Hydrogen as Source of High-Temperature Charge Instability in the Buried Oxide of SOI Structures and MOSFETs

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1. Introduction

The nature and mechanisms of high-temperature charge instability (HTCI) in gate dielectrics such as negative bias thermal instability (NBTI) and positive bias thermal instability (PBTI) are still widely debated in the literature [1]. In SOI FD MOSFETs the HTCI in the buried oxide (BOX) can play a significant role that results in the threshold voltage variations when devices are operated at high temperature. This paper is devoted to a comprehensive analysis of the HTCI in the SOI structures and FD MOSFETs fabricated on UNIBOND SOI wafers, and the demonstration of the charge generation, charge transport and neutralization in the BOX and of their link with the presence of hydrogen.

2. Experimental

FD inversion-mode (IM) SOI n-MOSFETs and n-type capacitors have been fabricated using UNIBOND material, in the same chip with identical CMOS process sequence. The thickness of the BOX, silicon layer and gate oxide were 400, 80 and 35 nm, respectively. In addition, other capacitors were made using a simplified process sequence on some starting UNIBOND wafers.
The drain current *vs.* back gate voltage $I_D(V_{BG})$, the drain current *vs.* measurement time $I_D(t)$ after different applied gate voltages have been measured on FD SOI MOSFETs in the 20^0C-320^0C temperature range. Besides, the dynamic currents through the BOX of CMOS capacitor $\Delta I(V_{BG})$ were studied. Thermally stimulated polarization/depolarization (TSP/TSD) currents with linear heating in the same temperature range on the silicon layer/BOX/silicon substrate capacitor structures were measured.

3. Results and discussion

3.1. Generation of HTCI

The HTCI in buried oxide was created by applying a negative voltage to the substrate of the SOI structure or SOI MOSFET at temperature higher than 200^0C. Under such conditions, a current peak was generated in the dynamic ΔIV_{BG} current through the BOX (Fig.1a). The peaks' amplitude increases with the increase of the hold time and measurement temperature. Analysis of the ΔIV_{BG} characteristics associates the observed current peaks to the transport of positive charges through the BOX. Using the dependence of the generated charge (calculated from the area under the current peak) on the hold time and hold temperature, an activation energy of the generation process can been estimated. The results show that, for UNIBOND SOI wafers, this process is not monoenergetic, and the activation energies range from 0.9 to 1.5eV. The generation of the current peak in the ΔIV_{BG} characteristics is completely correlated with the appearance of a drain current jump near zero V_{BG} in the $I_D(V_{BG})$ characteristics after negative bias has been applied to the substrate (Fig.1 b).

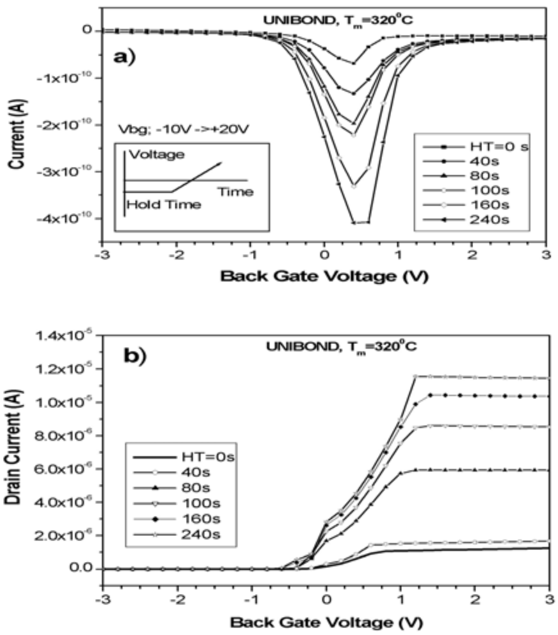

Fig.1: *(a) ΔIV_{BG} characteristics and (b) (I_DV_{BG}) characteristics for applied V_{BG}=-10V with different hold times.*

Measurements made using the TSD/TSP method shown that the application of a negative voltage to the substrate of the virgin SOI structure results in the formation of wide current spectra in temperature range of 150 to 350^{0}C (Fig.2, curve 2) corresponding to negative charge transport from the BOX/substrate interface to the BOX/Si film interface. The activation energies of that process range from 0.8 to 1.2 eV. It should be noted that after such a polarization sequence, subsequent temperature heating with positive bias on the substrate results in the appearance of a low-temperature current peak that occurs at 60^{0}C (Fig.2, curve 3) and an activation energy of approximately 0.3 eV. Thus, we can conclude that the high-temperature generation of mobile positive charges that are located near the BOX/substrate interface under negative substrate bias can proceed with electron injection and have activation energy from 0.9 to 1.5 eV.

