Proceedings of 1997 International Semiconductor Device Research Symposium,
December 10-13, 1997, Omni Charlottesville Hotel

Single-Electron Spectroscopy of Individual Slow Interface Traps in Submicron MOSFETs

B.I.Fouks
Institute of Radioengineering & Electronics of RAS, Moscow, 103907, Russia

It is discussed the effect of infrared radiation on random two-level switching in the drain current in a small area MOSFET, which is commonly referred to as a random telegraph signal (RTS). It is shown that the mean duration of one of two current states of the RTS has to depend highly on the intensity, the spectrum, the direction, the polarization of the radiation, that permits to create a novel single-electron spectroscopy of individual slow interface traps giving a lot of unique physical and device information.

The RTSs are caused by random capture and emission of an electron by a single interface trap with the very long mean capture and emission times, τ_c and τ_e.[1] Believing these times to be equal to their equilibrium values, τ_c^e and τ_e^e, one finds the energy level of the trap ε_t with the use of the relationship:

$$\frac{\tau_c^e}{\tau_e^e} = \frac{f}{1-f} = \frac{1}{g}\exp\left(-\frac{\varepsilon_t - \varepsilon_F}{T}\right) \tag{1}$$

(f is the electron occupancy of the level, g is its degeneracy, T is the temperature in energy units, ε_F is the Fermi level). A large body of research has revealed many nontrivial features of these traps, among which are: the sharp temperature dependence of the capture cross section, σ, $\sigma = \sigma_0 \exp(-\Delta E_B/T)$; relatively high activation energy $\Delta E_B \gg \varepsilon_t$; a big scatter of ΔE_B from trap to trap; a drastic change of ε_t with the change of the gate voltage, V_g; and others.[2]

These data fit well the theory of the fluctuation traps.[3, 4]. According to this theory such traps are set up by the charges built-in the oxide at the $Si:SiO_2$ interface and distributed at random along it. This causes a random potential pattern with a high amplitude in the near-surface layer of silicon. The wells and mountains of the pattern localize electrons and holes, respectively, nearby this surface. Therein lies the reason of the U-shaped density of the fast interface states.[5] Among these localized states exist some created by the small-scale cluster of attracting charges falling inside the large-scale repulsive fluctuation (Fig.1(a)). The cluster represents the Z-charged nucleus that localizes in its vicinity in *Si* an electron with a high binding energy ε_b. The large-scale fluctuation surrounds the nucleus with a high and broad barrier, with the height ε_B and the radius l, that slows the capture of electrons by this trap and rises its level: $\varepsilon_t = \varepsilon_B - \varepsilon_b$ (Fig.1(b)). Owing to this ε_t appears to be close to ε_F. As the trap captures mainly the electrons activated over the barrier, $\Delta E_B = \varepsilon_B$; as the captured electrons tunnel through the upper part of the barrier into a resonance level of the trap, $\Delta E_B < \varepsilon_B$. The most probable values ε_t and ΔE_B calculated by the optimum fluctuation method, as well as the calculated V_G-dependencies of τ_c and τ_e, of the RTS amplitude, and the like are in a good agreement with those observed at different temperatures.[3, 4] Also a slow trap can be created if a like attractive nucleus falls within the potential barrier confining the width of the inversion channel.[3,4]

Consider the effect of a radiation on the RTS produced by such a trap. Under the photon flux I the mean emission time of an electron from the trap must be equal to:

$$\frac{1}{\tau_e} = \frac{1}{\tau_e^e} + \sigma_{ph}^{eff} I, \tag{2}$$

where σ_{ph}^{eff} is the effective photoionization cross section of the trap. Calculating it at the photon energy $\hbar\omega$, such that $0 < \hbar\omega - \varepsilon_b \ll \varepsilon_b$, with the hydrogen-like-center model and neglecting by quantization of electrons in the inversion layer and the reflection of incident radiation from interfaces one obtains that:

$$\sigma_{ph}^{eff} = \sigma_{ph}^0 = 2\pi^2 \frac{e^2}{\hbar c} \frac{\hbar^2}{\sqrt{\varepsilon_s} m^* \varepsilon_b} \left[0.73 \sin^2\theta_a + 1.41 \cos^2\theta_a\right], \tag{3}$$

where m^* and ε_s are the electron mass and the permittivity of Si, θ_a is the angle between the vector-potential of the incident radiation and the normal to the interface. This model serves as an approximation only, but is adequate in many respects. Equation (3) differs from the famous expression for the ionization of a hydrogen-like atom by numerical and angle factors, for an electron moves here in a half-space. At $\varepsilon_b = 0.5eV$ that is usual at near-room temperatures and $m^* = 5\times 10^{-28} g$ it gives $\sigma^0_{ph} \approx 10^{-16} cm^2$, and from Eq. (2) it follows: if the emission time of an unirradiated trap is far longer than 1 *s*, it falls to 1 *s* under irradiation by the flux $I = 10^{16} cm^{-2} s^{-1}$. Thus, the effect is pronounced.. At low temperatures the values ε_b are noticeably less and σ^0_{ph} is to be higher, that allows to observe this effect still easier.

