ENHANCEMENT OF INJECTION CURRENT AT THE METAL-INSULATOR INTERFACE*

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MASTER

Very deep traps may exist in amorphous insulators near a metal interface. When such traps are populated by photocarriers, large distortions in the electric field at the contact may result in carrier injection. A model of the time dependence and magnitude of the injection current is developed and compared with experimental results for the Si-SiO₂ interface and the Metal-PET (polyethyleneterephthalate) interface.

INTRODUCTION

The electronic properties of metal-insulator contacts have always been difficult to study and understand for a variety of reasons. Among them are the difficulty in distinguishing charge displacement in the bulk of the insulator from currents at the contact, and violent, non-uniform current instabilities at high-electric fields which often lead to destructive dielectric breakdown. There have been some reports of non-destructive switching in metal-insulator-metal sandwiches,¹ but there are severe reproducibility problems and evidence that the current is flowing in filaments, rather than uniformly as in the better understood crystalline semiconductor switches. In trying to understand these phenomena, a serious problem is the lack of information about the conditions existing at the interfacial region just before and during switching. In addition, the mechanisms for transferring charge carriers from the metal into the conduction states in the insulator are apparently not well understood even if the electric fields in the contact region are known.²

An interesting, "mild" form of electronic switching can occur if there are deep trapping states for charge carriers in the interfacial region so that very large changes in the electric field at the contact can be induced by populating those traps with holes (at the cathode) or electrons (at the anode). There is ample evidence that such traps exist in wide gap insulators.³ At room temperature, these traps do not empty in any reasonable time, even in the presence of very large electric fields (up to 10⁷ V/cm). Two commercial devices that depend on such traps for their operation are the electron-beam-charged electret and the MNOS memory transistor. It should be pointed out that these traps not only resist depopulation by high-electric fields and heat, but do not even form impurity conduction bands when their concentration is very large (over 10¹⁵ cm⁻³). It appears that the only way to depopulate such traps at room temperature is to provide free carriers of the opposite sign to produce recombination or to photoemit them to the conducting states.

In this paper I will focus on the consequences of having relatively trap free insulators, which have a high density of these deep traps near their surfaces. At the present time we have two insulators which fit this model fairly well: amorphous SiO₂ and thin films of polyethyleneterephthalate (PET).

THEORY

Consider a metal-insulator-metal sandwich with a trap free wide gap insulator which has no thermally generated free carriers in the bulk. There are large barriers at both interfaces for the injection of either electrons or holes. The photocurrent observed in the external circuit for this device will be

$$I = gel \text{ A/cm}^2 \quad (1)$$

where g is the rate of electron-hole pair production in the bulk (e.g. by x-rays or weakly absorbed light) in units of electron-hole pairs/cm³/s, e is the electronic charge, and l is the thickness of the insulator. If carriers are created near one contact (e.g. by strongly absorbed light or low-energy particles) the current will be $I = ge, \text{ A/cm}^2$ with g in units of electron-hole pairs/cm²/s. The surface traps will not affect this current if they are sufficiently close to the metal so that little variation in electric field in the bulk occurs. The model will be developed in terms of holes being trapped near the cathode and the change in interface field as a function of N ; the trapped charge, will be given by

$$E = E_0 + \frac{e}{\epsilon \epsilon_0} N^+ \text{ in V/cm} \quad (2)$$

where ϵ is the dielectric constant of the insulator in the interfascial region, and ϵ_0 is $8.85 \times 10^{-14} \text{ F/cm}$.

The field dependence of the electron injection at the contact is necessary for the prediction of the switching current. For large gap insulators at room temperature and the high fields necessary for observable injection currents, it is expected from the simple model of the barrier that most of the current will be due to tunneling directly from the metal Fermi level to the conduction band of the insulator. The best agreement with this Fowler-Nordheim characteristic was found for different metals into thermally grown SiO₂ by Lenzlinger and Snow.⁴ However, there are no other insulators (including FET) where the data are as close to the expected tunneling currents in both slope and magnitude as for SiO₂. The I-E characteristic in Ref. 4 is close to a simple exponential over two or three orders of magnitude in I , and for simplicity in the switching model the best fitting $I = A \exp(EE)$ function will be used for the measured current levels.

