SiO_2 LAYER CHARGE STATE VARIATION IN FOWLER–NORDHEIM TUNNELING REGIME

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The charge build-up and its changes in the amorphous SiO_2 layer incorporated into a Si MOSFET as a gate oxide due to Fowler–Nordheim tunneling electron injection were investigated. Electron and hole trapping/detrapping by native and generated trap centres were studied by monitoring the charge state of the SiO_2 traps by means of a drain-source current versus gate-source voltage technique. New interesting effects were observed and their possible mechanisms are presented.

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1. Introduction

Charge carrier trapping and detrapping in a silica layer used as a gate insulator in a MOS structure are of great importance in the physics and technology of microelectronic devices. Large scale integration results in a high electric field being present in oxide layers which causes unwanted hot electron and hole injection due to Fowler–Nordheim tunneling, followed by their trapping and detrapping in the oxide. This in turn leads to changes of the electrical parameters of a device, such as channel threshold voltage shift and transconductance degradation in MOSFETs and affects the write/erase characteristics of electrically eraseable programmable read only memories (EEPROMs). Charge generation in the SiO_2 layer by high electric field stress is a well known phenomenon described in the literature [1–12]. In spite of many studies carried out on that topic, the understanding of the physical mechanisms of this process is not satisfactory. Since silicon dioxide layers undergo different electric field stresses during MOS device operation, it is important to know how the charge state of the layer depends on a given field stress. Therefore this paper is aimed to the study of the effect of the specific high electric field stress sequence on the net charge state of the SiO_2 layer. As far as we know the experiments carried out in this work, bearing in mind together the type of the structure, the experimental procedure and the measurement technique are reported for the first time.

2. Experimental

An n-channel Si MOS transistor from a standard p-well CMOS technology was used as a test structure. The starting material was (100) n-type with a resistivity of 3–5 Ω cm. The channel dimensions were: width $W = 9000\ \mu$m, length $L = 3\ \mu$m. Investigated SiO_2 layer was made by thermal oxidation ($T = 1000°$C) of p-well substrate in dry O_2 with 2% HCl to a thickness of 50 nm. This type of structure allowed to perform intentional, spatially uniform, substrate hot electron injection (SHEI) into the SiO_2 layer from the n substrate – p well junction located beneath the gate.

The measuring method included:

i) Isochronal electric field stimulated emission of charge carriers (IEFSE) technique for charge trap depopulation [5]. This technique is based on a sequence of electric field stresses (consisting of isochronal field steps) applied to the oxide layer. During each field stress the average electric field in the oxide was increased from 1 to 8.5 MV/cm, in steps of 0.1 MV/cm with a hold time of $\Delta t = 300$ s for each step. When the electric field in SiO_2 becomes sufficiently high (> 6.5 MV/cm [13]) electrons are injected into the oxide by the Fowler–Nordheim tunneling (FNTEI). The current flowing through the oxide layer (gate current I_G) during each field stress step was measured to monitor the electron charge fluence $[Q_{inj}]_{FN}$ injected by FNTEI (given in the inset of Fig. 1 and 2).

ii) Nonavalanche dc injection of hot electrons from the Si substrate into the SiO_2 layer (NIHE) technique [14] for intentional trap charging by SHEI. This technique was used between some field stresses to check the influence of additional substantial electron injection at low electric field (1 MV/cm) on the oxide charge state. The values of injected charge density $[Q_{inj}]_{SHE}$ have been measured and are given in the inset of Fig. 2.

iii) Drain-source current versus source-gate voltage (I_{DS} vs. V_{SG}) technique for monitoring the charge state of the SiO_2 layer at the end of each step, determined by charge created due to electron and hole trapping and detrapping from native (as fabricated) and generated traps in SiO_2 layer. The variations of charge state of the SiO_2 layer, i.e. the area density of charge created in the oxide ΔQ_t after each applied electric field step and/or electron injection can be determined from the voltage shift of the current–voltage characteristics using the formula [14]:

$$\Delta Q_t = \frac{\varepsilon\varepsilon_0}{\bar{x}} \Delta V_{SG0}, \qquad (1)$$

where ε is the SiO_2 electric permittivity, ε_0 is the vacuum electric permittivity, $\bar{x}$ is the created charge centroid and ΔV_{SG0} is the shift of the source-gate voltage. V_{SG0} is defined as a value of V_{SG} (with zero gate potential) for $I_{DS} = 1\ \mu$A and corresponds to frequently used channel threshold voltage with minus sign.

