Investigation of intervalley scattering processes and of the surface structure with the aid of transverse focusing of electrons

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Focusing of conduction electrons by a transverse homogeneous magnetic field [V. S. Tsoĭ, JETP Lett. **19**, 70 (1974)] is used to investigate intervalley scattering processes occurring when electrons are reflected from a surface, and to determine the crystallographic structure of the surface. Results of a direct observation of intervalley scattering in reflection of electrons from a bismuth sample boundary are presented.

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1. INTRODUCTION

Transverse focusing of conduction electrons by a magnetic field (EF)[2] was previously used (see the review[1]) principally as a differential method for the measurement of the probability q of specular reflection of electrons from the surface of a sample at normal incidence. This method was used to investigate reflection of electrons in Bi, Sb, W, Cu, and Ag samples. The value of q is determined by the ratio of the amplitudes of the neighboring EF lines. This was precisely the quantity measured in the experiments. The decrease of q from unity can be due to intervalley scattering from the surface, and this makes it possible to determine, from the known value of q, the maximum possible probability $1-q$ of intervalley scattering produced when an electron collides with a crystal boundary.[3] It will be shown in this paper that a detailed study of EF–observation of additional series of lines and measurement of their amplitudes—makes it possible, first, to obtain more detailed information on the intervalley scattering processes, namely, to determine the probability and character of these processes, and second, determine the parameters of the regular structure of the sample surface. The development of methods of investigation of intervalley scattering processes is of considerable interest, inasmuch as in collisions of electrons with the boundary this type of scattering alters radically the kinetic properties of a bounded sample and gives rise to a large number of physical phenomena—anisotropic size effects.[4] The possibility of determining the structure of a surface from the character of the reflection of conduction electrons from it is of particular interest.

As a result of the presence of intervalley scattering with absence of correlation between momenta of the incident and reflected electrons, the effective charges of valley s, focused on the surface, have a definite probability of striking any point of, say, the valley s'. This produces a voltage spike at a distance $L' = cD_{s'}^{\rm extr}/|e|H$ from the point of the focusing of the electrons of valley s (c is the speed of light, e is the electron charge, H is the magnetic field, and $D_{s'}^{\rm extr}$ is the extremal dimension of the valley s' along the normal to the sample surface). Observation of this spike and measurement of its amplitude not only confirm the existence of intervalley scattering, but also determine the probability of this process.

The condition that the reflection of the electron from the conductor boundary be specular, which calls for conservation of the energy and of the tangential component of the electron quasimomentum $\mathbf{p}_\tau$, do not always ensure a single-valued state of the reflected electron.[5] In multivalley conductors they do not obstruct, generally speaking, intervalley transfer of electrons, which in turn is the cause of the decreased amplitude of the EF lines in fields that are exact multiples, and of the appearance of additional potential peaks whose amplitude is proportional to the probability of the intervalley transition.

In the case when the states of the incident and reflected electrons are correlated (both intravalley and intervalley processes are possible) and there is a finite set of vectors $\Delta\mathbf{p}_\tau$, by a linear combination of which the tangential component of the electron momentum can change upon reflection from the surface, additional series of EF lines appear and make it possible to determine the set $\Delta\mathbf{p}_\tau$ from the known experimental conditions of their observation and from the geometry of the Fermi surface (FS). It is shown in Ref. 5 that if the translational symmetry of the surface layer of the atoms differs from the translational symmetry of an atomic plane parallel to the surface, but lying in the valley of the crystal (the well known reconstructed surfaces constitute a particular case of surfaces of this type), then there exists a set of vectors $\Delta\mathbf{p}_\tau$, determined by the structure of the surface, by which $\mathbf{p}_\tau$ can change when the electron interacts with the crystal boundary. It is possible to determine $\Delta\mathbf{p}_\tau$ by solving the problem of electron diffraction by a surface layer of atoms (two-dimensional surface lattice). The possible states of the reflected electron are determined by the energy conservation laws and by $\mathbf{p}_\tau$, accurate to the reciprocal surface lattice vector. Thus, the set of vectors $\Delta \mathbf{p}_T$, which constitute the basis vectors of the lattice that is the inverse of the crystallographic two-dimensional lattice of the surface layer of atoms. It is precisely this circumstance that makes it possible to determine the structure of the crystal surface by studying the EF. The diffraction problem includes the case of an ideal surface, when the translational symmetry of the surface layer of the atoms coincides with the translational symmetry of the internal layer of the atoms, parallel to the surface of the crystal, and the reflection takes place with conservation of the tangential component of the quasimomentum when reflection is treated in the repeating band scheme.[5] In this situation, the number of nonequivalent states of the electron after reflection, even in the case of a spherical Fermi surface, is determined by the crystallographic orientation of the reflecting surface.

Figure 1 illustrates the case of a quadratic two-dimensional lattice for the surface (12). If an electron incident on the surface is located at point A of momentum space (Fig. 1b), then if the energy and tangential component of the quasimomentum are conserved, the possible states of the electron after reflection from the surface are determined by the intersection of the straight line passing through the point A and parallel to the normal and to the sample surface, with the equal-energy surfaces (points $B, B', B'', \ldots, C, C', \ldots$, the remaining points correspond to the states of electrons moving towards the surface). The number of nonequivalent states of the reflected electron is equal to 2; in the "reduced-band" scheme (the "reduced band" is bordered in Fig. 1b by a thick line) these are the states B and D. Thus, in the "reduced-band" scheme the reflection takes place with change of the tangential component of the quasimomentum by an amount

$$\Delta p_\tau = g \sin\alpha = 2\pi\hbar/d,$$

where d is the lattice constant of the surface layer of atoms (Fig. 1a) and consequently $\Delta \mathbf{p}_T$ is the vector of the reciprocal surface lattice.

In this paper we consider theoretically the phenomena described above and present results of observation of EF in bismuth, due to intervalley scattering of electrons upon reflection from the trigonal face of the crystal.

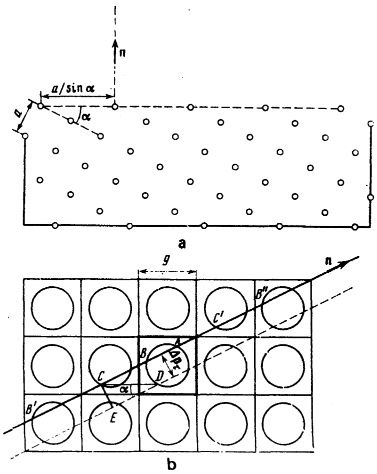

FIG. 1.

