Photogalvanic effect induced by an electric field

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Abstract. Light-induced charge transport that occurs in crystals containing centres with permanent dipole moment due to their polar orientation is considered. Principal attention is paid to the situation when such dipolar centres are oriented by application of an external electric field. In this case, we may regard the current generation as caused by an electric-field-induced photogalvanic effect. In contrast to conventional photogalvanic phenomena, the effect under consideration can be observed in crystals of arbitrary symmetry and even in any condensed matter containing photoactive dipolar centres. A remarkable feature of the effect is noncollinear orientation of the current vector with respect to the electric field vector, which is a consequence of the discrete set of orientations available for the dipole centres’ positions. It is shown that this feature could significantly facilitate experimental observation of the electric-field-induced photogalvanic current. Here, a phenomenology description and qualitative model of the effect are presented and its possible impact on the effect of absolute negative conductivity is discussed.

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1. Introduction

The impurities or impurity complexes (including associates with intrinsic lattice defects) in crystals frequently possess noticeable permanent dipole moment. The off-centre impurity ions, polar molecules (OH, CN) or complexes of a type of donor–acceptor pairs arising due to the local compensation of excess charges are typical representatives of the dipolar centres. Physical phenomena such as the optical alignment of dipolar centres [1]–[4] and the linear photogalvanic effect (LPGE) (see [5] and references therein) stem from certain symmetry features of dipolar centres resulting from the existence of permanent dipole moment. While the first effect is caused by anisotropy of the light absorption coefficient of the dipolar centres, the microscopic origin of the second effect is based on asymmetry (with respect to the electron momentum) of optical excitation from, radiative recombination on, or scattering of free charge carriers from the dipolar centres. Recently the existence of new effects caused by symmetry features of dipolar centres has been discussed [6]–[8]. In particular, electric polarization of piezoelectric crystals due to optical alignment of dipolar centres occupying asymmetric positions in the lattice has been predicted [8]. It was shown also that some effects originating from the asymmetry of electronic processes can be observed under the conditions of electric current flow through a sample [6, 7].

In this paper, a novel class of transport phenomena is discussed, which depend on the sample polarization, $P_{\text{ext}}$, caused by reorientation of dipolar centres. Principal attention is paid to the electric-field-induced LPGE (FIPGE). It manifests itself as the generation of the steady-state photocurrent, $J^{\text{DG}}$, arising from the momentum asymmetry of electronic processes occurring with participation of dipolar centres oriented by means of the external electric field, $E_{\text{ext}}$. In contrast to LPGE (which occurs only in crystals without inversion symmetry) there is no symmetry restriction for observation of FIPGE. Therefore, it can be found in crystals of arbitrary symmetry and even in any condensed matter containing the photoactive dipolar centres. According to the theory of the photogalvanic effect [5], the relaxation time of the photogalvanic current is determined by the process of isotropization of the asymmetric distribution function for photoexcited non-thermalized electrons. In other words, this is the process of the electron’s momentum relaxation due to interaction (scattering) with phonons and impurities. This relaxation time is usually of the order of $10^{-12}$–$10^{-14}$ s, which is much faster than the lifetime of photoexcited charge carriers in the corresponding band. Such a fast relaxation time was recently confirmed in experiments with circular photogalvanic currents [9]. Therefore, new photo-receivers possessing extremely short response time could be developed on the basis of FIPGE.
Figure 1. Asymmetry of elementary electron processes of free carriers interacting with dipolar centres due to their non-central local potential. Light-excited electrons have a preferential pulse along the positive direction of the $x$-axis, while the electrons with opposite direction of pulse have higher probability to recombine with the centre. Asymmetry of the process of elastic scattering of free electrons can be also taken into account in the equilibrium. $U_1$ is the ground energy level of the electron in the dipolar centre.

Below we present a phenomenological description of FIPGE in nonpolar crystals, which originates from the asymmetry of optical transitions of electrons excited from dipolar centres to the conduction band by unpolarized light. A simple microscopic model illustrating the underlying physical mechanism of FIPGE is considered. Possible experimental observation of the effect based on the noncollinear direction of $J^{DG}$ in respect to $E^{ext}$ at high applied fields and/or low sample temperatures is discussed. Discussion of possible influence of FIPGE on the phenomenon of absolute negative photoconductivity (ANP) is also presented [10, 11].

