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Evidence for Critical-Field Switching in Amorphous Semiconductor Materials

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We have investigated the role of thermal and electronic effects in threshold switching in an amorphous semiconductor of memory composition. Evidence is presented to show that switching is a bulk field effect, and that, if thermal effects are discounted or eliminated, the switching field is independent of pulse width for pulses longer than 1 nsec. This was the shortest pulse width measured. Short-pulse (1.5 nsec) measurements indicate that a previously unreported conduction region is established at the critical switching field.

Threshold switching mechanisms[1] in amorphous semiconductors have been studied intensively for several years. Attempts to explain the switching mechanism theoretically can be divided into thermal models, which interpret switching as a result of a thermal instability, and electronic models, which assume a breakdown of the electronic equilibrium as a result of an applied field or current. In order to account, at least qualitatively, for much of the experimental data, simple thermal models were inadequate, and it became necessary to include a field-dependent electrical conductivity. Several electronic models have been proposed and have recently received support because of the observation of polarity, contact, and critical-field effects.[2] In particular, Haberland and Stiegler[3] reported evidence for bulk switching based on charge accumulated prior to switching. Henisch and Smith[4] concluded, from high-field photoconductivity measurements, that switching occurred at a critical uniform field. Switching models were generally reviewed recently by Adler[5] and Fritzsche.[6]

Investigation of the threshold switching phenomenon is subject to a number of experimental difficulties due to compositional and geometric uncertainties which limit the usefulness of some of the experimental data previously gathered. Some of these difficulties are discussed below.

Amorphous semiconductors generally exhibit monostable switching for structurally stable compositions, and memory switching for compositions which exhibit a reversible phase change. In memory compositions, threshold switching precedes the structural transformation. The tendency of many compositions to undergo phase separation on heating, together with the known filamentary nature of the conducting state, causes further experimental difficulties. As a result, data gathered by repetitive switching of single devices are subject to large uncertainties in both the switching geometry and composition unless careful attention is paid to device fabrication.[7]

Additional uncertainties are introduced by the experimental test device or measuring technique. For example, measurements made by means of a metal probe on the amorphous semiconductor are subject to large uncertainties in the switching area and thickness due to the unknown extent of the penetration of the probe into the amorphous semiconductor. This is especially a problem with thin-film measurements. Some of the earlier thin-film devices consisted of two hemispherical carbon electrodes coated with a thin amorphous-semiconductor film and maintained in contact by spring pressure. This arrangement can result in a poorly defined, nonreproducible switching geometry, which may change because of the mechanical instability of the device.

The measured switching voltage is also a function of the switching method. For slowly varying wave forms, changes in the temperatures of the amorphous semiconductor result from Joule heating due to the leakage current during the period prior to switching. Even if an electronic switching mechanism is assumed, the switching parameters are expected to vary with temperature, and experimental measurements will, therefore, be affected by these self-heating effects.

In order to avoid some of these problems, we have performed measurements using thin-film devices of well-defined geometry.[8] These consisted of a thin film of amorphous semiconductor sandwiched between two electrodes. A silicon-dioxide film insulated the electrodes from each other, and a pore, etched in the oxide, defined the switching area of the device. The amorphous semiconductor used was the memory-composition chalcogenide $Ge_{17}Te_{19}Sb_2S_2$. These devices were fabricated by thin-film vacuum deposition, photolithography, and etching, and exhibited reproducible characteristics within the limits of film-thickness and geometry definition typical of these technologies. Because the chalcogenide composition used here is a memory composition, there is a high probability of phase separation after switching. Therefore, in order to avoid compositional uncertainties, we took advantage of the reproducibility of the device characteristics and limited all our measurements to virgin devices. A virgin device was switched once only, and then discarded, thus ensuring that each datum point was collected on a sample of well-defined geometry and composition. It is expected that thermal effects will be most important for slowly varying switching wave forms. Faster switching minimizes the duration of the preswitching leakage-current heating, and hence minimizes changes in the temperature of the amorphous semiconductor. Since the switching voltage is not uniquely defined, but is affected by the thermal constraints of the device structure and by the switching method, we have adopted the usual convention of referring to the dc switching voltage (or field) as the threshold voltage (or field). Measurements made by other switching methods are referred to as switching voltages. Because of the importance of threshold switching to the amorphous memory device, measurements were made on a memory material. It is important to note, that in general, memory materials have a higher electrical conductivity than threshold materials. Consequently, thermal effects are more important in memory materials.

