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T.M. Nazarova[1], V.S. Lysenko[2], A.N. Nazarov[2], V.M. Tomashik[2], D. Flandre[3]

Hydrogen as a Source of High-Temperature Charge Instability in Silicon-on-Insulator Structures and Field Effect Transistors

[1]National Technical University "KPI", Prospekt Peremogy 37, 03056 Kyiv, Ukraine
[2]Institute of Semiconductor Physics, NASU, Prospekt Nauki 45, 03028, Kyiv, Ukraine
[3]Microelectonics Lab. (DICE), Universite Catholique de Louvaine,
Place du Levant, 3, Louvain-la-Neuve, 1348, Belgium

Study of the high-temperature charge instability (HTCI) phenomenon in the buried oxide (BOX) of Silicon-On-Insulator (SOI) fully depleted (FD) inversion mode (IM) n-MOSFETs and high-temperature dynamic currents in capacitors, fabricated in silicon implanted by oxygen (SIMOX) and silicon bonded with dioxide silicon (UNIBOND) materials with similar CMOS process sequence, is performed. It was shown, that nature of the HTCI process is associated with protons generation in imperfect region near the BOX/ silicon substrate interface at temperature above 200^0C. Activation energy for protons generation process is obtained (1.2 eV for SIMOX and from 0.9 to 1.5 eV for UNIBOND material), and the diffusion coefficient for the proton movement in the BOX is calculated ($D = 4x10^{-4}exp(-0.55/kT)$, cm^2/s).

Key words: protons, buried oxide, silicon-on-insulator, high-temperature charge instability

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Introduction

In papers [1 - 3] the high-temperature charge instability (HTCI) effect in buried oxide (BOX) of MOS field-effect transistors (MOSFETs) fabricated in silicon-on insulator (SOI) structures obtained by oxygen ion implantation in silicon (SIMOX) technique [4] has been observed. This effect consists in the creation of a drain current jump after a negative voltage has been applied to the substrate at temperature above 200^0C. Some suggestions have been proposed to explain such phenomenon [2, 3], however up to now the exact origin of this effect is still under speculation. In this paper we show, that the HTCI is also observed in MOSFETs, fabricated on basis of UNIBOND SOI material [4], and we present a number of evidences that the phenomenon is associated with proton generation near the BOX/silicon substrate interface in conditions of high temperature and electric field.

I. Experimental

Fully depleted (FD) inversion mode (IM) SOI n-MOSFETs have been fabricated in standard single implanted (SI) SIMOX and UNIBOND materials with similar CMOS process sequence. In the same chip, n-type capacitor has also been fabricated. The thickness of the BOX, the silicon layer and the gate oxide were 400, 80 and 35 nm, respectively.

The source-drain current of the MOSFETs and dynamic current through the BOX of the capacitors [5, 6] as a function of the back-gate voltage (I_DV_{BG} and DIV_{BG}, correspondingly) have been measured in the temperature range from 20 to 320 ^{0}C. In Figure 1 a schematic representation of the measurement circuits of the using devices are depicted. The negative front gate voltage ($V_G = -1V$) was applied to avoid the charge coupling effect between potentials at front and back silicon film/dielectric interfaces.

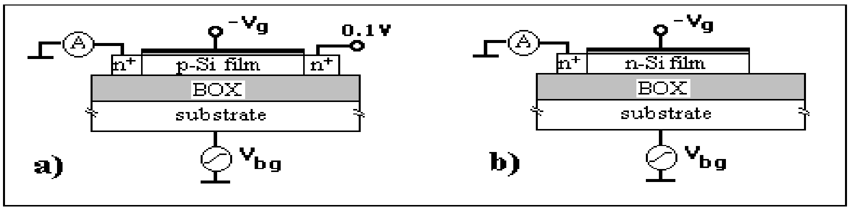


Fig. 1. Schematic presentation of SOI IM n-MOSFET (a) and capacitor (b) using for measurements in this paper.