2. General remarks

The appearance of directed charge transport induced by light irradiance in an asymmetric system (crystals) is known as the photogalvanic effect [5]. It is conventional to subdivide this phenomenon into two groups: so-called linear and circular effects in which the current is generated by light with linear and circular polarizations, respectively. However, in crystals possessing spontaneous polarization (pyroelectrics), the LPGE occurs even under unpolarized illumination [5]. There are three main physical reasons for this effect in pyroelectrics, all related to the non-central energy potential, which leads to asymmetry of free-charge-carrier excitation, their radiative recombination, and scattering (see figure 1) [5]. Therefore, the probabilities of these processes obey the following inequalities

$$W^{ex,l}(-k) \neq W^{ex,l}(k), \quad W^{sc}(k, -k) \neq W^{sc}(-k, k),$$

(1)
\[ W^\text{ex}(k) = W^r(-k). \] (2)

Here, \( W^\text{ex}(k) \), \( W^r(k) \) and \( W^\text{sc}(k, -k) \) are the probabilities of excitation, recombination and scattering of free carriers, respectively, and \( k \) is electron momentum.

In the case of impurity-related optical absorption, the above-mentioned peculiarities of pyroelectrics stem from the predominant polar orientation of dipolar centres along the polar axis of the crystal. That is why, for example, the recombination component of the photogalvanic current does not vanish after averaging of currents generated at elementary recombination acts over the polarizations and the wave vectors, \( \mathbf{q} \), of emitted photons. In contrast, similar current in nonpolar crystals disappears as the result of additional averaging over all possible orientations of dipolar centres. Therefore, for generation of photogalvanic current in a centrosymmetric crystal, the photoactive dipolar centres have to be polar oriented. The natural method of polar orientation is application of the dc-electric field to a sample. In this case, the appearance of nonvanishing current \( J^{\text{DG}} \) due to asymmetry of electronic processes involving nonthermalized charge carriers and dipolar centres should be considered as FIPGE.

It is important to note that FIPGE is only one representative of a wider class of physical phenomena in which the steady-state current (independently of its origin) is proportional to the orientation polarization of a crystal. Such a current can arise, for example, in experiments where the field \( \mathbf{E}^\text{ext} \) leads both to the dipolar-centre orientation and the ohmic current flow serving as the source of nonequilibrium distribution of electrons. It is also clear that, properly speaking, the conventional photogalvanic currents in pyroelectrics come within the above definition of FIPGE at least in the case of the dipolar centre-involved effect.

Impurity complexes of a donor–acceptor-pair (figure 2) formed by impurities or associates of impurity ion and a lattice defects, for example vacancies, will be considered below as relevant dipolar centres. One of the centres comprising the pair (A-centre in figure 2) is assumed to be practically immobile whereas the second centre (D-centre in figure 2) is supposed to be capable of thermally activated hopping between crystallographically equivalent positions around the first centre. Thus the complexes can be reoriented under the influence of \( \mathbf{E}^\text{ext} \). Note that below, for the sake of clarity, existence of only one type of dipolar centre in the crystal is assumed.

3. Phenomenological description

The density of direct electric current induced in a homogeneous sample when it is illuminated by polarized light with the unit polarization vector \( \mathbf{e} \) under application of \( \mathbf{E}^\text{ext} \) can be expanded as follows [5]

\[ J_i = \sigma_{ij} E_j^{\text{ext}} + \alpha_{ijk} E_j^{\text{ext}} E_k^{\text{ext}} + \beta_{ijk} e_j e_k^* I + \sigma^\text{ph}_{ijkl} E_j^{\text{ext}} e_k^* I + \cdots, \] (3)

