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Effect of pressure on the properties of Al–SiO_2–*n*-Si⟨Ni⟩ structures

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Abstract. We investigated the effect of hydrostatic pressure on relaxation characteristics of the three-layer $\mathrm{Al-n-Si}\langle\mathrm{Ni}\rangle-\mathrm{SiO_2-Al}$ structures. It was found that 20 min exposure to a pressure of 8 kbars results in reduction of the integral density of surface states, while exerting no influence on the generation centers in the bulk.

Keywords: MOS structure, hydrostatic pressure, Schottky diode.

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1. Introduction

At present many semiconductor devices and structural elements of integrated circuits (ICs) involve the Si-based metal-oxide-semiconductor (MOS) structures. The characteristics of the semiconductor-oxide interface can considerably influence the parameters of produced devices and structural elements [1, 2].

There exists a number of papers (see, e.g., [3-7]) devoted to investigations of the effect of such external actions as thermal treatment and γ-irradiation on the parameters of interfaces. As to the effect of pressure, the available works deal predominantly with an analysis of the bulk properties variation in the layers of MOS structures [8-11]. The authors of [8-10] related the parameters variation in MOS structures subjected to a uniaxial elastic strain to changes in the concentration and mobility of the majority charge carriers in semiconductors. In [11] the observed variations of relaxation characteristics under pressure were related to production of defect centers in insulator layers, while in [12] these characteristics were explained from the viewpoint of crystallographic orientation of the semiconductor crystal.

The objective of this work was to investigate the effect of hydrostatic pressure on the density of electron states localized at the $\mathrm{Si-SiO_2}$ interface.

2. Test samples

The structures to be investigated were prepared on the basis of crystalline silicon КЭФ-5 with crystallographic orientation (100) that is most often used in microelectronics. Diffusion doping of silicon with Ni was made (at a temperature T = 1200 °C for 2 hours) from metal nickel deposited onto the Si plate surface. The Ni dopant was chosen because its introduction influences the density of surface states distribution over the silicon bandgap [13].

A SiO_2 layer (thickness of 2000–3000 Å) was grown using thermal oxidation of the silicon plates (T = 900 °C for 40 min) in a chlorine-containing environment. The MOS structures were prepared using vacuum deposition of aluminum onto the silicon dioxide surface. The control electrode diameter was 3 mm. The structures made were subjected to hydrostatic pressure up to 2–8 kbars (with a step of 2 kbars and retention interval of 20 min) using a setup similar to that described in [14]. The energy levels of nickel in silicon were identified using the procedure described in [15]. To this end, we made $\mathrm{Au-n-Si}\langle\mathrm{Ni}\rangle$ Schottky diodes using chemical removal of the SiO_2 layer and vacuum deposition of Au.

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3. Method of investigation

Let us write down the electrical neutrality condition for a MOS structure:

$$kqNx + Q_P + Q_{SS} = Q_{CS}. \qquad (1)$$

Here k is the ohmic contact area, q is the electron charge, $N = N_m$ is the concentration of low-level impurity, x is the width of the space-charge region (SCR), Q_P is the charge in the inversion layer, Q_{SS} is the charge at the surface states and Q_{CS} is the charge at the gate of the MOS structure.

After differentiating the left and right parts of Eq. (1) with respect to time t, we obtain the expression that describes charge change with time:

$$kqN\frac{dx}{dt} + \frac{dQ_P}{dt} + \frac{dQ_{SS}}{dt} = \frac{dQ_{CS}}{dt}. \qquad (2)$$

Since the charge at the metal electrode does not change during relaxation $\left(\frac{dQ_{CS}}{dt} = 0\right)$, Eq. (2) becomes

$$kqN\frac{dx}{dt} + \frac{dQ_P}{dt} + \frac{dQ_{SS}}{dt} = 0. \qquad (3)$$

The changes of the charge in the inversion layer and at the surface states may be written, respectively, as $\frac{dQ_P}{dt} = Aqkx$ (where A is the charge carrier generation rate in the semiconductor bulk) and $\frac{dQ_{SS}}{dt} = Sqk$ (where S is the surface charge carrier generation rate). Then Eq. (3) takes the form

$$kqN\frac{dx}{dt} + Aqkx + Sqk = 0 \qquad (4)$$

or, after some simplification,

$$-\frac{dx}{dt} = \frac{A}{N}x + \frac{S}{N}. \qquad (5)$$

This is a first-order differential equation. After solving it for x, we obtain:

$$x = C\exp\left(-\frac{A}{N}t\right) - \frac{S}{A}, \qquad (6)$$

where C is a constant of integration. To determine it, let us make use of the initial condition $x(t = 0) = x_0$ (the SCR width value at the start of relaxation process). Then the solution of Eq. (8) that gives the time dependence of SCR width is

$$x = \left(x_0 + \frac{S}{A}\right)\exp\left(-\frac{A}{N}t\right) - \frac{S}{A}. \qquad (7)$$

This result can be used for determination of the surface and bulk generation rates by comparing it with the experimental time dependence of the SCR width. Using the conventional model of MOS structure, one can show that the time dependence of measured capacitance (without allowing for the effect of charge accumulation in the inversion layer) is of the following form:

$$C(t) = \frac{\varepsilon\varepsilon_0 K C_i}{K + x(t)C_i}. \qquad (8)$$

Here, K is the control electrode area, C_i is the insulator layer capacitance, ε is the semiconductor permittivity, and ε_0 is the electric constant. C_i is determined from the high-frequency capacitance-voltage characteristic. $C(t)$ value can be determined, for any moment t, from the experimental relaxation characteristic of MOS structure.