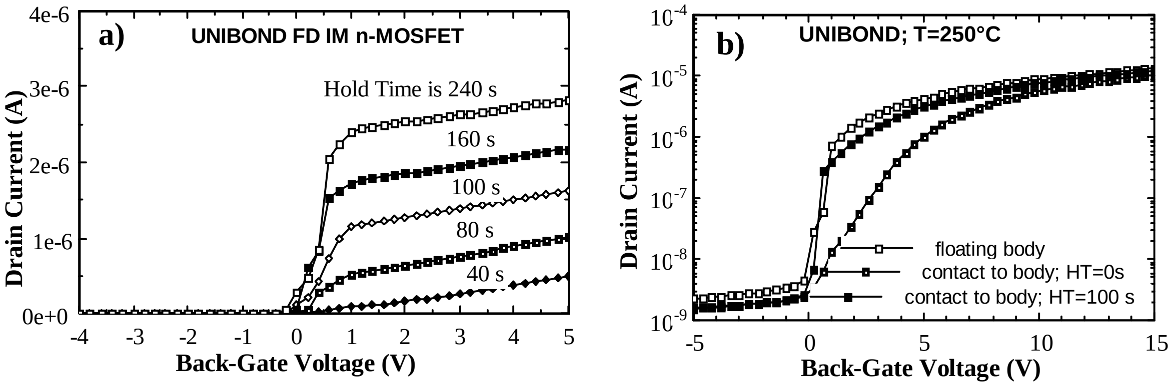


Fig. 2. Drain current vs. back-gate voltage of UNIBOND SOI FD n-MOSFETs as a function of hold time at –10 V (a) applied to substrate at temperature 280 ^{0}C and for floating body and contact to silicon film (b) measured at 250 ^{0}C (back gate voltage changes from –10 V to +20 V).

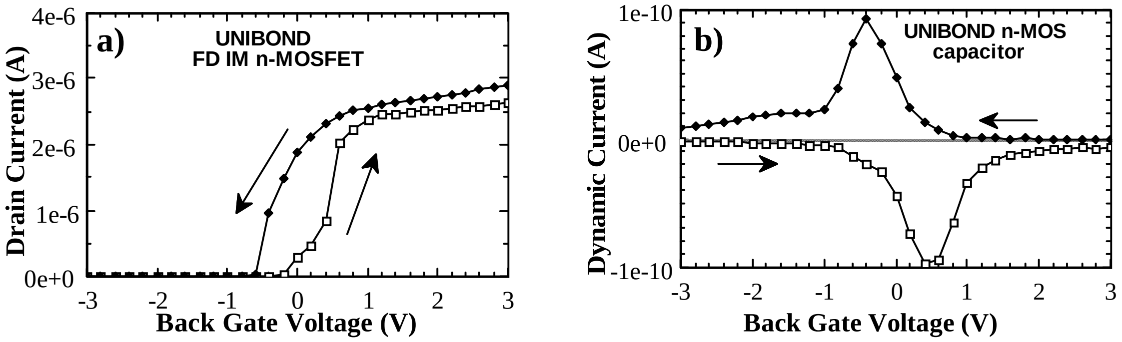


Fig. 3. I_dV_{bg} (a) and dynamic IV_{bg} (b) characteristics measured at back-gate voltage changing from –10 V to +20 V and back at 280 ^{0}C.

II. Results and discussion

High-temperature back-gate charge instability in SOI n-MOSFETs and the BOX of capacitors

When a negative voltage at temperature above 200^{0}C is applied to the substrate of the SOI FD IM n-MOSFET fabricated both in SIMOX and UNIBOND wafers, holds some time and changes towards a positive voltage a significant drain current “jump” near zero volt is observed. Increase of hold time at negative voltage results in increase of the current “jump” (Figure 2a). The observed phenomenon is not abolished by grounding of the silicon film (Figure 2b), that attests the charge processes in the BOX can play considerably role in the arising instability, but not floating body effects.