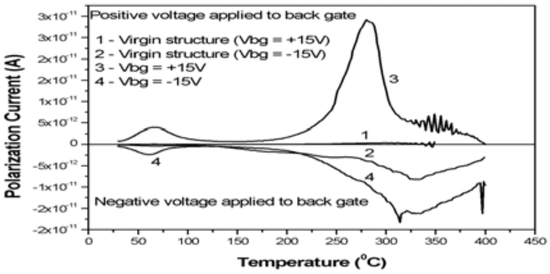

Fig.2: *Thermally-stimulated polarization (V_{BG}=-15V, spectra 2,4) and depolarization (V_{BG}=+15V, spectrum 3) currents in the SOI UNIBOND structure.*

3.2. Positive charge transport

Using of ΔIV_{BG} characteristics allows us to determine the diffusion coefficient, D, of the positive charge transport inside of the BOX after it generation. It has been shown that D can be written in the following form

$$D = 4x10^{-4}exp(-0.55/kT) \quad (cm^2/s)$$

and corresponds to proton transport more than other ion transport (such as Na^+, K^+) [2].

The peak observed at low-temperature TSD corresponds to mobile positive charges with an activation energy near 0.3 eV and is also probably associated with proton transport in the BOX. The decreased activation energy (compared with the results obtained from the ΔIV_{BG} measurement) can be linked to the higher electric field applied to the BOX during the TSD/TSP measurement. Thus, the process of proton generation can be described by the following reaction [3]

$$O_3\equiv \text{Si–H H–Si}\equiv O_3 \longrightarrow O_3\equiv \text{Si–H–Si}\equiv O_3 + e^{(-)} + H^+ + 0.9\ \text{eV}$$

where the energy needed for the reaction is very similar to that obtained from our experiments, and the energy distribution can be associated with the spatial separation of Si-H bonds at the BOX/substrate interface.

3.3. Charge neutralization

If a positive voltage is applied to the substrate at high temperature (above 200^{0}C) after generation of mobile protons, a decrease of the drain current jump in the $I_D(V_{BG})$ characteristics is observed (Fig.3). This effect is evidence of neutralization of the generated mobile positive charge.

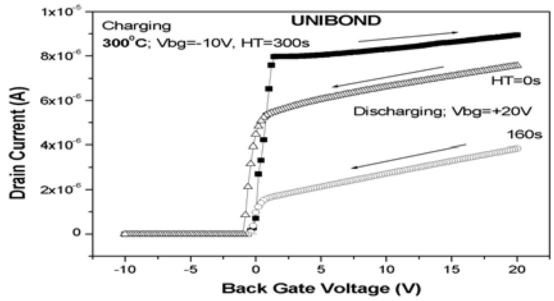

Fig.3: *Transformation of $I_D(V_{BG})$ characteristics after reversing the voltage sweep direction.*

To study the neutralization process the $I_D(t)$ characteristics at high temperature after switching of the substrate voltage from negative to positive have been investigated. It was shown that an increase of positive back-gate voltage increases the relaxation time of the positive charge neutralization (Fig.4a), that corresponds to a decrease of capture probability for the electrons injected into the BOX from the Si film by positively-charged hydrogen centers. The temperature dependence of time relaxation reveals an activation energy of approximately 1.0 eV. Such a temperature dependence is probably associated with a potential barrier which electrons have to overcome for being injected into the BOX from the back inversion channel, and TSD currents that present a peak at 300^{0}C can be explained by this electron injection process (Fig.2).

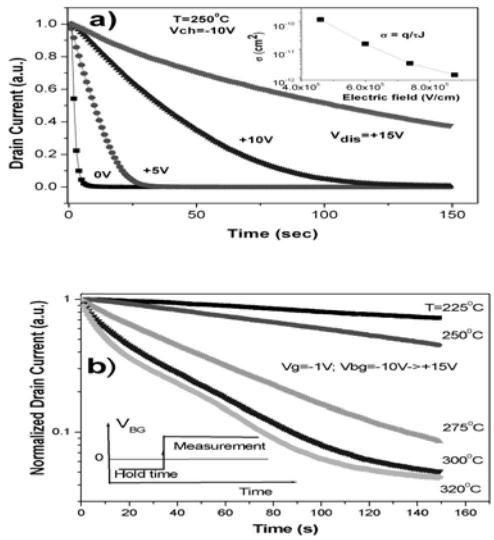

Fig.4: *Dependence of drain current relaxation (a) when applying a discharging voltage to the substrate, and (b) varying measurement temperature.*

References

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