THE PHOTOELECTRET STATE IN THERMALLY TREATED SILICON FILMS WITHOUT EXTERNAL POLARIZING FIELD

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A simplified technology for the fabrication of Si films in the photoelectret state (PES), which is based on the thermal treatment of the films in air, is reported. The state arises due to the illumination of a film without the application of an external polarizing field. The results of experimental researches are discussed, and their physical interpretation in the framework of the model with two deep levels is given.

It is known [1] that the PES is observed in semiconductors on the generation of nonequilibrium charge carriers in them, spatial separation of electrons and holes by an external electric field, and fixation of separated carriers at deep local levels. In work [2], the possibility for a PES to emerge—without the application of an external polarizing field—in semiconductors with $p-n$-junctions was demonstrated, and the corresponding theory was elaborated. The role of a polarizing field is played by internal fields at $p-n$-junctions. In work [3], the theory of PES in homogeneous semiconductors with the Dember mechanism of photovoltage was developed. Unlike the case of traditional photoelectrets, the photoelectret of this type can be created—as was done in work [2]—making use of illumination without the application of an external field. In this case, the difference between electron and hole mobilities becomes the polarizing factor.

The PES was experimentally found in Na_2S:Sb_2S_3 [4] and CdTe:Ag [5] films held in air at room temperature, Si films [6], and Si:Ag films [7].

The technology used for the film fabrication and the film doping [4, 5, 7] is a complicated process which depends on the temperatures of the substrate and the evaporator, the composition and the pressure of residual gases in the chamber, the film thickness, and so on. At the same time, the technology, where films are held in air at room temperature for a long time (3 to 4 months and even longer), is not always controllable.

The purpose of this work was to elaborate a simplified controllable technology for the fabrication of photoelectrets on the basis of Si films, to study their properties, and to give physical interpretation of the results obtained.

The fact that the PES was found in thermally treated Si films extends the range of materials, where this state has been observed, and the number of methods appropriate for the fabrication of those materials without the application of an external polarizing field. The studies of PES induction without an external polarizing field are important for both the physics of the photoelectret effect in semiconductors and the researches of properties of thin films. From the practical point of view, it is of interest to produce photoelectrets with large values of photoelectret voltage by means of illumination only.

Films to study were fabricated by the thermal evaporation of single-crystalline silicon under vacuum of about 10^{-5} mmHg from a crucible made of BeO onto glass substrates treated beforehand in distilled water, acetone, and alcohol in turn, and dried in air. The crucible was heated to a temperature of $(1350-1450)$ °C by passing a current through it. Substrates were heated by an furnace built into a substrate holder. The temperature of substrates was 350 °C, their thickness $1.5-2$ μm, and the molecular beam stroke the substrate at an angle of $(45-50)^\circ$. The films obtained were cooled down in vacuum; then they were removed in air.

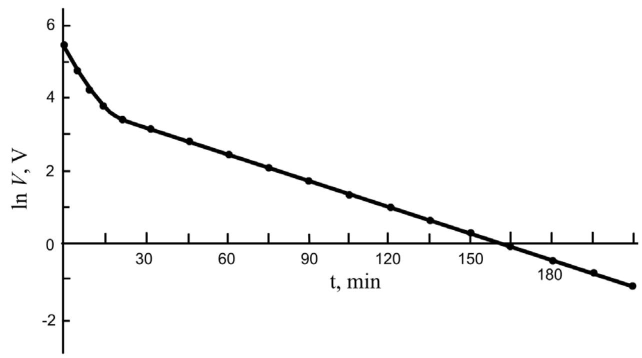
The photovoltage was measured by means of S-50 and S-95 electrostatic voltmeters. The films fabricated in a way described above generated an anomalously high photovoltage [8, 9]; however, the photoelectret voltage was absent in such as-evaporated films.