2. THEORY

A theoretical investigation of EF in the geometry of the experiments performed in Ref. 1 is the subject of a paper by Korzh,[6] who analyzed, on the basis of a method developed by Azbel' and Peschanskii,[7,8] the dependence of the potential on the measuring contact on the magnetic field, and showed which characteristics the Fermi surface can be determined from the position of the EF lines. The scattering of the carriers by the boundary was taken into account in Ref. 6 with the aid of a specularity parameter that did not depend on the momentum of the incident electron or on the coordinate of the surface point. In this section we consider EF in multivalley conductors using a more general form of the boundary condition for the nonequilibrium distribution function of the electrons of the valley s

$$f^s(\mathbf{r},\mathbf{p}) = f_0(\varepsilon_s) - \frac{\partial f_0}{\partial \varepsilon_s}\psi^s(\mathbf{r},\mathbf{p})$$

in the form of a linear integral relation

$$\psi^s_{v_x>0}(\mathbf{R},\mathbf{p}) = \sum_{s'=1}^{\nu} \langle w_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R})\psi^{s'}(\mathbf{R},\mathbf{p}')\rangle_-^{s'} + \psi_s^*(\mathbf{R},\mathbf{p}). \qquad (1)$$

The kernel of the integral operator[9,10]

$$w_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R}) = w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R}) + \frac{v_x(\mathbf{p}')\langle w_{ss'}^{(0)}(\mathbf{p}'',\mathbf{p}';\mathbf{R})\rangle_+^s + \langle v_x(\mathbf{p}'')w_{ss'}^{(0)}(\mathbf{p}'',\mathbf{p}';\mathbf{R})\rangle_+^s}{\langle v_x\rangle_-^s} \qquad (2)$$

automatically ensures conservation of the normal components of the partial currents of each valley through the surface $i^s(\mathbf{R})$:

$$\frac{2e}{(2\pi\hbar)^3}\Big[\langle v_x\psi^s(\mathbf{R},\mathbf{p})\rangle_+^s + \sum_{s'=1}^{\nu}\langle\langle w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R})\rangle_+^s v_x(\mathbf{p}')\psi^{s'}(\mathbf{R},\mathbf{p}')\rangle_-^{s'}\Big] = i^s(\mathbf{R}). \qquad (3)$$

Here $\mathbf{R}=(0,R_y,R_z)$ is a two-dimensional vector in the plane of the sample surface; $w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R})$ is the probability that an electron incident on the boundary with momentum $\mathbf{p}'$ from the valley s' will have after reflection a momentum $\mathbf{p}$ belonging to the valley with number s; ν is the number of valleys; the angle brackets $\langle\ldots\rangle_\pm^s$ denote integration over that part of the valley s of the Fermi surface, where the velocity component normal to the surface is $v_x \gtrless 0$; $\psi_s^*(\mathbf{R},\mathbf{p})$ are specified distribution function of the electrons on the contacts; ε_s is the energy of the electron of the valley s; $2\pi\hbar$ is Planck's constant.

To solve the equation

$$\mathbf{v}\frac{\partial\psi^s}{\partial\mathbf{r}} + \frac{e}{c}[\mathbf{v}\times\mathbf{H}]\frac{\partial\psi^s}{\partial\mathbf{p}} + \hat{W}\psi^s = e\mathbf{E}\mathbf{v} \qquad (4)$$

with boundary condition (1) we use a method proposed in Refs. 9 and 10. In Eq. (4), $\mathbf{E}$ is the intensity of the electric field, $\mathbf{v}$ and $\mathbf{r}$ are the velocity and coordinate of the electron, and $\hat{W}\psi^s$ is the integral of the collisions inside the volume. To observe the transverse EF it is necessary that the distance l_{EK} between the emitter E and the collector K (see Fig. 4 below) not exceed the smallest volume relaxation length l of the carriers. To avoid cumbersome formulas, we assume henceforth that $l_{EK} \ll l$ and that the main mechanism of the electron-current dissipation is scattering of the charges by the surface.

The complete system of the equations of our problem consists of the kinetic equation (4) with boundary condition (1) and the electroneutrality equation

$$\sum_{s=1}^{\nu} \langle \psi^s(\mathbf{r},\mathbf{p}) \rangle^s = 0. \tag{5}$$

The general solution of (4) can be easily obtained by the method of characteristics and is of the form

$$\psi^s(\mathbf{r},\mathbf{p}) = F^s(\mathbf{r}-\mathbf{r}(\mathbf{p})) e\varphi(\mathbf{r}), \tag{6}$$

where $F^s[\mathbf{r}-\mathbf{r}(\mathbf{p})]$ is an arbitrary function of the characteristics, which must be obtained with the aid of the boundary condition (1); $\varphi(\mathbf{r})$ is the potential of the electric field. Knowing $F^s[\mathbf{r}-\mathbf{r}(\mathbf{p})]$ we can determine the value of the potential at any point:

$$\varphi(\mathbf{r}) = \left(e \sum_{s=1}^{\nu} \langle 1 \rangle^s\right)^{-1} \sum_{s=1}^{\nu} \langle F^s(\mathbf{r}-\mathbf{r}(\mathbf{p})) \rangle^s. \tag{7}$$

Since the function F^s has a constant value on the trajectory of the electron between two collisions with the boundary, it follows that condition (1) makes it possible to find its variation as a result with collision with the surface:

$$F_i^s(\mathbf{R}_i-\mathbf{R}(\mathbf{p}_i)) = \sum_{s'=1}^{\nu} \int_{\substack{\varepsilon_{s'}(\mathbf{p}^{(i)})=\varepsilon_0,\\ v_x<0}} d\mathbf{p}^{(i)} w_{ss'}(\mathbf{p}_i,\mathbf{p}^{(i)};\mathbf{R}) F_{i+1}^{s'}(\mathbf{R}_i-\mathbf{R}(\mathbf{p}^{(i)})) + \psi_s^*(\mathbf{R}_i,\mathbf{p}_i) \tag{8}$$

