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ON TRAP GENERATION IN SiO_2 FILMS OF Si MOSFETS BY HOT ELECTRONS

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Trap generation in amorphous SiO_2 films with thickness about 500 Å was studied by nonavalanche injection of hot electrons. The trap density, the electron capture cross-section of native and generated traps and the effective trap generation constant for the oxide fields of 1–4 MV/cm, injected charge density up to 3×10^{19} e/cm^{-2} and injected current density in the range 2–300 μA/cm^2 were determined and discussed.

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1. Introduction

Charge trap creation in SiO_2 films incorporated into silicon metal- oxide-semiconductor field-effect-transistors (MOSFETS) as a gate insulator by hot carriers is currently one of the most important problems in integrated circuits physics and technology [1–3]. Hot electron damage in SiO_2 resulting in trapping centers generation and followed by trap charging is of great importance phenomenon causing the instability and degradation of MOS type devices. In spite of many works done on that issue, the trap generation mechanisms are not well known yet and the results obtained are controversial.

2. Experimental details

The measuring structure consisted of an n-channel Si MOS transistor and two p–n junctions, for supplying the substrate with electrons, located laterally on both sides of the poly-Si gate. The substrate was p-type, Si ⟨100⟩, wafer with resistivity of 9–14 Ω cm. To examine the role of hydrogen related species at low concentration level in trap generation mechanism two types of the gate oxide were made by thermal oxidation of substrate in dry O_2 without HCl and with 2% HCl to a thickness of 520 Å and 490 Å, respectively.

The measurement method was based upon the idea of nonavalanche injection of hot electrons into silicon dioxide conduction band [4]. Electron trapping by native (as fabricated) and generated traps in SiO_2 films has been studied by monitoring the charging of the traps during injection of electrons into the film. The density of trapped charge Q_t was calculated from the shifts of the drain-source current versus gate-source voltage $I_{DS}(U_{SG})$ characteristics along the voltage axis measured after each subsequent injection. The density of injected charge Q_{inj} was numerically integrated from electrometrically measured gate current. The injections of electrons into gate oxide were performed for different oxide fields in the range of 1–4 MV/cm and for different densities of electron current in the range of 2–300 μA/cm^2. The total injected charge densities were up to 3×10^{19} e/cm^{-2}.

3. Results and discussion

Typical $Q_t(Q_{inj})$ curves for all applied oxide fields are presented in Fig. 1. The strong increase in charge trapping at higher fields is the most striking feature, whereas at low fields trapped charge density tends towards a saturation. For

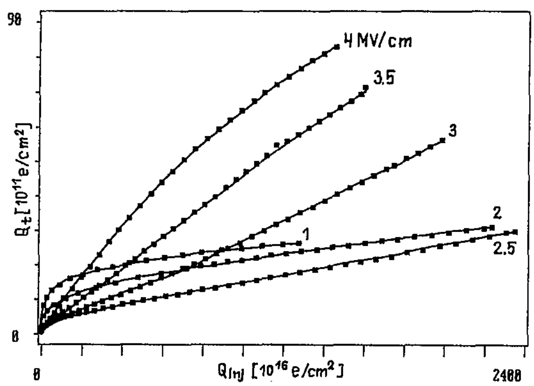

Fig. 1. The trapped charge density Q_t versus injected charge density Q_{inj} for all applied electric field.

further analysis all oxide field values have been divided into two ranges: low fields (1.0–2.0 MV/cm) and high fields (2.5–4.0 MV/cm).

One can expect that at low fields the trap generation, if exists, can be linearly approximated. According to this model the increase in trapping sites concentration is proportional to the injected charge density: $dN_t = (G/e) \cdot dQ_{inj}$, where G is the trap generation constant. Under this assumption a first-order kinetic equation [2] for many type-trap model yields the following dependence $Q_t(Q_{inj})$:

$$Q_t = \sum_i N_{ti} e[1 - \exp(-\sigma_i Q_{inj}/e)] + G Q_{inj} - (Ge/\sigma)[1 - \exp(-\sigma Q_{inj}/e)],$$

where N_{ti} and σ_i are the initial density and the capture cross-section respectively of i-th type of native traps, σ is the capture cross-section of generated traps.

