

Interface state degradation of metal/ ultra-thin oxide/semiconductor structures under electron injections at high field

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In this paper we analyze the interface state of the metal/ ultra thin oxide/ semiconductor structures and their degradation under an electrons injection from the metal or the semiconductor, by Fowler-Nordheim effect, at high electric field (> 10 MV/ cm). The metal used is chromium and the oxide layer thickness is in the range of 60\AA - 130\AA . Before injection the energy distribution of the interface state in the semiconductor gap present a peak of energy of 0.25eV above the semiconductor valence band edge. The peak density (N_{ssmax}) decreases with the oxide thickness. After injection the degradation of the N_{ssmax} density depends on the oxide thickness, and increases with injected charge independently on the injected field and the polarization mode ($V<0$, $V>0$) of the structure for the high injected charge ($Q_{inj} > 2 \cdot 10^{-1} \text{ c/cm}^2$). The injection influence on the interface state density (N_{ssmid}) at mid gap is not important. The N_{ssmid} density is lower than $10^{10} \text{ eV}^{-1}\text{cm}^{-2}$ for all the injection charges ($V<0$, $V>0$). Also, we showed that the sensitivity to the degradation by electrons injection decreases with the oxide thickness. In comparing with the literature results we deduced a lower interface state density on our structures, and a satisfactory sensitivity to the degradation to high injecting fields.

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I- Introduction

The design and the optimization of the field effect transistors (MOS, MOSFET,...)[1-4] on the silicon requires a perfect restraint and an excellent reproducibility in time of the threshold voltage and of the transconductance. These two parameters are essentially controlled by the quality of the oxide (SiO_2)/semiconductor(Si) interface; all defect electrically active (interface state) modifies the static and dynamic behavior of the devices. The carriers of the channel can communicate with the sites of the interface states. Their mobility is then decreased, as well as the transconductance of the transistor. By elsewhere, the interface state degrade the other semiconductor device performances for example the EEPROM memories, RAM[5,6], ...

Currently, a lot of studies are devoted to decrease the interface state density as lower possible [7-9]. So, it is necessary to know their density, their energy distribution in the semiconductor gap and analyze their degradation by carriers or constant current injection [10]. Under these electrical stress influences, we observe the degradation of the oxide/semiconductor interface [11,12]. In the literature, most of the studies concerning the oxide/ semiconductor interface degradation were made on the metal/ oxide/semiconductor structures having the oxide layer relatively thick ($> 150 \text{\AA}$). While, few results concern the degradation of the oxide layers thinner than the hundred of Angstroms and in particular at high fields injection (>10 MV/cm).

In this work, in order to have a good understanding of the ultra thin oxide/ semiconductor interface behavior of the metal/ ultra thin oxide/ semiconductor structures where the thickness is lower than the hundred of Angstroms, we analyze from capacitance-voltage measurements the energy distribution of the interface state as well as the degradation of their density by injected electrons at high field (>10 MV/cm) from the metal or the semiconductor.

II- Experimental procedures

The samples are capacitors on P-type silicon wafers, $\langle 100 \rangle$ oriented, with a doping level $1\text{-}3 \times 10^{15} \text{ cm}^{-3}$. The substrates are prepared by a standard procedure [13] including the growth of a sacrificial oxide of 3500\AA thickness followed by an attack and a cleaning in a bath (HF/Ethanol) [14]. The growth of oxide, D_{ox} thickness, is obtained in a chlorinated atmosphere diluted in Nitrogen at 900°C , followed by an annealing at 1050°C in nitrogen [15]. A chromium gate contact (area $S = 10^{-4} \text{ cm}^2$) is then deposited, photoetched and annealed at 450°C in "Forming Gas".

The tests are carried out using the capacitance-voltage $C(V)$ measurements (at high (1MHz) and low (1kHz) frequencies), and the voltage (V) measurements at constant current injection [10,16]. The currents are injected in direct ($V<0$) and in inverse ($V>0$) modes without reaching the breakdown [10,17] of the structures. The electrical field corresponding to the current injection varies from 10 MV/cm to 12 MV/cm . These measurements enable us to obtain the thickness of the oxide layer (D_{ox}), the doping concentration of silicon and the interface state density (N_{ss}) according to their energies ($E-E_v$) in the semiconductor gap above the valence band edge (E_v).

The capacitance versus voltage $C(V)$ was measured using an impedance analyzer HP4192A (Hewlett-packard). The constant current injection measurements were taken using an HP4145A semiconductor parameter analyzer in the fast sampling mode.

