

Long term charge loss in EPROMs is modeled by a two-step multiphonon-assisted tunneling process via oxide traps. The field and temperature dependence of the mechanism is studied and compared with resonant tunneling. Charge loss experiments were performed on commercial 4 Megabit EPROMs proving that leakage is through one of the oxides of the ONO dielectric, likely through the bottom oxide. Excellent agreement between numerical simulations based on the new model and measured field and temperature characteristics of the loss current is found. The model provides for the first time a reasonable physical base for the observed strong temperature dependence of the long term charge loss.

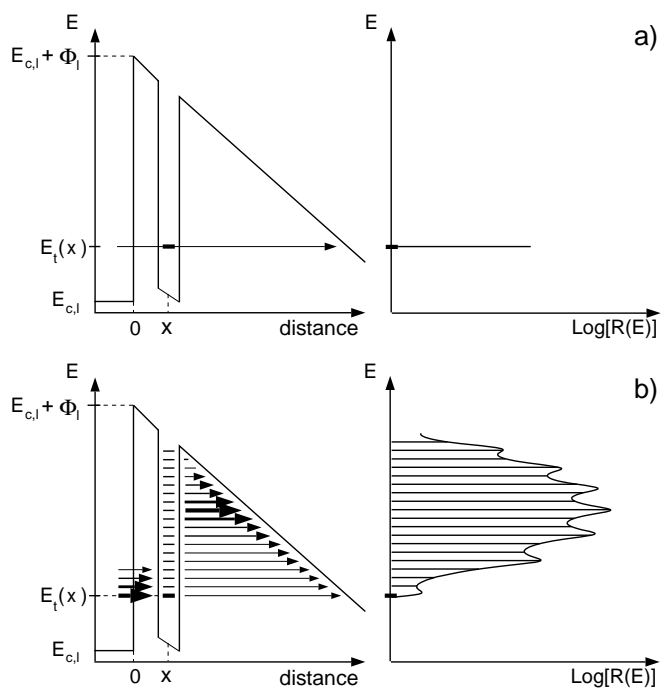
## 1. INTRODUCTION

To achieve good retention characteristics in Non-volatile Semiconductor Memory devices, it is important to understand the mechanism of the loss in the stored charge during the retention mode. It has been pointed out by several authors, e.g. <sup>1)</sup>, that the long term charge loss in EPROMs can not be explained by direct Fowler-Nordheim tunneling, since the effective barrier width gives far too small leakage currents. In recent papers <sup>2),3)</sup> leakage currents through oxide layers were calculated within simplified two-step tunnel models, neglecting i.e. the initial thermal carrier distribution and a possible strong electron-phonon coupling of the deep levels. Furthermore, the time constants were used as fit parameters.

In our new model the carriers are assumed to be captured by traps and subsequently emitted into the substrate (or nitride in case of a sandwich ONO) by a multiphonon-assisted tunneling process <sup>4)</sup>. We show that such a model yields excellent agreement between numerical simulations and measurements of the charge loss characteristics of commercial 4 Megabit EPROMs.

## 2. NEW CHARGE LOSS MODEL

The two-step multiphonon-assisted tunneling process is illustrated in Fig.1, where it is compared with resonant tunneling under the same conditions (upper part). Coupling of the defect state to oxide phonons results in a broadening of the resonance level, which



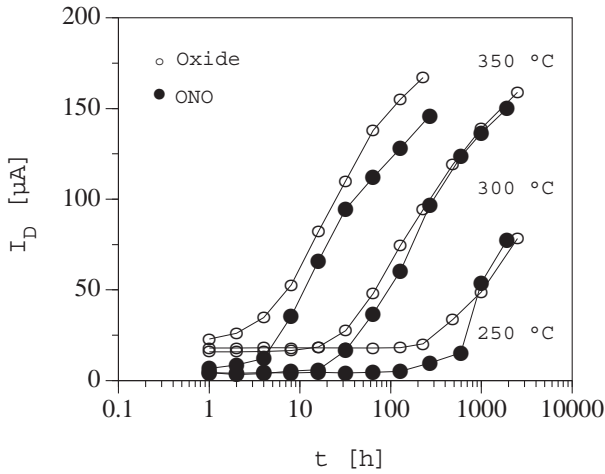
**Figure 1:** Upper part: one-step resonant tunneling process via an oxide trap (left) and resulting delta-like transition rate (right). Lower part: two-step multiphonon-assisted tunneling process (left) and resulting transition rate (right).

allows for more effective tunneling paths (lower part). The simplest description of that broadening is provided by a shifted Gaussian, where shift and broadening depend on the lattice relaxation energy  $\epsilon_R$ . As a consequence, the second step is thermally activated which enhances the total transition rate. Under steady state conditions (long term charge loss)

is retrieved and the two-step process is restricted to the corresponding transition energy. The rate distribution shown in Fig.1 results from the interplay of thermal activation and tunneling probability with a distinct maximum explaining the observed activation behavior of the current. The oscillations are due to quantum reflection (no WKB approximation has been used) and the arrows indicate the number of participating phonons. The time constants of both steps and hence the current density were calculated explicitly using a 3D delta potential for the trap.

