A STUDY OF INJECTION CONDITIONS IN THE SUBSTRATE HOT ELECTRON INDUCED DEGRADATION OF n-MOSFETs

L. Selmi, C. Fiegna, E. Sangiorgi, R. Bez*, and B. Riccò

DEIS, Viale Risorgimento 2, 40136 Bologna, Italy

* SGS-Thomson Microelectronics, Via C. Olivetti 2, 20041, Agrate Brianza, Italy

The dependence of homogeneous nMOSFET degradation on the energy of the electrons impinging at the interface is a controversial issue not yet completely clarified [1,2]. In this work we address the issue by comparing experiments on nMOSFET degradation due to optically generated substrate hot electrons (SHE [3]) with accurate simulations of the gate current (I_G) and the electron energy distribution (EED) at the $Si-SiO_2$ interface. Differently from previous works, we focus on the range of small injected charges (Q_{inj}), where injection conditions are expected to play a fundamental role. The results suggest that in its earliest stages degradation is mainly due to electrons with energy below the $Si-SiO_2$ energy barrier (E_B).

The degradation experiments were performed on LDD nMOS transistors featuring 2 μm gate length, 200Å oxide thickness and $6\times10^{16} cm^{-3}$ surface doping concentration. Fig.2 shows the measured equivalent trapped charge density (Q_T) due to the injection of up to 10^{19} $charges/cm^2$; as observed in [2], Q_T increases rapidly for increasing oxide field (F_{ox}), while no significant dependence is found with respect to changes in the substrate voltage (V_{SB}), hence in the electron energy. However, for small injected charges, and in spite of some spread in the data due to unavoidable differences between devices, the trapped charge (Fig.3) and the density of surface states (proportional to the shift in the charge pumping current ΔI_{CP}, Fig.4) exhibit a decreasing dependence on V_{SB} not observed in previous works [1,2]. Such a dependence becomes vanishingly small at large Q_{inj} (i.e. in the range explored in [1,2]), probably due to the changes induced by the corresponding trapped charge on the internal field distribution.

To interpret the observed phenomena the SHE experiment has been simulated by means of an injection model already proven to accurately account for hot electron injection and gate current over a wide range of F_{ox}, V_{SB} and doping profiles [4,5]. The program is based on the iterative technique of solving the Boltzmann transport equation and implements the electron transport model of [6], which provides a satisfactory approximation of the silicon energy bands up to 3.4 eV. I_G is calculated adding the contributions of Shottky emission above the $Si-SiO_2$ energy barrier ($E_B = 3.1\ eV$) and of tunneling. This latter term is computed, consistently with the calculated EED, by means of the Fowler-Nordheim expression of the tunneling probability. The model does not include charge trapping or surface state generation phenomena. Consistently with this simplification we restricted our analysis to the early stages of device degradation, when Q_{inj} is so small that the corresponding trapped charge has not substantially changed the field distribution inside the device. The injection model was tested by comparing measured and calculated values of the injection probability from silicon into silicon dioxide [3,5]; sample results demonstrating the accuracy of the model in predicting the gate current are reported in Fig.5.

As for the interpretation of the experiments, Fig.6 shows the EED of the overall and injected electrons for two different V_{SB} normalized to reflect a condition of equal injected charge. As can be seen, the number of injected electrons below $\approx 3\ eV$ decreases for increasing V_{SB}, thus exhibiting the same bias dependence as the observed degradation. This strongly suggests that, in the beginning, degradation is mainly due to electrons with energy below $\approx 3\ eV$. Fig.7 compares the calculated increase in the number of electrons injected from different energy levels with the increase exhibited by the trapped charge ($\triangle$) and the density of surface states ($\square$) for constant values of the injected charge ($Q_{inj} < 10^{18}$ $charges/cm^2$). As can be seen the measured degradation increases as much as the number of electrons injected at $\approx 2.8-2.9\ eV$, thus suggesting that the initial degradation may be preferentially due to those electrons (see Fig.6) tunneling through the top of the energy barrier. This physical picture is confirmed by the data in Fig.8, referring to different oxide fields in the range below the threshold for substantial generation of oxide traps. As F_{ox} is increased, tunneling becomes possible from lower energy levels; correspondingly, the increase of the trapped charge and the density of surface states resembles more closely that exhibited by the number of electrons injected from progressively lower energy levels.

In summary, degradation experiments performed at very small values of the injected charge have been interpreted by means of an accurate injection model; the results indicate that in the first steps of device degradation the damage is mainly due to electrons with energy below E_B and, in particular, to those injected through the top of the energy barrier.

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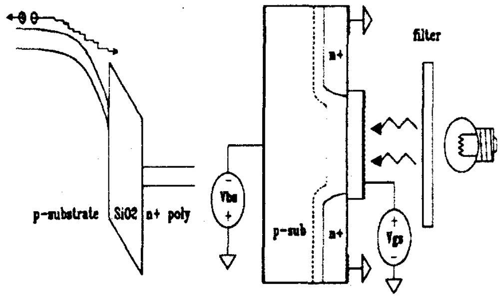

Fig.1 Typical setup for substrate hot electron injection experiments.

