INFLUENCE OF PHOTON GENERATION ON THE LOW-ENERGY ELECTRON BAND-REFLECTION

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1. INTRODUCTION

An interest to the small angle reflection of relativistic particles from the crystal surface was initiated due to Kumakhov's papers [1, 2] where a possibility to carry the charged particle beams by reflection from the solid surface was shown. For reflection of positive particles with intermediate and high energies under glancing incidence the classical description is applicable and if the conditions of planar channeling are satisfied the mirror reflection will be observed at incidence angle less than the critical angle of planar channeling [3-5]. During reflection a positive particle is deflected by the crystal surface and electromagnetic radiation is generated. First theoretical consideration of this phenomenon was performed by Rozhkov [3, 4]. Under axial semichanneling particles are expected to be scattered by laying on a surface of atomic rows. When works [1, 2] were published the reflection of low-energy electrons due to scattering from surface atomic strings was studied by computer simulation [6] based on the pair collision model. It was shown that a significance part of particles (up to 15%) may be reflected owing to a correlative interaction. Later the mechanism of small-angular reflection of electrons and positrons, the main feature of which is the rainbow scattering on atomic strings, was proposed in [7] and the processes which cause electromagnetic radiation have been investigated [8-9]. However, from viewpoint of classical theory the reflection of low-energy electrons under planar semichanneling is impossible and the quantum consideration is required. Authors of [10] proposed a specific quantum mechanism of small-angular reflection of electrons from crystas surface i.e band reflection. The full theoretical and numerical investigation if this effect was made in [11]. It was established, that at some energies and crystals one can observe a band reflection for angles up to half of Lindhard angle. In addition, it has been noted that a band reflection is a result of coherence interaction of electron with a system parallel to surface atomic planes. That objection may follow to increase a radiation transition probability. In our work [12] this problem was studied and a new quantum coherent mechanism of electromagnetic radiation under planar semichanneling of electrons has been manifested. It has been shown that the transitions with caption of particles in surface channeling have a higher probability and it is expected to change the number of reflected particles. In present paper the influence of radiation processes on band reflection appearance is considered and showed that these effects have a maximum magnitude at quite different conditions.

2. REFLECTION COEFFICIENT

If spine effects ares neglected, the wave function of electron under planar semichanneling is a solution of well- known Schrodinger equation with the relativistic electron mass:

$$\frac{\hbar^2}{2M}\psi''(x) + \left(E_\perp - U(x)\right)\psi(x) = 0, \quad E_\perp = \frac{p_\perp^2}{2M},\; p_\perp = p\theta . \qquad (1)$$

Here $M = E/c^2 = m\gamma$ is the relativistic mass of electron; E and m are its energy and rest mass; θ is the glancing angle; function $U(x)$ is equal to 0, if $x < 0$ (vacuum) and has the period d_p, if $x > 0$ (crystal), where d_p is the distance between atomic planes being parallel to the surface. Under condition $x > 0$ a solution of Eq. (1) satisfies the Bloch theorem:

$$\psi\left(x + d_p\right) = \exp\left(iqd_p\right)\psi\left(x\right), \quad \psi'\left(x + d_p\right) = \exp\left(iqd_p\right)\psi'\left(x\right) \qquad (2)$$

In a forbidden band of spectrum of Eq. (1) the quasi-wave number q is complex and the amplitude of $\psi(x)$ decreases as the distance x from surface increases. In this case a total reflection of particles from surface is realized [10]. The positions of forbidden bands are determined by condition $D > 1$, where the discriminant D is defined by the formula

$$D = \frac{1}{2}\left(\psi_1\left(d_p\right) + \psi_2'\left(d_p\right)\right), \quad \psi_1(0) = 1, \psi_1'(0) = 0,\; \psi_2(0) = 0, \psi_2'(0) = 1 . \qquad (3)$$

The probability of radiation transition is dependent on a matrix element of the flax operator. It has been shown in [12] that the main part of this element arises from the «crystal» wave function ψ_{cr} or, in other words, the function $\psi(x)$ under $x > 0$. The value $\left|\psi_{cr}\right|^2 dx$ is proportional to a probability that an electron in the interval $[x, x + dx]$ will be found. Let us consider N_0 particles in the same quantum state. In this situation $\left|\psi_{cr}\right|^2 dx$ is proportional to a number of particles $dN(x)$, which have been detected in the interval $[x, x + dx]$:

$$dN(x)/N_0 = \left|\psi(x)\right|^2 dx \Big/ \int_0^\infty \left|\psi(x)\right|^2 dx .$$