3. Results and discussion

In order to check the influence of the electric high field stress and of the electron injection on the net charge state of the oxide layer, two kinds of experiments were performed. Figure 1 shows the results for the oxide, which was subjected to the sequence of high electric field stresses only (with FNTEI). The results for the

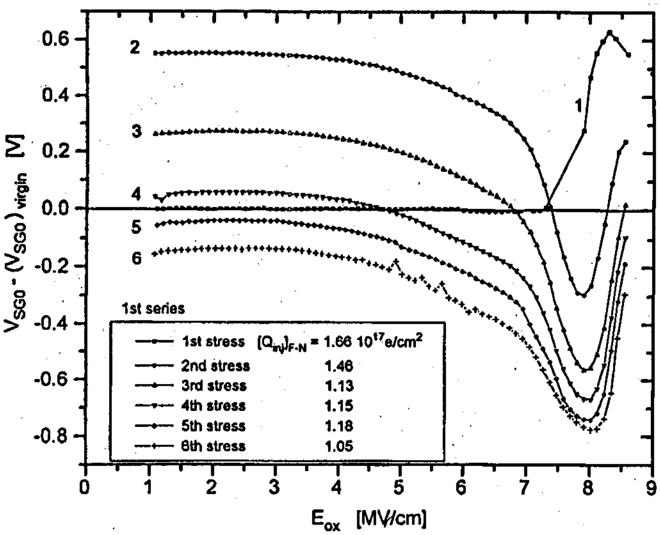

Fig. 1. The oxide charge state variation due to electric field stresses with FNTEI only.

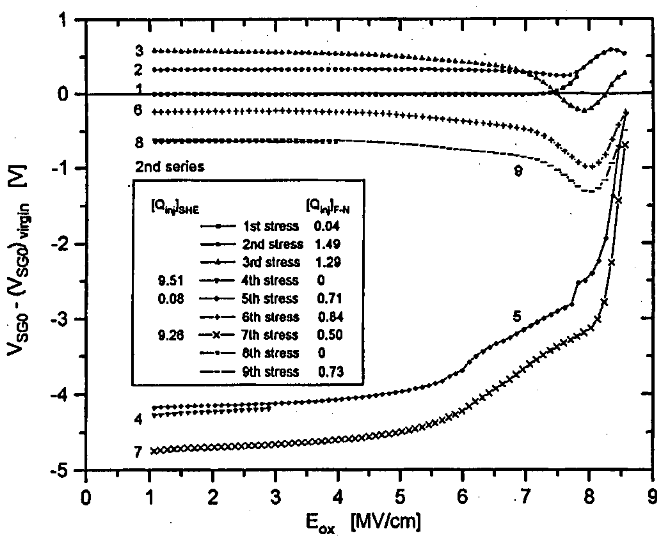

Fig. 2. The oxide charge state variation due to electric field stresses with FNTEI and additional SHEI between some stresses. The values of $[Q_{inj}]_{SHE}$ and $[Q_{inj}]_{F-N}$ are in 10^{17} e/cm^2.

oxide layer investigated with additional high fluence electron injection by means of SHEI between some electric field stresses in the sequence of stresses are presented in Fig. 2.

Three different types of the oxide charge state variations can be deduced from the experimentally measured current–voltage characteristics shifts (ΔV_{SG0}).

The first one is typical of the virgin structures. It is seen from the figures that an electric field stress up to about 6.5 MV/cm does not change the oxide charge state of virgin structures (1st stress) significantly. At fields above this value the FNTEI causes a positive ΔV_{SG0} shift. Hence, the electric field stress produces positive charge with nonlinearly increasing rate up to 8 MV/cm. For the fields 8.0–8.3 MV/cm the positive charge creation rate decreases and for even higher fields $\Delta V_{SG0} < 0$, indicating negative charge creation but for the highest field used leaving the net charge state positive compared to the virgin state.

