Phonon-coupled trap-assisted charge injection in metal-nitride-oxide-silicon/silicon-oxide-nitride-oxide-silicon structures

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A phonon-coupled trap model is proposed for trap-assisted injection mechanism in silicon-oxide-nitride-oxide-silicon (SONOS)/metal-nitride-oxide-silicon (MNOS) structures at low voltages. On the basis of this model, a theory of charge injection in SONOS/MNOS has been developed. Charge injection experimental data was fitted by this theory. Obtained trap parameters are close to those previously reported [K. A. Nasyrov *et al.*, J. Appl. Phys. **96**, 4293 (2004)], where the current dependence on temperature and electric field was investigated in MNOS. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3151711]

I. INTRODUCTION

Silicon-oxide-nitride-oxide-silicon (SONOS) structures received a great amount of attention for nonvolatile semiconductor memory applications.[1–6] Two of the most important characteristics of SONOS are write/erase (W/E) and retention properties. W/E properties characterize the initial memory window of SONOS, while the electron and hole retentions are responses to the memory window after a long time (10 years). In Refs. 1 and 3 a W/E model was developed based on modified Fowler–Nordheim (MFN) tunneling in SONOS which quantitatively explained the W/E properties at high pulse voltages (high electric fields). A retention model for SONOS was developed in Ref. 2 which considered the following processes: (1) electron back-tunneling from nitride traps to the Si conduction band, (2) electron back-tunneling from nitride traps to the Si/SiO_2 interface traps, and (3) tunnel hole injection from the Si valence band to the nitride traps. Although back-tunneling is temperature insensitive, nevertheless, increasing the temperature accelerated the discharge process in the experiment.[7,8] Furthermore, no model was proposed for hole retention in SONOS.

Here, we would like to emphasize the difference between the W/E and retention processes. For W/E processes, the applied voltages are sufficiently large and there is no doubt about the validity of MFN at such high electric fields. However, the retention characteristics are investigated at zero applied voltage, where the electric field inside the SONOS structure is only due to accumulated charge and is relatively low. For such low electric fields, the direct charge injection from the semiconductor substrate into traps in the nitride or the back-tunnel escape of electrons from charged traps play the most important roles.

From our knowledge, the first model of direct resonance electron tunnel into traps having a single trap energy level was proposed by Svensson and Lundstrom (SL),[9] and explained the experimentally observed extra injection current in comparison with MFN theory. However, in our opinion, this theory encounters some problems. One of them is that according to theory,[9] trap-assisted injection (TAI) is impossible if the trap level near the oxide-nitride interface is lower than the conduction band of the substrate semiconductor (see Fig. 1). It is obvious that TAI becomes zero for fields in oxide larger than

$$F_{\mathrm{ox}} = \frac{\Phi_1 - \Phi_2 - \Phi_t}{d_{\mathrm{ox}}}, \tag{1}$$

where d_{ox} is the thickness of the oxide, Φ_1 is the electron barrier height at the semiconductor/oxide interface, Φ_2 is the barrier height at the oxide/nitride interface, and Φ_t is the trap energy levels. For $Si/SiO_2/Si_3N_4$ structures, $\Phi_1 = 3.1$ and $\Phi_2 = 1.1$ eV. Therefore, to explain TAI observed for moderate voltages one must assume relatively shallow trap energy.

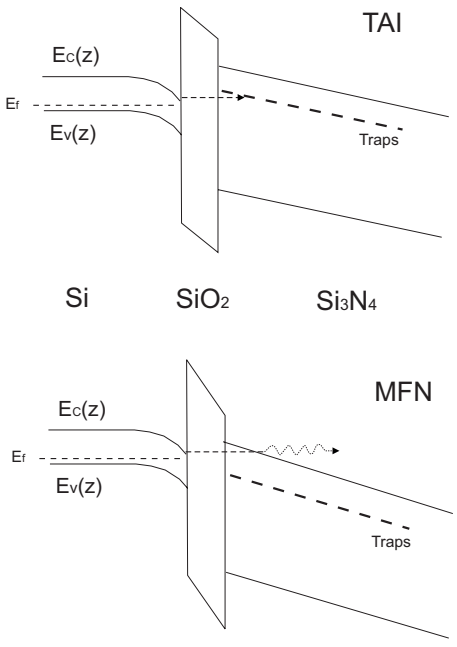

FIG. 1. Upper diagram illustrates the trap-assisted electron injection at low electric fields. The lower one shows the MFN tunnel injection of electron for large electric fields.

