Journal of Engineering Physics and Thermophysics, Vol. 82, No. 6, 2009

REFLECTANCE SPECTRA OF A 6H-SiC SINGLE CRYSTAL PLACED IN A STRONG HOMOGENEOUS MAGNETIC FIELD

E. F. Venger,[a] A. I. Evtushenko,[b] L. Yu. Melnichuk,[b] and A. V. Melnichuk[b]

UDC 621.315.592

We have made a theoretical study of the external reflection coefficients of a uniaxial anisotropic SiC (6H polytype) single crystal exposed to a strong homogeneous magnetic field (in the cases of Faraday and Voigt configurations). For the first time, in the external reflection spectra of a 6H-SiC single crystal, regions of the appearance of new oscillations due to the action of a strong homogeneous magnetic field have been revealed. The interrelationship between the phonons and plasmons in a 6H-SiC single crystal exposed to a strong homogeneous magnetic field has been studied.

Keywords: *silicon carbide, external reflectance spectrum, SiC (6H polytype) single crystal.*

Introduction. The optical properties of dielectrics and semiconductors are known to change depending on their position in a magnetic field [1–8]. In [9, 10], the influence of magnetic fields on the characteristics of nonmagnetic crystals was studied experimentally. For the first time the influence of a magnetic field on the reflection coefficient of crystal dielectrics Al_2O_3, LiF, and MgO was revealed and investigated in [11]. For the first time theoretical and experimental studies of the IR-reflectance spectra of ZnO not exposed to a strong homogeneous magnetic field and exposed to it were made in [12, 13]. The authors showed that the reflectance spectra in optically anisotropic nonmagnetic crystals deform under the action of a magnetic field in the region of "residual rays." On the magnetoreflectance spectra sharp peaks in the frequency ranges where the reflectivity of the crystal in the absence of magnetic field was minimal were observed. But in the literature there is no information on the interaction of the phonon and plasmon subsystems in polar uniaxial semiconductors exposed to a strong homogeneous magnetic field.

In the present work, we have investigated the effect of a magnetic field on the IR-magnetoreflection coefficients of a silicon carbide (6H polytype) single crystal taking into account the plasmon-phonon interaction in the Faraday and Voigt configurations.

Samples and Experimental Procedure. To investigate the influence of a strong homogeneous magnetic field on the properties of optically anisotropic semiconductors in the IR regions of the spectrum, we used a silicon carbide (6h polytype) single crystal characterized by a strong anisotropy of the properties of the plasmon subsystem and a weak anisotropy of the phonon system.

Experimental IR reflectance spectra were obtained in the 200–1400-cm^{-1} frequency range with the aid of a SPECORD M-80 spectrometer and an attachment for reflection with the use of a standard mirror. The reflectance spectra were registered with a polarizer with a degree of polarization 0.98. All measurements were made at room temperature and in the absence of the influence of a magnetic field on the single crystal. In the work, we used a hexagonal 6H-SiC single crystal of size $5 \times 5 \times 0.5$ mm^3 with a natural surface etched for 15 min in hydrofluoric acid.

Results and Discussion. The electron density in the c-zone was determined by measuring the transmission of samples at $\mathbf{E} \perp C$ at the wavelength $\lambda = 0.628$ μm and is given in Table 1. The data obtained are in good agreement with the measurement data for the Hall effect for these samples.

Tables 1 and 2 give the interconsistent electrophysical and volume parameters of 6H-SiC obtained from the IR reflectance spectra in the region of plasmon-phonon interaction with the use of polarized light at various angles of incidence [14, 15].

---

[a]V. E. Lashkarev Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, 42 Nauka Ave., Kiev, 03028, Ukraine; [b]N. V. Gogol Nezhin State University, 2 Kropivyanskii Str., Nezhin, 16602, Chernigov Region, Ukraine; email: ealyona@ukr.net. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 82, No. 6, pp. 1187–1193, November–December, 2009. Original article submitted October 9, 2008.