The second type of variations is observed in the cases of "normal" stresses, i.e. stresses which are preceded by stresses with FNTEI only. In these cases at fields up to 4 MV/cm the oxide charge state at the beginning of stresses initially positive (the 2nd, 3rd, 4th stress in first series in Fig. 1 as well as the 2nd and 3rd run in series 2 in Fig. 2) decreases for increasing fields. For further stresses (the 5th, 6th in first series and the 6th, 9th in series 2) the initially negative charge state is getting to be more negative. In the range of 4.0–6.5 MV/cm negative charge creation becomes more distinct and at fields from 6.5 MV/cm (when FNTEI starts to become essential) to 7.5 MV/cm, the negative charge creation rate fast increases leading to a maximum negative charge value. Then, despite the increase in FNTEI current, the negative charge creation rate decreases until it approaches zero at 8.0 MV/cm. In the range of 8.0–8.3 MV/cm ΔV_{SG0} becomes positive, indicating positive net charge creation. Finally above 8.3 MV/cm the positive charge creation rate fast decreases after reaching maximum.

The third type of oxide layer charge state variations is observed in the course of field stresses which follow SHEI (4th, 5th, 7th stress in 2nd series). Due to a large amount of electrons injected by SHEI at low electric field in the oxide the initial charge state is highly negative and remains negative during all steps of the field stress. However, field stresses cause positive shifts of the source-gate voltage ($\Delta V_{SG0} > 0$) indicating negative charge depopulation or positive charge creation in the oxide layer. The rate of the net positive charge creation depends on the electric field strength. Below 4 MV/cm it is very low, increases in the range of 4.0–7.0 MV/cm and then decreases between 7.0 MV/cm and 8.0 MV/cm when FNTEI starts to become effective. It is noted that some of the electrons injected by SHEI can be trapped at the tunneling portion of the oxide barrier, increasing its height and width. In the range of 8.0–8.3 MV/cm the rate of positive charge creation rises fast and above 8.3 MV/cm again decreases.

The results presented in this work show the complex and manifold character of the charge state variation of the SiO_2 layer under high electric field stress and electron injection. This indicates that many different physical processes are operative in these conditions and need to be considered.

The most probable mechanisms of these processes are the following:

(a) Virgin stress

Positive charge creation results from hole generation caused by hot electrons injected through Fowler–Nordheim (F–N) tunneling and final hole trapping [3, 15]. This effect can be accompanied by electric field stimulated emission of electrons from neutral native traps due to trap-conduction band tunneling or Poole–Frenkel emission [5]. Negative charge creation observed at higher field stress steps and larger F–N electron injection current is caused by FNT injected electrons trapping at native and also new traps which are generated (nonlinearly) by hot electrons [16]. Generated positive charge, thus, is partially neutralized by trapping of injected electrons. The annihilation of hole traps, due to hydrogenation mechanism (oxides were fabricated with 2% HCl) may also reduce the positive charge creation [3].

(b) Stresses following the FNTEI

Negative charge creation and/or positive charge annihilation observed from the beginning of the stresses (for the low electric fields) can be caused by injected electrons trapping at traps generated by FNTEI at high field steps during previous stress. Another processes like trapped hole recombination or trap to band hole emission [10], can be considered as very probable mechanisms in this case. The negative charge creation rate increases, due to electron trapping, when FNTEI becomes essential. The feature of decreasing negative charge creation rate and then, positive net charge creation observed at high enough fields may be brought about by:

— more effective, electric field stimulated electron detrapping [5],

— hole generation by electron impact band-gap ionization [9] and enhanced hole injection followed by hole trapping [10].

This effect may also result from:

— reduced trapping due to electron capture cross-section decreasing with increasing electric field [2],

— limited concentration in the oxide of species which can be converted into electron traps [3],

— annihilation of electron traps [5].

(c) Stresses following the SHEI

High negative charge state observed at the beginning of stress is due to a large fluence of injected electrons (at low electric field by SHEI) which are mostly being trapped at native and generated electron traps. Therefore during all steps of electric field stress we observe a negative charge state of the oxide layer but its changes reveal the emission of electrons from filled traps followed by typical strong positive charge creation in the range of 8.0–8.3 MV/cm which can be caused by mechanisms mentioned already.

Experiments carried out in this work showed that in order to anticipate the charge state of the SiO_2 layer in an MOS structure and/or an MOS type device careful consideration is required. It has turned out that this state is determined not only by the value of stressing electric field but also by the history of the structure (particularly prior treatment). In other words, typical judgment referring to F–N stresses that for lower electric fields the charge created in the oxide layer is positive and for higher fields is negative (real for virgin, native oxide and not too high fields) is not sufficient to explain the experimental findings in all cases. It is expected that the results of this work, though exhibiting some speculative features, will contribute to a better understanding of the important processes in

MOS type devices. But still further studies are needed in order to determine which process is dominant and/or which one can be neglected.

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