

FIG. 3. Interface-state density N_{ss} versus surface potential, with and without trapped nitride charge.

voltage plot on an X-Y recorder. At regular intervals during the slow ramp the sample is biased to accumulation for a time interval τ_a in order to fill the interface states in the upper half of the energy gap and then swept to depletion by a fast (100 μ s) linear voltage ramp. The C-V curves produced by the fast ramp are displayed on a storage oscilloscope. From these, a plot of V_{fb} versus V_g is obtained, as shown in Fig. 2, and the slope dV_{fb}/dV_g is used in Eq. (4) to calculate N_{ss} . The time interval τ_a is chosen to be sufficiently long (1 ms) so that the contribution to dV_{fb}/dV_g of the interface states with time constants $>\tau_a$ is negligible, while still assuring that no measurable disturbance of the nitride charge occurs. The experimental procedure assures that the interface-state occupancy remains essentially the same each time the sample is swept through the flat-band point by the fast ramp, whether or not all states remain in equilibrium during the

fast-ramp sweep. The charge centroid is determined in a separate experiment.^{3,4}

Figure 3 shows the interface-state density obtained with different amounts of trapped nitride charge. The density-of-states spectrum shows the same general characteristics as are exhibited by the Si-SiO₂ interface: a nearly constant density of states near the midgap, increasing steeply toward the band edge.^{1,5} The nitride charge is seen to have no effect on the interface-state density. This may be contrasted with the correlation between the fixed oxide charge and interface-state density frequently observed in the MOS system.^{1,6} The lack of correlation in this case may be due to the larger distance between the nitride charge and the silicon space charge. It is also possible that, when such correlation exists, it is caused by a common chemical origin of the oxide charge and interface states rather than by Coulombic interaction between the charges in the insulator and in the semiconductor space-charge region.

The authors are indebted to P. Müräu and B. Singer for useful discussions and for providing the experimental samples.

¹A. Goetzberger, E. Klausmann, and M.J. Schulz, *CRC Crit. Rev. Solid State Sci.* **6**, 1 (1976).

²J.J. Chang, *Proc. IEEE* **64**, 1039 (1976).

³B.H. Yun, *Appl. Phys. Lett.* **25**, 340 (1974).

⁴H. Maes and R.J. Van Overstraeten, *Appl. Phys. Lett.* **27**, 282 (1975).

⁵E. Arnold, *IEEE Trans. Electron Devices* **ED-15**, 1003 (1968).

⁶E. Arnold, J. Ladell, and G. Abowitz, *Appl. Phys. Lett.* **13**, 413 (1968).

Charge retention of MNOS devices limited by Frenkel-Poole detrapping^{a)}

K. Lehovc and A. Fedotowsky

University of Southern California, Los Angeles, California 90007

(Received 26 September 1977; accepted for publication 20 December 1977)

A simple analytical expression is derived for charge retention in MNOS memory devices assuming that retention loss is limited by Frenkel-Poole release from monoenergetic traps. This model shows that charge retention becomes eventually independent of the initial charge distribution. Experimental data obtained at elevated temperatures confirm this model and provide a trap depth of 1.5 eV, Frenkel-Poole coefficient of about $6 \times 10^{-4} \text{ cm}^{1/2} \text{ V}^{-1/2} \text{ eV}$, and effective escape attempt rate factor of $1.2 \times 10^8 \text{ sec}^{-1}$.

PACS numbers: 73.40.Qv, 73.60.Hy, 85.30.Tv, 72.20.Jv

Charge retention loss in thin oxide MNOS memory devices ($t_{ox} \lesssim 30 \text{ \AA}$) is dominated in its early stages by

charge tunneling through the oxide from traps located at or near the oxide-nitride interface,¹⁻³ and in latter phases by Frenkel-Poole emission of charge trapped in the nitride and charge transport through the nitride.^{3,4} In this paper we derive a simple analytic expression for the decay of retained charge based on Frenkel-Poole

^{a)}Supported by the Army Research Office, Grant DAAG29-77-G-0123.

emission from monoenergetic traps. Following our procedure, an analytic expression can be derived for any other detrapping mechanism which depends solely on the local electric field intensity. The effect of re-trapping can be accounted for by modifying the effective escape attempt factor.