### 3. MEASUREMENTS

Charge loss measurements were made on commercial 4 Megabit EPROMs fabricated in 0.8  $\mu\text{m}$  technology. The  $\text{SiO}_2$  between floating gate and substrate had a thickness of about 20 nm, the ONO interpoly dielectric consisted of a 10 nm bottom oxide, a 7 nm nitride, and a 7 nm top oxide. After programming the cells of 15 devices, bakes at 250  $^\circ\text{C}$ , 300  $^\circ\text{C}$ , and 350  $^\circ\text{C}$  were performed. On each device, the drain-source current of 2000 cells was measured at 8 V control gate voltage and 1 V drain voltage at intermediate time steps. An additional charge loss experiment with oxide for the interpoly dielectric verified that charge transport is limited by electron conduction through one of the oxides of the ONO <sup>5</sup>, likely the bottom oxide.



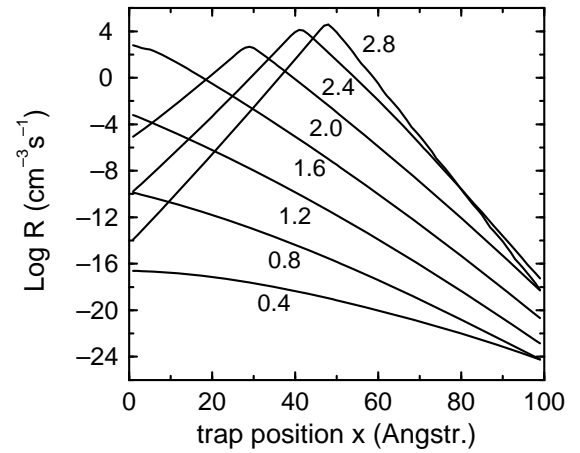
**Figure 2:** Average drain-source current of 2000 cells at intermediate time steps for different bake temperatures. The oxide thicknesses of both lots (ONO and single oxide) were the same.

### 4. DISCUSSION

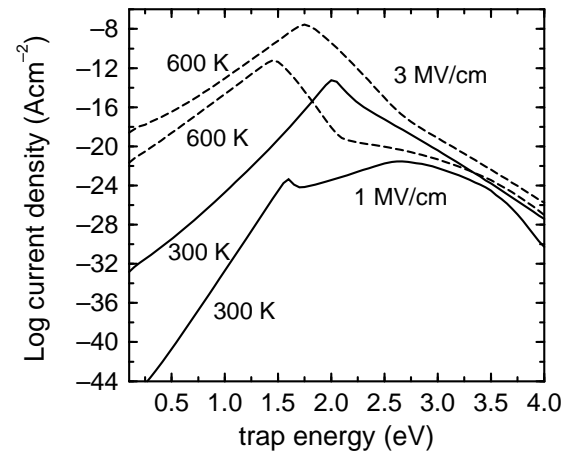
Studying the transition rate as a function of trap position  $x$  for different trap levels  $\Phi_t$  at room tem-

of the gate-oxide interface (see Fig.3). This behavior is caused by the fact that the first step restricts the complex process due to the very small thermal occupation of the corresponding energy levels in the gate. Since the transition energies of the first step remain pinned to the floating gate band edge, the electrons see a high barrier. The condition of balanced partial rates for a maximum total rate then demands for a large tunnel probability in the first step, i.e. for  $x \approx 0$ . The deeper the trap level the more the maximum of the distribution shifts towards the center of the oxide layer. Even trap levels below the floating gate Fermi level can be occupied due to the presence of virtual excited states.

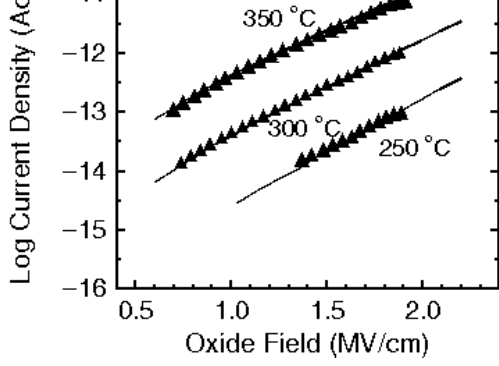
In Fig.4 we show the current density as function



**Figure 3:** Transition rate  $R$  as function of trap position for  $T = 300 \text{ K}$ ,  $F_{ox} = 1 \text{ MV/cm}$ ,  $N_t = 10^{17} \text{ cm}^{-3}$ , and different trap energy levels  $\Phi_t$  measured in eV from the oxide conduction band edge.



