Role of Capacitive Discharge Energy in the Switching of Semiconducting Glasses

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Incorporation of capacitive discharge energy in the heat equation yields results consistent with some aspects of the observed behavior of threshold switching devices not only for the case in which all points on the V-I curve are accessible, but also for the case in which abrupt switching at constant current is observed. The type of switching displayed by a given device is material dependent. We present a relationship for the prediction of device behavior.

In a recent paper,[1] Fritzsche and Ovshinsky have classified threshold switching devices (TSD) into two categories: the "current-controlled negative-resistance (CCNR) device" and the "constant-current switching (CCS) device." The voltage-current (V-I) characteristics of these devices are schematically depicted in Fig. 1. For the CCNR device all points on the V-I curve are accessible; for the CCS device there is an abrupt transition from the high-resistance to the low-resistance state at some critical device current. In the latter case [corresponding to a transition from point A to point B in Fig. 1(b)] no intermediate points can be accessed. Both types of devices have been fabricated, and numerous theoretical explanations for their respective behaviors have been presented. The observation that switching in TSD's may be energy controlled[2-5] suggests the examination of switching as a thermal process, i.e., a process resulting from dissipation of Joule heat in a medium which has an electrical conductivity, σ, which increases strongly with temperature. In the past, thermal theories have accounted only for the Joule heating in the device and have been successfully applied only to CCNR devices. We show below that solution of the heat equation, which includes capacitive discharge energy as well as Joule heating, predicts both types of behavior reported for threshold switching devices. The distinction between CCNR and CCS device behavior results from the relative magnitudes of the Joule-heating to capacitive-discharge-heating terms and results from material constraints.

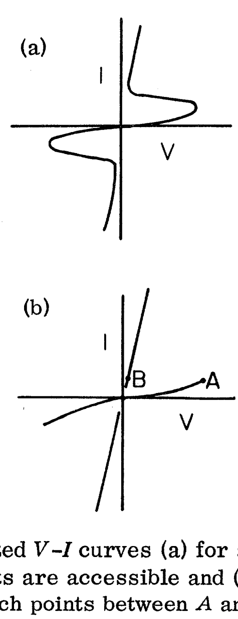

FIG. 1. Idealized V-I curves (a) for a CCNR device in which all points are accessible and (b) for a switching device in which points between A and B are inaccessible.

Most thermal theories apply to devices subjected to a constant electric field, $\mathcal{E}$, in which the temperature distribution is approximated by solution of

$$\kappa\nabla^2 T + \sigma\mathcal{E}^2 = C\partial T/\partial t. \tag{1}$$

In the above, κ is the thermal conductivity and C is the heat capacity per unit volume of the semiconducting glass under investigation. Numerical solutions of Eq. (1) have been obtained for boundary conditions relevant to practical device geometries,[6-11] and in each case lead to V-I curves of the type associated with the CCNR device. Fritzsche and Ovshinsky[1] and Böer[11] argue that such thermal results are inconsistent with the observed V-I characteristics of many threshold devices studied (the CCS devices). Equation (1) applies to actual device operation only when $\mathcal{E}$ is held constant during switching. Customarily a TSD is connected in series with a voltage source and a load resistor. Upon application of a voltage to the resistor-TSD combination, the TSD acquires an electric field. As the TSD switches to the low-resistance state, the field decreases and the stored capacitive energy is dissipated in the device. Use of the constant-field assumption in the theoretical calculation of the TSD V-I curve should be questioned further because empirical determination of such a curve is made with a regulated current source. Modification of Eq. (1) to include internal capacitive discharge yields

$$\kappa\nabla^2 T+\sigma\mathcal{E}^2-\epsilon\mathcal{E}\frac{\partial\mathcal{E}}{\partial t}\bigg|_{\text{int}}=C\frac{\partial T}{\partial t}, \tag{2}$$

in which ϵ is the permittivity of the semiconducting glass under study. The heating effect of $\partial\mathcal{E}/\partial t$ occurs only when this derivative results from internal discharge and thus care should be exercised in its determination. Upon application of a voltage source, for example, the field across the TSD acquires some new value. During this time $\partial\mathcal{E}/\partial t$ is not zero, but there is no heating in the TSD resulting from this externally controlled field change.

In order to examine the degree of applicability of the constant-field theories mentioned above, the relative magnitudes of the capacitive-discharge and Joule-heating terms should be determined over the switching cycle. It is commonly observed that when a voltage step sufficient to cause breakdown is applied to a TSD through a load resistor, there is a delay time τ_1 during which $\mathcal{E}$ remains constant. At the end of this preswitching period, the device acquires its low-resistance state within a period τ_2 much smaller than τ_1. Values of τ_2 as small as 150 psec have been reported,[12] and τ_1 is on the order of a microsecond. Since $\mathcal{E}$ remains constant during the preswitching period, Eq. (1) is applicable and the thermal results mentioned above[6-11] apply. At the onset of switching $(\partial\mathcal{E}/\partial t)_{\text{int}}$ becomes very large and additional heat is added to the TSD very rapidly. The conditions by which this extra heat may be sufficient to make the region between the high- and low-resistance state of a CCS device inaccessible will now be calculated.