where \( I \) is the light intensity. Besides the ohmic and the photogalvanic components of the current described by the material tensors \( \sigma_{ij} \) and \( \beta_{ijk} \), respectively, there are also components corresponding to the quadratic conductivity, \( \alpha_{ijk} \) [12] and photoconductivity, \( \sigma^\text{ph}_{ijkl} \), on the right-hand side of equation (3). The latter term can be separated into conventional photoconductivity, \( \sigma^\text{ph}_{ijkl} = \sigma^\text{ph}_{ij} \delta_{kl} \) (where \( \delta_{kl} \) is the Kronecker symbol), and anisotropic photoconductivity [13, 14]. A
Figure 2. Orientation of dipolar complex disposed in a simple cubic host lattice. Both acceptors (A-centres) and donors (D-centres) substitute the host atoms. A-centres are supposed to be non-movable but D-centres can occupy any of four sites marked by dashed arrows. The direction of the external electric field is shown on the right.

similar phenomenological approach can be applied for phenomenological description of FIPGE current, $J^{\text{DG}}$.

$$J_{i}^{\text{DG}} = \sigma^{\text{DG}}_{ijkl}(P_{\text{or}}) E_{j}^{\text{ext}} e_{k} e_{l}^{*} I.$$  (4)

Here, we should notice that alignment of dipolar centres in a polar manner manifests itself as macroscopic polarization, $P_{\text{or}}$, of a sample. This polarization (as well as $J^{\text{DG}}$) naturally depends on the degree of orientation of dipolar centres. The latter allows us to introduce, at least in the phenomenological sense, the dependence of $J^{\text{DG}}$ versus $P_{\text{or}}$. Consequently, the material coefficient $\sigma^{\text{DG}}_{ij}$ depends on the polarization $P_{\text{or}}$. The value and the shape of $\sigma^{\text{DG}}_{ij}(P_{\text{or}})$ are determined by physical characteristics of dipolar centres and sample properties. It is natural, however, to assume that in the first approximation $\sigma^{\text{DG}}_{ij}$ is linear in $P_{\text{or}}$. Since, as in the case of pyroelectrics, the polarization of incident light is not principal for generation of $J^{\text{DG}}$, equation (4) can be rewritten:

$$J^{\text{DG}} = k_{1} I P_{\text{or}},$$  (5)

where $k_{1}$ is a material parameter relevant to properties of dipolar centres and the sample. It is supposed, in addition, that the concentration of photoexcited charge carriers linearly depends on the light intensity.

Sample polarization, $P_{\text{or}}$, linearly depends on the external field, $E^{\text{ext}}$, when the latter is weak, satisfying the condition:

$$(\mu E^{\text{loc}}) \ll k_{B} T.$$  (6)
where $E^{\text{loc}}$ is a local (internal) electric field affecting the dipolar centres, $\mu$ is the dipole moment of dipolar centres, $k_B$ is Boltzmann’s constant and $T$ is absolute temperature. In this approximation, equation (5) is transformed to the following:

$$J^{\text{DG}} = k_1 I \hat{\varphi}(\mathbf{n}) \chi E^{\text{ext}},$$

(7)

Here, $\chi$ is a coefficient characterizing the polarizability of the dipolar centre-system as a whole, $\hat{\varphi}(\mathbf{n})$ is a dimensionless tensor describing the dependence of $P_{\alpha\beta}$ on the direction of the applied field, and $\mathbf{n} = E^{\text{ext}}/|E^{\text{ext}}|$. In general, the form of $\hat{\varphi}(\mathbf{n})$ depends on the local symmetry of the dipolar centres. In this case, the local symmetry is determined by the position of immobile ion and the symmetry of the nearest coordination sphere formed by discrete numbers of crystallographically equivalent positions of the second centre [15]. In the particular case when the local symmetry of the dipolar centres coincides with the symmetry of the crystal, $\chi \hat{\varphi}(\mathbf{n}) = \hat{\chi}$, where $\hat{\chi}$ is the second-rank material tensor describing the orientation component of the dielectric susceptibility of the sample. Therefore, equation (7) can be presented in the tensorial form

$$J_{i}^{\text{DG}} = k_1 I \hat{\chi}_{ij} E_{j}^{\text{ext}}.$$  

(8)

As follows from equation (8), the FIPGE current $J^{\text{DG}}$ can be observed in crystals of arbitrary symmetry and even in any condensed matter containing the photoactive dipolar centres. In this sense, it is similar to the term of equation (3) corresponding to the usual photoconductivity current. It should be noted here, without detailed discussions, that the current $J^{\text{DG}}$ as well as photoconductivity or LPGE may have components depending on the light polarization. The simplest origin of such polarization dependence may be the anisotropy of the macroscopic absorption coefficient of dipolar centres due to their polar orientation.