If the transverse energy lies in a forbidden band a total reflection occurs and all N_0 will be reflected by crystal. In this case $dN(x)$ defines the number of particles which have penetrated from the surface up to a distance x and then undergo reflection in $[x, x + dx]$. Therefore, a value $dN(x)/N_0$ is equal to the probability of such events. Denoting $dN(x)/N_0$ as $W_{ref}\, dx$ and taking into account (2), one can obtain that the density $W_{ref}(x)$ is defined from the following formulae

$$W_{ref}(x)=\frac{\left|\psi(x)\right|^2}{N_e d_p\left\langle\left|\psi\right|^2\right\rangle_{ref}},$$
$$N_e=\frac{1-\exp\left(-2\left|q\right|N_{cr}d_p\right)}{1-\exp\left(-2\left|q\right|d_p\right)}, \qquad (4)$$
$$\left\langle\left|\psi\right|^2\right\rangle_{ref}=\frac{1}{d_p}\int_0^{d_p}\left|\psi(x)\right|^2dx$$

where N_{cr} is the common number of atomic planes being parallel to the surface. If electron has been reflected at the distance x, it moved in the crystal during $t=2x/\upsilon_\perp$, where $\upsilon_\perp=\frac{c\theta}{\gamma}\sqrt{\gamma^2-1}$ is the classical velocity along x direction. If, the function $W_{ref}(x)$ is known then it is easily to derive the analogous distribution of particles with respect to time intervals t:

$$\tilde{W}_{ref}(t)=\frac{\left|\psi(\upsilon_\perp t/2)\right|^2\upsilon_\perp}{2N_e d_p\left\langle\left|\psi\right|^2\right\rangle_{ref}}.$$

It follows from this equation that the value $d\tilde{N}(t)=$ $=N_0\tilde{W}_{ref}(t)dt$ is the number of electrons which will be in a crystal during the time t and cross the crystal-vacuum interfaceat the moment between t and $t+dt$. Some of this electrons will make radiation transition. Let $d\tilde{N}_{rad}(t)$ denote the number of such transitions

$$d\tilde{N}_{rad}(t)=\left(1-\exp\left(-W_{rad}t\right)\right)d\tilde{N}(t),$$

where W_{rad} is full probability of photon radiation. Common number of radiation transitions $\tilde{N}_{rad}$ is equal to

$$\tilde{N}_{rad}=\int_0^\infty d\tilde{N}_{rad}(t)=\int_0^\infty\left(1-\exp\left(-W_{rad}t\right)\right)d\tilde{N}(t)=$$
$$=N_0\int_0^\infty\left(1-\exp\left(\frac{-2W_{rad}x}{\upsilon_\perp}\right)\right)W_{ref}(x)dx \qquad .(5)$$

Using (4) one can obtain from (5) the part of electrons which have made the transition

$$n_{rad}=1-\frac{N_r}{N_e}\frac{\left\langle\left|\psi\right|^2\right\rangle_{rad}}{\left\langle\left|\psi\right|^2\right\rangle_{ref}}. \quad (6)$$

and the part of elastic scattered electrons:

$$n_{rad}=\frac{N_r}{N_e}\frac{\left\langle\left|\psi\right|^2\right\rangle_{rad}}{\left\langle\left|\psi\right|^2\right\rangle_{rad}}. \qquad (7)$$

In (6)-(7) used were the values N_r and $\left\langle\left|\psi\right|^2\right\rangle_{rad}$ which are expressed from the formulae

$$N_r=\frac{1-\exp\left(-2\left(\left|q\right|+\frac{W_{rad}}{\upsilon_\perp}\right)N_{cr}d_p\right)}{1-\exp\left(-2\left(\left|q\right|+\frac{W_{rad}}{\upsilon_\perp}\right)d_p\right)}, \qquad (8)$$
$$\left\langle\left|\psi\right|^2\right\rangle_{rad}=\frac{1}{d_p}\int_0^{d_p}\left|\psi(x)\right|^2\exp\left(-2\frac{W_{rad}}{\upsilon_\perp}x\right)dx$$