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Svensson and Lundstrom[9] have found trap levels of 0.7 eV for electrons and 0.95 eV for holes. However, these values are too low and contradict the experiments with current dependence on voltage because for such shallow traps, the current value should be much more than observed in experiments performed at the high voltage region. Moreover, in Ref. 10 they applied TAI theory to discharging experiments in MNOS structures and have found different trap levels: 1.55 eV for electrons and 0.75 eV for holes.

The theory of retention proposed in Ref. 2 also predicts a shallow electron trap level, 1 eV, which also contradicts the low value of stationary current observed at higher voltages. Unlike previous investigators who used the trap model with a single energy level, we propose to apply more complicated trap model, which was successfully applied to explain the current behavior of electric field and temperature in semiconductors[11] and recently[12] in silicon nitride. In this paper we propose the theory of TAI on the base phonon-coupled trap at low voltages. By fitting the low voltage injection experiments results on the base of proposed theory, trap parameters are obtained.

II. MODEL OF TRAP

Here, we base our model of traps on the Makram-Ebeid and Lannoo (ML) approach.[11] In this model, the trap is consisted by a lattice oscillator, or "core," which can capture an electron. This oscillator, or "core," is characterized by its "coordinate" Q. The energy of a trapped electron is linear dependent on Q. As a result, the ML approach of potential energy of trap with captured electron can be written in a parabolic form as function of Q

$$U(Q) = \frac{1}{2}\hbar\omega Q^2 - W_t, \tag{2}$$

where W_t is the thermal energy of trap and ω is the oscillator frequency. For simplicity, we refer to the energy of traps at the nitride conduction band edge as zero. Also, we can write the bonding energy of electron as

$$E(Q) = -W_t - \hbar\omega\sqrt{S}Q - S\hbar\omega, \tag{3}$$

where S is the so-called Huang–Rhys coupling constant. We choose the coordinate Q so that the equilibrium point of a trap with an electron is $Q=0$. One can represent the energy in Eq. (2) as a sum of electron energy in Eq. (3) and the energy of a free oscillator

$$U_0(Q) = \frac{1}{2}\hbar\omega(Q + \sqrt{2S})^2, \tag{4}$$

and we can see that equilibrium point of free oscillator is shifted by $-\sqrt{2S}$. Figure 2 shows the energy diagrams of a system with a filled or empty bound state. With this picture, the meaning of trap parameters W_t and W_{opt} becomes evident. Thus, W_t is the minimal energy needed to ionize the trap so that after ionization, the free electron is at the bottom of the conduction band and the free oscillator has minimal energy. W_{opt} is the so-called optical energy needed for "direct" or "optical" transition related to an ionization process when the free electron has energy corresponding to the bottom of the nitride conduction band and the free oscillator is excited to the vibration state with energy $W_{\text{opt}} - W_t$, as it is shown in Fig. 2. W_{opt} can be expressed by Huang–Rhys constant as

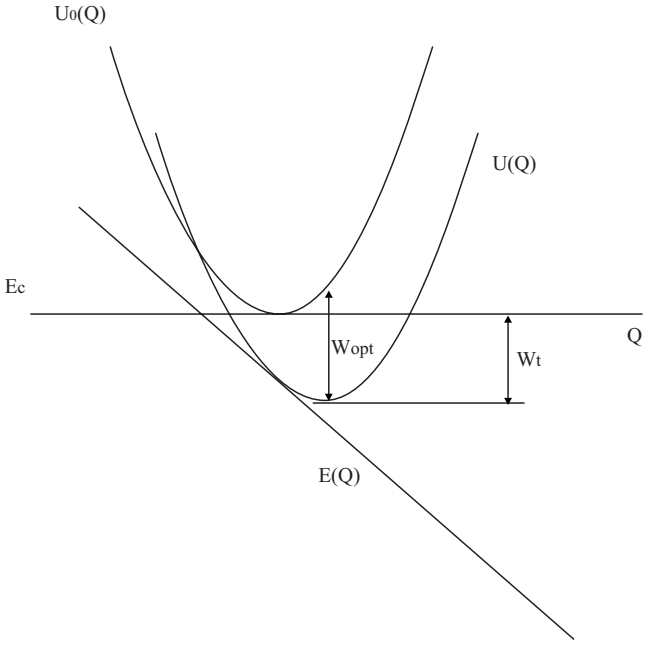

FIG. 2. Energy diagram of unoccupied trap and with captured electron.