(ε_0 is the Fermi surface). Using the recurrence relation (8) we obtain for the function $F_1^s[\mathbf{R}_1-\mathbf{R}(\mathbf{p}_1)]$ the expression

$$F_1^s(\mathbf{R}_1-\mathbf{R}(\mathbf{p}_1)) = \psi_s^*(\mathbf{R}_1,\mathbf{p}_1) + \sum_{n=1}^{\infty}\sum_{s_1=1}^{\nu}\cdots\sum_{s_n=1}^{\nu} \int_{\substack{\varepsilon_{s_1}=\varepsilon_0\\ v_x<0}} d\mathbf{p}^{(1)}$$

$$\times w_{ss_1}(\mathbf{p}_1,\mathbf{p}^{(1)};\mathbf{R}_1)\ldots \int_{\substack{\varepsilon_{s_n}=\varepsilon_0,\\ v_x<0}} d\mathbf{p}^{(n)} w_{s_{n-1}s_n}(\mathbf{p}_n,\mathbf{p}^{(n)};\mathbf{R}_1-\Delta\mathbf{R}^{s_1}(\mathbf{p}^{(1)})-\ldots-\Delta\mathbf{R}^{s_n}(\mathbf{p}^{(n)}))$$

$$\times\psi_{s_n}^*(\mathbf{R}_1-\Delta\mathbf{R}^{s_1}(\mathbf{p}^{(1)})-\ldots-\Delta\mathbf{R}^{s_n}(\mathbf{p}^{(n)});\mathbf{p}^{(n)}), \tag{9}$$

$$\Delta\mathbf{R}^{s_n}(\mathbf{p}^{(n)}) = \mathbf{R}(\tilde{\mathbf{p}}^{(n)}) - \mathbf{R}(\mathbf{p}_{n-1}). \tag{10}$$

The electron momenta $\tilde{\mathbf{p}}^{(n)}$ and $\mathbf{p}_{n-1}$ are related by the condition that the reflection be specular:

$$\varepsilon_{s_n}(\tilde{\mathbf{p}}^{(n)}) = \varepsilon_{s_n}(\mathbf{p}_{n-1}), \quad [\mathbf{n}\times\tilde{\mathbf{p}}^{(n)}] = [\mathbf{n}\times\mathbf{p}_{n-1}], \tag{11}$$

where $\mathbf{n}$ is the inward normal to the surface of the conductor. Substituting the solution (9) in (7) we obtain the distribution of the potential over the sample surface:

$$\varphi(\mathbf{R},\mathbf{H}) = \left(e\sum_{s=1}^{\nu}\langle 1\rangle^s\right)^{-1} \sum_{s=1}^{\nu} \langle F^s(\mathbf{R}-\mathbf{R}(\mathbf{p})) + F^s(\mathbf{R}-\mathbf{R}(\mathbf{p})-\Delta\mathbf{R}^s(\mathbf{p}))\rangle_-^s. \tag{12}$$

Equations (9) and (12) show that if the emitter is pointlike, i.e., the function $\psi_s^*(\mathbf{R},\mathbf{p})$ differs from zero only in a small vicinity of the point $\mathbf{R}=0$ near the contact, the distribution of the potential over the surface at a fixed magnetic field is inhomogeneous, owing to the strong inhomogeneity of $\psi_s^*(\mathbf{R},\mathbf{p})$. We shall assume henceforth that the distribution with respect to the momenta of the electrons injected by the contact E are isotropic, i.e.,

$$i_E^s(\mathbf{R}) = \frac{2e}{(2\pi\hbar)^3}\langle v_x\rangle_+^s \psi_s^*(\mathbf{R}),$$

an assumption that appears to be realized in experiment.

We examine now some consequences of the derived formulas, assuming that the magnetic field is parallel to the z axis and lies in the plane of the sample surface. The collector K is assumed for simplicity pointlike. The scattering processes will be classified in accordance with the "reduced-band" scheme.

1. *Intervalley processes with conservation of the tangential component of the electron quasimomentum* ($\Delta\mathbf{p}_\tau \equiv 0$). We separate in the kernel $w_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R})$ of the integral operator the term connected with reflection, wherein the electron-quasimomentum component tangential to the surface is conserved

$$w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R}) = h_{ss'}(\mathbf{p},\mathbf{R})\delta(\mathbf{p}-\mathbf{p}') + W_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R}), \tag{13}$$

$$\sum_{s'=1}^{\nu} \int_{\substack{\varepsilon_{s'}(\mathbf{p}')=\varepsilon_0,\\ v_x<0}} d\mathbf{p}' w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R}) = 1, \tag{14}$$

where $W_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R})$ is a certain function that is smooth compared with the first term. We note that the tensor $h_{ss'}(\mathbf{p},\mathbf{R})$ has nonzero off-diagonal components only when the specularly reflected electron corresponds to several points in $\mathbf{p}$ space, belonging to different valleys of the Fermi surface. This form of the function $w_{ss'}^{(0)}$ makes it possible to separate the fraction of electrons that pass through the current and potential contacts and is reflected specularly by the surface of the sample. The nonmonotonic part of the potential, which is connected with this group of charges and has the strongest singularities, can be written in the form

$$\varphi^{\mathrm{nm}}(\mathbf{L},\mathbf{H}) = \sum_{s=1}^{\nu}\langle Q_s(\mathbf{p},\mathbf{L}) i_E^s(\mathbf{L}-\Delta\mathbf{R}^s)\rangle_-^s$$

$$+\sum_{n=2}^{\infty}\sum_{s_1=1}^{\nu}\cdots\sum_{s_n=1}^{\nu}\prod_{k=1}^{n-1}\left\langle h_{s_k s_{k+1}}\left(\mathbf{p}_k,\mathbf{L}-\sum_{q=k}^{n}\Delta\mathbf{R}^{s_q}\right)\right.$$

$$\left.\times Q_{s_n}(\mathbf{p}_n,\mathbf{L}) i_E^{s_n}\left(\mathbf{L}-\sum_{q=1}^{n}\Delta\mathbf{R}^{s_q}\right)\right\rangle_-^{s_n}, \tag{15}$$

where $\mathbf{p}_k$ is the momentum of the electron belonging to the valley s_k, and by virtue of the specularity conditions (11) is a function of the momentum $\mathbf{p}_n$ of the valley s_n, with which the charge was injected by the emitter; $\Delta\mathbf{R}^{s_q} \equiv \Delta\mathbf{R}^{s_q}(\mathbf{p}_q)$,

$$Q_s(\mathbf{p},\mathbf{L}) = (2\pi\hbar)^3\left(2e^2\sum_{s'=1}^{\nu}\langle 1\rangle^{s'}\right)^{-1}\frac{1}{\langle v_x\rangle_+^s}\sum_{s'=1}^{\nu}\left\{\delta_{ss'}+h_{s's}(\mathbf{p},\mathbf{L})\right.$$

$$+\frac{\langle 1\rangle_-^{s'}}{\langle v_x\rangle_-^{s'}} v_x(\mathbf{p})\langle W_{s's}(\mathbf{p}',\mathbf{p};\mathbf{L})\rangle_+^{s'} + \langle W_{s's}(\mathbf{p}',\mathbf{p};\mathbf{L})\rangle_+^{s'}$$

$$\left.+\frac{\langle 1\rangle_-^{s'}}{\langle v_x\rangle_-^{s'}}\langle v_x(\mathbf{p}')W_{s's}(\mathbf{p}',\mathbf{p};\mathbf{L})\rangle_+^{s'}\right\}. \tag{16}$$