After a charging pulse, the trapped nitride charge induces a charge of opposite polarity in the silicon and at the gate electrode (Fig. 1). This charge is not necessarily located at the silicon surface, as has been indicated, and there can be a potential drop, not shown in Fig. 1, across the silicon space-charge region. Ramifications of the charge distribution in the silicon and of the corresponding potential drop are discussed later in this paper. The potential distribution in the nitride has a minimum at a distance x_m from the oxide.^{4,5} This minimum is located closer to the oxide than to the gate, i. e., $x_m < \frac{1}{2}t_N$, since the concentration of trapped charge decreases with increasing distance from the oxide.^{4,6-8} Consequently, the maximum nitride field during retention is located at the oxide interface. Thus detrapping occurs mostly near the oxide interface and the detrapped nitride charge shifts primarily toward the silicon. Therefore, the time dependence of the initial Frenkel-Poole-type detrapping in the region $0 \leq x \leq x_m$ provides a lower limit for charge retention.

The escape rate from traps will be assumed to obey the Frenkel-Poole law

$$\frac{\partial n_t}{\partial t} = -n_t \nu \exp[-\phi + \beta(E)^{1/2}], \quad (1)$$

where $n_t(x, t)$ is the local trapped charge density and $E(x, t)$ is the local field, both functions of time. The notation here is the same as that used in Refs. 4, 7, and 8. Trapped charge density and field are related by Poisson's law

$$\frac{\partial E}{\partial x} = \frac{n_t q}{\epsilon_N}. \quad (2)$$

Thus

$$q \frac{d}{dt} \int_0^{x_m} n_t dx = -\nu \exp(-\phi) \epsilon_N \int_0^{E_0} \exp[\beta(E)^{1/2}] dE + n_t(x_m) q \frac{dx_m}{dt} \quad (3)$$

with

$$E_0(t) = (q/\epsilon_N) \int_0^{x_m} n_t dx \quad (4)$$

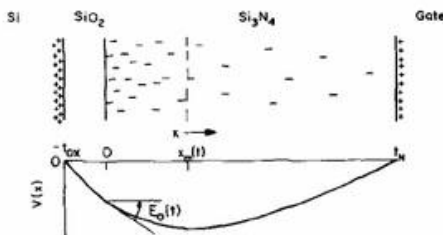


FIG. 1. A typical charge and potential distribution during retention. The potential drop across the silicon space-charge layer is not shown, but is considered later in the text.

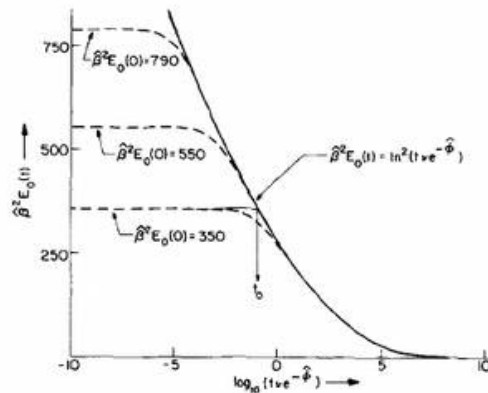


FIG. 2. The function $\beta^2 E_0(t)$ of $\nu t \exp(-\phi)$ according to Eq. (5) for different values of $\beta^2 E_0(0)$. In the range $\beta^2 E_0(t)^{1/2} \lesssim 1$, terms neglected in deriving Eq. (5) have been included in Fig. 2. to obtain $E_0(t) \rightarrow 0$ for $t \rightarrow \infty$.

the field in the nitride at the nitride/oxide interface, $x = 0$.

The second term on the right-hand side arises from the exchange of differentiation with respect to time, and of integration with respect to position, when proceeding from Eq. (1) to Eq. (3). For a constant potential applied between gate and silicon, the charge shift $qn_t(x_m)dx_m/dt$ can be related to the term on the left-hand side of Eq. (3), and to factors which involve the centroids of $q \int_0^{x_m} \partial n_t / \partial t dx$ and of the induced charge in the silicon. The latter is ϵ_s/C_{sp} , where C_{sp} is the low-frequency silicon space-charge capacitance. It can be shown that the right-hand side of Eq. (3) can be replaced by omitting the second term and multiplying the first term on that side by a factor η . This factor is significantly less than unity only in the depletion regime without inversion, and then only if $\epsilon_s/t_N C_{sp} \gtrsim 1$. The overall effect of this " η dip" is always small, however, since at high dopant concentrations the dip is shallow, while at low dopant concentrations the dip is narrow because the E_0 -field range pertaining to depletion without inversion becomes very small. We shall, therefore, neglect the last term of Eq. (3) in what follows.

