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Franz–Keldysh Effect in Silicon–Ultrafine (3.7 nm) Oxide–Polysilicon Structures

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Abstract—Manifestation of the Franz–Keldysh effect was found under indirect daylight illumination of Al–n^+-Si:P–SiO$_2$–(100) n-Si with ultrafine (3.7 nm) oxide. It is shown that the use of illumination even at low field voltages (up to 3 V) leads to an increase in the tunneling current through the oxide compared to the current in darkness by three orders of magnitude. A model is constructed for the influence of radiation on the process of electron tunneling through an ultrathin insulating layer. First, as a result of the Franz–Keldysh effect, a radiation quantum is captured by an electron and a given charge carrier tunnels through the barrier at a higher level compared to darkness. After a charge carrier enters a semiconductor, its energy is sufficient for several acts of electron–hole pair production during the impact ionization of silicon.

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INTRODUCTION

Silicon wafers coated with ultra-thin, less than 5 nm, insulating layers of SiO$_2$, are the main part of current and future nanoscale devices [1]. In metal–oxide–semiconductor (MOS) structures, the transparency of the barrier of such an insulator already at zero voltage between the field electrode and the semiconductor ($V_g = 0$) is so large that, in contrast to thick oxides, the effects of tunneling through the potential relief in a dielectric appear in measurements of the current–voltage characteristic (CVC) immediately after the violation of detailed equilibrium. In particular, it is known [2, 3] that electrons that tunnel from the gate into silicon of n-type, turn out to be strongly heated in the semiconductor, and their thermalization leads to an increase in the rate of generation of electron–hole pairs due to impact ionization.

Objective—To study the effect of illumination of a semiconductor on the conductive properties of an ultrafine oxide. It turns out that exposure to light leads to an increase by orders of magnitude of the tunneling current through SiO$_2$. We will discuss the experimental results of observing this phenomenon and the physical mechanism of its manifestation.

1. EXPERIMENTAL RESULTS

The experiments were carried out on samples from the group of structures that served as the objects of research [4, 5], in which there is practically no reaction to the field effect, such as damage, i.e., with an increase in the duration of exposure at field voltages of different polarity, up to the transition to a soft breakdown state, neither the conductivity through the oxide nor the distribution of the built-in charge practically change in the objects. High quality SiO$_2$ objects are also confirmed by low leakage currents through the insulating layer due to tunneling conduction. Si-MOS structures had field electrodes Al–n^+-Si:P (donor concentration in polysilicon $N_d^+ \approx 10^{20}$ cm^{-3}, field electrode area $S = 1.6 \times 10^{-3}$ cm^2) isolated from (100) n-Si-layer substrates obtained by high-temperature oxidation of SiO$_2$ with an optical thickness of 3.7 nm.

The experiments were carried out at room temperature on an automated setup [6], they included measurements of the CVCs and high-frequency capacitance–voltage characteristics of objects at frequencies of 1 MHz (C_1) and 0.5 MHz (C_2) using an Agilent E4980A precision LCR meter. Two types of characteristics were obtained: dark, when measuring samples under an opaque cap, and when illuminated, the samples were exposed to daylight (light from windows in the absence of direct solar irradiation). The experiments were carried out in a non-stationary special mode [4], when the values of high-frequency capacitances and current during their fixation correspond to almost the same state of the sample. Experience scheme: for each measurement point from the position of field voltage $V_g = 0$, specified bias V_g was applied to the sample; after the end of the RC processes (less than 0.3 s), current I through the oxide was

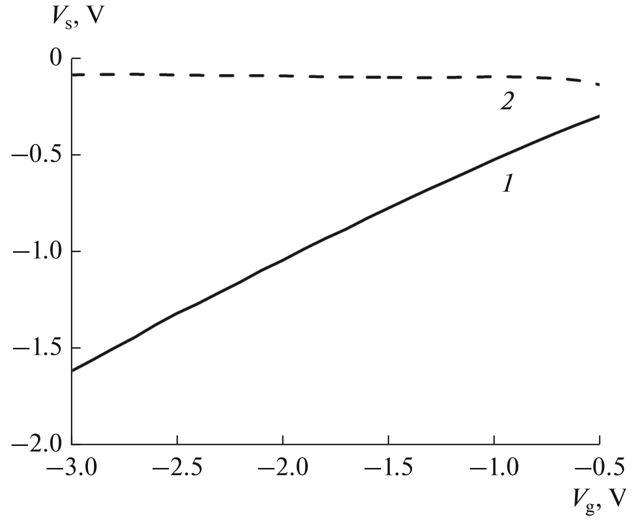

Fig. 1. Field dependence of the depleting band bending in silicon: (*1*) characteristics in the dark, (*2*) backlight characteristics.