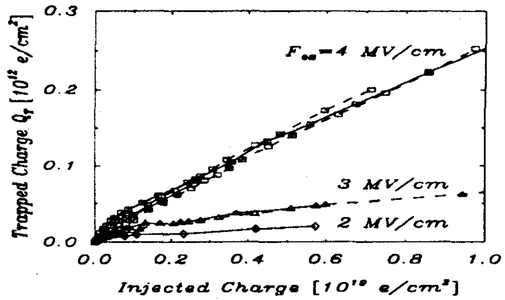

Fig.2 Equivalent charge trapped at the interface (Q_T) versus injected charge density (Q_{inj}).

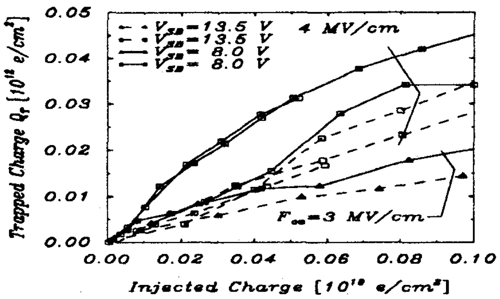

Fig.3 Expanded view of the data in Fig.2.

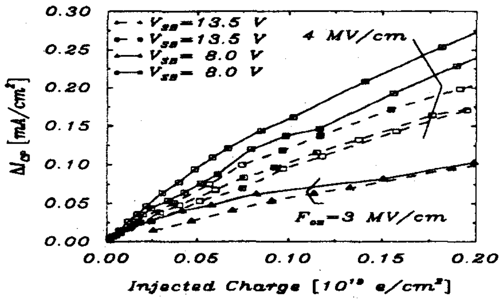

Fig.4 Charge pumping current shift (ΔI_{CP}) for small values of the injected charge.

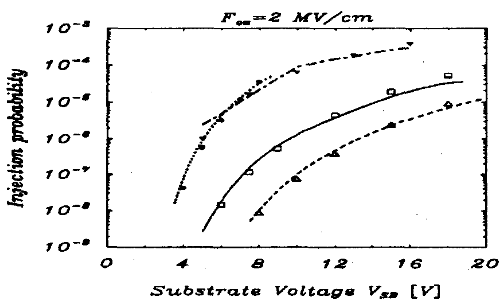

Fig.5 Injection probability as a function of V_{SB} for four different doping profiles. Lines: measurements; points: simulations. Experiments of this work (dash-dotted line); data from [1] (solid, dashed and dotted lines). Similarly good agreement between measured and modelled data was found up to $F_{ox} = 4MV/cm$.

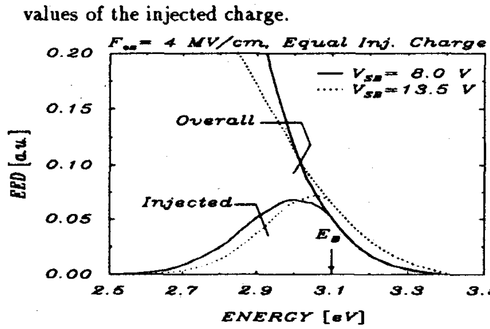

Fig.6 Injected and overall electron energy distributions for two different V_{SB}. The curves are normalized to reflect a condition of equal injected charge, i.e. the area below the distributions of injected electrons are equal. Injection below 3.1 eV is modelled by tunneling.

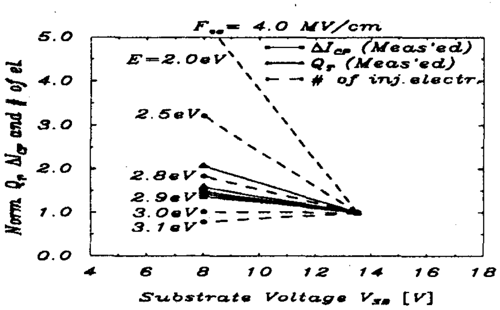

Fig.7 Normalized trapped charge (△) and surface states density (□) measured for small values of Q_{inj} versus V_{SB}. •) Normalized number of electrons injected towards the gate from different energy levels.

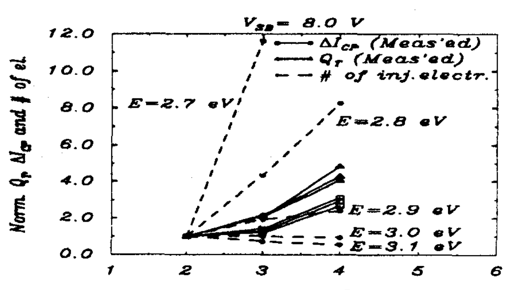

Fig.8 Normalized trapped charge (△) and surface states density (□) measured for small values of Q_{inj} versus F_{ox}. •) Normalized number of electrons injected towards the gate from different energy levels.