In obtaining the result (15), L was assumed to be much less than the distance between the current contacts as is usually the case in experiments. It is easy to note that the amplitude of the n-th peak of the EF is determined by the n-th term in the nonmonotonic part of the potential (15). Therefore for the first line formed by the electrons that move directly from contact to contact we obtain

$$\varphi_1^{\mathrm{nm}}(\mathbf{L},\mathbf{H})=\sum_{s=1}^{\nu}\langle Q_s(\mathbf{p},\mathbf{L})\, i_E^s(\mathbf{L}-\Delta\mathbf{R}^s(\mathbf{p}))\rangle_{-}^{s}. \tag{17}$$

The amplitude of the second EF line, due to the charges specularly reflected from the boundary of the conductor, is determined by the terms

$$\varphi_2^{\mathrm{nm}}(\mathbf{L},\mathbf{H})=\sum_{s,p=1}^{\nu}\langle h_{sp}(\mathbf{p}_p,\mathbf{L})\, Q_p(\mathbf{p}_p,\mathbf{L})\, i_E^p(\mathbf{L}-\Delta\mathbf{R}^s(\mathbf{p}_s)-\Delta\mathbf{R}^p(\mathbf{p}_p))\rangle_{-}^{p}. \tag{18}$$

Integrating (17) and (18) under the assumption that $i_E^s(\mathbf{R})$ is a function that varies rapidly near the emitter, we obtain for the amplitude of the first EF peak (the effective electrons are those with maximum diameter, which do not collide with the surface)

$$\tilde{\varphi}_1^{(s)}=A_s I_E R_E (b/L)^{3/2}. \tag{19}$$

The magnetic field in which the spike (19) is observed is equal to $H_0=cD_{xs}^{\max}/|e|L$; I_E and R_E are the total current through the emitter and its resistance.

In the asymptotic calculation of the amplitudes of the EF lines ($b/L\to 0$, b is the characteristic dimension of the emitter; see Eq. (19) and formulas (22), (23), (29), (33), (36) below), we assume the following: 1) the Fermi surface consists of ν convex centrosymmetric valleys; 2) the second derivatives $\partial^2 S_s/\partial p_z^{*2}$ and $\partial^2 D_{xs}/\partial p_y^{*2}$ are different from zero (S_s is the area of the intersection of the Fermi surface with the plane $p_z=p_z^*$, $\mathbf{p}^*$ is the momentum of the focused electron). Generalization to the case of a more complicated Fermi surface (see Ref. 6) entails no difficulties in principle. In real experiments, the result is valid when

$$\frac{b}{L}<\min\left\{\frac{(D_{ys}^{\max})^2}{D_{xs}^{\max}}\frac{\partial^2 D_{xs}}{\partial p_y^{*2}},\ \frac{D_{zs}^{\max}}{D_{xs}^{\max}}\frac{\partial^2 S_s}{\partial p_z^{*2}}\right\}, \tag{20}$$

i.e., the Fermi surface near the effective point is approximated with sufficient accuracy by a section of a spherical surface. In the opposite case the amplitude of the EF line has, generally speaking, a different dependence on the parameter b/L ($D_{is}^{\max}$ is the maximum chord of the equal-energy surface in the corresponding direction).

The "additional" singularities in the function $\varphi(\mathbf{R},\mathbf{H})$ are due to the fact that the maximum displacement of the electron along the line between the contacts after two hops with an intervalley transition upon reflection

$$\Delta R_y^{ps}(\mathbf{p}_{p1})=\Delta R_y^{p}(\mathbf{p}_{p1})+\Delta R_y^{s}(\mathbf{p}_s(\mathbf{p}_{p1})) \tag{21}$$

is no longer equal to double the maximum distance between the points of two collisions with the surface $2cD_{xs}^{\max}/|e|H$. The amplitude of the line due to the jumps of the carriers from one valley to another is described by the formula

$$\tilde{\varphi}_1^{(s,p)}=A_1^{(s,p)} h_{sp}(p_{p1}) I_E R_E (b/L)^{3/2}. \tag{22}$$

In addition, "steps" can exist on the $\varphi(\mathbf{R},\mathbf{H})$ curve, inasmuch as the smallest value of $\Delta R_y^{sp}(\mathbf{p}_p^{\min})$ differs from zero. The reason for the appearance of such an EF line is the abrupt decrease of the number of electrons incident on the measuring contact when $n\Delta R_y^{sp}(\mathbf{p}_p^{\min})$ becomes larger than L. The height of the "step," calculated from (18), is

$$\tilde{\varphi}_1^{\prime(s,p)}=A_2^{(s,p)} h_{sp}(\mathbf{p}_p^{\min}) I_E R_E (b/L)^2. \tag{23}$$

Here A_s and $A_{1,2}^{(s,p)}$ are dimensionless constants that depend on the carrier dispersion law and on the form of the current-conducting contact, which in each concrete case are calculated from (17) and (18). The values of the magnetic field at which the EF lines with amplitude (22) and (23) will be observed satisfying the conditions

$$\Delta R_y^{sp}(\mathbf{p}_p')=L,\quad \Delta P_z^{p}(\mathbf{p}_p')+\Delta R_z^{s}(\mathbf{p}_s(\mathbf{p}_p'))=0, \tag{24}$$

where

$$\mathbf{p}_p'=\mathbf{p}_{p1}\quad\text{or}\quad \mathbf{p}_p'=\mathbf{p}_p^{\min}.$$

The results (19) and (22), (23) show that a comparison of the amplitudes of the "additional" lines $\tilde{\varphi}^{(s,p)}(s\neq p)$ with the main focusing lines makes it possible to determine directly the probability h_{sp} of the intervalley transition with conservation of $\mathbf{p}_\tau$ upon reflection of the charge by the surface of the conductor.