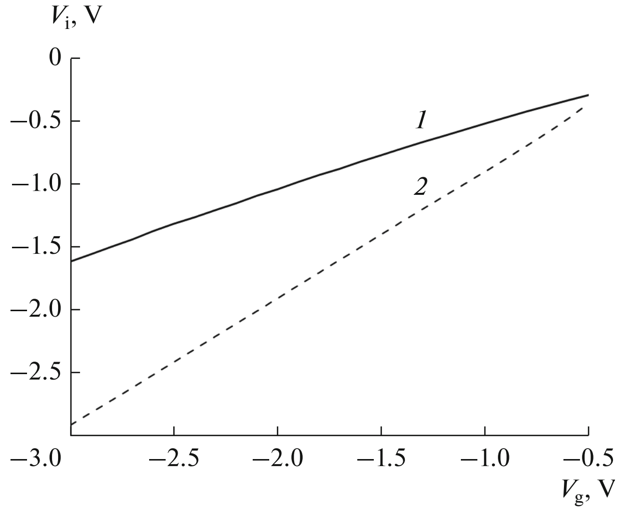

Fig. 2. Field dependence of the voltage drop across the oxide: (*1*) characteristics in the dark, (*2*) backlight characteristics.

fixed, and then within 3 s of capacity C_1 and C_2. After that, the applied voltage was dropped to zero, and the structure was held for 6 s. The total duration of current and capacitance measurements at the same value field electrode voltage significantly less than the characteristic time of the transient process associated with the recharging of localized electronic states at the Si–SiO$_2$ interface, (more than 15 s). This procedure makes it possible to minimize the duration of the sample's stay in pre-breakdown conditions during measurements. The current–capacitance characteristics data corresponding to two high frequencies make it possible to carry out certification of the sample [6, 7], i.e., to determine the concentration of donors at the Si–SiO$_2$ interface, the resistance of the semiconductor substrate, and plot the dependences on field bending voltage V_s of the zones in the semiconductor and external voltage drop V_i across the insulating layer [8].

2. RESULTS AND DISCUSSION

The results of processing the measured current values as a function of the voltage across the oxide and the coupling of this voltage, as well as the bending of the bands in a semiconductor with an external bias, are shown in Figs. 1–3. The range of data presented corresponds to the depletion region of the semiconductor, where the phenomenon of high photosensitivity of ultrafine oxide is most pronounced.

Already the first two figures indicate a significant difference in the states of the silicon surface under the same field effects in the dark and under illumination. In dark conditions, external field voltage V_g is divided between the semiconductor and the oxide; when illuminated almost all V_g is attached to SiO$_2$, depletion does not actually appear, the maximum bending of the zones does not exceed $4T/q$, where T is the temperature in energy units, q is the elementary charge. The main experimental result is the change in the CVC of the sample as a result of illumination (see Fig. 3). The tunnel current under illumination exceeds the dark one by three orders of magnitude, and this is at the same voltage drops across the oxide; if we compare the CVC at the same field voltage, then the difference between the currents during illumination and in the dark will increase even more, since in the experiment under a light-protective cap V_g is divided between silicon and oxide.

This pattern is due to two factors.

First, discussed in [2, 3] the production of electron–hole pairs during the impact ionization of silicon by charge carriers that have entered the semiconductor in a tunnel from the field electrode (see the band diagram of the structure in Fig. 4[1]). Moreover, since the energy of one such charge carrier is sufficient to participate in the acts of generation of several pairs[2], then the multiplication effect takes place: the number of electron–hole pairs produced per unit volume is greater than the flux density of tunneling electrons. It follows from experience (see Fig. 1, curve *2*) that the rate of generation of minority charge carriers upon illumination is so high that the concentrations of holes accumulating near the Si–SiO$_2$ interface is enough to

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[1] This figure is almost the same as Fig. 1 from [3], but with an important change regarding the illustration of the effect of light on the tunneling process.

[2] The energy of an electron that entered silicon during tunneling from the field electrode significantly exceeds the band gap in Si necessary for the generation of one pair.