In the model, the current in the "on" state comes from the field-induced injection of electrons from the cathode which pass through the space charge cloud on into the bulk of the insulator. The current is limited because a fraction of the emitted electrons will recombine with the trapped holes. There are two cases of interest: (1) the fields are so high that the drift velocity of the electrons is saturated and thus not field dependent. The recombination rate is

$$K_r = \frac{vN^+}{x_0} \quad (3)$$

where v is the recombination coefficient in units of cm³/s and x_0 is the thickness of the trapping region. The transit time of the electron across x_0 is $t_s = x_0/v_d$ where v_d is the saturated drift velocity. The probability of escape, PE, is given by

$$PE = \exp(-\frac{vN^+}{v_d}) \quad (4)$$

which is seen to be independent of x_0 . (2) In this case the drift velocity is proportional to the local field.

$$v_d = \mu E \quad (5)$$

where μ is the carrier mobility. The transit time now becomes a more complicated

function of N^+

$$t_s = \frac{x_0}{\frac{e}{\epsilon\epsilon_0} N^+ u} \ln \left(1 + \frac{\frac{e}{\epsilon\epsilon_0} N^+}{E_0} \right) \quad (6)$$

and the PE, still independent of x_0 , becomes

$$PE = \left[\exp - \left(\frac{V}{u} \right) \frac{\frac{e}{\epsilon\epsilon_0}}{e} \ln \left(1 + \frac{\frac{e}{\epsilon\epsilon_0} N^+}{E_0} \right) \right] \quad (7)$$

The external current in this model will always be given by

$$I = A \exp(BE) + g e l \quad (\text{bulk excitation})$$

$$I = A \exp(BE) + g e \quad (\text{surface excitation})$$

where E is given by Eq. (2).

The time dependence of E depends on N^+ , which is obtained integrating the differential equation

$$\frac{dN^+}{dt} = g - \frac{A}{e} \exp(BE)(1-PE) \quad (8)$$

The solution for $N^+(t)$ may or may not be analytical, depending on the form used for PE. Solutions for various parameters and forms for PE have been calculated, numerically when necessary, and the form of $I(t)$ always looks the same: a sigmoid shaped curve.

When $dN^+/dt = 0$, $g = A/e \exp(BE)(1-PE)$. The magnitude of the "on" current reveals the value of N^+ and the ratio of g to the "on" current allows an experimental determination of the recombination coefficient, γ , if the drift velocity is known (or the mobility). The model provides predictions of the "on" current as a function of the applied voltage ($E_0 = V/l$) and the magnitude of g .

When the exciting source is turned off, the space charge and current will die away through recombination with the operative differential equation being Eq. 8 with $g = 0$. Like the turn-on portion, the solution for $N^+(t)$ may or may not be analytical depending on the form for PE and the I-E characteristic. For PE a constant, which is a good approximation for the initial part of the decay, the analytical form for the current decay can be found from

$$\frac{dI}{dN^+} = \frac{Be}{\epsilon\epsilon_0} A \exp BE = BI(E) \frac{e}{\epsilon\epsilon_0} \quad (9)$$

and

$$\frac{dI}{dt} = \frac{B}{\epsilon\epsilon_0} I^2 (E)(1-PE) \quad (10)$$

which on integration gives

$$\frac{1}{I(t)} - \frac{1}{I(t=0)} = \frac{B}{\epsilon\epsilon_0} (1-PE)t \quad (11)$$

A plot of $1/I$ vs. t gives a straight line with $t = 0$ defined as the time when the photocurrent has died away (a minimum of the transit time across l). If PE is already known from the steady state, the only other parameter in the slope is B , which gives the field dependence in the I-E curve.

COMPARISON OF THE MODEL WITH EXPERIMENTAL RESULTS IN SiO_2

Recently, the transport of electrons and holes in amorphous- SiO_2 has received a great deal of attention. It has been established that electrons have a high mobility controlled for the most part by the optical phonons in SiO_2 . In very high electric fields ($E_0 > 10^6$ V/cm) the drift velocity of electrons becomes saturated at about 1.5×10^7 cm/s. The concentration of electron traps in a SiO_2 film of SiO_2 is low, so that any electron emitted from the cathode by field emission will quickly traverse the SiO_2 film, if it does not recombine in the space charge region close to the cathode. In high fields, holes will also drift across thin films of pure oxides, but it is often found that many traps of the type proposed in the model exist in the interfacial region with the Si (but often not on the metal side of the MOS structure).³

Powell³ has reported a switching behavior qualitatively similar to that predicted in the model for the current through MOS devices in which electron-hole pairs are created close to the anode by strongly absorbed VUV light. The current vs. time during the VUV excitation is given in Fig. 1 for the conditions of $E_0 = 5 \times 10^6$ V/cm, photon flux = 5×10^{11} photons/cm²/s.