In Fig. 1 we illustrate the variation of switching voltage with film thickness at room tempera-

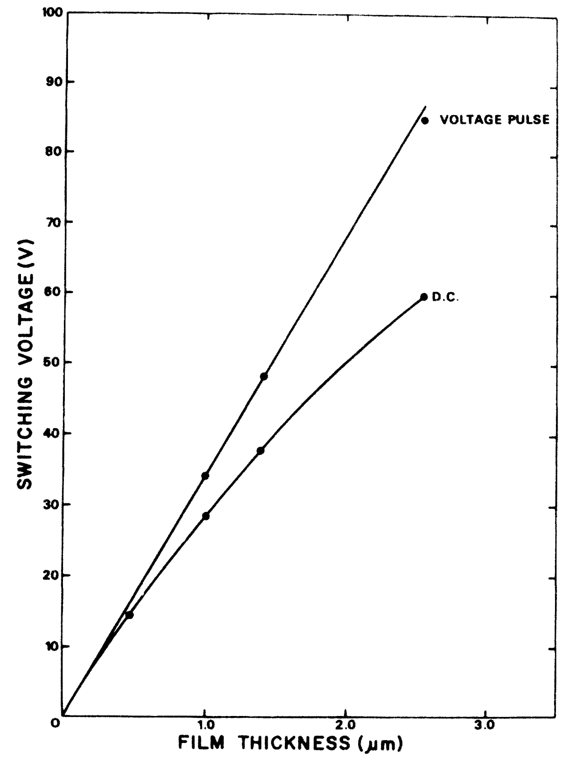

FIG. 1. The variation of switching voltage with film thickness for different switching methods. A linear variation of switching voltage with film thickness was observed when measurements were made using 0.2-μsec voltage pulses. A sublinear variation was observed for dc measurements.

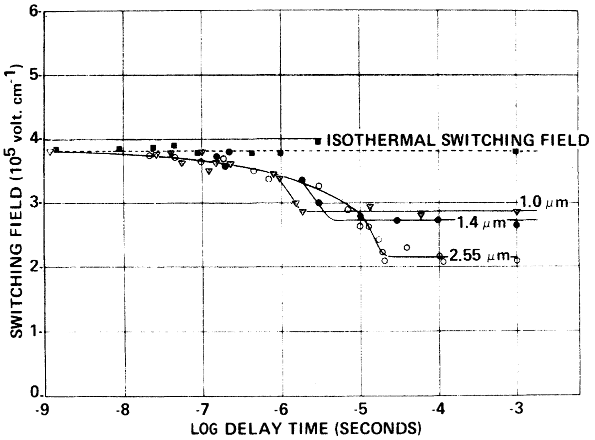

FIG. 2. The variation of switching field with the logarithm of the delay time for different amorphous film thicknesses.

ture for devices switched by two different techniques. The dc threshold voltage increases more slowly than the thickness and tends to become independent of the film thickness for thicker films. This tendency toward electrode-dominated switching is in agreement with observations previously reported in the literature. However, when devices are switched using 0.2-μsec pulses to minimize heating, a linear variation of switching voltage with thickness is observed. This observation corresponds to a switching field that is independent of the film thickness, and is an indication that switching is a bulk effect.

In order to investigate heating effects in detail, we measured the switching voltage as a function of film thickness and pulse width using square voltage pulses. These data which are presented in Fig. 2 have been normalized by dividing the measured switching voltage by the film thickness to obtain a switching field. There are two well-defined regions for each film thickness. For short pulses, the average switching field is independent of the film thickness and asymptotically approaches a limiting value. Therefore, in this region the applied voltage is uniformly distributed axially and switching is a bulk effect. For long pulses, the switching field saturates at the conventionally defined threshold field. The threshold field decreases with increasing film thickness. The transition between the two regions is well defined and occurs at shorter pulses for thinner films. We are able to explain these observations in terms of self-heating effects in the device. The pulse width which marks the transition between the two regions is equal to the thermal time constant of the device, which we estimated from the random-walk length of a phonon through half the film thickness.[9] This pulse width marks the transition from adiabatic heating for short pulses to approximately steady-state heating for long pulses. In the adiabatic region, the effect of self-heating is to raise uniformly the temperature of the amorphous semiconductor. Therefore, in this region, the applied voltage is uniformly distributed axially and the switching field is independent of the film thickness. In the steady-state region, an axial temperature gradient develops as a result of self-heating. Since the conductivity is thermally activated, an axially nonuniform distribution of the applied voltage results. This tends to concentrate the applied voltage near to the coldest regions of the film, next to the electrodes, and results in a calculated switching field which decreases with increasing thickness, in agreement with observation. The dotted line in Fig. 2 is the calculated value of the switching field corrected for the estimated change in the device temperature. These data are consistent with the existence of an isothermal switching field which is independent of the pulse width.