4. Microscopic model

The microscopic origin of the FIPGE will be illustrated on the basis of a two-dimensional model of a simple cubic-lattice crystal containing dipolar complexes of a donor–acceptor-pair type as shown in figure 2. To be unambiguous, the acceptor centres (A-centres) are assumed to be pinned to the sites of one of the crystal sublattices. The donor centres (D-centres) can occupy one of the four nearest-neighbour (relative to A-centres) sites in the second sublattice and they are able to jump between these positions because of thermally activated hopping. Such hopping provides the complex reorientation including the case of application of the field $E^{\text{ext}}$. The external electric field is supposed to make an angle $\theta$ with respect to the positive $x$-axis (figure 2). For a description of the complex-reorientation mechanism the simple Debay model is used in which the hopping rate obeys the well-known Arrhenius law

$$\tau^{-1} = \tau_0^{-1} \exp \left( - \frac{E_{\text{ac}}}{k_B T} \right).$$

(9)

Here, $\tau^{-1}$ is the hopping rate, $\tau_0^{-1}$ is the pre-exponential frequency factor, $E_{\text{ac}}$ is the height of the energy barrier separating crystallographically equivalent positions of the D-centres. Additionally it is assumed that the current $J^{\text{DG}}$ is generated when the sample is illuminated by unpolarized light, which gives rise to optical transitions of electrons from the A-centres to the conduction band.
Figure 3. Orientation distribution of dipolar complexes in cubic host lattice (a) without and (b) under external electric field applied to the sample. Magnitude of the electric field satisfies the condition of equation (6). Dipolar complexes are shown here by ellipses with the dipole-moment direction denoted by an arrow inside. For emphasis, the complexes with $\mu$ along the positive $x$-direction are shown in blue while those with opposite orientation are in red.

We should note here that the specific nature of both the host crystal itself and impurities forming dipolar complexes determine the origin and the degree of the asymmetry of the dipolar complexes with respect to processes of photoexcitation, recombination and scattering of free charge carriers. Discussion of this topic, however, is beyond the scope of this paper. Consider now generation of the current component, $J^\text{ex}$, concerned with the asymmetry of the optical excitation of free electrons. Such an asymmetry manifests itself in the difference of the probability rates of $W^\text{ex}(k, \mu)$ and $W^\text{ex}(-k, \mu)$ (averaged over both polarization and wave vectors of incident photons) for excitation of electrons having pulse $k$ directed along and opposite the dipole moment $\mu$ of complexes. Figure 3 shows a sketch of the idealized two-dimensional crystal attracting attention to possible orientations of dipolar centres denoted by ellipses. Centres with dipole moment parallel to the $x$-axis are coloured blue, while those having $\mu$ antiparallel to the $x$-axis are shown in red. ‘Blue’ complexes are characterized by $W^\text{ex}(k, \mu)$ while ‘red’ complexes are characterized by $W^\text{ex}(-k, \mu)$. The inequality $W^\text{ex}(-k, \mu) < W^\text{ex}(k, \mu)$ is assumed here. In the absence of the external electric field, complexes are oriented with equal probabilities along all four possible directions. Therefore after averaging overall orientations, the probability of electron excitation does not depend on the direction of $k$. Consequently, no macroscopic current is generated under illumination of the sample without the external field.

