Electrical Switching Device Based on Charge-Controlled Double Injection

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A new switching device is predicted which is based on field-induced double injection caused by accumulated charges attempting to escape through poor contacts. While electrical characteristics are predicted which are essentially identical to those recently reported by Ovshinsky, the present device is explicable in terms of conventional physical phenomena which do not necessarily require disordered materials.

ELECTRICAL characteristics of a switching device are predicted which are essentially identical to those recently reported by Ovshinsky.[1] The switching action in the present model device, however, is predominantly a contact phenomenon rather than a bulk phenomenon associated with carrier generation from localized states which are characteristic of amorphous materials as suggested by Ovshinsky.

The important physical action in the present device is best explained with reference to the idealized schematic inserted in Fig. 1. The essential structural feature depicted in this schematic is the insulating barrier on both contacts. In reality this insulative barrier (or insulator) may be a few atom layers of oxide or other insulative material which could have formed on either the semiconductor or the electrodes during fabrication.

Under low initial applied voltages, such that the voltage drop across the insulators is of the order of kT or less, the carrier concentration throughout the sample remains essentially at thermal equilibrium. Thus the $I-V$ characteristic starts out Ohmic. But, at intermediate voltages the carrier concentration in the bulk of the semiconductor tends to be depleted (starting from the upstream contact) while the carrier concentrations just in front of the insulators build up. In particular, electrons (N per cm^2) accumulate in front of the insulator (I_2) at the positive electrode, and holes (P per cm^2) accumulate in front of the insulator (I_1) at the negative electrode. At steady state, these accumulations adjust until emission from them balances injection from the opposite electrode. As the voltage across the sample continues to increase, the charge accumulations also increase, and when they reach a critical value, the electric fields associated with them start to enhance further injection. The latter results in a regenerative buildup of the accumulations, and leads to breakdown or transition to a highly conducting double-injection mode. The latter can be subsequently maintained at much lower applied voltages.

The important differences between the present model and the one proposed by Ovshinsky are: (1) the high-field conditions at the contacts in the conducting mode are maintained by accumulation layers rather than depletion layers, and (2) the current is supplied by temperature-assisted field emission from the electrodes rather than field-enhanced generation from deep traps. In fact, the concentration of deep-generation centers that would be needed to supply the current densities observed by Ovshinsky is untenably high.

To facilitate a quantitative description of the physical processes responsible for switching in the present conceptual device it is necessary to make a number of simplifying approximations. One of these is replacement of the normally rough and uneven insulators by perfectly uniform layers of average thickness (cf. Fig. 1) permitting a one-dimensional analysis. This results in a uniform current distribution of average density instead of a more realistic filamentary one. Other approximations are made later in the analysis. Despite the approximations, it is possible to describe the essential physics and obtain explicit expressions for threshold voltage (V_T) and time delay (t_d) for switching.

By slightly modifying Stratton's theory[2,3] to apply when injection through I_1 into the semiconductor (see insert in Fig. 2) is predominantly due to thermally assisted tunneling into states near the conduction-band edge of the semiconductor, it can be shown that at intermediate applied voltages we have

$$j_{1e} \doteq A \exp[-\alpha S\psi_c^{1/2} - \chi_c/kT + (1/kT - \alpha S/4\psi_c^{1/2})V_1], \quad kT \ll V_1 < \chi_c \tag{1}$$

where

$$A = 4\pi m_\perp^* q(kT)^2/h^3, \quad \alpha = 4\pi(2m_{\parallel}^*)^{1/2}/h,$$

and

$$\chi_c = \phi_c - \psi_c, \quad V_1 = E_1 S.$$

ϕ_c and ψ_c represent the entrance and exit energy barriers, respectively. S is the thickness of the insulator, which we take to be identical at both contacts. (The ensuing symmetry is a simplification which results in symmetric device behavior but is not a general requirement.) The quantities in A and α have their usual fundamental meaning as explained by Stratton. A more rigorous analysis which includes V_1 approaching and exceeding χ_c will be presented elsewhere. But for completeness, the current for this higher-voltage region is estimated in Fig. 1 by the dashed portion of j_{1e}, though it is not actually required for the present analysis of threshold voltage and switching time.

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[2] R. Stratton, Phys. Rev. 125, 67 (1962).