$$W_{\text{opt}} = W_t + S\hbar\omega. \tag{5}$$

So, the free trap can occupy the oscillator states n_f with energy

$$W_{n_f} = \hbar\omega(n_f + 1/2), \tag{6}$$

while the stationary state energy n_b of charged trap is

$$W_{n_b} = \hbar\omega(n_b + 1/2) - W_t. \tag{7}$$

Obviously for electron injection in the trap, the energy conservation law should take place. If an electron tunnels from the bottom of the semiconductor substrate's conduction band into a trap near the oxide/nitride interface, this condition gives the equation

$$W_{n_f} = W_{n_b} + \Phi_1 - \Phi_2 - F_{\text{ox}}d_{\text{ox}}, \tag{8}$$

or

$$F_{\text{ox}} = \frac{\Phi_1 - \Phi_2 - W_t + \hbar\omega(n_b - n_f)}{d_{\text{ox}}}. \tag{9}$$

Comparing Eqs. (1) and (9), one can see that there is no restriction on field value when TAI occurs. According to Eq. (9), for large fields the initial free trap in the state $n_f=0$ can capture an electron and occupy a high excited state (n_b). Then, this extra energy is rapidly distributed among lattice phonon modes and the charged trap falls to its equilibrium state with energy close to $-W_t$. As a result one can obtain the equation for TAI in the form

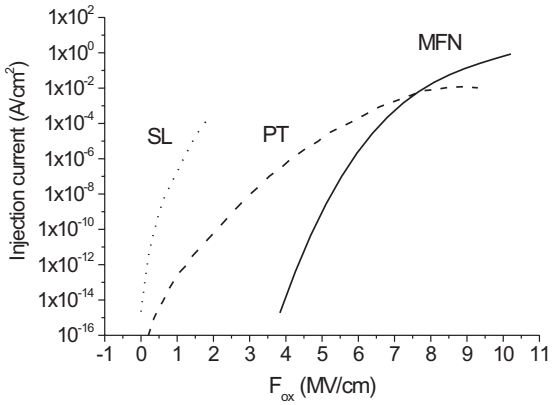

FIG. 3. Injecting electron current as a function of field in oxide. Current due to MFN mechanism is shown by a solid line, current due to direct tunneling into traps according to SL theory (trap level W_t=1.6 eV) is shown by a dotted line, and the injected current calculated by present theory (PT) is shown by dashed line. Calculations were made for following parameters: oxide thickness d_{ox}=2 nm, trap density $N=4\times10^{19}$ cm^{-3}, $m_{ox}=0.6m_0$, and $m_N=0.5m_0$.

$$\frac{d}{dt}n_t(z) = \mathrm{Inj}(z)[N_t - n_t(z)] - \mathrm{Ion}(z)n_t(z), \tag{10}$$

where N_t is the total density of traps in nitride, n_t is the density of filled traps, z is the distance from the oxide/nitride interface. The first term on the right side of Eq. (10) describes the injection process, while the second one describes the trap ionization when electrons escape back to the silicon substrate. The injection (Inj) and ionization (Ion) coefficients are derived in the next section. Also the terms related to MFN injection and trap ionization in the nitride conduction band should be included and will be done later.

We calculated TAI according to the SL model and our model for the case when thermal energy W_t and the single trap energy level of the SL model were the same and equal to 1.6 eV. These results are demonstrated in Fig. 3 in comparison with the MFN injection current. As one can see, our model shows that TAI dominates over MFN current up to $F_{ox}\approx 8$ MV/cm, whereas TAI according to SL theory continues only up to $F_{ox}\approx 2$ MV/cm, because at this field the trap energy level becomes lower than that of the substrate's conduction band. There is also the TAI due to electron tunneling from the valence band of the silicon substrate, but this current is much lower than MFN current for all field diapasons and therefore is not shown in the picture. The above discussion is also valid for hole traps. Of course, hole traps should have their own parameters, as W_{opt} and W_t, which, in general, do not coincide with ones for electron traps.