Application of $E^\text{ext}$ oriented preferentially along the positive direction of the $x$-axis (figure 3(b)) changes the situation since it leads to the energetic nonequivalence of two possible positions of D-centres with respect to this axis. This nonequivalence is expressed by the difference in the hopping rates of D-centres along and opposite to the positive direction of the $x$-axis:

$$\tau^{-1} = \tau_{0}^{-1} \exp \left( -\frac{E_{ac} \pm \Delta E}{k_{B}T} \right).$$

(10)

Here, $\Delta E = -||E^\text{ext}|| \cos \theta$ (for simplicity the local field $E^\text{loc}$ is supposed to be close to $E^\text{ext}$) and plus and minus signs correspond to the dipole moment $\mu$ oriented along the positive and negative directions of the $x$-axis, respectively. As a consequence, the steady-state concentration
of complexes with $\mu$ oriented along $E^{\text{ext}}$ becomes higher than the concentration of those in the opposite direction of $\mu$. The degree of polar orientation of complexes along the $x$-axis can be expressed by

$$p_x = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow},$$

(11)

where $N_\uparrow$ and $N_\downarrow$ are the concentration of complexes oriented along and opposite the external field, respectively. In the approximation of $\Delta E \ll k_B T$ and $\theta \ll 1$, the orientation degree is expressed as

$$p_x = \frac{\Delta E}{k_B T} \approx \frac{\mu E^{\text{ext}}}{k_B T}.$$  

(12)

Polar orientation of dipolar complexes makes our centrosymmetrical system similar to pyroelectric crystals in the sense of photogalvanic current generation. Therefore, knowledge of the degree of polar orientation (equation (12)) allows us to evaluate the current $J^{\text{ex}}$ by using a known expression for the photogalvanic current in pyroelectrics [5]:

$$J^{\text{ex}} = e \frac{\alpha I}{2h\nu} l_0 \xi^{\text{as}} N_\uparrow N_\downarrow = e \frac{\alpha I}{2h\nu} l_0 \xi^{\text{as}} p_x.$$  

(13)

Here, $e$ is the electron charge, $\alpha$ is the light absorption coefficient of the A-centres, $h\nu$ is the photon energy, $l_0$ is the free path of photoexcited nonthermalized electrons, and $\xi^{\text{as}} = (W^{\text{ex}}(-k, \mu) - W^{\text{ex}}(k, \mu))/(W^{\text{ex}}(-k, \mu) + W^{\text{ex}}(k, \mu))$ is the photoexcitation asymmetry parameter of the A-centres. According to the theory of photogalvanic phenomena [5], the Glass coefficient, $G$, is a convenient parameter typically used for comparison of LPGE in different materials and under different experimental conditions. The Glass coefficient is defined as the generated current normalized to the absorbed light intensity. Using equation (13) we get

$$G^{\text{DG}} = \frac{J^{\text{ex}}}{\alpha I} = e \frac{l_0 \xi^{\text{as}}}{2h\nu} p_x.$$  

(14)

One can estimate $G^{\text{DG}} \approx 2.5 \times 10^{-9}$ cm V$^{-1}$ after introducing the following parameters into equation (10): $h\nu = 2$ eV, $l_0 \approx 10^{-5}$ cm, $\xi^{\text{as}} \approx 10^{-2}$ and $p_x \approx 10^{-1}$. This magnitude of $G^{\text{DG}}$ is among typical values of the $G$s experimentally measured in ferroelectric crystals [5].

The above estimations were carried out in the approximation of small $\theta$, i.e. when the external field is almost parallel to the $x$-axis. Let us now determine the correct direction of the current $J^{\text{ex}}$ for weak external field (inequality (6) is valid) in the geometry of $0 < \theta < 45^\circ$. In this case, the dipolar complexes are polar oriented along the positive $y$-axis, as shown in figure 3(b). The degree of polar orientation with respect to this axis is determined by

$$p_y = \frac{\mu E^{\text{ext}} \sin \theta}{k_B T}.$$  

(15)