To determine the average values of σ_i, N_{ti} and G two-step calculations using the fitting procedure were applied. In the first step the unconstrained fit was done for all curves measured at low fields. The results were satisfactory when as much as three different native and one generated trapping sites were assumed. The average values of σ_i [10^{-18} cm^2] and G [10^{-8}] for low fields are:

$$E_{ox} = 1 \text{ MV/cm}, \quad \sigma_1 = 390, \quad \sigma_2 = 16.4, \quad \sigma_3 = 1.24, \quad G = 7.65,$$
$$E_{ox} = 2 \text{ MV/cm}, \quad \sigma_1 = 261, \quad \sigma_2 = 10.5, \quad \sigma_3 = 0.98, \quad G = 10.6.$$

It is important that for all fits the value of capture cross-section of generated trap was equal to the one of the values obtained for native traps ($\sigma = \sigma_i$). The most consistent results have been obtained when $\sigma = \sigma_2$.

In the second step of the calculations the values of the capture cross-section were kept constant and equal to the average of the values obtained in step one, therefore only the trap densities N_{ti} could vary. No statistically significant differences were found between the samples oxidized with and without 2% HCl, therefore subsequent analysis was carried out jointly for both types of samples. The average values of effective density of three kinds of native traps are: $N_1 = 2 \times 10^{11}/\text{cm}^2$, $N_2 = 2 \times 10^{11}/\text{cm}^2$, $N_3 = 4 \times 10^{11}/\text{cm}^2$.

For oxide fields greater than 2 MV/cm the results of fitting procedure were no longer consistent, therefore a new approach was necessary: the efficiency of trap generation have been described as a slope of linear approximation of the $Q_t(Q_{inj})$ curve. To this end the curves were divided into sections, each of them representing the value of injected charge density of 3×10^{18} e/cm^{-2}. However, the first section, for 1×10^{18} e/cm^{-2} is strongly nonlinear because of the trapping on native traps, therefore cannot be used for further analysis. For the rest of the curves the linearity of the sections were very good. In Fig. 2 the average values of the slopes for each of the sections are presented.For oxide fields of 3.5 and 4.0 MV/cm

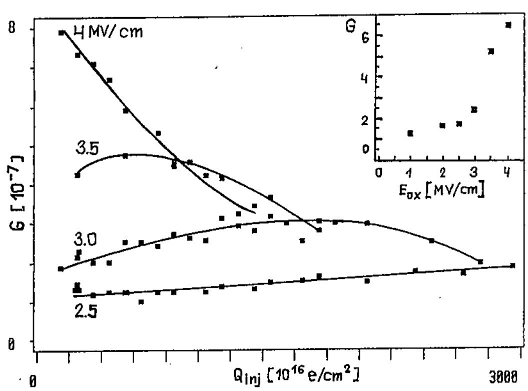

Fig. 2. The effective generation rate G versus injected charge density Q_{inj} for high oxide electric fields. The inset shows G as a function of oxide field for $Q_{inj} = 5 \times 10^{18}$ e/cm^{-2}.

the strong decrease in the slope value for high values of Q_{inj} is evident. In the inset of Fig. 2 the effective generation rate G is presented as a function of E_{ox} for $Q_{\mathrm{inj}} = 5 \times 10^{18}$ e/cm^{-2} .

The results of this work show:

i) The trap generation efficiency increases with oxide field and trap generation occurs even at the field of 1 MV/cm, contrary to the reported threshold value of 1.5 MV/cm [1].

ii) The trap generation is effective for the total injected charge density lower than the threshold value for generation (1 C/cm^2) cited in the literature [1].

iii) The trap generation rate dependence on the injection current density in the studied range of values 2–300 μA/cm^2 at oxide fields up to 4 MV/cm is not observable, e.g. is weak if any.

iv) For the low hydrogen concentration (thermal oxidation in dry O_2 with 2% HCl — typical NMOS technology) the influence of the hydrogen on the trap generation is negligible.

During hot electron injection into SiO_2 film four physical mechanisms are operative: charging of native and generated traps by electron trapping; discharging of filled traps via the field assisted thermal emission and the electron impact emission of trapped electrons; generation and annihilation of traps. Thus, the reported trap generation dependence on the oxide field, on the injection current density and on the injected charge density (as well as their threshold values for generation) may include the effect of mentioned above four mechanisms. This can explain the controversies in the interpretations of the results of different trapping experiments and conclusions about the trap generation characteristics found in the literature [1–3].

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