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Exciton polariton generation by field of a beta-particle moving into an ultrathin diamond-like layer

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Abstract

Beta-particles can be utilized as an independent tool of study of new semiconductors, in particular thin diamond films. They are still the secondary particles that are emitted as a result of nucleus reactions caused by irradiation of the crystal by other particles. In this Note, the effect associated with response of a quasi-two-dimensional diamond-like layer to the moving electron field is considered. The beta-particle field induces exciton modes to arise in the material. Coupled with the beta-particle electromagnetic modes they generate polaritons. Spectral density of the radiation intensity of the flashed polaritons has been estimated as a function of the layer thickness as well as of the scattering angle and the beta-particle velocity. ***To cite this article: V.V. Rumyantsev, C. R. Physique 7 (2006).***

Résumé

Génération de polaritons d'excitons par le champ d'une particule beta se déplaçant dans une couche ultra-fine de type diamant. Les particules bêta peuvent être utilisées comme outil indépendant pour l'étude de nouveaux semi-conducteurs, en particulier des films minces de diamant. Ils sont aussi les particules secondaires provenant de l'irradiation du cristal par d'autres particules. Dans le présent article, on considère l'effet associé à la réponse d'une couche quasi-bidimensionnelle de type diamant au champ d'un électron mobile. Le champ de la particule bêta induit des modes d'excitons. Le couplage de ces excitons avec les modes électromagnétiques de la particule bêta engendre des polaritons. La densité spectrale de l'intensité des polaritons est estimée en fonction de l'épaisseur de la couche, de l'angle de diffusion et de la vitesse de la particule bêta. ***Pour citer cet article : V.V. Rumyantsev, C. R. Physique 7 (2006).***

1. Introduction

Thin diamond-like structures and especially diamond thin films, which promise to be a new semiconductor rivaling silicon, are important materials for electronics [1]. Advance of technology allowing growth of ultrathin films and periodic structures with controlled characteristics has led to an increasing use of similar objects in special applications [2–4]. Search for methods of diagnostic of quasi-two-dimensional sample (such as thin film or near-surface crystal

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layer) enabling one to control of various processes in it is thus of a great importance. Irradiation of crystal by photons, neutrons or electrons is one of methods of examination of a crystalline structure. The present Note deals with the effect associated with response of a diamond-like crystal layer to the electromagnetic field of a moving electron. Study of a layer affected by a beta-particles flow should be of an interest for two reasons: first, irradiation by charged particles has become a frequently employed method for investigation of properties of different materials and, secondly, because irradiation of an arbitrary nature causes the material nuclei to emit secondary particles including beta-particles. Although charged particles interact strongly with material, depth of their penetration into crystal is relatively small [5]. It is therefore important to study excitation of the electronic subsystem of an ultrathin crystalline layer by a β-particle field. We find necessary conditions for generation of the Cherenkov radiation and calculate its spectral density.

2. Dispersion of exciton polariton, localized in ultrathin crystalline layer

Dispersion of polaritons in bulk samples was intensively investigated (see, e.g., [6]). This phenomenon presents an interest for study of nano-films of thickness d of the order of the excitation radius. This article concerns of an ultrathin diamond-like layer interaction with the electromagnetic field of a beta-particle moving into the layer. The interaction of excitonic and electromagnetic modes results in the arising of polaritons of a specific dispersion law for the quasi-two-dimensional layer.

Dispersion of polaritons near the exciton transition of the structural unit (SU) spectrum has been considered within the microscopic approach [7]. An appropriately chosen SU yields a common description for crystals with different chemical bonds, such as atomic cryocrystals (with the SU being a separate atom) or valent semiconductors (with the SU represented by the nearest neighbours σ-bond). Valent crystals quasi-molecular model [7,8] made it possible to utilize the calculating technique developed earlier for molecular crystals. This allowed one to describe the internal field in a diamond-like crystal and to calculate the limiting exciting frequencies for diamond and silicon. There is a significant difference between molecular and valent crystals though. An excited state in the former is a 'true' one; its living time is limited by radiation only. As for valent crystals, their excitons are metastable (excitation levels being in the continuous spectrum $h\omega > E_G$, where E_G denotes the forbidden band width). The life time of such excitons is limited by the electron-hole pair disintegration time. Note that diamond-like crystals such as silicon are indirect forbidden gap semiconductors. Distance between the points Γ_{15} and Γ'_{25} in the centre of their Brillouin zone is approximately 2.5 eV. Therefore optical transitions for $\hbar\omega$ exceeding this value are the direct ones [9,10].