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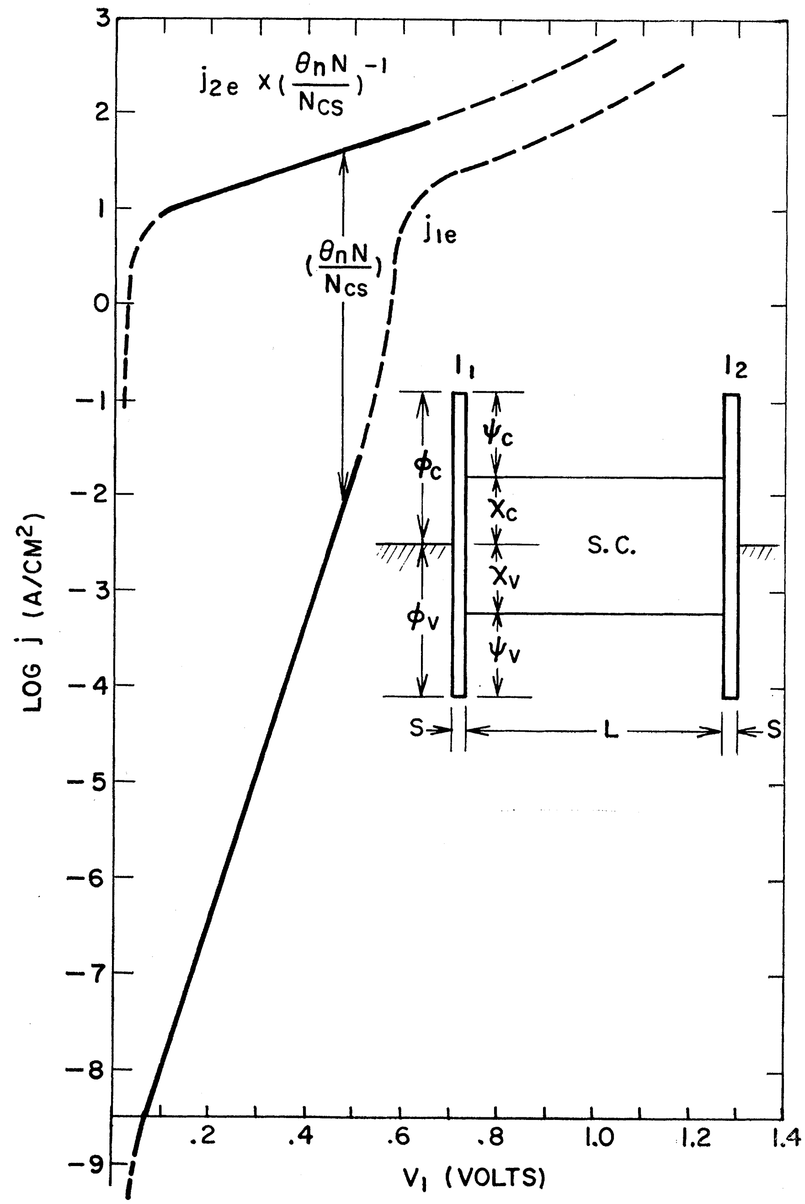

FIG. 1. Limiting injection and emission current densities through the insulators versus bias voltage across the insulators. Solid portions computed for parameters given in text and dashed portions estimated. Insert is schematic of device with no applied bias. The logarithm is to the base 10.

It can be argued that recombination (indicated by r_1 and r_2 in Fig. 2) must be negligible in the preswitched condition if a stable high-resistance mode is to be realized. Thus an analysis of the threshold and transition region merely requires examination of the emission rates from the accumulation regions. To formulate an explicit expression for the emission of electrons through I_2, it is now assumed that the distribution of states near the semiconductor-insulator interface is such that electron emission occurs predominantly via tunneling from occupied states in the conduction band. This leads to

$$j_{2e}(V_2,N) = (\theta_n N/N_{cs})A \times \exp[-\alpha S\psi_c^{1/2} + (\alpha S/4\psi_c)^{1/2}V_2], \quad (2)$$

where N_{cs} ($\sim 10^{13}$ cm^{-2}) is the effective surface density of conduction-band states in the accumulation region and θ_n is the fraction of the total electron surface density (N) which occupies the N_{cs} "surface" states. The remaining factors may be recognized as the tunnel-current equivalent of j_{1e} that would be expected if the conduction band of the semiconductor in the accumulation region were just degenerate. This limiting emission current is shown in Fig. 1 as $j_{2e}\times(\theta_n N/N_{cs})^{-1}$. In general, θ_n must vary as degeneracy is approached and it could be readily generalized to include the effect of any tunneling from traps (or localized interface states) in those cases where tunneling from such localized states is significant. For the present, however, the θ factors