In the particular case when it is possible to neglect completely the intervalley processes and when the scattering is completely within the valley, the tensor $w_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R})$ is diagonal, i.e., $w_{ss'}=w_s\delta_{ss'}$. We replace the integration with respect to the momenta p_x, p_y, and p_z in (15) by an integral with respect to ε_s and $\mathbf{R}_s=\Delta\mathbf{R}^s(\varepsilon_s,p_y,p_z)$. We recognize also that $\partial f_0/\partial\varepsilon_s=-\delta(\varepsilon_s-\varepsilon_0)$ at low temperatures $T\ll\varepsilon_0$. After simple transformations, expression (15) can be rewritten in the form

$$\begin{aligned}\varphi^{\mathrm{nm}}(\mathbf{L},\mathbf{H})=\frac{c}{|e|H}\sum_{s=1}^{\nu}\int d\mathbf{R}_s\Bigg\{&\Bigg|\left(\frac{v_{y2}}{v_{x1}}+\frac{v_{y1}}{|v_{x1}|}\right)\Bigg(\frac{\partial^2 S_s}{\partial p_z^2}\\ &-p_y\left[\frac{1}{\rho_1}\left(1+\frac{v_{z1}^2}{v_{x1}^2}\right)^{3/2}+\frac{1}{\rho_2}\left(1+\frac{v_{z2}^2}{v_{x2}^2}\right)^{3/2}\right]\Bigg)-\left(\frac{v_{z2}}{v_{x2}}+\frac{v_{z1}}{v_{x1}}\right)^2\Bigg|^{-1}\\ &\times\frac{Q_s(\varepsilon_0,p_y,p_z;\mathbf{L})}{|v_x|}\Bigg[i_E^s(\mathbf{L}-\mathbf{R}_s)\\ &+\sum_{n=2}^{\infty}\prod_{k=1}^{n-1}h_s(\varepsilon_0,p_y,p_z;\mathbf{L}-k\mathbf{R}_s)\, i_E^s(\mathbf{L}-n\mathbf{R}_s)\Bigg]\Bigg\}_{\mathbf{R}_s=\Delta\mathbf{R}^s}.\end{aligned} \tag{25}$$

All the quantities under the sign of integration with respect to $\mathbf{R}_s$ pertain to the valley s; ν_{x1}, ν_{z1} and ν_{x2}, ν_{z2} are the projections of the velocity of the incident and of the specularly reflected charges ($\nu_{x2}>0$, $\nu_{x1}<0$); ρ_i is the radius of curvature of the intersection of the valley s of the FS by the plane $p_z=$const at the point $i=1,2$:

$$S_s(\varepsilon_0,p_y,p_z)=\int_{p_{x1}}^{p_{x2}} p_y\, dp_x. \tag{26}$$

For an emitter with small dimensions, the main contribution to the integral will be made by a small region defined near the points p_y, p_z by the relations

$$nR_{sz}=n\Delta R_z^s(p_y,p_z)=\frac{cn}{eH}\int\limits_{p_{x1}}^{p_{x2}}\frac{v_z\,dp_x}{v_y}=0, \quad (27)$$

$$nR_{sy}=n\Delta R_z^s(p_y,p_z)=-\frac{cnD_{xs}}{eH}=L, \quad (28)$$

where $D_{xs}=p_{x2}-p_{x1}$. For the extremal diameter of the Fermi surface $D_{xs}(p_{y0},p_{z0})$, the amplitude of the n-th peak of the potential formed by the electrons of the s valley is equal to

$$\Phi_n=A_sI_ER_E(b/L)^{5/2}\prod_{k=1}^{n-1}h_s(\varepsilon_0,p_{y0},p_{z0};\mathbf{L}-k\Delta\mathbf{R}^s(\varepsilon_0,p_{y0},p_{z0})) \quad (n>1). \quad (29)$$

The result (29), which was obtained analytically, yields the same order of magnitude of the amplitude with respect to the parameter b/L as the previously proposed "geometric model" of the EF,[11] and also makes it possible to describe the experimentally observed decrease of the amplitudes of the individual peaks in the presence of an imperfect section between the contacts.[11]

2. *Correlation processes with nonconservation of the tangential component of the quasimomentum.* The existence of processes with conservation of $\mathbf{p}_T$, accurate to a quantity that is a multiple of $\Delta\mathbf{p}_T$ (we consider here for simplicity the case when only one value of $\Delta\mathbf{p}_T$ exists) means that part of the function $w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R})$, which describes the strictly correlated scattering of electrons by the sample boundary, constitutes a sum of terms, each of which describes the probability of scattering in which the tangential component of the quasimomentum changes by $k\Delta\mathbf{p}_T$, i.e.,

$$w_{ss'}^{(0)}(\mathbf{p},\mathbf{p}';\mathbf{R})=\sum_k h_{ss',k}(\mathbf{p},\mathbf{R})\,\delta(\mathbf{p}-\tilde{\mathbf{p}}_k')+W_{ss'}(\mathbf{p},\mathbf{p}';\mathbf{R}), \quad (30)$$

where $\tilde{\mathbf{p}}_k'=\tilde{\mathbf{p}}'+k\Delta\mathbf{p}_T$ and $\mathbf{p}_T=\tilde{\mathbf{p}}_T'$. Using the recurrence relation (8), we arrive at the following expression for the nonmonotonic part of the potential difference between the measuring contact and the peripheral point of the sample:

$$\varphi^{nm}(\mathbf{L},\mathbf{H})=\sum_{s=1}^{\nu}\langle Q_s(\mathbf{p},\mathbf{L})\,i_E^s(\mathbf{L}-\Delta\mathbf{R}^s)\rangle_-^s$$
$$+\sum_{n=2}^{\infty}\sum_{s_1\ldots s_n=1}^{\nu}\sum_{k_1\ldots k_n}\prod_{i=1}^{n-1}\Big\langle h_{s_is_{i+1},k_i}\Big(\mathbf{p},\mathbf{L}-\sum_{q=i}^{n}\Delta\mathbf{R}_q^{s_q}\Big)$$
$$\times Q_{s_n}(\mathbf{p},\mathbf{L})\,i_E^{s_n}\Big(\mathbf{L}-\sum_{q=1}^{n}\Delta\mathbf{R}_q^{s_q}\Big)\Big\rangle_-^{s_n}, \quad (31)$$

where $Q_s(\mathbf{p},\mathbf{L})$ is defined in(16), in which

$$h_{ss'}=\sum_k h_{ss',k},\quad \Delta\mathbf{R}_n^{s_n}=\Delta\mathbf{R}^{s_n},$$

$$\Delta\mathbf{R}_q^{s_q}=\mathbf{R}\Big(\tilde{\mathbf{p}}^{(q)}+\sum_{i=1}^{q}k_i\Delta\mathbf{p}_\tau\Big)-\mathbf{R}\Big(\mathbf{p}_q+\sum_{i=1}^{q}k_i\Delta\mathbf{p}_\tau\Big)\quad (q\neq n).$$

The EF lines that result from processes with correlated change of $\mathbf{p}_T$ are described by the second term of (31).