Response of an ultrathin crystalline layer to the electromagnetic wave of the frequency ω and the wave vector $\vec{q}$ ($d \ll 2\pi/q$) lying in the plane of the film was studied as a model problem in [11]. The field-induced polarization $\vec{\Pi}$ of the quasi-two-dimensional layer has been described within a continual approximation. In this case, it is convenient to employ the Maxwell equations with sources on the surface in the $(\omega, \vec{q}, z)$-representation. This way we will be able to eliminate the field components normal to the film, expressing them in terms of the planar components using $(\vec{\alpha}, \vec{\beta}, \vec{n})$ vector basis ($\vec{\beta} = \vec{q}/q$, $\vec{\alpha} = \vec{n} \times \vec{\beta}$). The resulting set of equations will consist of two linearly independent systems describing s- and p-modes. Polaritons will arise as a result of interaction between excitonic and electromagnetic modes (of the $\vec{E}_e$ field of a β-particle). The dispersion relations for one normal n-mode and two planar t-modes localized in the layer are the following:

$$\begin{aligned}
&\left\{2\pi\left(q^2 - \omega^2/c^2\right)^{1/2} + \left[\chi_{t(\beta\beta)}(\omega)\right]^{-1}\right\}\Pi_\beta = a^{-3}\left[E_e(\omega,\vec{q})\right]_\beta \\
&\left\{2\pi q^2\left(q^2 - \omega^2/c^2\right)^{-1/2} - \left[\chi_{n(nn)}(\omega)\right]^{-1}\right\}\Pi_n = a^{-3}\left[E_e(\omega,\vec{q})\right]_n \\
&\left\{2\pi\frac{\omega^2}{c^2}\left(q^2 - \omega^2/c^2\right)^{-1/2} - \left[\chi_{t(\alpha\alpha)}(\omega)\right]^{-1}\right\}\Pi_\alpha = a^{-3}\left[E_e(\omega,\vec{q})\right]_\alpha
\end{aligned} \tag{1}$$

Here a, $\hat{\chi}$ are the lattice constant and the layer polarizability respectively. Dispersion curves corresponding to Eqs. (1) are shown in Fig. 1. Fig. 2 depicts the geometry of a scattering electromagnetic wave.

Let us consider the particular case of a β-particle moving into a diamond-like crystalline layer. Its velocity $\vec{v} = v\vec{e}$ is assumed to be directed along the normal, $\vec{e} \parallel \vec{n}$. We want to express the velocity v as $v = \gamma c$ (where c is light velocity and γ is the value of velocity of the particle reduced with respect to c) and the vector $\vec{k}$ of the β-particle electromagnetic wave as $\vec{k} = k\vec{s}$. In terms of these notations we get $\vec{v} = (v_\alpha, v_\beta, v_n) = (0, 0, -c\gamma)$, $q = k\sin\theta$, $\vec{e}\cdot\vec{s} = \cos(\pi - \theta) = -\cos\theta$, $s_n = \cos\theta$, $s_\beta = \sin\theta$ (see Fig. 2). Hence the Fourier components of the electromagnetic field $\vec{E}_e$ are the following:

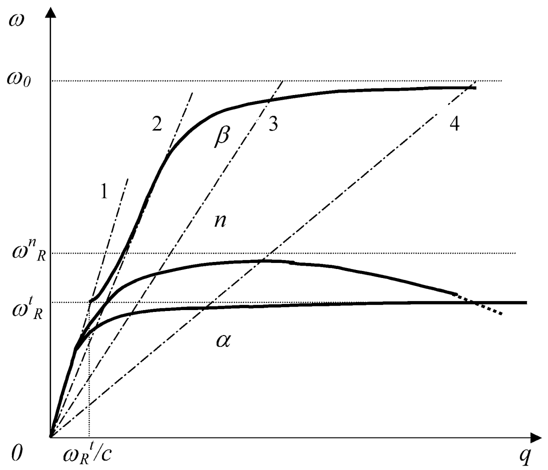

Fig. 1. The points of crossing of lines $\omega = \gamma cq\,\mathrm{ctg}\,\theta$ with polariton curves reflect the double resonance (both on frequency ω and wave vector $\vec{q}$) and correspond to generating of polariton localized in layer.