4. Results and discussion

Fig. 1 shows the experimental (1^1) (measured at a frequency of 250 kHz and temperature of −15 °C) and theoretical (1^2) capacitance vs relaxation time curves $C(t)$ for one of the reference $Al-n\text{-}Si\langle Ni\rangle-SiO_2-Al$ structures. The curves were obtained after voltage switching $V_1 \rightarrow V_2$ ($V_1 = 7$ V, $V_2 = 14$ V). The values of the bulk (A) and surface (S) generation rates were determined using the Eqs. (7) and (8) by applying the optimal fitting technique: $A = 9\times10^{13}\,s^{-1}\,cm^{-3}$, $S = 4\times10^{9}\,s^{-1}\,cm^{-2}$. With the above A and S values, the calculated $C(t)$ curve is in a good agreement with the experimental one. Some distinction between the two curves at the end of relaxation process is caused by the effect of charge accumulation in the inversion layer and increase of the probability of generated charge carrier recapturing.

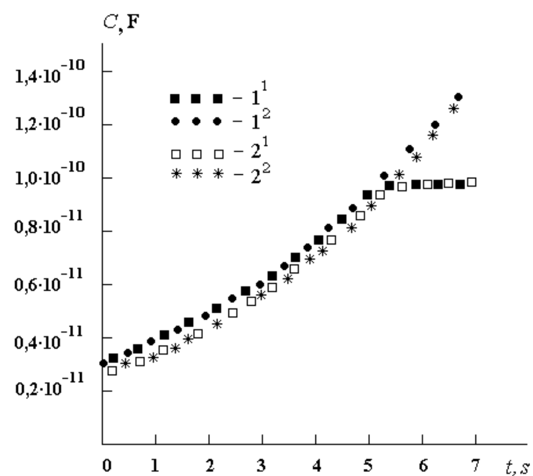

Fig. 1. Experimental (1^1, 2^1) and theoretical (1^2, 2^2) capacitance C vs relaxation time t curves for the $Al-n\text{-}Si\langle Ni\rangle-SiO_2-Al$ structures (1^1 and 1^2 – reference structures, 2^1 and 2^2 – structures subjected to pressure).

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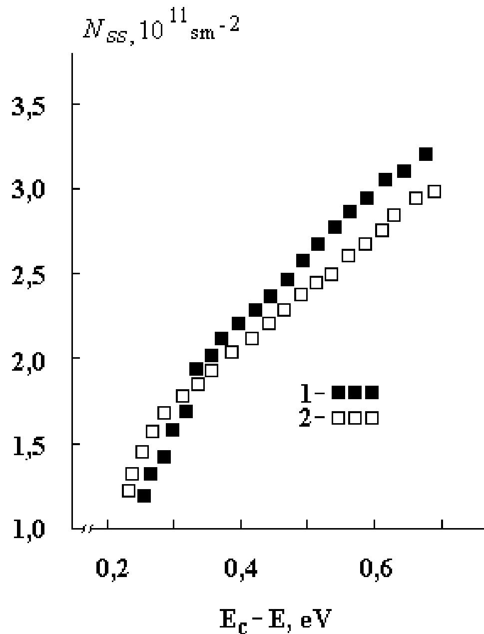

Fig. 2. Distribution of the integrated density of surface states (N_{SS}) over the silicon bandgap for the $\mathrm{Al-n\text{-}Si\langle Ni\rangle - SiO_2 - Al}$ structures (*1* – reference structure, *2* – structure subjected to a pressure of 8 kbars).

The curves (2^1) and (2^2) obtained under the similar conditions correspond to a sample subjected to hydrostatic pressure up to 8 kbars. One can see from Fig. 1 that the calculated curve 2^2 is in a good agreement with the experimental one 2^1 at $A = (8-9)\times 10^{13}\,\mathrm{s^{-1}\,cm^{-3}}$, $S = (1-2)\times 10^{9}\,\mathrm{s^{-1}\,cm^{-2}}$. We consider this as an indication that, at the mentioned pressure values, the concentration and energy distribution of the Ni impurity centers practically do not change, while reduction of the surface generation rate is due to variation of the density of surface states.

To verify the above assumption, we removed (by treating in hydrofluoric acid vapor) the SiO_2 layer from the structures subjected to pressure and then used them to fabricate $\mathrm{Au-n\text{-}Si\langle Ni\rangle}$ Schottky diodes. After this, using the isothermal capacitance relaxation method [14], we identified the Ni impurity and determined its concentration. An analysis of the results obtained showed the following. In all the Schottky diodes (both reference and made on the plates subjected to pressure) the Ni impurity level position ($E_C - 0.4 \pm 0.03$ eV and $E_V + 0.2 \pm 0.03$ eV) and concentration $n = (3-5)\times 10^{12}\,\mathrm{cm^{-3}}$ practically did not change. The spread of their values for different diodes was 5-7%, i.e., lied within the limits of experimental errors.

We made the direct measurement of density of surface states using the high-frequency capacitance-voltage technique [2, 12]. For the structures subjected to pressure, it was shown that, at energies over $E_C - 0.35$ eV, the integrated density of surface states lying in the silicon bandgap was smaller than that for the reference structures (see Fig. 2).

5. Conclusion

The results obtained in this work make it possible to conclude that subjection of the $\mathrm{Al-n\text{-}Si\langle Ni\rangle - SiO_2 - Al}$ structures to a pressure up to 8 kbars for 20 min leads to restructuring of the $\mathrm{Si-SiO_2}$ transition layer. As a result, the integrated density of electrically active surface states decreases. At the same time, the above pressure has no pronounced effect on the properties of bulk generation centers.

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