It should be noted that a origin of the drain current “jump” in the I_DV_{BG} characteristic correlates with creation of the dynamic current peak in the DIV_{BG} (Figure 3). It is well known that creation of current peaks at high temperature in dynamic current-voltage characteristic of MOS capacitor is associated with ion movement inside of the dielectric [5, 6]. Furthermore the observed hysteresis of the subthreshold region of the MOSFET’s I_DV_{BG} characteristic and current peak in the dynamic IV_{BG} (see Figure 4) corresponds to positively charged ion movement through the BOX.

Increase of the hold time of the negative voltage applied to the substrate results in an increase of the ion current peak amplitude in the DIV_{BG} characteristic (Figure 4a) similar way as the drain current “jump” in the SOI MOSFET’s I_DV_{BG} characteristic (Figure 2a). Accumulated positive charge, calculated from the drain current “jump” of the I_DV_{BG} characteristics (as that was suggested in [2]), and ion moving charge, calculated from the dynamic current peak square, possesses sufficient good correlation (Figure 4b).

Thus, we can conclude that the positively charged ions generated in the BOX at high temperature are mainly responsible for the drain current “jump” in the I_DV_{BG} characteristics of the SOI MOSFETs. The negative bias applied to the substrate during the generation of the moving positive charge testifies that the phenomenon occurs near the BOX/substrate interface, which is a most imperfect location both in SIMOX and UNIBOND materials [7].

Determination of the moving charge parameters

At temperature above 200^{0}C a maximum of the current peak in the dynamic IV_{BG} characteristics occurs at voltage whose value only slightly depends on measurement temperature. Thus, in these conditions the ion diffusion process in the BOX can be described by so-called equilibrium model [5], in which the ion distribution is determined by inner and outer electric fields, and trapping in the volume and the interfaces of

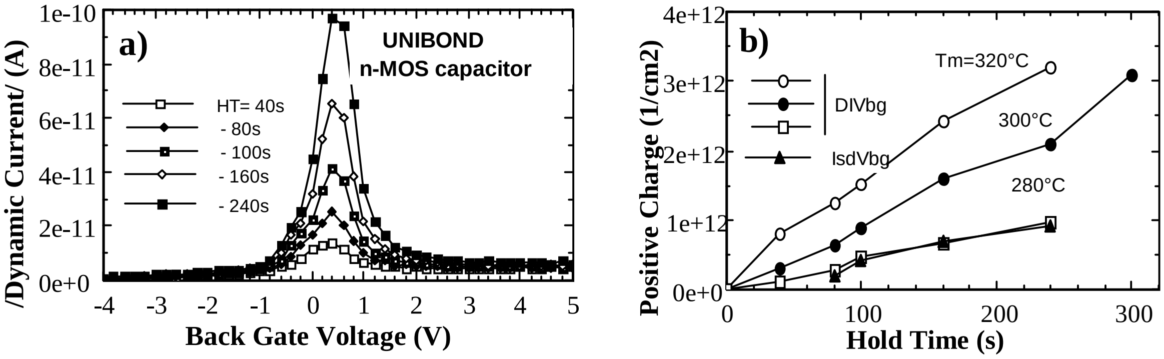


Fig. 4. Dynamic IV_{bg} characteristics of SOI capacitor as a function of hold time at –10V applied to the substrate (a) and charge determined from square under dynamic current curve and from drain current "jump" vs. hold time at –10V as a function of measurement temperature.