Such a polar orientation gives rise, by virtue of the same physical mechanism, to the component of $J^{\text{ex}} = J^{\text{ex}}_y = J^{\text{ex}}_x \tan \theta$. As a result the total current is parallel to the polarization $P_\omega$, which coincides with $E^{\text{ext}}$ in crystals of cubic symmetry in accordance with equation (8). Another scenario occurs if a strong enough field (and/or low temperature) is applied to the crystal so that...
the condition of equation (6) is violated. In this case, the majority of complexes will be oriented along the positive direction of the $x$-axis. In the extreme situation, complete polar orientation of all complexes along the $x$-axis could be achieved (see figure 4). Consequently, no complexes remain with dipole moment along the $y$-axis. In contrast to the situation of weak external field, macroscopic polarization $P_{or}$ is now directed along the $x$-axis, which is not parallel to $E^{ext}$. The current $J^{ex}$ is also directed along the polarization $P_{or}$. Therefore, an unexpected situation occurs in which the electric current flowing in the centrosymmetric crystal of the cubic symmetry *(i.e. in the macroscopically isotropic sample) is noncollinear with the applied electric field.* This is certainly a consequence of noncollinear orientation $P_{or}$ versus $E^{ext}$, which is in turn due to a discrete set of possible orientations for one species of dipolar centres in the crystal lattice [15].

It is worth noting that the direct experimental validation of noncollinear behaviour of $P_{or}$ with respect to $E^{ext}$ seems to be a more complicated problem than the measurement of the noncollinear component of $J^{DG}$, especially taking into account that real samples usually contain a variety of different species of dipolar centres, not all of them being photoactive.

5. Discussion

In this section, we discuss problems of the experimental observation of the field-induced photogalvanic effect. Possible participation of FIPGE in the phenomena of absolute negative conductivity [10,11] is also considered.

As follows from the estimations based on equations (13) and (14), the experimental observation of $J^{ex}$ is no more complicated a task than the measurement of LPGE-currents. It is evident, however, that the current $J^{DG}$ should be separated from the background photoconductive...
current, $J_{ph}$, which does naturally exist under applied electric field. This current is equal to

$$J_{ph} = \frac{\alpha I}{h\nu} \mu^* \tau_e E_{ext},$$

(16)

where $\mu^*$ is the free-electron mobility and $\tau_e$ is the lifetime of thermalized electrons. Comparison of equation (16) with equation (13) allows us to evaluate the ratio of $J_{ph}$ and $J_{ex}$:

$$\frac{J_{ex}}{J_{ph}} = \frac{l_0 \xi_{as} p}{\mu^* \tau_e E_{ext}}.$$  \hspace{1cm} (17)

In the case of weak electric field, equation (17) is transformed into the following expression:

$$\frac{J_{ex}}{J_{ph}} = \frac{\mu \xi_{as}}{2 \mu^* \tau_e k_B T}.$$  \hspace{1cm} (18)

These equations can be used for estimation of the material parameters at which FIPGE-current will be comparable with the photoconduction current. The ratio of equation (17) is about the unity when the material possesses the parameters $\mu \approx 1.6 \times 10^{-29}$ Km, $l_0 \approx 10^{-5}$ cm, $\xi_{as} \approx 10^{-2}$ and $\mu^* \tau_e \approx 10^{-12}$ cm$^2$ V$^{-1}$ under an external field $E_{ext} \approx 10^5$ V cm$^{-1}$ and $T = 12$ K ($k_B T = 10^{-3}$ eV). The external conditions ($E_{ext}$ and $T$) are enough for essential polar orientation of dipolar centres with the above-mentioned dipole momentum. In principle, the free-electron relaxation time $\tau_e$ of $10^{-11} - 10^{-12}$ s can be taken with the value of $\mu^* \tau_e$ being compatible with the band model of electron transport. These $\mu^* \tau_e$ values correspond, however, to the case of insulating or semi-insulating photoconductors rather than semiconductor ones. Thus, semi-insulating photoconductors under strong electric field and low temperatures are the most favourable for experimental study of the field-induced photogalvanic effect.