A moderate radiation affects only the time τ_e, for the thermal emission of an electron from a slow trap is very low. Its effect on the drain current and the capture time is negligible. This latter permits to find which current state of the RTS, the high or the low, corresponds to the filled trap and which to the empty. No other experiments exist, solving this problem being quite ambiguous at low temperatures.[1]

It may be that the reflection of the incident electromagnetic wave by the gate reduces severely its electric field around the trap, causing the effective cross section σ^{eff}_{ph} to be much less than σ^0_{ph}. Consider with the opaque metal gate how to avoid this under the following real conditions:

$$\sqrt{\varepsilon_s}\Big/\Omega_p\tau_p \ll \beta \equiv \sqrt{\varepsilon_s}\,\omega\Big/\Omega_p \ll 1, \qquad d^2\Omega_p^2\varepsilon_{ox}\Big/c^2\varepsilon_s \ll 1. \tag{4}$$

Here τ_p and Ω_p are the carrier momentum relaxation time and the plasma frequency in the metal, ε_{ox} and d are the permittivity and the thickness of the oxide. If the radiation is polarized along the interface plane, σ^{eff}_{ph} is less than σ^0_{ph}, as the factor $4\beta^2$ estimated as 0.1÷0.01 depending on the gate metal, for the plasma frequency in metals is very high. If the electric field of the wave lies in the plane of its falling:

$$\sigma^{eff}_{ph} = 2\pi^2 \frac{e^2}{\hbar c}\frac{\hbar^2}{\sqrt{\varepsilon_s}\,m^*\varepsilon_b} 4\cos^2\theta \frac{1.41\sin^2\theta + 0.73\beta^2}{\cos^2\theta + \beta^2}. \tag{5}$$

θ is the angle the incident wave makes with the normal to the interface. σ^{eff}_{ph} is highly θ-dependent. At $\theta = 0$ and $\theta = \pi/2$ it is much less than σ^0_{ph}, as the same factor $4\beta^2$, but it turns out even to be several times higher than σ^0_{ph} as the angle differs slightly from $\pi/2$: $\beta < \pi/2 - \theta \ll 1$. Both considered limiting cases (see Eqs. (3), (5)) permit to expect that in intermediate cases with the radiation diffraction caused by the real gate structure, one can obtain a high value σ^{eff}_{ph}, if irradiates the MOSFET by a proper way.

The above estimations show a high photosensitivity of RTSs. Thus one can find the spectral curve $\sigma^{eff}_{ph}(\omega)$ from the measured ω-dependence of τ_e and Eq. (2). For hydrogen-like atoms this curve rises by step from nil at the photon energy being equal to the binding energy of an electron by the ion. For real semiconductor traps it rises not by step, but more or less smoothly depending on the deviation of the real electron-trap interaction from the attractive Coulomb potential. The distributed nucleus and the fact that, the height of the barrier is higher along the interface than in the normal direction,[3] are the added factors of a smooth rise of $\sigma^{eff}_{ph}(\omega)$ for these slow traps. The curve $\sigma^{eff}_{ph}(\omega)$ may also exhibit a certain structure in the range $\hbar\omega \approx \varepsilon_b$, being besides θ_a-dependent. Absorbing a photon the captured electron may pass into the free states with a few athimutal quantum numbers L: the transitions in the states with $L = 2$ cause the factor before $\sin^2\theta_a$ in Eq. (3) and in the states with $L = 1,\ 3$ cause the factor before $\cos^2\theta_a$. The threshold energy for these transitions may be estimated as: $\varepsilon_b + \hbar^2 L(L+1)\big/2m^* r_m^2$, where r_m is the distance of the barrier maximum from the nucleus. So the transitions in the free states with $L = 1,\ 2,\ 3$ have to decay at different photon energies, that has to be marked in the curve.