The value of the photocurrent in the first 50 seconds or so can be seen to be slowly increasing. Our studies of hole transport in a- SiO_2 indicate that the transport is dispersive, that is, all the holes do not drift at the same velocity.⁵ The dispersion results in some deviation from the simple steady state current predicted by Eq. 1 and it can be shown from the transient photoconductivity data that the current should increase slowly with time like

$$I(t) \propto \ln(1+10^3 t)$$

Considering that the quantum efficiency for electron-hole pair production even at this high field is about .9, the flux, g , is taken to be 4.5×10^{11} holes/cm² sec which is good to about $\pm 5\%$. Not all holes which arrive at the interface are trapped, the fraction in this sample was shown to be .13 by a separate experiment.³ Thus, the true value of g for this sample was $g = 5.85 \times 10^{10}$ holes/cm²/s. The function $I(E)$ employed in the fit was $I(E) = 9.6 \times 10^{-24} \exp(5.3 \times 10^{-6} E)$.

The steady state current for the set of conditions in Fig. 1 is 1.6×10^{-6} cm², which implies a steady state N^+ of 5.3×10^{12} trapped holes/cm². The ratio of g to the injection current is 6.5×10^{-3} which in the model $\propto N^+/v_d$. The recombination coefficient is then found to be 2×10^{-8} cm³/s; this is the first measurement of this recombination coefficient at this very high field (7.4×10^6 V/cm).

The measured v can then be used to compute the shape of the switching curve in Fig. 1, following the model. There are no adjustable parameters for the solid theory line in Fig. 1. The effect of the dispersive transport has been added to the current predicted by the model.

The decay of the "on" current after the flux of holes is turned off is shown in Fig. 2, along with the same data replotted as $I(t)^{-1}$ vs. t to give a straight line dependence as in Eq. 10. The slope in Fig. 5 should depend only on B , which has been previously given by the $I(E)$ plot and 1-PE, which was determined from the steady state current. The fit is quite good, although it would have been informative if Powell's data were extended to longer times, where the 1-PE value is predicted to change as the value of N^+ drops.

The most interesting "adjustable" parameter in the fit to the data is the magnitude of the recombination coefficient. It is almost three orders of magnitude smaller than at low fields, and without the strong field dependence of the switching effect would be barely noticeable. The detailed theory of the field dependence of v is not yet in hand for SiO_2 . The fit of the simple theory given here is excellent, especially with the perspective of the complicated behavior found in many semiconductor Schottky barriers.

Fig. 1. The total current as a function of time under excitation at the anode at the rate of 4.5×10^{11} holes/cm²/s. The dots are from the data in ref. 3 and the solid line is from the theory described in the text.

Fig. 2. The current decay after the excitation source is turned off. The dots are from the data in ref. 3 plotted as current and also reciprocal current. The solid lines are from the model described in the text.

THE METAL-PET INTERFACE

Films of Dupont Mylar (PET) in thicknesses range from 3.8μ to 25μ display the slow switching effect.⁷ Detailed results, including the dependence of (1-PE) on field and value of "g" will be given in a forthcoming publication.⁸ One example is given in Fig. 3, where $E_0 = 1.6 \times 10^6$ V/cm and $l = 3.8 \mu$. Electron-hole pairs were generated in the bulk of the film by x-rays from a Ge-XRD-6 machine operating at 60 KV. The $I(E)$ curve used for the fit was $1.8 \times 10^{-10} \exp(10^{-6} E)$. The value of B comes from the decay of the current given in Fig. 4. The recombination coefficient derived from the saturation current was 8×10^{-11} cm³/s, assuming a mobility of 10^{-3} cm²/V-s which was measured in transient photoconductivity experiments.⁹ Data taken at higher fields indicates that the ν is decreasing with increasing field as in SiO₂.⁶

SUMMARY

The presence of deep traps at the metal-insulator interface has been shown to be responsible for a switching effect when populated by photocarriers. The magnitude of the switching will be much larger in materials with traps of lower ν and the time dependence of the switching provides new information about the electronic nature of these important interfaces.

Fig. 3. The dots give the total current through 3.8μ PET sample at two different values of g : 1.25×10^{10} holes/cm²/s for the upper curve and 2.8×10^9 holes/cm²/s for the lower. The solid line gives the theory.

Fig. 4. The decay in the current from the upper curve in Fig. 3 is given by the dots and the theory by the solid curve.

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