III. THEORY OF TRAP-ASSISTED CHARGE INJECTION AND IONIZATION ON THE BASE OF PHONON-COUPLED TRAP MODEL

Suppose, that a trap with a captured electron fills the state n_b with probability a_{n_b}. We can write the following balance equation for this probability:

$$\frac{d}{dt}a_{n_b} = \frac{2\pi}{\hbar}\sum_{n_f,n_b}|\langle f|V|b\rangle|^2\delta[E_{e_f}+W_t+\hbar\omega(n_f-n_b)][a_{e_f}a_{n_f} - a_{n_b}(1-a_{e_f})], \tag{11}$$

where a_{n_f} is the probability for an empty trap to occupy the oscillator state n_f, a_{e_f} is the probability for a free electron to occupy state e_f with energy E_{e_f}, and $\langle f|V|b\rangle$ is the matrix element of potential V, through which the electron tunnels from a free state into a local trap state. The first term inside the rectangle brackets describes the process of electron injection into the trap, while the second term describes the trap ionization. Note that the ionization term is proportional to the factor of $1-a_{e_f}$, due to Fermi statistics of electrons, and therefore the ionization probability should be suppressed by this factor.

Now we have to define the wave functions of occupied traps and state when the quantum system is composed by a free electron or free oscillator. Thus, one can write

$$|f\rangle = \psi_f(\mathbf{r})\chi_{n_f}(Q+\sqrt{2S}), \tag{12}$$

where $\mathbf{r}$ is the electron coordinate, ψ_f is the electron wave function in a free state, and χ_{n_f} is the wave function of a free oscillator in state n_f. The bounded state of trap with a captured electron can be presented by the function

$$|b\rangle = \psi_b[\mathbf{r},E(Q)]\chi_{n_b}(Q), \tag{13}$$

where $\psi_b[\mathbf{r},E(Q)]$ is the wave function of bounded electrons whose energy depends on oscillator position Q, and $\chi_{n_b}(Q)$ is oscillator eigenfunction in state n_b. Since potential V depends only on electron position, the matrix factorizes to

$$\langle f|V|b\rangle = \langle\chi_{n_f}(Q+\sqrt{2S})|\chi_{n_b}(Q)\rangle\langle\psi_f(\mathbf{r})|V|\psi_b[\mathbf{r},E(Q)]\rangle. \tag{14}$$

We use the Condon approximation when integrating over $\mathbf{r}$ in the second factor should be performed for fixed values of Q when the transition from bounded to free state takes place for equal values of trapped and free electron energies $E(Q)=E_{e_f}$.

For calculation of the matrix element we will assume that the capturing potential for electrons in the trap is short-range, so that the approximation of δ-like tridimensional potentials can be used. In this approximation the calculation of the matrix element takes the form of integral overlapping between wave functions of free and bounded electrons

$$\langle\psi_f(\mathbf{r})|V|\psi_b[\mathbf{r},E(Q)=E_{e_f}]\rangle = \frac{\hbar^2\sqrt{\kappa}}{m}\exp\left(-\frac{1}{\hbar}\int|p_z|dz\right), \tag{15}$$

where $|p_z|$ is the impulse of a tunneling electron in the region between trap position and the domain of free electrons, m is the mass of the electron located on the trap, and $1/\kappa$ is the length of electron localization in the trap, since the typical energy of a localized electron in the trap is $-W_t$, $\kappa \approx \sqrt{2mW_t}/\hbar$.

Also we assume that all states in the oscillators, as well as free electron states, are occupied according to thermal distributions. This means

$$a_{n_f} = (1-w)[1-e^{-(\hbar\omega/T)}]e^{-(\hbar\omega/T)n_f},$$

$$a_{n_b} = w[1-e^{-(\hbar\omega/T)}]e^{-(\hbar\omega/T)n_b}, \tag{16}$$

where T is the temperature, and w is the probability for trap to be occupied. Following Ref. 11 we introduce the function

$$W_k^C = \sum_{n_b} [1-e^{-(\hbar\omega/T)}]e^{-(\hbar\omega/T)n_b}|\langle\chi_{n_b+k}(Q + \sqrt{2S})|\chi_{n_b}(Q)\rangle|^2. \tag{17}$$

