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EFFECT OF CHARGE SEPARATION ON A *pn* JUNCTION IN THE DIAMOND-LIKE CARBON-SILICON SYSTEM STIMULATED BY OPTICAL RADIATION

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The possibility of creating efficient silicon solar cells in the diamond-like carbon-silicon system is investigated. It is ascertained that a necessary condition is retention in an iron-doped carbon film of the short-range order of a diamond lattice that is coordinated with a silicon lattice and the formation of a pn junction on this basis.

Introduction. We investigate the mechanism of processes in a thin carbon film that has an oriented diamond lattice in the short-range order and reveals when doped with iron the properties of an *n*-region as part of a silicon solar cell. A lightly doped *p*-type silicon water with orientation (111) served as a medium for producing a charge plasma in a solid by irradiation with visible light. To separate light-generated charges on the silicon surface, we created an optically transparent n^+-layer of carbon of diamond modification whose composition analysis and method of production are given below.

1. General Conditions Required for the Operation of a Solar Cell. The evolution of the solar cell brought the *pin* (or *nip*) structure into being. The *i*-region, which is not doped by intrinsic conductivity, forms the main region of light absorption, whose thickness for single-crystal silicon is about 10 μm. Charge separation, i.e., the generation of an electromotive force under the action of sunlight, occurs once the free charge carriers that are produced by the photoeffect reach the current-collecting electrodes at the boundaries of the *p*- and *n*-regions. In the general case, the efficient operation of a solar cell is possible if the drift length of the charge carriers $L = \mu\tau E$ is of the same order as the thickness of the absorption region. If the *pn* structure is entirely based on a basis of the single-crystal silicon structure where the charge carriers has a large diffusion length ($\simeq$ 200 μm), charge separation occurs without special evolution of an *i*-region. In the special case in which the *pn* structure of the solar cell is made of a polycrystalline or amorphous material, when the diffusion line of the charge carriers is insignificant (for example, in polycrystalline silicon α-Si:H, it is $\simeq$ 100 nm), one should take into account the field dependence of the drift length L and the effective dimensions of the *i*-region [1].

Further improvement of the solar cell is limited by the poor electrical properties of the doped and especially *p*-regions (the insignificant drift length, the small lifetime of the charge carriers). The fraction of the light absorbed by these sections (for example, in the case of the α-Si:H structure) practically does not lead to the formation of free charge carriers. The way out can be found in the variation of different materials for the *p*- and *n*-regions. Taking into account the possibility of producing diamond-containing films that reveal, for orientations $(110)_C$ // $(110)_{Si}$ and $[111]_C$ // $[011]_{Si}$, epitaxial growth of carbon of diamond modification [2] that is coordinated with the silicon lattice, it seems possible to use this material to solve the indicated problem.

2. Diamond-Like Carbon Film as an n^+-Region of a Silicon Solar Cell. To deposit a layer of diamond-like carbon on silicon, we used the decomposition of carbon-containing compounds in a plasma of low pressure. For this purpose, we used a Radical ion source, into the discharge gap of which a mixture of hydrocarbon vapors and argon in a 1:2 ratio was supplied via an SNA-2 batching system. At a pressure of 0.1 – 1 Pa, the ion flow was guided to a grounded screen made of iron, after the reflection from which active particles of the plasma hit the silicon

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Fig. 1. Typical electron-diffraction pattern for the texture of carbon of diamond modification in the initial stage of film growth.

Fig. 2. Typical electron-diffraction pattern of a diamond-like film in a later stage of deposition after filling of the silicon surface with carbon.

specimen, which was heated to the substrate temperature of 873–1073 K. The state of the crystallization medium was controlled by diagnosing the static potentials of the plasma by the procedure presented in [3]. An electron diffraction analysis of diamond microformations produced in the process was performed most completely earlier in [2]. A typical picture of the texture of the carbon of diamond modification in the initial stage of growth of the C-film is presented in the electron-diffraction pattern of Fig. 1. Here, we can see a weak ring of a finely divided phase of the polycrystalline diamond, which corresponds to interplane distance 111 in the overall image of the multidomain texture in the direction $[011]_C$ of the diamond lattice, which coincides with the direction of the electron beam of the microscope for an electron energy of 120 keV. In the later stage of the deposition of the diamond-like carbon film, once the silicon surface is filled with the carbon the main and forbidden reflections of the reciprocal lattice on the electron-diffraction pattern change to Debye–Sherrer rings, after which the electron-diffraction pattern of the diamond-like film appears as a superposition of polycrystals whose interplane distances are not strictly identified (see Fig. 2). Therefore, in this case it can be stated that for the general violation of the long-range order at distances that correspond to the domain dimensions, the short-range order formed by sp^3-bonds of the diamond lattice of the carbon is retained. The general orientation of the microfragments of the diamond-like film lattice with respect to the silicon substrate that corresponds to orientation relations in nucleation is also retained. In general, this ensures a reduction in the potential barrier between the two lattices.

According to the assumption of [4] that a material does not lose its semiconductor properties as long as its short-range order is retained, the long-range order of the crystal has only a minor effect on its semiconductor properties proper. In our case, the efficient use of the diamond-like film produced is favored by its transparency in the visible optical range, a refractive index that is close to that of natural diamond, the possibility of doping, and mechanical strength.

To achieve an appreciable light-induced charge-separation effect in the silicon, we deposited onto its surface the above-described diamond-like film with a thickness of under 0.1 μm doped with iron in deposition by sputtering of a metal screen by argon ions. In this case, *n*-type conductivity of the film with respect to the substrate ions was attained. Not only did the analysis of the electron spectra confirm the presence of atoms of the sputtered metal in the film but also made it possible to reveal an appreciable presence of oxygen. This is explained by the penetration of oxygen atoms from the atmosphere with the subsequent passivation of excess ruptured bonds in the freshly prepared film.

The dark resistance of the *pn* junction when a potential of 1 V was applied had the order 10^3 Ω in the forward direction and 10^4 Ω in the reverse. In illumination by by a 60-W daylight lamp, the stably maintained no-load voltage of the photocell turned out to be equal to 0.5 V, which is certainly associated with the forbidden band of the silicon. However, a smooth increase in the no-load voltage to 2 V with subsequent breakdown was simultaneously observed. The indicated voltage peak is most likely associated with activation of the forbidden band of the diamond. This maximum voltage could be stably maintained by using special regimes of doping. Increasing the n^+-region thickness over 0.1 μm led, in our case, to a sharp reduction in the maximum voltage, since most of the free charge carriers, because of the limited drift, did not reach the current-collecting surface of the diamond-like film.

On the whole, the operating efficiency of the solar cell produced can be characterized by the fact that by increasing the illumination we were able, for an initial voltage of several millivolts, to record an increase in the no-load voltage of the cell by 2–3 orders.

The obtained results demonstrate the possibility of creating efficient silicon solar cells in the diamond-like carbon-silicon system. A necessary condition is retention of the short-range order of the diamond lattice coordinated with the silicon lattice with the formation of a *pn* junction on this basis.

NOTATION

L, drift length for charge carriers; μ, charge carrier mobility; τ, lifetime of charge carriers; E, internal electric field strength.

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