To illustrate the result, we consider one particular case. Let the Fermi surface have one valley and let the maximum possible number of nonequivalent states of the reflected electron by equal to 2, i.e., upon reflection $\mathbf{p}_T$ can change only by $\Delta\mathbf{p}_T$ or by $-\Delta\mathbf{p}_T$. When these conditions are satisfied we should observe EF lines analogous to the series of the peaks with the amplitudes (22) and (23), which were considered above. The effective carriers are those for which the path

$$\Delta R_y^{(2)}(\mathbf{p}_2)=\Delta R_y(\mathbf{p}_2)+\Delta R_y(\mathbf{p}_2\pm\Delta\mathbf{p}_\tau)$$

along the straight line joining the emitter and collector is a maximum or a minimum. For example, for a spherical Fermi surface the minimal displacement is that of the electrons of the points $p_{y2}^{\min}=\pm p_0, p_{z2}^{\min}=0$ (p_0 is the radius of the Fermi surface), and the maximal displacements—by the electrons belonging to a chord located at a distance $\pm\frac{1}{2}\Delta\mathbf{p}_T$ ($p_{y2}^{\max}=\pm\frac{1}{2}\Delta p_T, p_{z2}^{\max}=0$) from the maximum diameter. The magnetic field at which potential spikes are produced on the measuring contact are determined by the conditions

$$n\Delta R_y^{(2)}(\mathbf{p}_2)=L,\quad n[\Delta R_z(\mathbf{p}_2)+\Delta R_z(\mathbf{p}_2+\Delta\mathbf{p}_\tau)]=0, \quad (32)$$

and the amplitude of the lines is equal to

$$\Phi_n=\alpha h_{\pm1}^{2n-1}(\mathbf{p}_2)I_ER_E\begin{cases}(b/L)^2, & \mathbf{p}_2=\mathbf{p}_2^{min}\\ (b/L)^{5/2}, & \mathbf{p}_2=\mathbf{p}_2^{max}\end{cases}. \quad (33)$$

Here α is a certain constant, the concrete form of which depends on the dispersion law and on the geometry of the current contact. Thus, the probability of reflection of an electron with change of tangential component of the quasimomentum by $\pm\Delta\mathbf{p}_T$ can be determined from the ratio of the amplitude of the first fundamental EF line (19) to the amplitude of the line (33) with $n=1$. An essential role is played by the position of the line (32) on the magnetic-field scale, since it contains information on the vector $\Delta\mathbf{p}_T$, from which we can obtain the reciprocal vectors of the surface lattice of the crystal. The results can be easily generalized to the case of a change of the tangential component of the quasimomentum $\mathbf{p}_T$ by $k\Delta\mathbf{p}_T$ ($k=\pm2,\pm3,\ldots,\pm m$). It follows from (31) that there should exist series of EF lines formed by electrons with minimal and maximal displacement after $k\leq m$ jumps.

For a multivalley Fermi surface, the state with $\mathbf{p}_2\pm\Delta\mathbf{p}_T$ can belong to another valley. The expression for the amplitude takes a form similar to (33), and $h_{ss',k}$ is the probability of reflection with a momentum transfer $k\Delta\mathbf{p}_T$ from one valley of the Fermi surface to another.

3. *Random intervalley scattering.* If the specularity of reflection of the electrons of the valley s is small, then it becomes possible to observe EF lines connected with diffusely scattered carriers. The absence of a rigorous correlation between the specular reflection (11) for the momenta of the electrons interacting with the surface leads to additional averaging over the momenta $\mathbf{p}_2,\ldots,\mathbf{p}_n$ of the charges that arrive at the point L after executing $2,\ldots,n$ jumps. This smoothes out the potential-difference extrema due to the intra- and intervalley scattering. We separate the nonmonotonic potential term connected with the charges that have undergone in the first reflection with the surface of the crystal a transition with an uncorrelated change of $\mathbf{p}_T$:

$$\varphi_2^{nm}(\mathbf{L},\mathbf{H})=\sum_{s,p=1}^{\nu}\langle\langle W_{sp}(\mathbf{p}_1,\mathbf{p}_2;\mathbf{L}-\Delta\mathbf{R}^p(\mathbf{p}_2))\,Q_s(\mathbf{p}_1)$$
$$\times v_z(\mathbf{p}_2)\,i_E^p(\mathbf{L}-\Delta\mathbf{R}^s(\mathbf{p}_1)-\Delta\mathbf{R}^p(\mathbf{p}_2))\rangle_-^s\rangle_-^p. \quad (34)$$

If follows therefore that an "additional" series of peaks will be observed at those magnetic-field values for which

$$D_{xs}^{\max}(\mathbf{p}_{s0})+D_{xp}^{\max}(\mathbf{p}_{p0})=\frac{|e|HL}{c},\quad \Delta R_z^{s}(\mathbf{p}_{s0})+\Delta R_z^{p}(\mathbf{p}_{p0})=0. \tag{35}$$

It can be shown that the ratio of the amplitude of such a line $\tilde{\bar{\varphi}}_2^{(p,s)}$ to the amplitude of the first line of focusing without scattering (19) for a cylindrical dispersion law $\partial S_s/\partial p_z=\partial D_{xs}/\partial p_z\equiv 0$ is equal to

$$\frac{\tilde{\bar{\varphi}}_2^{(p,s)}}{\bar{\varphi}_1^{(s)}}=\frac{B^{(s,p)}}{A_s}W_{sp}(\mathbf{p}_{s0},\mathbf{p}_{p0};\mathbf{L}-\Delta\mathbf{R}^{p}(\mathbf{p}_{p0}))\left(\frac{b}{L}\right)^{1/2}, \tag{36}$$

where $B^{(s,p)}$ is a certain constant that depends on the dispersion law and on the shape of the emitter, and can be calculated from (34). It should be noted here that the EF lines described by the term in the potential (17) are connected with the extremum of a sum of two diameters of different Fermi-surface volumes, while the lines (34) are connected with the sum of the extremal diameters. This makes it possible to determine, for a conductor with a known dispersion law, which of the lines (18) or (34), is being measured.

