CHARGE INSTABILITY IN MIS STRUCTURES WITH DIELECTRIC SILICON DIOXIDE–PHOSPHORO-SILICATE GLASS LAYERS UNDER CONDITIONS OF HIGH-FIELD TUNNEL INJECTION

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The processes of charge degradation in MIS structures with dielectric silicon dioxide–phosphoro-silicate glass (PSG) layers are investigated for high-field tunnel electron injection from silicon. A model for their description is proposed. It is shown that in a PSG film the interband shock ionization intensity significantly decreases compared to SiO₂. This phenomenon is quantitatively described within the framework of the model examined. It has been found that in structures with polysilicon gate doped with phosphorus the PSG film can be formed at the gate-semiconductor interface, which results in the formation of electronic traps in the dielectric and in a decreased thickness of the SiO₂ layer in which the interband shock ionization proceeds.

INTRODUCTION

The silicon dioxide–phosphoro-silicate glass (PSG) system is widely used in many field-effect devices to stabilize their electrical characteristics. The formation of PSG films can also be observed in Si-SiO₂-polycrystalline silicon (Si*) systems doped with phosphorus. This provides the basis for modern large-scale integrated circuits (LSIC) [1]. However, most works [2--4] devoted to the study of the charge instability in the MIS Si-SiO₂-PSG structures were experimental in character. Theoretical analysis with the construction of a mathematical charge degradation model in the structures being investigated was not performed. The lack of a mathematical model for a quantitative description of the charge degradation in the MIS structures with a silicon dioxide film passivated with PSG makes the preparation of dielectric films with preset charge characteristics difficult and gives no way of investigating the physical phenomena in MIS structures with a two-layer SiO₂-PSG dielectric beyond the experimental capabilities.

In this work, the charge degradation of the MIS Si-SiO₂-Al, Si-SiO₂-PSG-Al, and Si-SiO₂-Si* structures is investigated for the model proposed in [5] for the case of high-field tunnel electron injection from silicon in the direct-current regime. The model parameters are also discussed and refined.

CHARGE-STATE MODEL

In the case of high-field charge-carrier injection in a gate dielectric under conditions of direct current flowing through an MIS structure, the main parameter that characterizes the charge degradation in a sample is a change in the voltage on the MIS structure [6]. Charges accumulated in the dielectric engender changes in local electric fields within the dielectric film volume. Therefore, to ensure the direct injection current, it is necessary to change the voltage applied to the MIS structure. Thus, the change in the voltage on the MIS structure characterizes the charge density accumulated within the dielectric volume with consideration of its localization region.

Three main mechanisms of the charge-state change are taken into account in the charge-degradation model [5] for the MIS Si-SiO₂-PSG-Al structure. First, the positive-charge accumulation as a result of the interband shock ionization in SiO₂ with the formation of electron-hole pairs and subsequent hole capture in the oxide with consideration of the injected electron capture by filled hole traps [7]. Second, the electron capture by the initial electron traps in SiO₂ is considered [8]. Third, the electron capture in PSG is also considered [3]. Then the net change of the MIS-structure voltage caused by the charge degradation with the direct injection current will have the following form:
\[ \Delta V_t = \Delta V_p + \Delta V_e + \Delta V_{pg}, \]  

where \( \Delta V_p, \Delta V_e, \) and \( \Delta V_{pg} \) are changes in the voltage on the MIS structure caused by the hole accumulation and electron capture in \( \text{SiO}_2 \) and PSG, respectively.

The change in the voltage caused by the positive-charge accumulation in the oxide is determined as

\[ \Delta V_p = \frac{q}{\varepsilon \varepsilon_0} (T_{ox} - x_p) p, \]

where \( q \) is the electronic charge, \( \varepsilon \) is the relative permittivity of the oxide, \( \varepsilon_0 \) is the permittivity of the vacuum, \( T_{ox} \) is the dielectric thickness, \( x_p \) specifies the position of the positive-charge centroid measured from the Si-\( \text{SiO}_2 \) interface, and \( p \) is the captured hole density.

The captured hole density was found by the numerical solution of the fourth-order differential equation by the Runge-Kutta method [7]

\[ \frac{dp}{dt} = J_n \cdot P_{mf} \left[ \frac{E}{E_{th}} - 1 \right]^4 \sigma_p \cdot (N_p - p) - J_n \cdot \sigma_e \cdot p, \]

where \( t \) denotes time, \( N_p \) is the density of the neutral hole traps existing in the initial conditions, \( J_n \) is the tunnel injection current, \( P_{mf} \) is the coefficient depending on the oxide thickness, \( E \) is the electric field intensity in the dielectric (MV/cm), \( E_{th}^{ii} \) is the threshold shock ionization field intensity (MV/cm), \( \sigma_p \) is the hole capture cross section, and \( \sigma_e \) is the injected electron capture cross section by filled holes. The capture cross section \( \sigma_e \) characterizes the capture of holes generated due to the interband shock ionization in the silicon dioxide volume on neutral traps located near the Si-\( \text{SiO}_2 \) interface. The capture cross section \( \sigma_e \) has the field dependence \( \sigma_e = b_0 E^{-3} \).

The threshold shock ionization field \( E_{th}^{ii} \) is defined as

\[ E_{th}^{ii} = E_{th}^{m} \left[ 1 + \frac{T_i}{T_{ox} - T_d} \right]. \]

For an oxide thickness of more than 30 nm, the parameters entering into Eq. (4) were the following: \( T_d = 8.2 \) nm and \( T_i = 1.56 \) nm [7]. The constant threshold shock ionization field \( E_{th}^{m} \) corresponds to the stable state of charge carriers observed in dielectric films of large thickness. In accordance with [7], \( E_{th}^{m} = 6.4 \) MV/cm for the thermal \( \text{SiO}_2 \) films considered in the paper.

The change in the voltage on the MIS structure caused by the electron capture in silicon dioxide and PSG is described by the following formulas:

\[ \Delta V_{e} = \frac{q}{\varepsilon \varepsilon_0} (T_{ox} - x_n) \cdot N_e \left[ 1 - \exp \left( -\frac{\sigma_e \cdot J_n \cdot t}{q} \right) \right], \]

\[ \Delta V_{pg} = \frac{q}{\varepsilon \varepsilon_0} (T_{ox} - x_{pg}) \cdot \sum_{i=1}^N N_{pg} \left[ 1 - \exp \left( -\frac{\sigma_{pg} \cdot J_n \cdot t}{q} \right) \right], \]

where \( x_n \) and \( x_{pg} \) specify the positions of the corresponding charge centroid measured from the Si-\( \text{SiO}_2 \) interface, \( N_e \) and \( \sigma_e \) are the density and capture cross section of initial electron traps in \( \text{SiO}_2 \), and \( N_{pg} \) and \( \sigma_{pg} \) are the density and capture cross section of electron traps of the \( i \)th type in the PSG film.