Silicon films were thermally treated in air, in a muffle furnace, and at temperatures ranging from 50 to 450 °C. The treatment was carried out in the following regime. Specimens to study were put into the muffle furnace, which had already been heated up to the given temperature, and held inside at this temperature for a definite time interval. Then, the specimens were withdrawn from the muffle furnace, cooled down to room temperature, and subjected to measurements. The maximal photoelectret voltages were observed when the heat treatment was carried out for 5 min at 300 °C.

When the silicon films were illuminated, an anomalously high photovoltage arose across them, which was registered by an electrometer. Then, the electrodes were short-circuited in darkness for a few seconds, in order to exclude the direct influence of free charge carriers that appeared at the illumination. When the specimen was connected to the electrometer again, the latter showed the presence of a photoelectret voltage V. The corresponding V-value first increased in time (within 10 to 15 s), reached the maximum, and then slowly relaxed. The maximal value of the photoelectret voltage and the relaxation time constitute the key characteristics of the PES.

The results of our study of the relaxation of a photoelectret voltage across thermally treated silicon films are depicted in the figure. The relaxation curve can be considered as consisting of two components: the first one is a section with a rather fast declination, and the second is characterized by a slow declination. The analysis of the dependence $\lg(It)$ on $\lg I$, where I is the intensity of light and t the time of photopolarization, showed that the law of interchangeability [10], which is obligatory for the photoelectret effect to manifest itself, is obeyed.

To explain our experimental results, we—similarly to what was done in work [6]—assume that, when Si films are thermally treated, oxide layers Si–SiO_2 are formed on the surface of small Si crystals, which the films consist of. It is known [11] that two systems of surface levels with two relaxation times are typical of such junctions. Let us apply the theory developed for single-level systems [2, 3] to this case. We assume that the levels do not interact, and the concentration of nonequilibrium carriers is much lower than the concentration of equilibrium ones. Then, taking the electroneutrality condition into account, we



Relaxation of the photoelectret voltage in Si films thermally treated at 300 °C for 5 min

obtain

$$V = V_1 \exp\left(-\frac{t}{\tau_1}\right) + V_2 \exp\left(-\frac{t}{\tau_2}\right), \quad (1)$$

where (V_1, τ_1) and (V_2, τ_2) are the maximal photoelectret voltage and the characteristic lifetime of nonequilibrium charge carriers at the first and the second level, respectively, and V is the resulting photoelectret voltage at the time moment t.

The initial section, where V falls down rather quickly, corresponds to a shallow level; it is described by the first term in expression (1). The second level participates in the relaxation process too, but its contribution to the total photoelectret voltage is much less here. Such a situation is observed till $t = \tau_1$, when the contributions of both levels become of the same order. Afterwards, the concentration of nonequilibrium charge carriers generated by heat from the second level is higher than the concentration provided by the first level, and V is governed by the second term in expression (1).

We used this plot to determine the main characteristics of the relaxation process: $V_1 = 165$ V, $V_2 = 55$ V, $\tau_1 = 8$ min, and $\tau_2 = 35$ min.

Thus, in this work, it was demonstrated that photoelectrets can be fabricated making use of thermally treated silicon films, by illuminating them without the application of an external polarizing field. The law of interchangeability, which is necessary and sufficient for the PES to exist, was shown to be fulfilled. It was demonstrated that the PES in thermally treated silicon films can be explained in the framework of a model with two deep levels. The main characteristics of the relaxation process were determined, and the role of each level in it was elucidated. The photoelectrets concerned can be implemented as memory elements and in electrophotography.

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ФОТОЕЛЕКТРЕТНИЙ СТАН БЕЗ ЗОВНІШНЬОГО ПОЛЯРИЗУЮЧОГО ПОЛЯ В ТЕРМООБРОБЛЕНИХ ПЛІВКАХ КРЕМНІЮ

Г.А. Набієв

Р е з ю м е

Наведено розроблену спрощену технологію одержання плівок Si з фотоелектретним станом, що виникає без зовнішнього поляризуючого поля в результаті одного лише освітлення, яка заснована на термічній обробці плівок на повітрі, експериментальні дослідження та фізичну інтерпретацію одержаних результатів на основі моделі з двома глибокими рівнями.