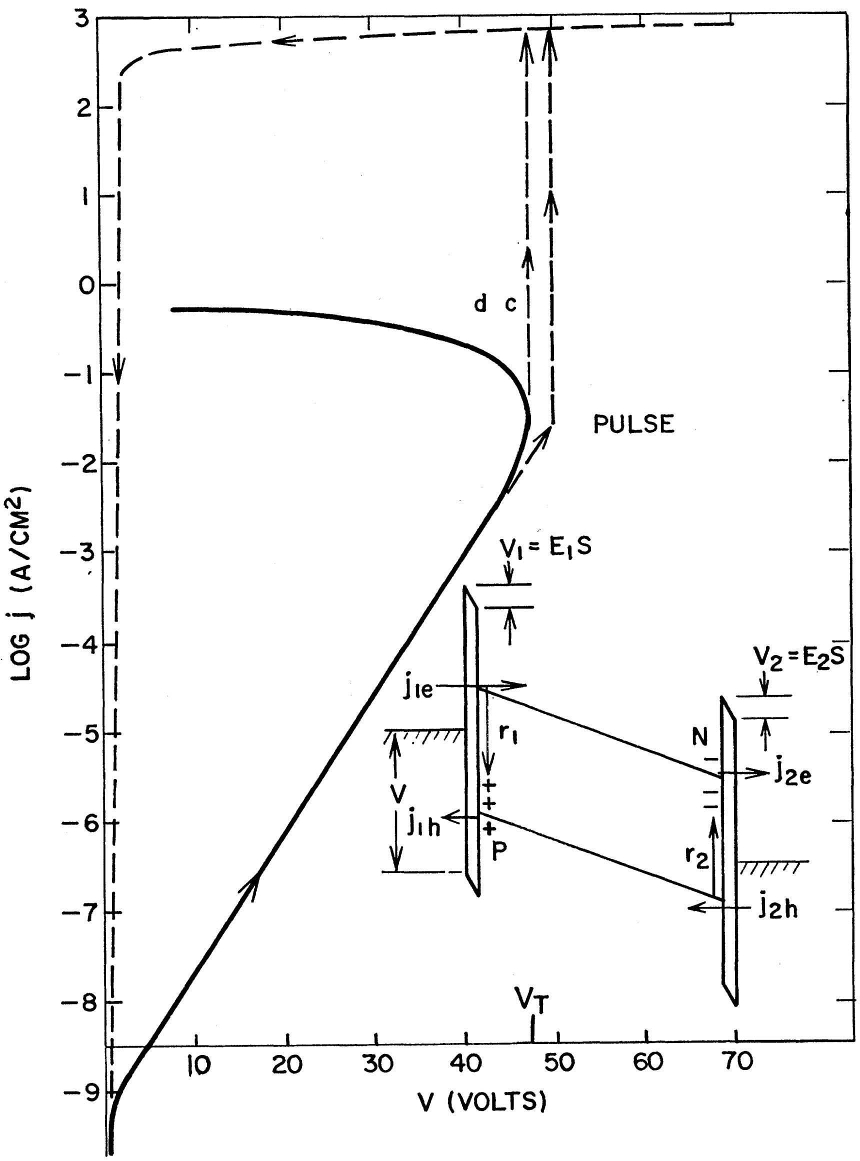

FIG. 2. Typical current-voltage characteristic under conditions discussed in text. Solid portions computed and dashed portions estimated. Insert is schematic under injection-limited conditions.

can be regarded as the familiar ratio of free to trapped charge.

All of the above considerations for the electrons apply to holes traveling in the opposite direction as well. Thus expressions for injection and emission of holes, equivalent to Eqs. (1) and (2), can be similarly formulated by simple replacement of the appropriate parameters.

Now the essential feature of the present model device is stabilization of the high-resistance state via sufficient emission to balance injection in the low- and intermediate-voltage range. Thus we have

$$j_{1e}(V_1)=j_{2e}(V_2,N)\,, \tag{3}$$

$$j_{2h}(V_2)=j_{1h}(V_1,P)\,, \tag{4}$$

$$j=j_{1e}+j_{1h}\,. \tag{5}$$

To obtain the related voltage across the sample, a further simplification is now achieved by assuming that the space charge in the semiconductor is negligible except in the accumulation regions. This assumption is particularly valid for short devices fabricated from "nearly instrinsic" or compensated semiconductive material; generalization to include any such space charge is straightforward. However, neglecting space charge, Gauss's law at the interfaces provides