Integration of the thus simplified Eq. (3), considering Eq. (4), provides

$$\beta[E_0(t)]^{1/2} = \beta[E_0(0)]^{1/2} - \ln[1 + \nu t \exp(-\phi) \times \exp[\beta(E_0)^{1/2}]], \quad (5)$$

where certain terms have been neglected for convenience, assuming that $\beta[E_0(t)]^{1/2} \gg 1$. The function $\beta^2 E_0(t)$ versus $\log[\nu t \exp(-\phi)]$ is shown in Fig. 2 for various values of $\beta^2 E_0(0)$ chosen to provide $t_0 = \nu^{-1} \exp[\phi - \beta^2 E_0(0)^{1/2}]$ of 10^{-1} , 10^{-3} , and 10^{-5} sec, respectively. All curves merge into the same unique function

$$\beta^2 E_0(t) = \ln^2[\nu t \exp(-\phi)] \quad (6)$$

for

$$t_0 \ll t \ll \nu^{-1} \exp(+\phi). \quad (7)$$

The field intensity $E_0(t)$ in the nitride at the boundary of the oxide can be related to the threshold voltage by the following considerations. The threshold voltage with nitride charge differs from that without nitride charge

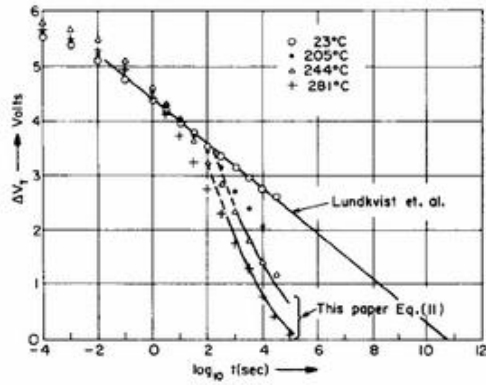


FIG. 3. Experimental charge retention loss fitted by Eq. (11).

(so-called "intrinsic state") by

$$\begin{aligned} V_T(t) - V_T(\infty) &= \left(\frac{q}{\epsilon_N}\right) \int_0^{t_N} n_t(t_N - x) dx \\ &= \left(\frac{qt_N}{\epsilon_N}\right) \int_0^{x_m} n_t dx - \frac{q}{\epsilon_N} \int_0^{x_m} n_t x dx \\ &\quad + \left(\frac{q}{\epsilon_N}\right) \int_{x_m}^{t_N} n_t(t_N - x) dx. \end{aligned} \quad (8)$$

The first of the last three terms is $E_0(t)t_N$; the second term is the potential drop between $x=0$ and x_m ; and the third term is the potential drop between x_m and t_N . In a typical retention experiment a constant bias voltage V_A is applied between gate electrode and silicon substrate. Since

$$\begin{aligned} V_A + V_B &= V_{sp} - \left(\frac{\epsilon_N}{\epsilon_0}\right) t_{ox} E_0 - \left(\frac{q}{\epsilon_N}\right) \int_0^{x_m} n_t x dx \\ &\quad + \left(\frac{q}{\epsilon_N}\right) \int_{x_m}^{t_N} n_t(t_N - x) dx, \end{aligned} \quad (9)$$

where V_{sp} is the potential across the space-charge layer in the silicon and V_B is the built-in potential between gate and substrate, Eq. (8) can be transformed into

$$V_T(t) - V_T(\infty) = E_0(t)[t_N + \epsilon_N t_{ox} / \epsilon_{ox}] + V_A + V_B - V_{sp}. \quad (10)$$

The built-in potential compensates closely the space-charge layer potential in case of a p^+ -polysilicon gate and an n -type substrate if the nitride charge induces an inversion layer in the silicon. Under this condition, one obtains from Eqs. (10) and (6) for retention at zero gate to substrate bias voltage

$$V_T(t) - V_T(\infty) \approx t_N \hat{\beta}^{-2} \ln^2[\nu t \exp(-\hat{\phi})]. \quad (11)$$

This equation is valid for $t \gg t_0$.