The sum in Eq. (17) can be calculated and W_k^C can be expressed in the explicit form

$$W_k^C = \exp\left(k\frac{\hbar\omega}{2T} - S\coth\frac{\hbar\omega}{2T}\right)I_k\left[\frac{S}{\sinh(\hbar\omega/2T)}\right]. \tag{18}$$

For the free electron wave function, we use the Wannier function in the semiconductor domain so that we can use the usual approach

$$\sum_{e_f} \to \int N(E)dE, \quad a_{e_f} \to f(E) = \frac{1}{1+e^{(E-E_f)/T}}, \tag{19}$$

where $N(E)$ is the state density, $f(E)$ is the Fermi distribution of electrons, and E_f is the Fermi energy.

Since the semiconductor has band structure, valence band (V), conduction band (C), and a forbidden band in between, the density of state distribution has a form in accordance to band structure. This means that $N(E)$ is zero for $E_V < E < E_C$ and for valence and conduction bands, the approximation is often used

$$N(E) = M_C\frac{\sqrt{2}}{\pi^2}\frac{\sqrt{E-E_C}}{\hbar^3}m_e^{3/2}, \quad E > E_C,$$

$$N(E) = M_V\frac{\sqrt{2}}{\pi^2}\frac{\sqrt{E_V-E}}{\hbar^3}m_h^{3/2}, \quad E_V > E, \tag{20}$$

where M_C and M_V are the number of equivalent valleys in the conduction and valence bands of the semiconductor. For simplicity we use $M_C=1$ and $M_V=1$. Equation (20) allows for the introduction of the effective impulse of electron in the conduction band and hole impulse in the valence band, so that

$$E = E_C + \frac{p_e^2}{2m_e}, \quad E > E_C,$$

$$E = E_V - \frac{p_h^2}{2m_h}, \quad E_V > E. \tag{21}$$

Also we can introduce "parallel" and "orthogonal" electron energies

$$E_z^e = \frac{p_{z,e}^2}{2m_e}, \quad E_\perp^e = \frac{p_{\perp,e}^2}{2m_e}, \tag{22}$$

where parallel and orthogonal impulse vectors $\mathbf{p}=(p_z,\mathbf{p}_\perp)$ with respect to the normal vector of semiconductor and oxide surface are introduced. Similar notations can be introduced for hole energies.

As result, the integral over particle energy can be divided to two parts: "electron" and "hole"

$$\int N(E)dE = \frac{\pi(2m_e)^{3/2}}{(2\pi\hbar)^3}\int dE_\perp^e d\sqrt{E_z^e} + \frac{\pi(2m_h)^{3/2}}{(2\pi\hbar)^3}\int dE_\perp^h d\sqrt{E_z^h}. \tag{23}$$

Next, we can sum over n_b in the Eq. (11) and integrate over $E_\perp^{e,h}$ to obtain the final equation for carrier tunnel injection into the trap

$$\frac{d}{dt}w = \mathrm{Inj}(1-w) + \mathrm{Ion}w,$$

$$\mathrm{Inj} = \frac{1}{\pi\hbar}\sqrt{\frac{W_t}{m^3}}\sum_k W_k^C T_k f(U_C - W_t - k\hbar\omega)e^{-(k\hbar\omega/T)},$$

$$\mathrm{Ion} = \frac{1}{\pi\hbar}\sqrt{\frac{W_t}{m^3}}\sum_k W_k^C T_k[1-f(U_C - W_t - k\hbar\omega)], \tag{24}$$

where function T_k should be calculated by the equation

$$T_k = m_e^{3/2}\int_0^{\sqrt{U_C-E_C-W_t-k\hbar\omega}} D(E_C+E_z^e)d\sqrt{E_z^e} + m_h^{3/2}\int_0^{\sqrt{E_V-U_C+W_t+k\hbar\omega}} D(E_V-E_z^h)d\sqrt{E_z^h}, \tag{25}$$

where we define U_C as the energy of the nitride conduction band edge in trap position and

$$D(\varepsilon) = \exp\left(-\frac{2}{\hbar}\int\sqrt{2m^*[V(z)-\varepsilon]}dz\right), \tag{26}$$

where m^* is the tunnel electron mass. If we are reminded that $w=n_t/N_t$, then one can see that Eq. (24) is equivalent to Eq. (10).

