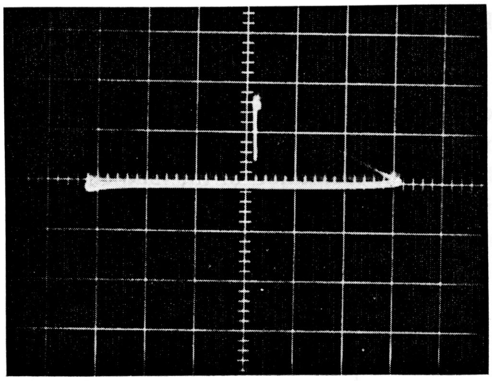


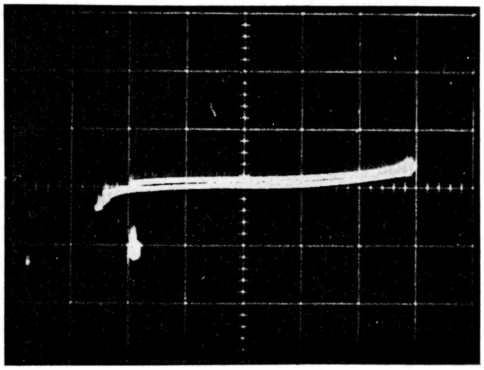
Fig. 5 Contact area depencence of A_e/A_t. For comparison the data of the point contact are added, supposing that contact area of point contact is equal to zero.



(b)



(a)



(c)

Fig. 6 (a), (b) Asymmetric switching using a degenerate Ge as a top contact instead of gold contact. Bottom electrode is a gold. (c) Both electrodes are gold.

Second, Fig. 6(a) shows the example for the asymmetric switching observed only in the forward direction, which is obtained when a mirror polished degenerate *p*-type germanium is used as a top contact instead of gold contact (i.e. Ge is pressed on (6) in Fig. 1). Curiously, when the surface of the degenerate Ge is polished again (i.e. the different surface is exposed), an asymmetric switching is observed only in the reverse direction as shown in Fig. 6(b), even if the Ge is pressed on the same place of the surface of the device. Figure 6(c) shows an asymmetric switching observed when both electrodes are gold. These experimental results indicate that a certain irregularity in potential distribution or an inhomogeneity (i.e. a "patch") exists at the interface of the electrode and semiconductor. Many and various kinds of patch may exist and only the most dominant one grows and triggers a thermistor-type switching in the way as discussed before.

4. Conclusions

Switching mechanism of a sandwich-type amorphous semiconductor device was studied. An another type of switching model has been proposed. A local inhomogeneity (named as a "patch") at the electrode-semiconductor interface may trigger a thermistor-type thermal switching, particularly in large area devices. The current concentrates in a low resistivity patch region which enables a Joule heating in this region, further lower the resistivity and in turn enhances the current concentration. The patch region is heated and grows, resulting in the formation of a hot electrode-like projection penetrating into the device. Thus a filamentary current path is formed from the one electrode to the other and a patch-induced thermal switching is performed. The model was supported by experimental results including the applied voltage dependence of the delay time and the contact-area measurement. Asymmetric switchings were observed in the electrode system of Au–Au Au-degenerate Ge. Furthermore we often experience the fluctuation of the value of threshold voltage in these samples. These may be due to such a localized inhomogeneity. We could not estimate the size of a patch. But we are sure that the existence of a small patch is believable, since the larger the electrode area, the larger the probability for a patch to be found should be. This paper will be published in J. Non-Crys. Solids.

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