Fig. 1. Les points de croisement des lignes $\omega = \gamma cq\,\mathrm{ctg}\,\theta$ avec les courbes correspondent aux polariton reflètent la double résonance (à la fois pour la fréquence ω et le vecteur d'onde $\vec{q}$) et correspondent à la génération de polaritons localisés dans la couche.

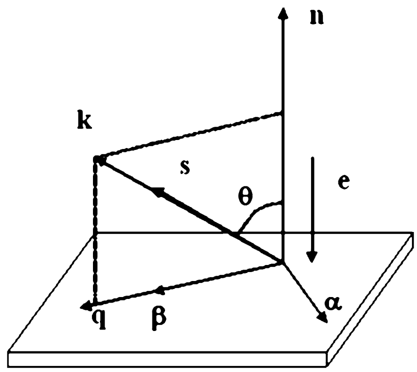

Fig. 2. Geometry of the scattering electromagnetic wave accompanying β-particle.

Fig. 2. Géométrie de l'onde électromagnétique qui accompagne la particule.

$$
\begin{aligned}
&E_\alpha(\omega,\vec{q}) = 0\\
&E_\beta(\omega,\vec{q}) = -4\pi\,\mathrm{ie}\frac{\sin^2\theta}{q(1-\gamma^2\cos^2\theta)}\delta(\omega - \vec{k}\cdot\vec{v})\\
&E_n(\omega,\vec{q}) = -4\pi\,\mathrm{ie}\frac{\sin\theta\cos\theta(1-\gamma^2)}{q(1-\gamma^2\cos^2\theta)}\delta(\omega - \vec{k}\cdot\vec{v})
\end{aligned}
\tag{2}
$$

The corresponding Green functions have the form:

$$
G_{\beta\beta}(\omega,q) = \frac{1}{2\pi}\left(\sqrt{q^2 - \frac{\omega^2}{c^2}} + \frac{2}{d(\varepsilon_\infty - 1)}\right)^{-1}, \qquad G_{nn}(\omega,q) = \frac{1}{2\pi}\left(\frac{q^2}{\sqrt{q^2-\omega^2/c^2}} - \frac{2\varepsilon_\infty}{d(\varepsilon_\infty-1)}\right)^{-1} \tag{3}
$$

The dielectric permeability ε_∞ has the value 5.7 for diamond, 11.7 for Si and 11 for GaAs.

3. Spectral density of radiation induced by field of a beta-particle moving into ultrathin diamond-like layer

Similarly to the case considered in [11], the generation of exciton polariton of a certain polarization in diamond-like quasi-two-dimensional layer by field of a moving β-particle is possible only at the condition of the double resonance (at the frequency ω and wave vector $\vec{q}$). Of the polaritons localized in the layer only those corresponding to intersection of the linear part of the dispersion curve (Fig. 1) with the direct line (which is the dispersion law for the β-particle field) are flashed immediately. It is readily seen in Fig. 1 that the intersection is possible only if the direct line characterizing β-particle lies between lines 1 and 2 which correspond to the velocity values v_1 and v_2. Polaritons moving at the velocities beyond v_2 (see Fig. 1) are flashed after scattering in the crystalline layer. This results in decrease of the polariton wave vector absolute value down to that typical for the linear part of the dispersion curve.

The intensity of radiation by layer SUs excited by β-particle field equals to the total work $\sum_l \vec{E}_{e\perp}(\vec{r}^l,t)\cdot\frac{\mathrm{d}\vec{P}^l_\perp}{\mathrm{d}t}$ produced by SU-dipoles $\vec{P}^l_\perp$ (where l is the index of the crystalline lattice cells) against the electromagnetic field of the β-particle. Summing over l can be replaced by surface integration as follows:

$$
I(t) = \int\limits_S \mathrm{d}^2 r\,\vec{E}_e(\vec{r},t)\cdot\frac{\mathrm{d}\vec{\Pi}(\vec{r},t)}{\mathrm{d}t} \tag{4}
$$