The specific feature of the noncollinearity of $J^{DG}$ and $E_{ext}$ under strong electric field significantly simplifies the problem of experimental observation of FIPGE-current. Consider the geometry shown in figure 5 in which a sample of the crystal shown in figure 2 is cut out in the form of a thin plate with the $x$-axis of the crystal making an angle $\phi$ ($\phi < 45^\circ$) with its planes. The field $E_{ext}$ is applied to the sample by means of two electrodes situated on the planes. The value of $E_{ext}$ and the sample temperature are supposed to allow reorientation in the overwhelming majority of complexes in the positive direction of the $x$-axis. After switching on the light, the photoconductivity current arises in the sample volume along the applied field. Nevertheless, the current $J^{DG}$ directed along the vector $P_{or}$ being parallel to the $x$-axis (figure 5) has components both orthogonal and parallel to the sample planes. The transverse current equal to $J_{TR} = J^{DG} \sin \phi$ yields the appearance of the voltage, $V_{TR}$, between the sample ends:

$$V_{TR} = J_{TR} R_{TR},$$

(19)

where $R_{TR}$ is the transverse resistance of the plate. Thus the problem of observation of the FIPGE-current is reduced to the task of correct measurement of voltage $V_{TR}$. We should note important circumstances concerned with the aspect ratio, $a$, of the plate (the ratio of its transverse size to the thickness). One can expect significant increase of the voltage $V_{TR}$ in a sample with large $a$. 

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Figure 5. Possible geometry of the experiment for observation of the field-induced photogalvanic current $J_{DG}$ under the strong electric field used. The crystal is cut so that the crystallographic $x$-axis makes an angle $\phi$ with the electric field. Vector $P_{or}$ shows the macroscopic polarization of the sample after reorientation of dipolar complexes (similar to figure 4). The external electric field is applied to longer electrodes while shorter electrodes are used for measuring the voltage induced by transverse component of the current, $J_{TR}$, flowing orthogonally to the photoconductive current $J_{ph}$.

As is known, the phenomenon of ANP manifests itself as generation of photocurrent in the opposite direction with the applied electric field in an insulating sample [10, 11]. Even though this phenomenon was theoretically predicted long ago, there is evident progress in research of ANP in microwave irradiated two-dimensional electron systems (see for example [16] and references therein). We think that ANP may have straightforward relations with the discussed FIPGE. Anomalous photoelectric phenomena observed in ruby crystals heavily doped with Cr$^{3+}$ ions have been in particular attributed to ANP [17]–[19]. Theoretical models qualitatively explaining the experimental data were proposed in the works [20, 21]. In the model of [20], the photogalvanic mechanism based on the two-step process of the photoexcitation of free carriers was considered. In the first stage the chrome ion, which is capable of occupying any of two crystallographically equivalent positions along the trigonal axis of the ruby lattice, turns into the metastable state with a prominent dipole moment. The applied electric field in the model provides inequality in the concentrations of metastable ions occupying two different positions. From the phenomenological point of view the approach developed in [20] is very close to our model of the FIPGE wherefrom the possible participation of $J_{ph}$ in the ANP evidently follows. In our opinion, the above-mentioned relation between $J_{ph}$ and $J_{ex}$ is evidence for this assumption. Therefore, one can talk about the physical basis for realization in insulating photoconductor mechanism of ANP involving photogalvanic current due to the optical excitation of dipolar centres polar oriented by means of an electric field applied to a sample.

It is worth noting that interest in the photogalvanic effect has been recently renewed with the studies of Brownian motors or ratchets (for reviews see [22, 23]). In this context, the
The phenomenology and a qualitative model of a new photoelectric phenomenon in condensed matter are presented. The effect appears in the form of generation of steady-state current by nonequilibrium charge carriers due to the asymmetry of processes of their optical excitation from, radiative recombination with, and scattering from the impurity centres having permanent dipole moment while these centres are polar oriented by an applied electric field. This phenomenon, called ‘FIPGE’, can be observed, in contrast to the traditional photogalvanic effect, in crystals of arbitrary symmetry and even in any condensed matter containing dipolar centres. A remarkable feature of the effect, at least for the case of a centrosymmetric crystal of cubic symmetry, is noncollinear orientation of the current vector with respect to the electric field vector, which is a consequence of the discrete set of orientations available for the dipole centre positions. It is shown that this feature could significantly facilitate experimental observation and measurement of the electric-field-induced photogalvanic current.

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