The photoionization of slow traps is also possible at $\hbar\omega < \varepsilon_b$ owing to the tunneling of the excited carrier through the barrier surrounding such a trap. At such photon energies the cross section decreases with decreasing ω primarily because of the tunneling exponent that gives:

$$\ln\sigma^{eff}_{ph}(\omega) = C - \frac{\varepsilon_b - \hbar\omega}{\varepsilon_d}, \tag{6}$$

where C is a certain constant. For the optimum slow interface trap[3] the energy ε_d can be estimated as:

$$\varepsilon_d = \left(\eta Z e^2 \hbar^{2^*} \big/ 2\pi^2 m^* \kappa r_m^3 \right)^{1/2}, \tag{7}$$

where η lies from 0.5 to 1, $\kappa = (\varepsilon_s + \varepsilon_{ox})/2$. This gives $\varepsilon_d = 0.006\ eV$ for the values being typical at near-room temperatures: $Z = 4$, $r_m = 5\ nm$, $\kappa = 8$. In the range $\hbar\omega < \varepsilon_b$ the curve $\sigma_{ph}^{eff}(\omega)$ may also have the spikes at certain frequencies that is caused by the optical transitions of the captured electron from the ground state to the resonance ones and its following tunneling through the barrier.

Of considerable interest are the variations of $\sigma_{ph}^{eff}(\omega)$ with the temperature and, especially, with the gate voltage. For understanding these latter consider how the change of V_G varies the structure of a slow trap. Such a trap has 3 different typical lengths: $l \gg r_m \gg a_Z$; here $a_Z \equiv a_1/Z$ is the typical radius of the nucleus, $a_1 = 4\kappa\hbar^2/m^* e^2$ is the scale of the wave function of an electron localized by a sole charge $+e$ built into the $Si{:}SiO_2$ interface.[3] The main effect is caused by the electron screening of the large-scale barrier. The longer its radius l, the easier it is screened and the sharper the decrease of its height ε_B as V_G increases (see Fig. 1(b)). This causes only the corresponding sharp lowering of ε_t and decrease of the capture time and has no effect on the emission time and the photoionization spectrum. These latter depend on the change of ε_b, which is relatively slight, as is determined by the shorter length r_m. The energy ε_b increases as V_G increases.[3] This causes the corresponding increase of τ_e^e and shift of the photoionization threshold being correlated to one another. The spacing r_m lengthens as V_G increases that affects the above-discussed near-threshold structure of the curve $\sigma_{ph}^{eff}(\omega)$. One can calculate this variation using the derived V_G-dependence of the potential energy in the near-nucleus region.[3]

In most papers the slow traps are thought to be placed not in silicon but in the oxide. Consider why the oxide-trap model can not explain the observed V_G-dependencies of τ_c^e and τ_e^e. and why the optical measurement is to clarify the genesis of the traps and to indicate, where they are placed, in SiO_2 or in *Si*.

By the oxide-trap model the RTSs are caused by multiphonon capture of carriers from the inversion layer into a trap placed in SiO_2 (Fig. 2). The observed decrease of the ratio τ_c^e/τ_e^e, that is, lowering of ε_t (see Eq. (1)), with increasing V_G is explained in this model by the fact that the trap is offset by the distance h from the interface: $h = d \times \partial\varepsilon_t/\partial eV_g$.[1, 2] In such a case it must be: the longer h, the sharper the increase of τ_e^e as V_G increases, whereas τ_c^e is independent of the shift of ε_t and decreases rather slightly. The experiments have shown just the reverse: the traps with the sharpest decrease of τ_c^e/τ_e^e have a sharp decrease of τ_c^e and a slight increase of τ_e^e,[2] as it must be in the fluctuation-trap model. The oxide-trap model can not also explain the following. At multiphonon capture of an electron from silicon to an oxide trap its capture cross section incorporates not only the probability of thermal activation, $\exp(-\Delta E_B/T)$, but also the probability of electron tunneling through the oxide, $\exp(-h/\lambda)$. Hence the factor σ_0 in the observed relation, $\sigma = \sigma_0 \exp(-\Delta E_B/T)$ must have the form: $\sigma_0 \sim \exp(-h/\lambda)$. The barrier of this tunneling U is very high (*>3 eV*) for all the studied traps having the level ε_t nearby the Fermi one, and the tunneling length is very short: $\lambda = \hbar/\sqrt{8 m_{ox} U} \sim 0.1\ nm$, where $m_{ox} = 1.2\ m_0$ is the electron effective mass in SiO_2. From the V_G-dependencies of ε_t it has been found for most of the studied traps that $h > 1\ nm$; whence it follows that the probabilities of electron tunneling into these traps have to be less than 10^{-4} that causes very small values of σ_0. But the measurements at near-room temperatures have given the high values: $\sigma_0 \sim 10^{-14} \div 10^{-15}\ cm^2$,[2] being typical for attractive centers in Si. In addition, for a number of the traps the V_G-dependence of ε_t is so abrupt that it has been found: $h \sim 10\ nm$. The electron transfer from Si in so distant oxide traps is impossible at all.