$$E_2=\gamma E_s+qN/\epsilon_i\,, \tag{6}$$

$$E_1=\gamma E_s+qP/\epsilon_i\,, \tag{7}$$

where $\gamma=\epsilon_s/\epsilon_i$ is the ratio of permittivities in the semiconductor and insulators, respectively, and E_s, E_2, and E_1 are the electric fields in the different layers. Integration of the electric field over the space coordinate gives the applied voltage

$$V = V_1 + V_2 + E_s L. \tag{8}$$

It is important to recognize that the emission currents j_{2e} and j_{1h} are functions of the accumulations as well as the electric fields in the insulators. Thus elimination of the five variables E_1, E_2, E_s, N, and P from the six equations (3)–(8) leaves one relation between current and applied voltage which can be used to determine the threshold or transition voltage V_T.

By manipulation of Eqs. (1)–(8) the voltage across the sample can be written

$$V = 2V_1 + \Delta + (L/\gamma S)(V_1 - A_p V_{1d}), \tag{9}$$

where

$$\Delta \equiv V_2 - V_1 = V_{2d} A_n - V_{1d} A_p, \tag{10}$$

$$A_p \equiv P/N_{vs} = \theta_p^{-1} \exp[-\chi_v/kT + b_v V_1 + (b_v + \alpha S/4\psi_v^{1/2})\Delta], \tag{11}$$

$$A_n = N/N_{cs} = \theta_n^{-1} \exp[-\chi_c/kT + b_c V_1 - (\alpha S/4\psi_v^{1/2})\Delta] \tag{12}$$

define convenient variables and

$$V_{1d} \equiv sqN_{vs}/\epsilon_i, \qquad V_{2d} \equiv sqN_{cs}/\epsilon_i,$$
$$b_c \equiv 1/kT - \alpha S/2\psi_c^{1/2}, \qquad b_v \equiv 1/kT - \alpha S/2\psi_v^{1/2}$$

define convenient parameters. These quantities facilitate computations because Δ remains small in the high-resistance state until the accumulations grow enough to produce significant positive feedback. The latter is manifest in Eq. (9) by the term proportional to A_p, the normalized hole accumulation.

Solution of the foregoing equations is complicated by the fact that Eq. (10) determines Δ only implicitly. Thus numerical methods are needed to handle cases of practical interest. But fortunately, the important physical action can be fully appreciated by considering the very simple hypothetical case in which all the hole parameters are identical to the electron parameters. In this case Δ vanishes identically and the threshold voltage V_T is readily determined by setting $(dV/dV_1) = 0$, whence

$$V_T = \frac{2 + L/\gamma S}{b_v} \left(\frac{\chi_v}{kT} - 1 + \ln \frac{\theta_p(1 + 2\gamma S/L)}{b_v V_{1d}} \right). \tag{13}$$

This shows that the principal factors determining threshold voltage are the injection barrier χ_v and the electrical thickness ratio $L/\gamma S$. Since $L/\gamma S$ is typically of the order of 100 (or more), with S of the order of 20 Å, typical threshold voltages should occur at average fields (V_T/L) of the order of 10^6 V/cm.

The variation in size of the accumulations in the neighborhood of the threshold voltage shows up more graphically in Fig. 1. For the case when $V_1 = V_2$, the vertical height between j_{1e} and the degenerate emission limit $j_{2e}(\theta_n N/N_{cs})^{-1}$ provides a measure of the accumulation strength. And inspection of Eq. (2) shows that the vertical distance between the two current curves depends most strongly on the escape barrier Ψ_c. It follows then that the critical accumulation strength needed for switching is easier to achieve, particularly for lower escape barriers, when trapping in the accumulation regions is more prevalent (i.e., the θ factors are smaller). Physically, trapping assists the growth of accumulations by simply slowing the emission rate. For this reason only, amorphous materials, which naturally contain a high concentration of nontransporting states (traps), favor laboratory discovery, or intentional fabrication, of such devices.

The exemplary curves shown in Figs. 1 and 2 were computed for a case in which electron and hole parameters are equal, and $\alpha = 1$ eV$^{-1/2}$ Å^{-1}, $A = 10^7$ A/cm^2, $S = 15$ Å, $\gamma = 3.3$, $L = 5 \times 10^{-4}$ cm, $\phi = 1.5$ eV, $\psi = 0.6$ eV, $V_{1d} = 1$ V, and $\theta = 10^{-2}$. With this choice of parameters the net current shown in Fig. 2 becomes injection limited at $V \sim 1$ V, the lower-voltage region being Ohmic. At higher voltages a negative-resistance region appears which is unstable to transition to a high-current state (shown dashed.)