III- Results & discussion

III-1- Interface state before the electron injection

($Q_{inj} (\text{c/cm}^2) = 0$)

Figure 1 (curves corresponding to $Q_{inj} (\text{c/cm}^2) = 0$) shows the typical N_{ss} density according to the energy distribution of the interface state in the semiconductor gap. It appears an energy

distribution of the interface state which are of acceptor type. The maximal density N_{ssmax} (peak) is located around the energy of 0.25 eV above E_v . We have verified that this energy peak is independent of the oxide layer thickness.

In the literature, the analysis of the energy distribution of the interface states shows one peak of $E_v + 0.75$ eV in the case of the thick oxide (500 Å) [18], and two peaks of respectively $E_v + 0.18$ eV and $E_v + 0.52$ eV in the case of thinner oxide layers (20-40 Å) [19]. In the last case S. Kar *et al* [19] showed that the position of the energy peaks depends on the nature of the metal, and their densities (N_{ssmax}) increase with the decrease of the oxide layer thickness.

Figure 2 shows, as a function of the oxide thickness, the densities N_{ssmax} and N_{ssmid} which correspond to the interface state density at mid gap. We notice that the N_{ssmax} density decreases with the oxide thickness in preserving a reasonable value particularly for the thinnest oxides. The N_{ssmid} density is in order of $1.7 \times 10^{10} \text{ eV}^{-1} \text{ cm}^{-2}$ for oxide thickness of 65 Å; above 65 Å N_{ssmid} is lower than $10^{10} \text{ eV}^{-1} \text{ cm}^{-2}$. These different values were confirmed in reference [20]. Concerning the interface state density, we generally find in the literature the density of states corresponding to the semiconductor mid gap. It is

acquired that this value is approximately independent of the fabrication conditions of the devices. It was found nevertheless that the interface state density was more important in the case of thinner oxide layers (20 Å-40 Å) [19].

The results found on our structures confirm the literature observations and allow to make the comparison between the layer thicknesses lower and greater than 100 Å: the interface state density decreases with the oxide layer thickness until 100 Å, over 100 Å it appears constant. In addition, our N_{ssmax} and N_{ssmid} values are ten times lower than those reported in the literature in the case of the polysilicon gates [23-25].

III-2- Interface state degradation by the electron injection

Figure 1 shows the typical evolution of the spectral interface state for the both metal and semiconductor injection modes as a function of the injected charges. It appears that the density of the interface states depends on the injection mode of electrons and on the injected charges. The injected charge influence is more pronounced on the states which have energies near the peak ($E_v + 0.25$ eV). In the case of electron injection by the semiconductor, the interface state density increases with the injected charge. On the other hand during the electron injection by the metal, the density of the interface state first decreases and then increases with the injected charges. Also on all the structures, the energy corresponding to the peak is relatively independent on the injected charges and on the oxide layer thicknesses. In the literature, opposite results are obtained by Y. Nishioka

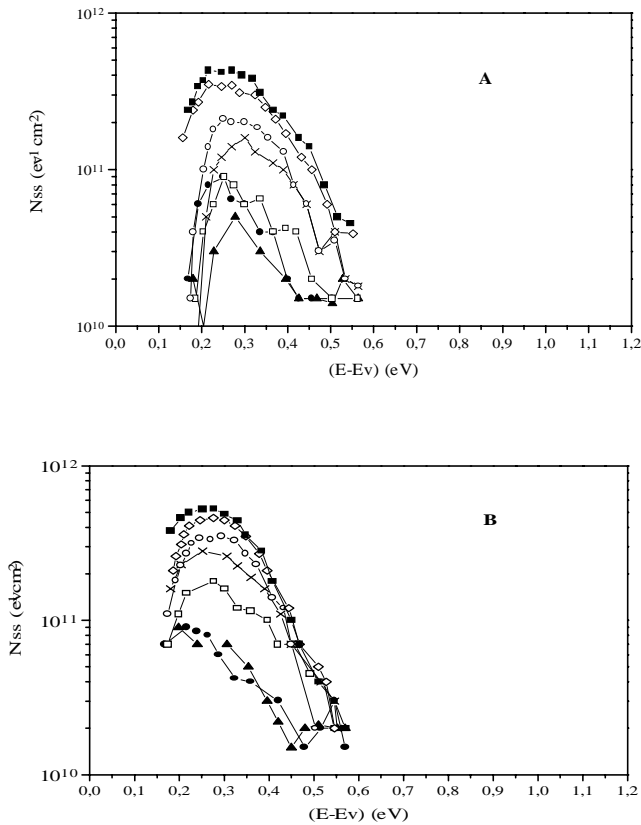


Figure 1 : Typical energy distribution of an interface state under an electron injection in the case of oxide field of order of 11.2 MV/cm. $D_{ox} = 125 \text{ Å}$.