Therefore the expression $\langle I\rangle = I_\alpha(\theta,\gamma,d) + I_\beta(\theta,\gamma,d) + I_n(\theta,\gamma,d)$ for the averaged intensity of radiation (represented in the general case by α-, β-, n-polaritons) takes the form:

$$I_i(\theta,\beta,d) = \frac{1}{(2\pi)^2}\int_S \mathrm{d}^2 r \int I_i\big(q,\{\theta,\gamma,d\}\big)\exp(\mathrm{i}\vec{q}\cdot\vec{r})\,\mathrm{d}^2 q \tag{5}$$

where $i=\beta,n$. As we consider electron motion normal to the surface (see Fig. 2), therefore $I_\alpha = 0$. Spectral density $I_i(q,\{\theta,\gamma,d\})$ depends on several parameters, which are the angle θ reflecting the geometry of the problem, the layer thickness d and the reduced β-particle velocity γ. The spectral density of β- and n-polarized polaritons is the following:

$$I_\beta\big(q,\{\theta,\gamma,d\}\big) = 8\pi\frac{\mathrm{e}^2 c}{a^3}\frac{\gamma\sin^3\theta\cos\theta}{(1-\gamma^2\cos^2\theta)^2}\int_0^{2\pi}\mathrm{d}\varphi\int_0^q \frac{\mathrm{d}q'}{|\vec{q}-\vec{q}'|\sqrt{1-\gamma^2\,\mathrm{ctg}^2\theta}+\frac{2}{d(\varepsilon_\infty-1)}} \tag{6}$$

$$I_n\big(q,\{\theta,\gamma,d\}\big) = 8\pi\frac{\mathrm{e}^2 c}{a^3}\frac{\gamma\sin\theta\cos^3\theta(1-\gamma^2)^2\sqrt{1-\gamma^2\,\mathrm{ctg}^2\theta}}{(1-\gamma^2\cos^2\theta)^2}\int_0^{2\pi}\mathrm{d}\varphi\int_0^q \frac{\mathrm{d}q'}{|\vec{q}-\vec{q}'|-\frac{2\varepsilon_\infty}{d(\varepsilon_\infty-1)}\sqrt{1-\gamma^2\,\mathrm{ctg}^2\theta}} \tag{7}$$

Here φ denotes the angle between wave vectors $\vec{q}$ and $\vec{q}'$. In order to obtain physically meaningful results from formulae (6) and (7) we must restrict the parameter θ value by the condition

$$\big[1-o(q,q',\varphi)\big]/\gamma < \mathrm{ctg}\,\theta \leqslant 1/\gamma \tag{8}$$

The small value $o(q,q',\varphi) = qd\frac{\varepsilon_\infty-1}{4\varepsilon_\infty}\sqrt{1+(\frac{q'}{q})^2-2(\frac{q'}{q})\cos\varphi}$ is of the order of $qd \ll 1$.

Angular variables should be expected to behave similarly when approaching zero. Hence we get spectral density (7) in the form:

$$I_n\big(q,\{\theta,\lambda,d\}\big) = (4\pi)^2\frac{\mathrm{e}^2 c}{a^3}\frac{\gamma(\gamma+1/\gamma)(1-\gamma^2)^2\sin\theta\cos^3\theta}{(1-\gamma^2\cos^2\theta)^2}\frac{2\varepsilon_\infty}{qd(\varepsilon_\infty-1)} \tag{9}$$