IV. CHARGE TRANSPORT IN DIELECTRIC

One can distinguish two time ranges. For short program times, when the most of the traps in nitride are empty, the current is determined by Eq. (10). For long program times, when steady state can be achieved, we have to take into account the trap ionization into the nitride conduction band because in this time domain the current in MNOS is a result of balance between injected carriers into the trap sites in nitride and the rate of trap ionization. For phonon-coupled traps, the rate P of electron ionization to the conduction band is given by equation[12]

$$P = \sum_n \exp\left[\frac{nW_{\rm ph}}{2kT} - S\coth\frac{W_{\rm ph}}{2kT}\right] I_n\left[\frac{S}{\sinh(W_{\rm ph}/2kT)}\right] P_i(W_T + nW_{\rm ph}),$$

$$P_i(W) = \frac{eF}{2\sqrt{2m^*W}}\exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar eF}W^{3/2}\right), \quad S = \frac{W_{\rm opt} - W_T}{W_{\rm ph}}, \tag{27}$$

where I_n is the modified Bessel function, and $P_i(W)$ is the tunnel escape rate through the triangular barrier of height W.

Thus, the electron transport in nitride is governed by a system of equations

$$\frac{\partial n(x,t)}{\partial t} - \frac{1}{e}\frac{\partial j(x,t)}{\partial x} = -\sigma\upsilon n(x,t)[N_t - n_t(x,t)] + n_t(x,t)P(x,t), \tag{28}$$

$$\frac{\partial n_t(x,t)}{\partial t} = {\rm Inj}n_t(x,t) - {\rm Ion}[N_t - n_t(x,t)] + \sigma\upsilon n(x,t)[N_t - n_t(x,t)] - n_t(x,t)P(x,t), \tag{29}$$

$$\frac{\partial F}{\partial x} = -e\frac{n_t(x,t)}{\varepsilon\varepsilon_0}, \tag{30}$$

where $F(x,t)$ is the local electric field, e is the electron charge, and σ is the capture cross-section. For large fields ($|F| > 5\times10^6$ V/cm) we use an approximation of saturated drift velocity $\upsilon = 10^7$ cm/s and charge current $j = -en\upsilon F/|F|$ while for low electric fields the drift-diffusion approximation

$$j = -e\mu Fn - \mu kT\frac{\partial n}{\partial x}, \tag{31}$$

is applied. The electron (hole) mobility is on the order of $\mu = 0.1-1$ cm^2 s V. The injection condition equation for free electrons n is a direct or MFN tunnel from the substrate. A similar set of equations were used for hole TAI.

V. EXPERIMENTAL RESULTS AND SIMULATION

In our experiment, we used metal-nitride-oxide-silicon (MNOS) structures with p-type Si substrates (equilibrium density of holes is equal to 2×10^{14} cm^{-3}). MNOS had an oxide thickness of $d_{\rm ox} = 2.1$ nm, a nitride thickness of $d_N = 53$ nm, and an Al as a gate contact. Constant voltage pulses of exponentially increasing width (0.8 μs÷1600 s) were applied on the gate. After every pulse, a flat band voltage shift $V_{\rm fb}$ was registered. The $V_{\rm fb}$ value was obtained by conventional capacitance-voltage measurements. Every MNOS unstressed sample demonstrated an initial flat band shift in $V_{\rm fb}^0 \approx -4.8$ V, which is related to the permanent positive charge at the Si/SiO_2 interface. This value is extracted from the measured flat band voltage shift. Under positive voltages applied to the gate, the value of $V_{\rm fb}$ increases. This means that electrons are being injected to into the nitride and negative charges are building in the nitride near the oxide interface. On contrary, for negative applied voltages, holes are injected from the Si substrate into the nitride. This process is manifested by decreasing $V_{\rm fb}$. The experimental measured values of $V_{\rm fb}$ are shown in Fig. 4 as the scatter lines for different applied gate voltages. Also in this picture, the results of simulations are presented as solid lines. In our simulations, we assumed that carriers are injected into the nitride due to MFN mechanism and direct tunneling into traps in nitride. We have found that only the combination of both mechanisms can explain the $V_{\rm fb}$ behavior for all applied voltage ranges. For example, simulations were performed when only MFN injection was taken into account. For the same parameters which best fit the $V_{\rm fb}$ behavior for ($\pm$32 V) of applied voltages (for MFN model), we performed the calculations for voltages +20, +18, −18, and −20 V. These curves are marked by △ and ○ in Fig. 4. One can see that these curves are shifted to the right in comparison with experimental results. Moreover, for an applied voltage of $\pm$14 V, the simulations do not show the changing of $V_{\rm fb}$ with time in the frame of the MFN mechanism. This fact directly proves the important role of tunnel injection of carriers into traps in nitride. Therefore, by proper selection of trap parameters we are able, on the basis of the aforementioned theory, to fit experimental data in both short and long time domains of programming. In our simulations, for fitting we use the following parameters: the optical energy $W_{\rm opt}^{e,h}$ of traps for electron and hole, thermal energy $W_t^{e,h}$, electron and hole tunnel masses on oxide $m_{\rm ox}^{e,h}$, and electron and hole masses in nitride $m_{\rm N}^{e,h}$. The best fit parameters are indicated in the caption of Fig. 4. These parameters are close to those obtained from fitting experiments with temperature and electric field dependent currents in MNOS reported in Ref. 12.