The experimental finding of the photosensitivity of the RTS emission time will serve as the reliable evidence of the fact that the electron captured by the interface slow trap is localized in silicon, not in the oxide. The photoionization cross section for the oxide traps under infrared radiation has to be many orders less than it follows from Eqs. (3), (5), for the electron under *~3 eV* barrier has a very small scale of its wave function, λ, and has to tunnel to silicon under this barrier through the distance $h \gg \lambda$.

Notice that the like spectroscopy of single defects was applied to $GaAs/Al_xGa_{1-x}As$ tunnel structures, where it revealed that the RTSs were exerted by the ordinary bulk traps placed in wide-gap regions.[6] The above-discussed specific slow interface traps are very different from the bulk silicon and oxide traps, and the spectroscopy is to show their unusual structure and properties. The $Si:SiO_2$ heterojunction differs by the fact that its height exceeds noticeably the gap of *Si*. This is why, taken alone, the observation of the radiation effect on one of the times of an RTS in MOSFET answers the principal question, where the slow traps are situated, in *Si* or in SiO_2. In addition, the energy levels of the traps in the $GaAs/Al_xGa_{1-x}As$ structures lie much below than the Fermi level, that permits to study only the light-induced RTSs. This renders impossible the independent temperature measurements of the energy level of the trap with the use of Eq. (1), the measurements of the V_g-dependence of this level, a comparison of these results and the results of the optical measurements. The full complex of these measurements has to provide the unprecedented extensive data on the properties of the discussed interface traps, the $Si:SiO_2$ interface.

References.

1. K.S. Ralls, W.J. Skocpol, L.D. Jackel, R.E. Howard, L.A. Fetter, R.W. Epworth and D.M. Tennant., Phys. Rev. Lett. **52**, 228-231(1984)
2. M.J. Kirton and M.J. Uren, Adv. Phys. **38**, 367-468 (1989)
3. B.I. Fuks, Sov. Phys. - JETP **75**, 294-305 (1992)
4. B.I. Fouks, Proc. ISDRS, Charlottesville VA, 241-244 (1993)
5. V.A.Gergel, R.A.Suris, Sov.Phys.-JETP **57**,415-420 (1983)
6. E.S. Snow, P.M. Campbell, and D.S. Katzer, Phys. Rev. **B47**, 16032-16035 (1993)

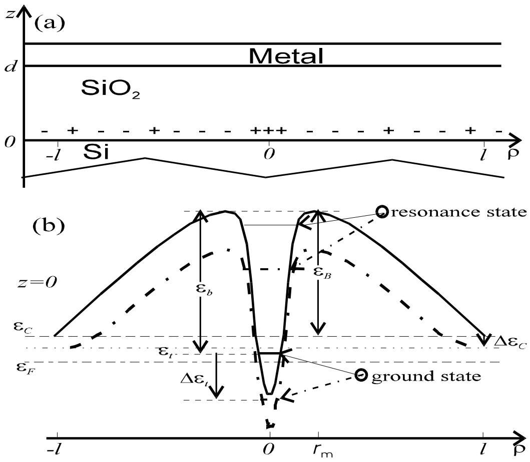

Fig.1 - (a) Random distribution of the charges built-in the oxide: a small-size attractive cluster within a large-scale repulsive fluctuation. (b) The corresponding energy diagram at the $Si:SiO_2$ interface: the local bending of the bottom of the silicon conductivity band (the solid curve); the position of this bottom averaged over the MOSFET (the dashed line); the local band bending as the gate voltage increases by the value ΔV_G (the dash-dotted curve). $\Delta\varepsilon_t$ and $\Delta\varepsilon_B = \varepsilon_{B'} - \varepsilon_B$ are the lowerings of the ground state energy and the height of the barrier of this slow interface trap under this voltage change.

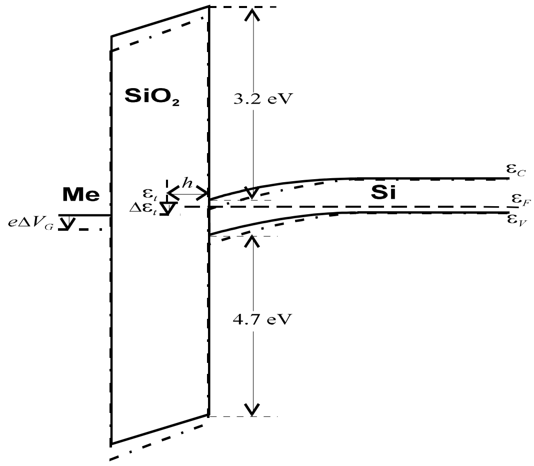

Fig.2 - Energy diagram of a MOS-structure with a slow trap in accordance with the oxide-trap model. (solid curves). The same diagram as the gate voltage increases by the value ΔV_G (dash-dotted curves).