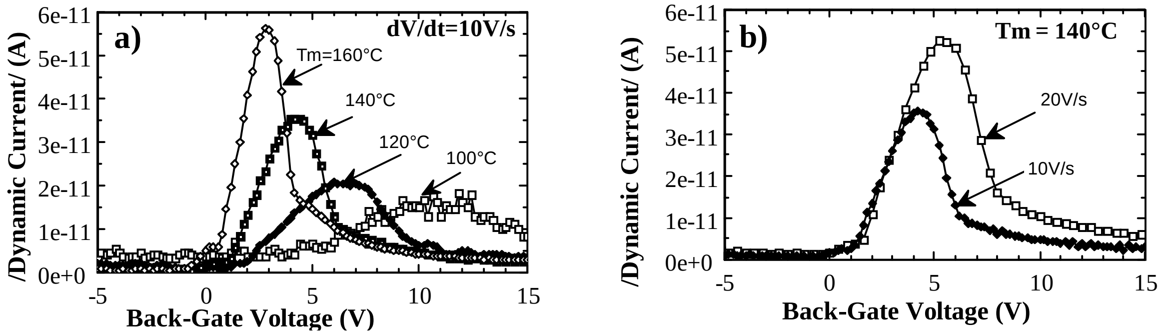


Fig. 5. Dynamic IV_{bg} characteristics measured at different temperatures (a) and back-gate voltage scan speeds (b) of the SOI capacitor. The back-gate voltage is changed from –10V to +20V.

the BOX is neglected. In this case the parameters of the diffusion process are not possible to determine. However the positively charged moving ions after generation can be remain in the BOX at low temperature (up to 50^0C) for quite long time. At these conditions the considerable shift of maximum of the current peak in the dynamic IV_{BG} characteristics measured at different temperatures and back-gate voltage scan speeds is observed (Figure 5).

The mobility of the ions, m, and their diffusion coefficient, D, can be calculated from expressions [6]:

$$m = 2d^2 a /(V_m^2), \qquad (1a)$$

and $$D = (kT/q)\ m, \qquad (1b)$$

where d is the BOX thickness, a is the back-gate voltage scan speed, V_m is the voltage at which the current maximum is observed, other quantities have their common meaning. Under deriving of the Eq. (1a) it was suggested that the current peak has a maximum when the ions pass through dielectric and reach the opposite interface. From data presented in Figure 6(a) dependences of the ion mobility and the diffusion coefficient versus temperature have been calculated:

$$m = 1.3\text{x}10^{-2}\exp(-0.55/kT),\ cm^2/V\ s \qquad (2a)$$

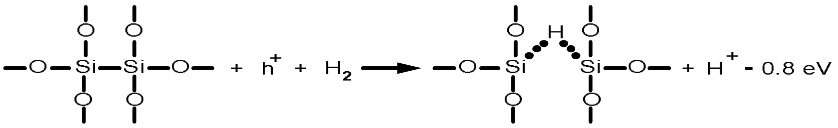
$$D = 4\text{x}10^{-4}\exp(-0.55/kT),\ cm^2/s. \qquad (2b)$$

Obtained activation energy, $E_A = 0.55$ eV, is slightly below than that for proton diffusion in the BOX of SOI structures ($E_A = 0.78$ eV [8]), which was annealed in hydrogen at high temperature (near 700 ^{0}C). However, firstly, the activation energy for proton diffusion in SiO_2 it was obtained to possess a values in wide range (from 0.3 to 1.2 eV) [8 - 10] and depends on the method of measurements; secondly, recalculation of the diffusion coefficient for 700 ^{0}C, using our value obtained from Eq.(2b), gives us the amount equals to 5.4 x 10^{-7} cm^2/s, which is in good accordance with those measured for proton diffusion coefficient in SIMOX BOX [11]. Diffusion coefficient for sodium ions, which often occurs in dioxides, at 140 ^{0}C is about 1x10^{-15} cm^2/s [12], that is considerable lower than for our case (6 x 10^{-11} cm^2/s). Thus, we can conclude that protons are probably responsible for the observed HTCI effect.

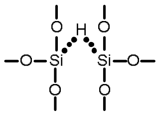
Mechanism of positive charge generation

As it was described above the positive moving ions (protons) are generated in the BOX near the BOX/substrate interface at high temperature under negative bias applied to the substrate. The activation energy of this positive charge generation, E_A^g, can be calculated from increase of value of the drain current "jump" versus hold time and temperature of measurement, as it was proposed in paper [2]. In case of the SIMOX wafers it was shown, that E_A^g = 1.2 eV [2]. For the UNIBOND wafer the calculation demonstrates the distributed value for E_A^g from 0 9 to 1.5 eV.