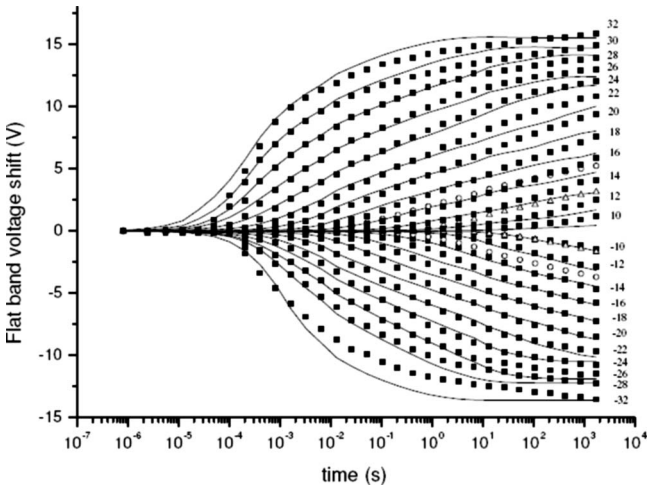

FIG. 4. Flat band voltage shift (scatter lines) for different values of voltage applied on MNOS structure (indicated by the column on the right side). Simulation results are presented as solid lines for the same applied voltages. Best fit parameters were: $W_{\rm opt}^e = 3.2$ eV, $W_t^e = 1.6$ eV, $m_{\rm ox}^e = 0.6m_0$, $m_{\rm N}^e = 0.5m_0$, $W_{\rm opt}^h = 3.0$ eV, $W_t^h = 1.6$ eV, $m_{\rm ox}^h = 0.48m_0$, and $m_{\rm N}^h = 0.5m_0$. The densities of electron and hole traps were the same value of 4×10^{19} cm^{-3}. Lines marked by ○ and △ indicate the simulation results for ±20 and ±18 V, respectively, with only the Fowler–Nordheim mechanism of carrier injection taken into account.

VI. CONCLUSION

On the basis of our developed theory, we performed simulations of charge injection into nitride for both polarities

of applied voltages. These simulations were evaluated with obtained experimental results of MNOS polarization. By fitting with experimental curves, we could extract trap parameters in nitride and carrier masses in oxide and in nitride. These parameters were the following: $W^e_{\rm opt}=3.2$ eV, $W^e_t=1.6$ eV, $m^e_{\rm ox}=0.6m_0$, $m^e_{\rm N}=0.5m_0$, $W^h_{\rm opt}=3.0$ eV, $W^h_t=1.6$ eV, $m^h_{\rm ox}=0.48m_0$, $m^h_{\rm N}=0.5m_0$, $E^{\rm ox}_g=8$ eV, and $E^N_g=4.5$ eV. We have found that the density of traps is 4×10^{19} cm^{-3}. In addition, obtained parameters are close to those previously reported in Ref. 12 and 13 where the current dependence on temperature and electric field was investigated in MNOS. We propose that retention properties of MNOS and SONOS devices can be predicted on the basis of our developed theory and numerical model.

Note that electron and hole trap parameters extracted from the experiment are mostly the same. This supports the conclusion previously made in Ref. 14 from experiment, when electrons and holes stored in nitride were pulled by a low external electric field.

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