(A) Injection by the metal : $Q_{inj} (\text{C/cm}^2)$: (•) 0, (▲) 8×10^{-3} , (◊) 2.8×10^{-2} , (x) 6.8×10^{-2} , (o) 2.88×10^{-1} , (◇) 4.88×10^{-1} , (◻) 8.88×10^{-1} .

(B) Injection by the semiconductor : $Q_{inj} (\text{C/cm}^2)$: (•) 0, (▲) 2.0×10^{-2} , (◊) 6.0×10^{-2} , (x) 1.4×10^{-1} , (o) 3.4×10^{-1} , (◇) 7.4×10^{-1} , (◻) 11.0×10^{-1} .

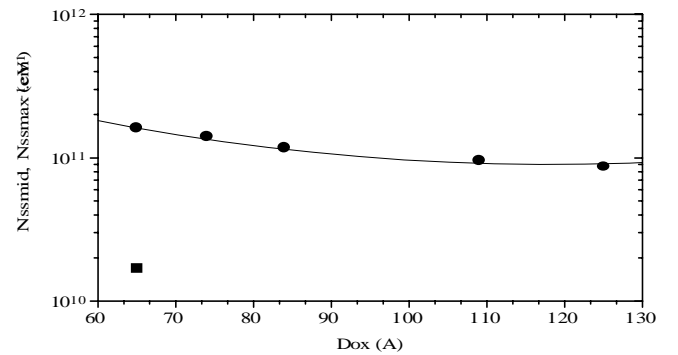


Figure 2 : Oxide thickness influence on the interface state density,

N_{ssmid} (■): semiconductor mid gap,

N_{ssmax} (•): peak of the interface states distribution.

et al [18] on the thick oxides (500 Å) where the metal is aluminum. These authors [18] show that the interface state depend on the mode of electrons injection: during the injection by the metal the density of interface states increases, during the

injection by the semiconductor the density of interface state corresponding to the peak of $E_v + 0.75 \text{ eV}$ decreases and the one corresponding to the peak $E_v + 0.35 \text{ eV}$ increases.

On figure 3 we represent the typical Nssmax plot as a function of the injected charges for the two injection modes. Concerning the energy states corresponding to the semiconductor mid gap the influence on their Nssmid density is not important, the Nssmid is lower than 10^{10} eV⁻¹cm⁻² for all oxide thicknesses.

From figure 3, we observe that Nssmax density does not depend on the field and varies with the injected charges (Qinj) following the expression: $N_{ssmax} = \beta Q_{inj}^\alpha$ -

1- Where, β , α : are constants which depend on the technological process [11],

During the electron injection by the semiconductor, Nssmax increases with the injected charges from an injected charge of the order of 10^{-2} c/cm².

For the charges injected lower than 10^{-2} c/cm², the injection influence is negligible. On the other hand, during the electrons injection by the metal, it appears:

- a reduction of Nssmax for the charges lower than 10^{-2} c/cm²,
- an important increase of Nssmax with the charges injected for the charges between 10^{-2} c/cm² and 2×10^{-2} c/cm²,
- for the charges greater than 2×10^{-1} c/cm², the interface states creation follows the expression -1- and does not depend on the injection mode.

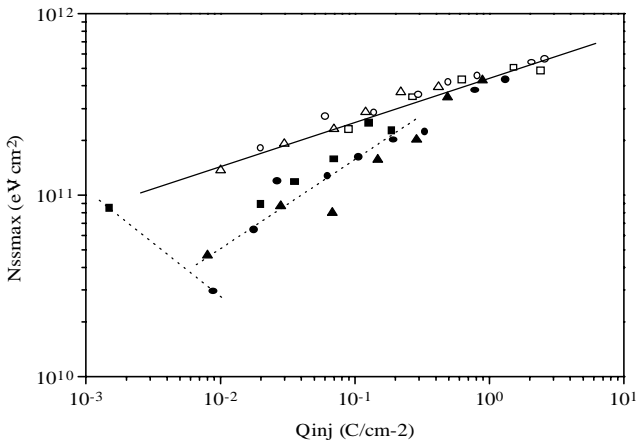


Figure 3 : Variation of Nssmax with the injected charges and fields in the oxide. Dox= 125Å.