Figure 3 shows experimental data supplied by Dr. M. Beguwala of Rockwell International. The nitride was charged by applying positive voltage pulse to the gate of an MNOS capacitor on n -type silicon substrate at various temperatures indicated in Fig. 3. The device was at its intrinsic threshold voltage prior to pulsing. The lack of a significant temperature dependence for

$t \lesssim 100$ msec suggests that retention loss is initially governed by tunneling. The straight line in Fig. 2 is the tunnel relation of Ref. 1. After about 1 sec detrapping appears to become the dominant factor for retention loss at the elevated temperatures. The retention period when initial charge distribution has an effect on the detrapping rate is masked by tunnel escape. The drop-off of the data points at 281 °C was fitted by Eq. (11) with $\beta = \hat{\beta} kT/q = 5.2 \times 10^{-4} \text{ cm}^{1/2} \text{ V}^{-1/2} \text{ eV}$, $\phi = 1.5 \text{ eV}$, and $\nu = 1.2 \times 10^8 \text{ sec}^{-1}$ determined as follows: A plot of $\ln V_T$ versus $\log_{10} t$ of the experimental values was matched to a plot of $\ln E_0$ versus $\log_{10} [\nu \exp(-\hat{\phi})t]$ according to Eq. (11); the displacement along the ordinate is $\ln(t_N \hat{\beta}^{-2})$ and the displacement along the x axis is $\log_{10}[\nu \exp(-\hat{\phi})]$. The parameters ν and ϕ have been separated by applying the same procedure to the data at 244 °C and assuming that ν is independent of temperature. The β value pertaining to 244 °C was $6.4 \times 10^{-4} \text{ cm}^{1/2} \text{ V}^{-1/2} \text{ eV}$. The slight temperature dependence of β should be confirmed by additional experimental data before attempting an interpretation. The β values are about twice the accepted value for the Frenkel-Poole coefficient.^{7,9-12} The comparatively small value of ν may be indicative of a positive temperature coefficient of the trap depths, $d\phi/dT > 0$, and of retrapping. The time t used in the theoretical expression (11) is the initial detrapping time, $t_{th} = \tau_i$. On the other hand, the time of the experimental points is the time when trapped electrons are removed from the nitride, i. e., $t_{exp} = \tau_i + \theta$. These times differ by the delay θ due to retrapping.

Since, by curve fitting, $\nu_{th} t_{th} = \nu_{exp} t_{exp}$ we have

$$\nu_{exp} = \frac{\nu_{th}}{1 + \theta/\tau_i} = \nu^* \exp \left[- \left(\frac{d\phi}{dT} \right) \left(1 + \frac{\theta}{\tau_i} \right) \right]^{-1}, \quad (12)$$

where ν^* is the intrinsic escape attempt frequency, usually assumed to be of the order of the vibrational lattice frequency. The delay time θ is expected to be a weak function of time, and this implicit time dependence should not affect Eq. (11) strongly.

The observed temperature dependence in the temperature range 154–205 °C was less than that expected by our theory, with ϕ and ν as derived from the data obtained at 244 and 281 °C. This discrepancy is attributed to a second, more shallow, trap level which becomes dominant (filled) at the lower temperatures and which is insignificant (empty) at the more elevated temperatures. Unfortunately, Eq. (3) written for the case of multiple trap levels cannot be integrated to provide a concise form such as Eq. (5) for the retention loss arising from the detrapping of electrons from a single trap level.

Our model provides a concise analytical expression for the charge retention loss if all traps have the same activation energy. During the latter periods of retention loss, this expression becomes independent of the initial charge distribution, and depends then only on trap depth, Frenkel-Poole coefficient, and an effective escape attempt rate factor which takes into account retrapping.

We thank Dr. M. Beguwala and Dr. Ross Williams of Rockwell International for supplying the experimental data and for helpful discussions.

- ¹L. Lundkvist, I. Lundstrom, and C. Svensson, *Solid-State Electron*, **16**, 881 (1973).
- ²B. H. Yun, *J. Appl. Phys.* **23**, 152 (1973).
- ³C. A. Neugebauer and J. F. Burgess, *J. Appl. Phys.* **47**, 3182 (1976).
- ⁴K. Lehovec and A. Fedotowsky, *IEEE Trans. Electron Devices* **ED-24**, 536 (1977).
- ⁵G. W. Taylor and J. G. Simmons, *Solid-State Electron*, **17**, 1 (1974).
- ⁶K. Lehovec, *J. Electron. Mater.* **6**, 77 (1977).
- ⁷K. Lehovec and A. Fedotowsky, *J. Appl. Phys.* **48**, 2955 (1977).
- ⁸P. C. Arnett, *J. Appl. Phys.* **46**, 5236 (1975).
- ⁹D. Frohman-Bentchkowsky and M. Lenzlinger, *J. Appl. Phys.* **40**, 3307 (1969).
- ¹⁰S. M. Sze, *J. Appl. Phys.* **32**, 2951 (1967).
- ¹¹E. J. M. Kendall, *Can. J. Phys.* **46**, 2509 (1968).
- ¹²D. Frohman-Bentchkowsky, *Proc. IEEE* **58**, 1207 (1970).