In papers [13, 14] simulations using of the first-principles density functional theory demonstrated that protons are effectively generated by following reaction



(3)

Thus, interaction of H_2 molecules which can be introduced in the BOX during technological processes with oxygen vacancy defects in dioxide results in creation of proton and hydrogen bridges (). This reaction progresses with uptake of energy equal to 0.8 eV, that is closed to those obtained from our experiment. Different local inviroment have to lead to changing of the energy in frame of ± 0.2 eV [14].

Presence of the oxygen vacancy defects near the BOX/substrate interface in SIMOX wafers is confirmed by EPR experiments [15]. Also, for SIMOX and UNIBOND wafers an existence of silicon enriched region near the BOX/substrate interface was found by our SIMS measurements [16]. The last attests the oxygen vacancy defect location in region near the BOX/substrate interface, where we observe the positive moving ions generation. Thus, protons can be generated at high temperature in silicon enriched region of the BOX of SOI structures that result in creation of observed HTCI phenomena in SOI MOSFETs.

Conclusions

It was shown that high-temperature charge instability in SOI structure and fully depleted SOI MOSFETs at applied voltage to silicon substrate is associated with proton generation on oxygen vacancy defects in the BOX located near the BOX/ silicon substrate interface. Activation energy for the proton generation was determined for SIMOX and UNIBOND SOI materials and accounted 1.2 eV for SIMOX and from 0.9 to 1.5 eV for UNIBOND materials. Diffusion coefficient versus temperature calculated from dynamic current-voltage characteristic of the SOI UNIBOND capacitor accounted $D = 4x10^{-4} \exp(-0.55/kT)$, cm^2/s.

Назарова Т.М. – старший викладач кафедри загальної та неорганічної хімії Національного технічного університету України «КПІ»;
Лисенко В.С. – завідувач відділом, чл.-кор. НАН України, Інститут фізики напівпровідників ім. В.Є. Лашкарьова НАН України;
Назаров О.М. – провідний науковий співробітник, доктор ф.-м.н., професор, Інститут фізики напівпровідників ім. В.Є. Лашкарьова НАН України;
Томашик В.М. – завідувач відділом, доктор хім. н., професор, Інститут фізики напівпровідників ім. В.Є. Лашкарьова НАН України;
Flandre Denis – professor, head of the Microelectronics Laboratory (DICE) of Université catholique de Louvain.

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Т.М. Назарова[1], В.С. Лисенко[2], О.М. Назаров[2], В.М. Томашик[2], Д. Фландре[3]

Водень як джерело високотемпературної нестабільності заряду в структурах кремній-на-ізоляторі та польових транзисторах

[1]Національний технічний університет "КПІ", пр. Перемоги, 37, Київ, 03056 Україна
[2]Інститут фізики напівпровідників НАН України, пр. Науки, 45, Київ, 03028, Україна
[3]Microelectonics Lab. (DICE), Universite Catholique de Louvaine,
Place du Levant, 3, Louvain-la-Neuve, 1348, Belgium

Досліджено явище високотемпературної нестабільності заряду в приповерхневому оксиді *n*-МОН структури з повністю виснаженою інверсною модою в кремнії-на-ізоляторі та високотемпературну динаміку носіїв струму в конденсаторах, виготовлених з використанням кремнію, імплантованого киснем, та кремнію в присутності SiO_2. Показано, що природа процесу високотемпературної нестабільності заряду зумовлена генерацією протонів в порушеній зоні поблизу границі “приповерхневий оксид–кремнієва підкладка” при температурах вище 200ºC. Визначено значення енергії активації процесу генерації протонів (1,2 еВ для SIMOX та від 0,9 до 1,5 еВ для UNIBOND матеріалів) і розраховано коефіцієнт дифузії протонів в при поверхневому оксиді ($D = 4{\cdot}10^{-4}$ exp(-0?55/kT), cm^2/s).