3. EXPERIMENT

Electron focusing due to intervalley scattering was observed in bismuth samples in which $\mathbf{n}\parallel C_3$. Figure 2a shows the structure of an ideal trigonal face of a bismuth crystal. The atoms lying in different planes perpendicular to C_3 are marked with dark and light circles. Figure 2b shows schematically the projection of the electron (ellipses) and hole (circles) valleys in the repeating-band scheme on a plane perpendicular to C_3. The valleys lying in one plane perpendicular to C_3 are designated by identical marks. The electron part of the Fermi surface constitutes three strongly elongated "ellipsoids" with principal axes ratio 14:1:1.3, elongated along directions close to the bisector axis C_1.[13] If the motion of the electrons of the central section of the Fermi surface in a magnetic field is considered, the ellipsoid can be replaced by a cylinder up to angles ~80° between H and the major axis of the ellipsoid. In experiments aimed to observe EF, two needle contacts, emitter and collector, are mounted on the surface of the crystal. Electric current is made to flow through the emitter and the potential difference $\varphi(\mathbf{L},\mathbf{H})$ between the collector and a peripheral point of the sample is measured. If the emitter and collector are mounted on the trigonal face of the crystal in such a way that the contact line L is perpendicular to C_1 (perpendicular to the major axis of one of the electron ellipsoids), and the magnetic field is directed in such a way that the trajectories of the electrons leaving the emitter are turned towards the collector, then voltage spikes are observed on the collector; they are periodic in the field H with a period $H_0=p_3c/|e|L\cos\theta$, where θ is the angle between H and the major axis of the ellipsoid (the cylinder axis, $\theta\lesssim 80°$), and p_3 is the extremal dimension of the electron ellipsoid along C_3. The electrons of the ellipsoids whose major axis is perpendicular to the line of the contacts are focused on the collector in fields mH_0 (m is an integer and $m>1$ is possible because of the specular reflection of the electrons from the sample surface). It is just these singularities of the EF which are illustrated in Fig. 3 (the upper curves).

Deflection of H from the major axis of the ellipsoid by an angle $\theta=20°$ leads only to a change, proportional to 1/cos20°, in the scale of the plot along the magnetic-field axis. If the contacts are mounted on the trigonal face of the crystal in such a way that $\mathbf{L}\parallel C_1$, while the magnetic field $\mathbf{H}\perp\mathbf{L}$ and turns around the electrons leaving the emitter towards the collector, then at the same value of L the first EF line is observed in a field $H_0=2p_3c/|e|L$. When the angle between H in the plane of the sample and the normal to L is 20° (lower curve on Fig. 3b), two weak EF lines are observed instead of a single intense one. One of

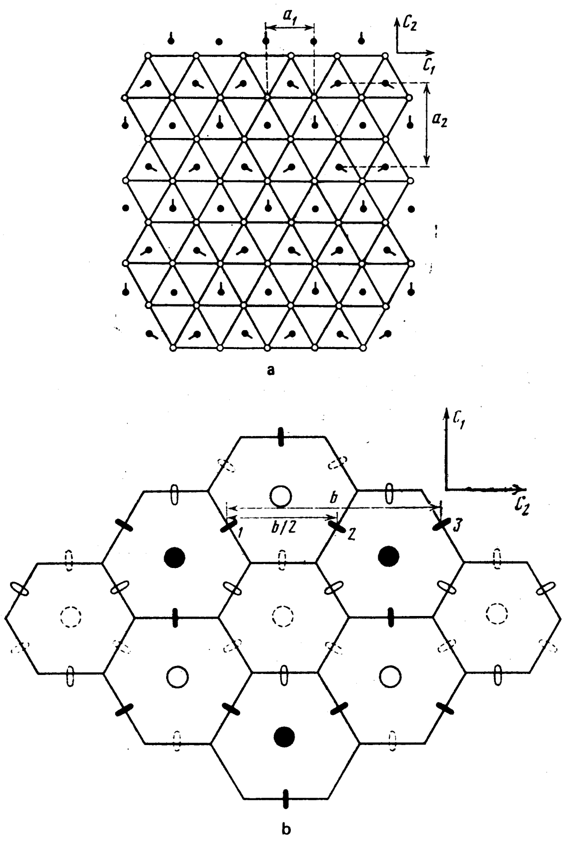

FIG. 2.

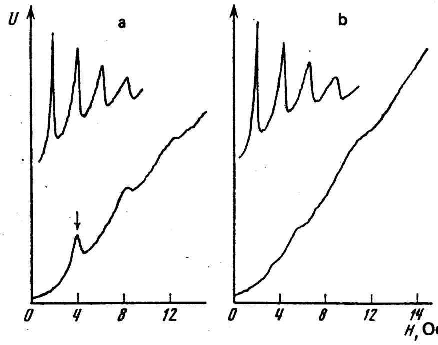

FIG. 3. Dependence of the collector voltage on the magnetic field *a*) $\mathbf{H}\perp\mathbf{n}$, *b*) $\mathbf{H}\perp\mathbf{L}$; $\measuredangle(\mathbf{HL})=70°$. The upper curves are for $\mathbf{L}\parallel C_2$, and the lower for $\mathbf{L}\parallel C_1$. To plot the lower curves the gain of the measuring circuitry was increased fivefold.

them practically disappears when θ is further increased to 30°, whereas the other line increases in amplitude and is displaced in the field $2p_3c\sqrt{3}/|e|L$ (cf. the behavior of the EF line at $L \parallel C_2$ upper curves of Fig. 3). Attention is called to the steeper decrease of the amplitudes of the EF lines with increasing H at $L \parallel C_1$ compared with the case $L \parallel C_2$. Many measurements on different samples have shown that this decrease is due precisely to the orientation of L relative to the crystallographic axes of the sample, and not to the quality of the surface in the region of the contacts.

4. DISCUSSION

The described singularities of EF at $L \parallel C_1$ cannot be explained by taking into account in φ the electrons of only a single valley. Such a possibility exists in principle because of the weak effect of the focusing of the electrons of the non-extremal section of the ellipsoid. However, first, this effect should be negligibly small, as is evidenced by the abrupt and considerable decrease of the amplitude of the EF line following a small deflection of L from the C_2 axis[2,13]; second, the observed fact that the position of the EF lines on the magnetic-field scale depends on the direction of H does not agree with this assumption. The results of the observation can be explained in the following manner (see Fig. 4).

As shown by experiment, effective electrons of three ellipsoids are radiated from the emitter—at a fixed position, EF is observed whenever the direction of L coincides with one of the axes $C_2(H \perp L)$, and focusing of electrons without reflections by the surface takes place in a field $H = p_3c/|e|L$. Assume that at $L \parallel C_1 \perp H$ the effective electrons of the ellipsoid 1 (2) (Fig. 4a), after leaving the emitter E, are focused at the point O (O') (Fig. 4b) on a line drawn at an angle 30° (−30°) to the line of contacts at a distance $EO = EO' = p_3c/|e|H\cos 30°$. If effective electrons of the ellipsoid 2 (1) are generated at the point O (O'), then they are focused on a straight line drawn at an angle −30° (30°) to the line of contacts, at the point K on the line of contacts ($OK = O'K = p_3c/|e|H\cos 30°$). Focusing should be observed in a field $H = 2p_3c/|e|L$, when $EO = OK = EO' = O'K = L/2\cos 30°$. If H is deflected away from the normal to the line of contacts by an angle θ, then $D_1 = EO = p_3c/|e|H\cos(30° + \theta)$, $D_2 = EO = p_3c/|e|H\cos(30° - \theta)$, and the collector can receive only electrons from the vicinities of the points of ellipsoids 1 and 2 (Fig. 4a), for which the length of the jumps over the surface D_1 and D_2 are in a prime-number ratio. Weak "focusing" of the electrons of the vicinities of the points of the nonextremal diameters of the Fermi surface will take place, in analogy with the situation with EF in an oblique field,[14] or in the case of a steplike angular dependence of the specularity coefficient of the reflection.[11] At $\theta = 30°$ we have $D_1 = 2D_2$ and the focused electrons are from the vicinities of the maximal diameters, parallel to n, of the central sections of ellipsoids 1 and 2. This explains the increased amplitude of the EF line and its shift in a field $H = 2p_3c \cdot 3^{1/2}|e|L$. The ratio of the amplitude of the line connected with the intervalley scattering to the amplitude of the first EF line (without collisions with the boundary), measured in the experiment described above, is equal to