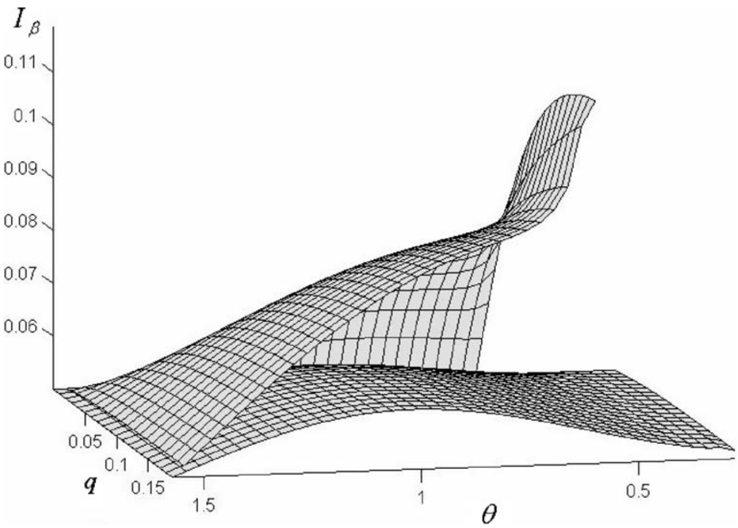

Fig. 3. Radiation spectral density I_β $(q,\{\theta,\gamma,d\})$ measured in units $(4\pi)^2\mathrm{e}^2c/a^3$ (q and θ are measured in units corresponding to $10a^{-1}$ and radians). First plot (below) relates to $\gamma=0.3$ and second—to $\gamma=0.7$, $d=5a$.

Fig. 3. Densité spectrale I_β $(q,\{\theta,\gamma,d\})$ mesurée en multiples de $(4\pi)^2\mathrm{e}^2c/a^3$ (pour θ l'unité est le radian et pour q elle est égale à $10a^{-1}$) pour $d=5a$. Le graphique du bas correspond à $\gamma=0{,}3$ et celui du haut à $\gamma=0{,}7$.

Substitution of the expression (9) into (5) allows calculating the radiation density, corresponding to flashing n-polaritons:

$$I_n(\theta,\gamma,d) = 32\pi \frac{e^2 c}{a^3} \frac{2\varepsilon_\infty}{(\varepsilon_\infty - 1)} \frac{\gamma(\gamma + 1/\gamma)(1-\gamma^2)^2 \sin\theta \cos^3\theta}{d(1-\gamma^2\cos^2\theta)^2} \frac{1}{r} \tag{10}$$

It follows from (10) that the radiation density of the layer SUs decreases as $1/r$ in the layer plane.

The results of numerical integration of (6) are presented in Figs. 3, 4 and 5. It is clearly seen that the dependence of I_β upon θ has the maximum at $\theta = 1.04$ for charged particles moving at small velocities (Fig. 3 corresponds to $\gamma = 0.3$). Comparison between Figs. 3 and 4 (corresponding to $d = 50a$) reveals a relatively weak dependence of I_β

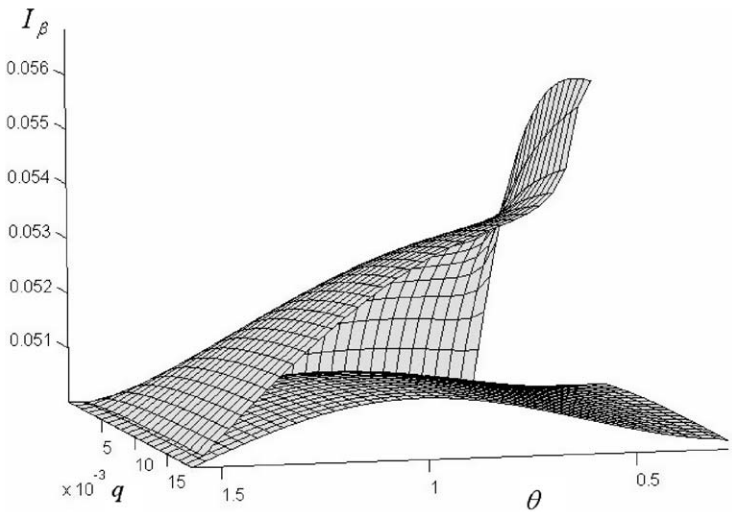

Fig. 4. Radiation spectral density I_β $(q, \{\theta, \gamma, d\})$ measured in units $(4\pi)^2 e^2 c/a^3$ (q and θ are measured in units corresponding to a^{-1} and radians). First plot (below) relates to $\gamma = 0.3$ and second—to $\gamma = 0.7$, $d = 50a$.

Fig. 4. Densité spectrale I_β $(q, \{\theta, \gamma, d\})$ mesurée en multiples de $(4\pi)^2 e^2 c/a^3$ (pour θ l'unité est le radian et pour q elle est égale à a^{-1}) pour $d = 50a$. Le graphique du bas correspond à $\gamma = 0{,}3$ et celui du haut à $\gamma = 0{,}7$.