What is actually observed, of course, depends on the circuit. Also, another complexity which particularly affects the possibility of observing the negative-resistance region is insulator uniformity. The curve shown in Fig. 2 really applies to one small area, and while this area enters the negative-resistance region another area just begins making the transition. This tends to make the negative-resistance region more abrupt and difficult to observe.

In a more complete analysis it can be shown that the high-current state may be stabilized by either emission or recombination at intermediate and high voltages and by recombination at low voltages (the nearly vertical dashed curve at about 1 V). But again the intermediate- and high-voltage region may not be measurable (owing to catastrophic power dissipation) except by very careful pulse techniques.

In response to a sudden voltage pulse, the current should follow the curve marked "pulse" in Fig. 2 with the vertical rise delayed by a time interval which depends on the magnitude of the overvoltage $(V - V_T)$. The actual time delay is determined by the time needed to build up the critical charge accumulation

$$\sigma_c = \int_0^{t_d} (j_{1e} - j_{2e})\, dt. \tag{14}$$

For appreciable overvoltages, this approximates to $\sigma_c \doteq j_{1e} t_d$. Now using Eqs. (1) and (9) and neglecting the feedback effect in Eq. (9) (the latter being justifiable for $\sigma<\sigma_c$),

$$t_d \doteq \sigma_c A^{-1} \exp\left[\alpha S \psi_c^{1/2} + \frac{\chi_c}{kT} - \left(\frac{1}{kT} - \frac{\alpha S}{4\psi_c^{1/2}}\right)\frac{V}{2+L/\gamma S}\right]. \quad (15)$$

Note that this expression can be written

$$t_d = \text{const}\ \exp(-V/V^*),$$

where

$$V^* = \left(2+\frac{L}{\gamma S}\right) \Big/ \left(\frac{1}{kT} - \frac{\alpha S}{4\psi_v^{1/2}}\right).$$

Thus the trends and magnitudes predicted for the present device are remarkably similar to the experimental observations reported by Ovshinsky.[1] It should be emphasized that the explicit temperature dependence exhibited for V^* and V_T is not general but a consequence of the restricted applicability of Eq. (1) to $V_1<\chi_c$. As switching occurs for $V_1\rightarrow\chi_c$, the temperature dependences of V^* and V_T tend to vanish. The recent experimental results on the time delay for switching of amorphous semiconducting devices recently reported by DeFeo and Calella[4] are in general agreement with the analytic results presented here except that V^* is slightly different from V_T and has a different temperature dependence.

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I. Phenomenological Theory of Thermoluminescence

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Thermoluminescence (TL) glow curves are investigated in detail for a single trap depth in the presence of thermally disconnected traps and a single type of recombination center. The different shapes of TL curves are discussed as they relate to the ratio of trapping probability to recombination probability, and to the densities of recombination centers and thermally disconnected traps. The influence of such equipment parameters as heating rate, initial occupancy of the traps, and initial temperature is also examined. As a result of our calculations, we conclude that TL by itself is not a suitable tool for determining trapping parameters of imperfections in crystals, that the simple experiments performed to date have not yielded unique values of the trapping parameters, and that even a sophisticated experiment is highly unlikely to yield unique values.

INTRODUCTION

The experimental simplicity of thermoluminescence (TL) and thermally stimulated electrical conductivity (TSC) has led to numerous papers which advocate their use for determining trapping parameters of imperfections in crystals. Despite considerable effort in this field during the last two decades, however, there is still little evidence that consistent quantitative information on trap depths and probabilities for retrapping or escape can be obtained by TL or TSC methods. It is not the purpose of this paper to give a thorough review of the literature on the subject. As a typical example, we will mention here only some of the work done on CdS, which has been studied in this context more thoroughly than any other material. Dittfeld and Voigt,[1] e.g., determined the trapping parameters of CdS by utilizing 11 of the methods known for the analysis of experimental TSC data, while Nicholas and Woods[2] did similar work employing eight different methods. Bube and co-workers[3] performed an analysis of CdS/CdSe mixed crystals in which they also compared different methods. The disagreement in the conclusions reached by those workers is characteristic of the situation in which the investigation of thermally stimulated processes is at the present time. Dittfeld and Voigt found that all the traps they investigated in CdS empty under fast retrapping conditions. This result is based on the consistency they obtain with methods based on a quasi-equilibrium between trapped and free electrons. Nicholas and Woods arrive, in a similar way, at exactly the opposite conclusion. They find that all but one of

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