$$\tilde{\varphi}_1^{(1,2)}/\tilde{\varphi}_1^{(1)} \approx 0.05. \tag{37}$$

This value is determined by the probability of the intervalley scattering of the electrons. The geometry of the present experiment is such that the EF line can be formed by electrons whose tangential components of the quasimomentum changes by $b/2$ upon reflection from the surface [Fig. 2b, Eq. (33)]. This situation is possible, for example, in the case of reconstruction of the trigonal face, shown in Fig. 2a, when the atoms marked by the bars are shifted from the equilibrium position and the translational vectors of the surface lattice is doubled, and consequently the reciprocal surface lattice vectors are decreased by one-half ($b \to b/2$). The presence of a random intervalley scattering also leads to the onset of an EF line at the same value of the magnetic field [Eq. (36)]. We have not succeeded so far in changing, at a fixed position of the contacts, the reflecting properties of the surface in the region of reflection of electrons from it, without changing at the same time the bulk properties of the sample, and to separate just the influence of the state of the boundary on the amplitude of the EF line, and not the mean free path, the contact dimension, and others. The absolute value of the amplitude of the EF line depends substantially on the number of difficult-to-control circumstances in the contact mounting procedure, therefore a comparison of the absolute values of the EF lines at different positions of the contact is only qualitative in character. Summarizing the foregoing, it seems to us that it is premature at the present stage to draw any definite conclusion on the type of intervalley processes (correlated or random) which cause the observed EF, or concerning their probability.

At $L \parallel C_1$, the ratio of the amplitude of the second EF line $\tilde{\varphi}_2^{(1,2)}$ to the amplitude of the first line $\tilde{\varphi}_1^{(1,2)}$ is 0.5 (lower curve in Fig. 3a). The main contribution to $\tilde{\varphi}_2^{(1,2)}$ is made by electrons that traverse the path $EOK(EO'K)$ (Fig. 4b) with additional specular intravalley reflection at the points $EO/2 = OK/2 = EO'/2 = O'K/2$. According to formulas (15), (34), $\tilde{\varphi}_2^{(1,2)}/\tilde{\varphi}_1^{(1,2)} \approx h_{11} \cdot h_{22}$. In our case $h_{11} \approx h_{22} \approx 0.65$ (upper curve in Fig. 3a), and consequently $\tilde{\varphi}_2^{(1,2)}/\tilde{\varphi}_1^{(1,2)} \approx 0.42$, which is in satisfactory agreement with the measured value 0.5.

5. CONCLUSION

The present investigation has shown that EF permits direct observation of intervalley scattering processes

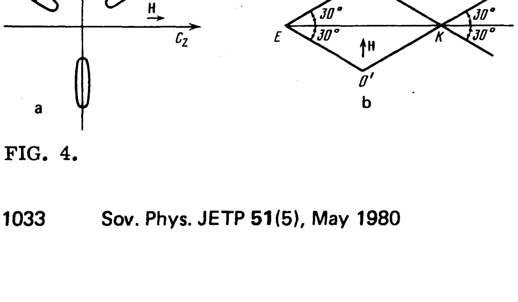

FIG. 4.

and a determination of the probability of intervalley scattering and of the presence of a correlation between the number of the electrons before and after reflection with an intervalley transition. The sensitivity of the EF to the crystallographic structure of the surface uncovers new methodological possibilities of the EF. It is of interest in this connection to use EF for the study of "brittle" two-dimensional structures on metallic surfaces. It is known that at helium temperatures and at very small degrees of coating (less than one monolayer) two-dimensional crystalline structures of impurity atoms are produced on the surfaces of metals. In a number of cases they have small defect-formation energies and are destroyed even when bombarded with slow electrons. From the Bragg condition $n\lambda = d\cos\theta$ it follows that to observe the diffraction of the electrons incident on the surface from the outside, the electron wavelength λ should be less than d, and consequently the electron energy $\gtrsim 10$ eV. The use of conduction electrons as a probe in these cases has obvious advantages, inasmuch as in EF the excitation energy of the focused electrons can be of the order of several degrees ($\sim 10^{-4}$ eV).

Interest attaches also to the possibility of determining with the aid of EF the crystallographic structure of the surface under a layer of adsorbed impurity atoms and molecules, whose presence does not interfere with the measurements, since the "irradiation" of the surface takes place "from the inside." Similarly, the EF can be used to determine the crystallographic structure of the interphase boundary.

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Resonant changes of optical orientation of electrons in anti-intersection of the spin levels of the nuclei of a semiconductor lattice

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We investigate the circular polarization of the luminescence of GaAlAs crystals under conditions of optical orientation of the electrons and mixing of the spin states of the lattice nuclei. This mixing is the result of local violation of the crystal cubic symmetry, and depends on the crystal orientation in the external magnetic field. Optical detection of NMR transitions at the triple Larmor frequency without change of the magnetic quantum number ($\Delta m = 0$) demonstrates the mixing of the states $\chi_{+3/2}$ and $\chi_{-3/2}$ of the As^{75} nuclei in a narrow angle range corresponding to anti-intersection of the spin levels. The change of the mixing with change of the crystal orientation in a magnetic field is resonant and leads to the onset of a region with two stable polarization states of the spin system near the anti-intersection point. Optical NMR detection in the anti-intersection region has made it possible to determine the electric-field-gradient asymmetry parameter ($\eta \leq 0.06$).

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Optical orientation of electrons in semiconductors in interband absorption of circularly polarized light is accompanied by dynamic polarization of the nuclei.[1] In turn, the polarized nuclei can exert a strong influence on the behavior of oriented nuclei on account of the hyperfine interaction.[2,3] The effective field H_N of the nuclei, which acts on the average electron spin $\langle S \rangle$, is determined by various factors. By studying the

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