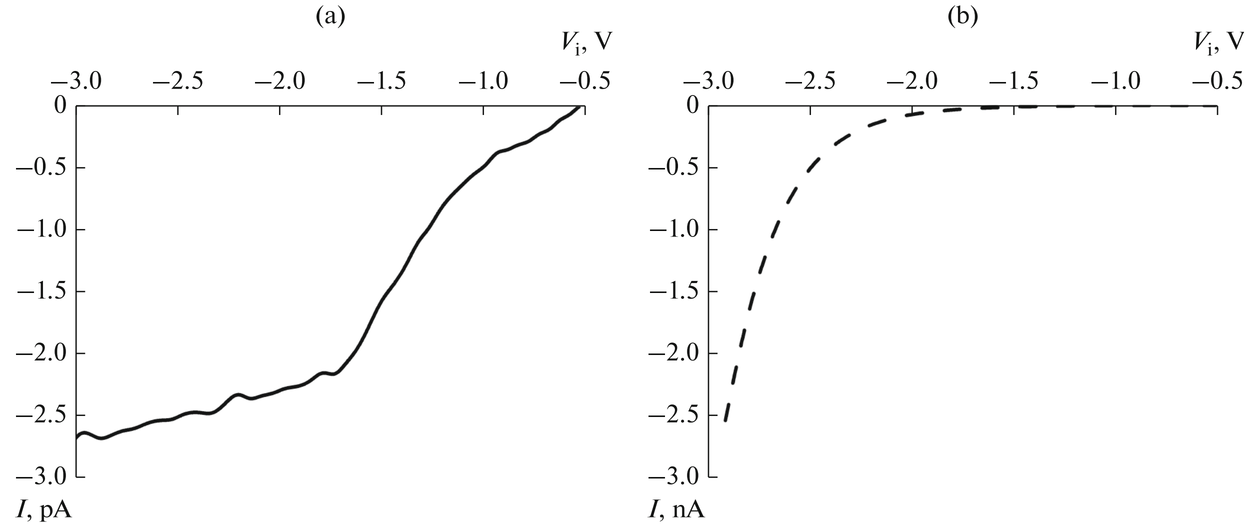

Fig. 3. Current–voltage characteristics of the insulating gap of the Si-MOS structure: (a) characteristics in the dark, (b) backlight characteristics.

practically compensate for the charge of the depletion layer and reduce its thickness to a size on the order of the Debye screening length. Note that, when the hole production rate increases and reaches a certain threshold value, then in the process of transfer of charge carriers of both types, instead of the depletion layer, the $Si-SiO_2$ interface in a region with local quasi-neutrality is formed, in which the recombination of holes and electrons will occur. Since the technique for processing high-frequency current-capacitance characteristics [8] is based on the Boltzmann distribution of the majority charge carriers, its results become inapplicable under conditions of the formation of such nonequilibrium regions with local quasi-neutrality at large V_g.

Secondly, the supernonlinear and much sharper than in the dark dependence of the current on the field in the oxide under illumination (see Fig. 3) indicates the direct effect of light on the process of electron tunneling through the barrier created by the insulating layer of the Si-MOS structure. It is natural to associate such behavior with the Franz–Keldysh effect [9–11]. The absorption of an electromagnetic field quantum by an electron in the field electrode is allowed, since the wave functions of free charge carriers here are not plane waves and sag significantly in classically inaccessible area under the barrier. The overlap of these functions in the sub-barrier region determines the probability of absorption of light energy and electron tunneling at a higher level through a reduced barrier (Fig. 4).

Note that structures with ultrathin tunnel-conducting insulating layers are suitable objects for the manifestation of the Franz–Keldysh effect. They have high internal fields and the observation of the results of

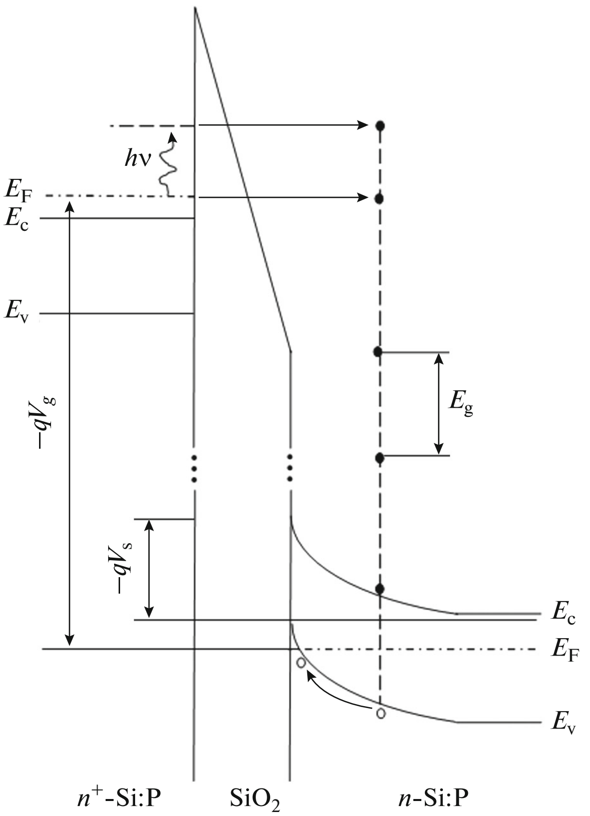

Fig. 4. Band diagram of the Si-MOS structure with ultrafine oxide in the depletion state: E_c is the bottom of the conduction band, E_v is the valence band ceiling, E_g is the band gap in silicon, E_F is the Fermi level, h is Planck's constant, ν is the frequency of the incident light wave.

exposure to light is possible at low external voltages almost immediately after the violation of detailed equilibrium.

CONCLUSIONS

The revealed high sensitivity of Si-MOS structures with ultrafine oxide to illumination when using low external voltages raises the question of the possibility of using these objects as sensors of electromagnetic radiation. The presence or absence of competitive advantages of such structures in comparison with the existing devices for fixing the electromagnetic field in various frequency ranges can be clarified only after detailed studies of the results of exposure to radiation. It is necessary to obtain spectral data on the sensitivity of Si-MOS structures with ultrafine oxide to irradiation and the reaction thresholds of these objects in different frequency ranges. Note that in the course of theoretical analysis in the course of these studies, it should be taken into account that the real shape of the potential barrier in the ultrathin SiO_2 insulating layer is far from rectangular [12, 13]. Therefore, direct application of the formulas of modern theory [11] to the experimental results of studying the Franz–Keldysh effect in Si-MOS structures with ultrathin oxide is impossible and modification of the necessary expressions will be required.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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