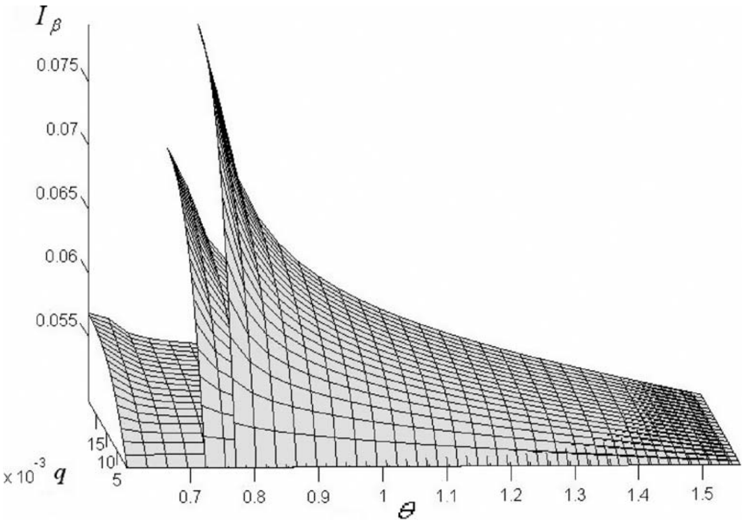

Fig. 5. Radiation spectral density I_β $(q, \{\theta, \gamma, d\})$ measured in units $(4\pi)^2 e^2 c/a^3$ (q and θ are measured in units corresponding to a^{-1} and radians). First plot (below) relates to $\gamma = 0.7$, second—to $\gamma = 0.9$ and third—to $\gamma = 0.99$, $d = 50a$.

Fig. 5. Densité spectrale I_β $(q, \{\theta, \gamma, d\})$ pour $d = 50a$. Les unités sont les mêmes que dans la Fig. 4. Les valeurs de γ sont, de bas en haut, $\gamma = 0{,}7$, $\gamma = 0{,}9$ et $\gamma = 0{,}99$.

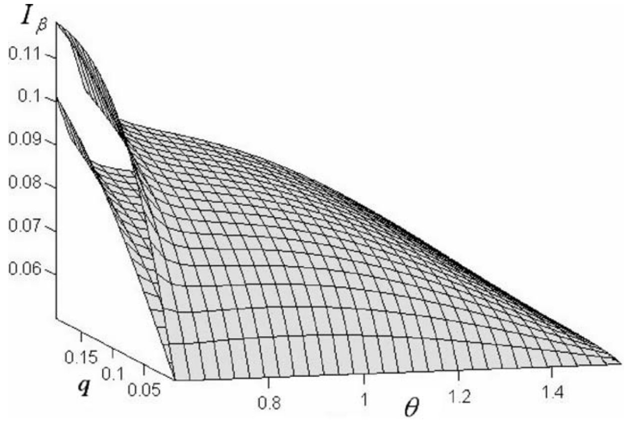

Fig. 6. Radiation spectral density I_β $(q, \{\theta, \gamma, d\})$ measured in units $(4\pi)^2 e^2 c/a^3$ (q and θ are measured in units corresponding to $10a^{-1}$ and radians). First plot (below) relates to diamond, second—to Si, $\gamma = 0.7$, $d = 50a$.

Fig. 6. Densité spectrale I_β $(q, \{\theta, \gamma, d\})$ pour $\gamma = 0{,}7$ et $d = 50a$. Les unités sont les mêmes que dans la Fig. 3. Le graphique du bas correspond au diamant et celui du haut à Si.

upon the layer thickness within the considered approximation $qd \ll 1$. Due to condition (8) the dependency $I_\beta(\theta)$ is left defined in a gradually shrinking range of θ values as γ increases (see Fig. 5). It also takes a monotonous character. Spectral density of radiation drops abruptly at $\theta \to \operatorname{arcctg} 1/\gamma$.

4. Conclusions

The present work deals with polaritons excited by field of a charged particle moving in an ultrathin diamond-like crystalline layer. Results concerning the intensity of the secondary electromagnetic radiation (being the flashing polaritons) were obtained. This may provide a way to solve one of the problems of detecting of particles (see, e.g., [12]). Similar problems arise when studying the influence of charged particles (e.g., proton 'solar wind') bombarding the surface layer of a semiconductor instrument (solar cells). Sustainable working of an installation applicable under the irradiation is then possible only at conservation of the material functional characteristics.

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