Injection by the metal, oxide field (MV/cm): (▲) 10.50 , (●) 11.00, (■) 11.20,
Injection by the semiconductor, oxide field (MV/cm): (○) 10.50, (Δ) 11.00, (□) 11.20

Figure 4 shows the values of the exponent α with respect to the oxide thickness. For the electron injection by the metal we represent the values obtained at high injected charges ($> 2 \times 10^{-1}$ c/cm²). It appears that Nssmax is not dependent on the injection mode and the exponent α decreases with the oxide thickness. This shows that the sensitivity to the current injection increases with the reduction of the oxide thickness. Therefore, the degradation of the ultra thin oxide/semiconductor interface is more pronounced when the oxide layer thickness decreases.

N. YASUDA *et al* [12] used MOSFET transistors for their experiment. The oxide thickness was 200Å and the gate was in

polysilicon, the electrons were injected by the semiconductor for fields equal to 7 MV/cm. From Nssmid plotted with respect to the injected charges, they show that the exponent α is equal to 1. In other works for the structures with polysilicon gates, S. Horiguchi *et al* [26] showed that the creation of the interface state is independent on the bias mode and on the field for the thicknesses lower than 100Å. Plossu *et al* [11] by injecting constant currents at high field on the structures having the oxide thickness in order of 100Å showed that the exponent α does not depend on the injection mode and equals to 0.75 and 0.25 for the aluminum and polysilicon gates.

These respectively different results show the dependence of the interface state creation with the oxide thickness and the nature of the gate.

By comparing these results with ours where the gate is in chromium we can deduce that for this last case the creation of interface state depends only on the injected charge, it is independent on the field and on injection mode for high injected charge. Concerning the sensitivity of the interface state creation with the injected charge for oxide thicknesses of the order of 100 Å, the gate in chromium is less sensitive (low value of α) than the gate in aluminum and have the same

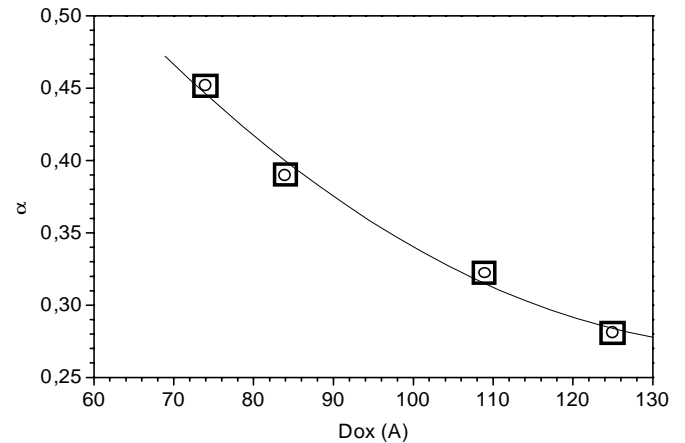


Figure 4 : Variation of exponent α with respect to the oxide thickness and the injection.

(□) Injection by the metal,
(○) Injection by the semiconductor.

sensitivity as the gate in polysilicon. Also, the interface state creation on the structures having thin oxide and gate in chromium is less sensitive to the injected charge than the case of the structures having thick oxide layers and gate in polysilicon.

Consequently, these results show the resistance of our structure to the degradation under current injection at high field. We may generally conclude that the technological process presented in this paper offers satisfactory performances.

III- Conclusion

The energy distribution of interface state in the semiconductor gap shows a peak which has an energy of 0.25 eV above the

valence band edge, and does not depend on the oxide thickness. The N_{ssmax} density corresponding to this peak decreases with oxide thickness down to 100Å, over 100Å it remains constant. N_{ssmid} in the semiconductor mid gap is lower than $10^{10} \text{ eV}^{-1}\text{cm}^{-2}$ on all the structures. The values of N_{ssmax} and N_{ssmid} are ten times lower than that found in the literature. The analysis of the interface state degradation at high field shows that the energy of the peak is independent on the injection charges and that the injection influence is negligible on N_{ssmid} . Also, N_{ssmax} increases with the injected charges in proportion with Q_{inj}^α (where: Q_{inj} is the injected charges and α is an exponent), and it is independent on injection mode for the high injected charges. In injecting the electrons by the metal, the interface state density decreases at the beginning of the injection charges ($Q_{inj} < 10^{-1} \text{ C/cm}^2$).

For the electron injection by the semiconductor and by the metal at high injected charges the value of α decreases with the oxide thickness. This result shows that the ultra thin oxide/ semiconductor interface is much sensitive to the degradation under injection when the oxide thickness decreases.

By comparing with the literature results we deduced a satisfactory performance on our structures. This allows us to conclude a good performance of the technological process.

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V- Bibliographies

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