The constraints to be imposed on our solution are that the TSD under study is being driven with a regulated current source, that external capacitance can be neglected, and that the device has a plane-parallel geometry with contact area A and thickness d. By limiting our interest to the time period $\tau_1 \le t \le \tau_1+\tau_2$ we can assume the heating process upon discharge to be adiabatic. It is a general property of threshold switching devices that breakdown is accompanied by the formation of a current-carrying filament extending between the electrodes and having cross-sectional area a.[13] A general result of previous thermal theories[6-11] is that during the preswitching period the temperature distribution in the device is fairly uniform, but that at τ_1 this distribution becomes sharply peaked at some geometrically favored location. Let us assume that the onset of filamentary conduction occurs at τ_1 and that capacitive discharge starts upon completion of the filament. It then follows that this discharge will occur primarily through this localized region.

A reasonable criterion for CCS-device behavior is that the cycle of quasisimultaneous events,

$$\begin{array}{ccc} \text{field change} & \rightarrow & \text{energy dissipation} \\ \uparrow & & \downarrow \\ \text{filament conductivity increase} & \leftarrow & \text{filament temperature rise} \end{array}$$

is self-sustaining as the field goes from $\mathcal{E}_A$ to $\mathcal{E}_B$ [corresponding to points A and B in Fig. 1(b)] at constant current. By replacing the $\partial\mathcal{E}/\partial t$ term of Eq. (2) by an appropriately weighted delta function of $t-\tau_1$, solution for the filament temperature rise on discharge, ΔT, yields

$$\Delta T=[A\epsilon(\mathcal{E}_A{}^2-\mathcal{E}_B{}^2)]/2aC. \tag{3}$$

If one denotes the maximum temperature in the device at threshold ($t=\tau_1$) by T_{th}, then the threshold current density J_{th} in the filament region is given by

$$J_{\text{th}}=\sigma(T_{\text{th}})\mathcal{E}_A. \tag{4}$$

The cycle will be self-sustaining in this system provided that

$$\mathcal{E}_B\geqslant\mathcal{E}_A\sigma(T_{\text{th}})/\sigma(T_{\text{th}}+\Delta T). \tag{5}$$

For systems in which the temperature dependence of σ is given by

$$\sigma=\sigma_0\exp(-\Delta E/2kT), \tag{6}$$

this condition becomes

$$\mathcal{E}_B\geqslant\mathcal{E}_A\exp\left\{\frac{-\Delta E}{2kT_{\text{th}}}\left[\frac{2aCT_{\text{th}}}{A\epsilon(\mathcal{E}_A{}^2-\mathcal{E}_B{}^2)+1}\right]^{-1}\right\}. \tag{7}$$

The inequality expressed in Eq. (7) will be favored by small filament area, high dielectric constant, and low threshold temperature. The ratio a/A is calculated by Ridley[13] to be

$$a/A=(J_{\text{th}}-J_0)/(J_v-J_0), \tag{8}$$

in which J_v is the filament current density in the valley of the TSD $\mathcal{E}$-J curve and J_0 is the uniform

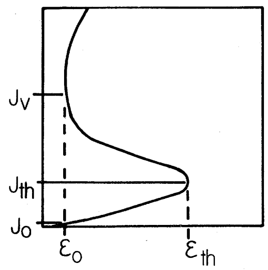

FIG. 2. Idealized $\mathcal{E}$-J curve of a threshold switching device showing the current densities used in calculating the filament area.

current density of the high-resistance state at a field equal to the valley field (see Fig. 2). An estimate of a/A can be obtained from the $\mathcal{E}$-J curve calculations of Stocker, Barlow, and Weirauch[9] which were made for As-Te-Ge glasses. Their results suggest that $a/A \simeq 10^{-4}$. Using the data of Sheng and Westgate[10] for an As-Te-Ge-Si glass (CCS device), $T_{th} = 500°K$, $\Delta E = 1$ eV, $C = 10^6$ J m^{-3} °K^{-1}, $\mathcal{E}_A = 2.5\times10^7$ V m^{-1} (at 300°K); and by further estimating $\epsilon \simeq 9\times10^{-11}$ F m^{-1} and $\mathcal{E}_A/\mathcal{E}_B \simeq 15$, we obtain a value of 3.14×10^5 V m^{-1} for the right-hand side of Eq. (7). Since this value is less than the observed value of $\mathcal{E}_B$, sufficient capacitive energy is available in the system to cause the CCS device behavior observed in devices made from this glass.

We have shown that the distinction between CCNR and CCS devices may result from the amount of capacitive energy released into the semiconducting glass during switching at constant current. If this energy is dissipated in a highly conductive filament, local temperature increases may be sufficient to increase regeneratively the conductivity to that corresponding to the switched state. In any case, this additional energy will cause a local heating effect which must be included in an accurate analysis of the transient behavior of these devices.

It is obvious that a more thorough test of this hypothesis is required. If the presently described mechanism is important, there should be a large and rapid temperature "spike" in the filament region accompanying the switching transient. Studies incorporating direct measurement of filament temperature during switching are in progress and should provide a suitable test for this model.

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