**Figure 4:** Simulated current density as function of trap energy level  $\Phi_t$  measured from the oxide conduction band edge for different temperatures and field strengths.



**Figure 5:** Current densities vs oxide field: measurement (triangles) and numerical results (solid lines). Parameters:  $d = 10$  nm,  $\epsilon_R = 0.36$  eV,  $N_t = 6.5 \times 10^{15}$  cm $^{-3}$ .

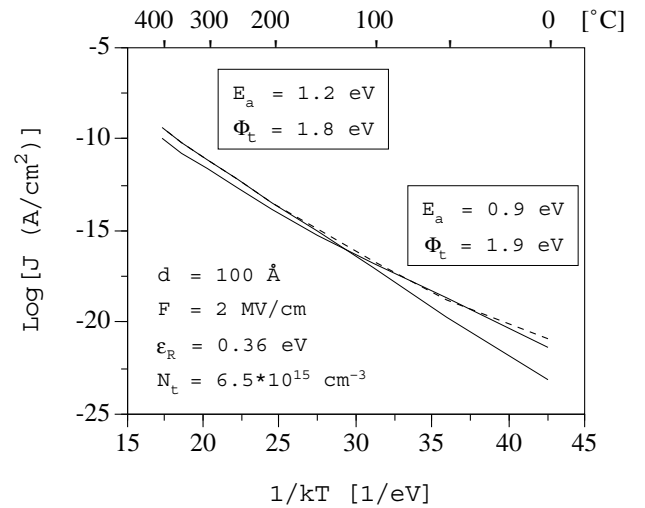
of the trap level for different oxide fields and temperatures. Whereas at room temperature a broad peak occurs in the range  $\Phi_t = 1.8$  eV – 3.5 eV for the weak oxide field of  $F_{ox} = 1$  MV/cm, at an elevated temperature of  $T = 600$ K the dominating peak arises at  $\Phi_t = 1.5$  eV. Increasing the field strength to  $F_{ox} = 3$  MV/cm makes tunneling more important for the complex process and the former broad peak at room temperature is exceeded by a distinct sharp peak at  $\Phi_t = 2.0$  eV. Such an optimum trap level is typical for a pure two-step tunneling transition<sup>3)</sup>.

Fig.5 compares measurement and numerical simulation. We assumed a quasi-continuous energetic distribution of trap levels. Although a refined version of the multiphonon theory was used, the only relevant fit parameter in the model is the lattice relaxation energy  $\epsilon_R$ . A variation of that parameter in the range from 0.2 eV to 0.6 eV has only little influence on the fit, which shows the robustness of the model. Only trap levels between 1.5 eV and 1.7 eV give significant contributions to the current density at high temperatures and low electric fields. Furthermore, only traps near the gate-oxide interface are active in the steady-state trapping and detrapping process under these conditions. Therefore, the leakage at elevated temperatures could be explained as well by phonon-assisted tunneling from gate-oxide *interface states*. At room temperature deeper trap levels contribute most, which favors traps around the center of the oxide layer.

Fig.6 shows the extracted activation energy assuming that the temperature dependence of the leakage current is dominated by  $\exp(-E_a/kT)$ . As can be seen the activation energy is not a constant but increases with temperature while the trap depth giving the largest contribution to the current density

Thus, the proposed multiphonon-assisted tunneling mechanism with  $\epsilon_R = 0.36$  eV consistently yields the right activation energy of the charge loss. Since the process is thermally activated, no daring assumptions on how to guarantee energy conservation, e.g. by gate-plasmon absorption<sup>6)</sup>, are necessary.

To conclude, a long term charge loss model for EPROM cells with ONO interpoly dielectric has been presented describing tunneling of electrons from the floating gate to oxide traps followed by emission into the nitride. The coupling of the trap state to oxide phonons results in virtual energy levels allowing for more effective tunneling paths. As a consequence, the second step is thermally activated. In the limit of strong oxide fields and low temperatures the pure two-step tunneling mechanism is recovered.



**Figure 6:** Arrhenius plot of the current density vs temperature using single trap levels (solid lines) and the respective level which yields the maximum current density (dashed line).

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