Let in the initial f-state the electron wave vector is $\vec{k}_f$. The g-state of electron after transition and the coefficient of reflection $R_{fg}(\vec{\kappa})$ are determined by $\vec{k}_f$ and by the wave vector $\vec{\kappa}$ of photon radiated. Therefore the effective coefficient of reflection in the f-state may be calculated as

$$R_{frad}=R_{0f}n_{ref}+\frac{n_{rad}}{W_{rad}}\int d^3\vec{\kappa}W_f(\vec{\kappa})R_{fg}(\vec{\kappa}), \quad (9)$$

where R_{0f} is the coefficient of reflection in the initial state, $W_f(\vec{\kappa})$ is the probability of transition from state (f) if the photon with the wave vector $\vec{\kappa}$ is emitted. Integrating in (9) is performed over all the possible forms of f-state radiation transitions [12].

3. DISCUSSION

The band reflection has a significance value if there is the wide forbidden band in the $E_\perp>0$ region the low bound of which lies near the $E=0$ level. An example of such a situation is the band «+1» in Fig. 1 Here the curve $D(\varepsilon)$ ($\varepsilon=(E_\perp/U_p)^{1/2}\mathrm{sign}(E_\perp)$, $U_p=2pZn_pe^2r_0$ is the typical value of a barrier of continuous plane potential, Z denotes the atom number of crystal atoms, n_p is the surface atom density of reflecting plane, r_0 is a screening length for potential of an isolated atom in the Thomas-Fermi model for the case of incidence of 0.819 MeV electrons on (111) surface of silicon (the value D was defined in (3)). It has been shown in [12] that only for neighbouring states radiation transitions will occur as an initial state belong to the band «+1». As the band «+1» has a large width for all states after transition with the sufficient accuracy the condition $R_{fg}(\vec{\kappa})\approx 1$ will be satisfied. Using (6)-(7) and that for the band «+1» $R_{0f}=1$ we have from (9) that

$$R_{frad}\approx R_{0f}n_{ref}+n_{rad}=1.$$

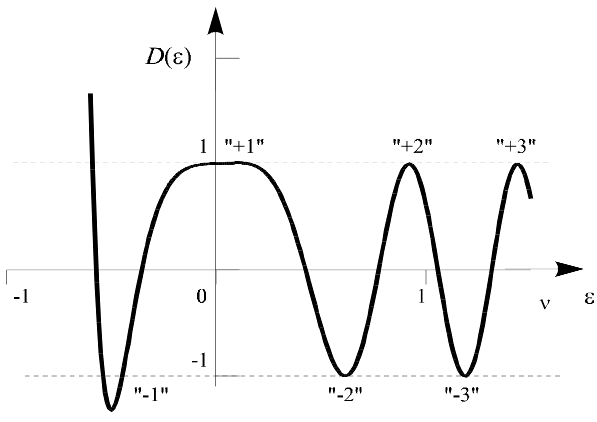

Fig. 1

It follows from this relation that under band reflection conditions the appreciable decreasing in the reflection coefficient owing to radiation processes is unexpected.

Let the transverse energy of initial state belongs to the band similar to that of «+2» in Fig. 1. In this case the band reflection actually is absent because of the very small forbidden bandwidth. For such states the probability of radiation transition is large and electrons goes to states with a small negative value of $E_\perp$. Such transitions correspond to radiation caption of particles into surface channeling motion. Because the state with $E_\perp < 0$ has a coefficient of reflection equal to zero, it is reasonable to substitute in (9) the relation $R_{fg}(\vec{\kappa}) \approx 0$ and after that action we have

$$R_{frad} \approx R_{0f} n_{ref} = n_{ref} .$$

Using (4), (7), (8) and taking into account that $|q|N_{cr} >> 1$, it is possible to find for value of n_{ref} the following condition

$$n_{ref} \le \frac{1 - \exp\left(-2\,|q|\,d_p\right)}{1 - \exp\left(-2\left(|q| + W_{rad}/\upsilon_\perp\right)d_p\right)} < 1 . \quad (10)$$

We can see that the reflection coefficient is less than 1, although the transverse energy of initial state lies in a forbidden band. Expression (10) demonstrates that at certain energies and an angle of incidence the number of reflected particles may be changed if the radiation processes ares very appreciable. However, our consideration shows, that the band reflection and electromagnetic radiation under planar semichanneling will appear in a different situation and the independent experimental examination for these interesting quantum effects is possible.

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