The data presented above are consistent with the delay-time measurements of Shanks[10] with the exception that we have extended the measurements to shorter pulses. We have shown that these results are due to nonuniform self-heating in the device.

In order to investigate electronic effects without the associated thermal effects, measurements were made by applying 2-nsec constant-voltage pulses to the device in series with a resistor. The voltage and current were measured by means of a Tektronix model 7504 sampling oscilloscope. By using short pulses we were able to make measurements in the "overvoltage" region; that is, with an applied voltage in excess of the dc switching voltage. Figure 3 illustrates the current-voltage characteristic of a device in the preswitching region, using the pulse method. As the voltage of the applied pulse was increased, the voltage across the device increased, until it became equal to the critical switching voltage. For higher applied voltages, the voltage across the device was constant, and the current was controlled by the external resistor. This is illustrated by the rapid increase in current at constant voltage in Fig. 3. We were able to increase and decrease the current reproducibly along the constant-voltage section of the curve.

We determined, from measurements on differ-

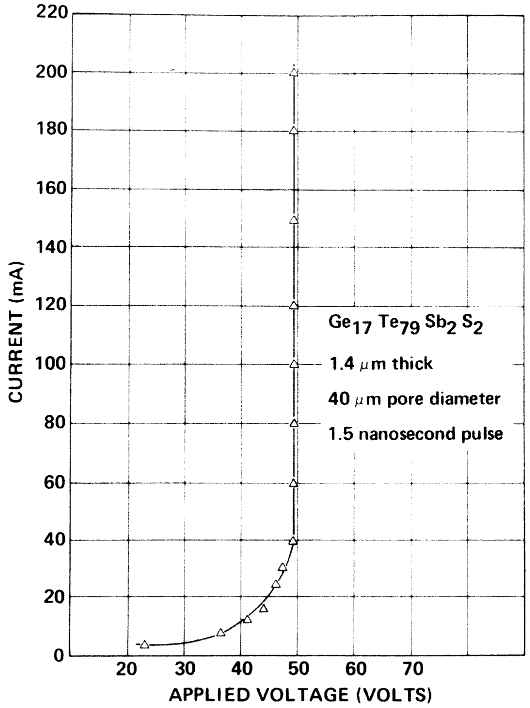

FIG. 3. The preswitching pulsed current-voltage characteristics for a discrete device.

ent film thicknesses and at different temperatures, that this constant-voltage region was established at the critical switching field. This effect was also independent of different load resistor values.

The constant-voltage conduction region (Fig. 3) has not been previously reported in the literature and, as a consequence, it is absent from electrothermal-switching models. If this new conduction region is a general characteristic of amorphous semiconductors, these models cannot fully describe the switching process.

In summary, we find that the threshold switching mechanism is a bulk electronic effect, in which, for long pulses, because of the temperature variation of the threshold voltage, secondary heating effects play a role, especially in thicker films. The evidence supporting this statement may be summarized as follows: (1) The switching voltage is independent of the pulse width if the temperature change due to heating is discounted. (2) The critical switching field is independent of film thickness, consistent with a bulk switching phenomena. (3) The discontinuous change in the preswitching current-voltage characteristic at the critical switching field is consistent with the onset of a previously unreported high-field conduction region. (4) Switching only occurs at a field for which the region described in (3) is dominant. (5) For short (2 nsec) voltage switching pulses the current during the pulse is constant and switching appears as a discontinuity in the current trace. The switching transition occurs in 10^{-10} sec or less. This time interval is not sufficient for a significant temperature increase ($\ll 0.1°\mathrm{C}$). (6) For long pulses, a continuous rise in current during the pulse is evident. However, the switching event is again indicated by a discontinuous change in the current-pulse profile. (7) The switching-current density is independent of pore area. This is further evidence of bulk switching. It implies that filament formation occurs after switching. (8) The calculated temperature rise for the short pulses in the adiabatic-heating range is less than 2°C. (9) All thermal models are dependent on an instability in the heat balance. Implicit in the adiabatic-heating regime is an assumption of zero heat exchange with the surroundings. Heat balance is, therefore, not a critical determinant in the switching mechansim.

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