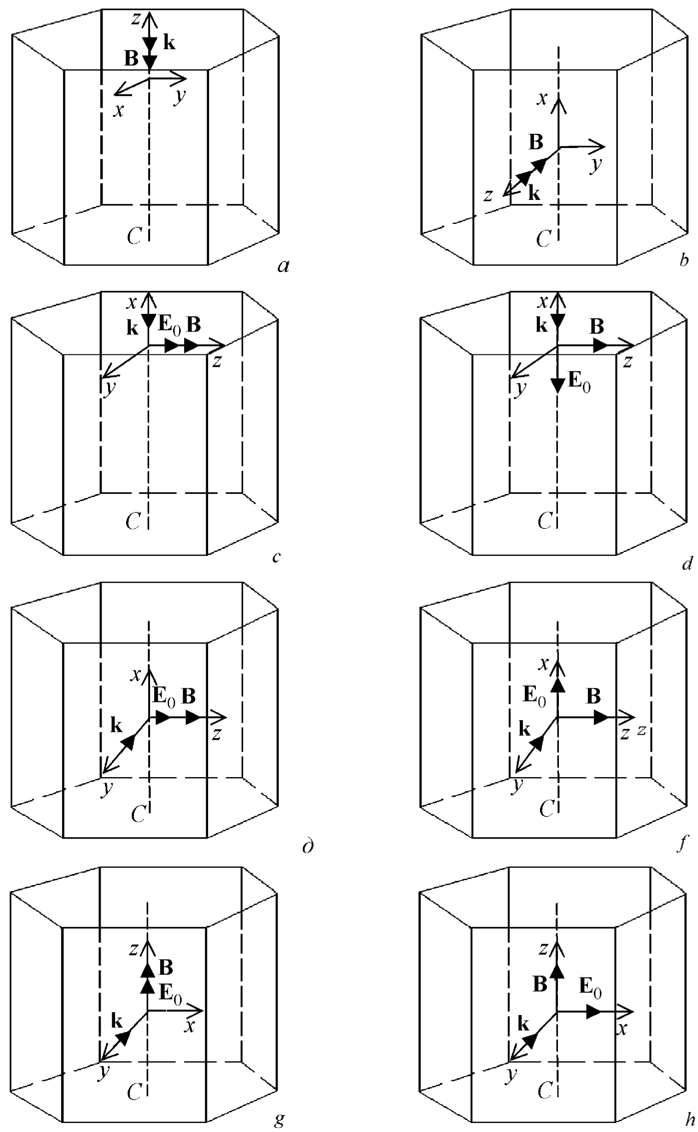

Fig. 1. Mutual arrangement of vectors **B**, $\mathbf{E}_0$, **k**, and C in 6H-SiC: a) Faraday configuration, the crystal axis is parallel to the magnetic field; b) Faraday configuration, the crystal axis is perpendicular to the magnetic field; c) Voigt configuration, the crystal axis is perpendicular to the reflecting surface and $\mathbf{E}_0 \parallel \mathbf{B}$; d) Voigt configuration, the crystal axis is perpendicular to the reflecting surface and $\mathbf{E}_0 \perp \mathbf{B}$; e) Voigt configuration, the crystal axis is parallel to the reflecting surface and perpendicular to the magnetic field B and $\mathbf{E}_0 \parallel \mathbf{B}$; f) Voigt configuration, the crystal axis is parallel to the reflecting surface and perpendicular to the magnetic field **B** and $\mathbf{E}_0 \perp \mathbf{B}$; g) Voigt configuration, the crystal axis is parallel to the magnetic field **B** and $\mathbf{E}_0 \parallel \mathbf{B}$; h) Voigt configuration, the crystal axis is parallel to the magnetic field **B** and $\mathbf{E}_0 \perp \mathbf{B}$.

Let us direct the z-axis of the rectangular coordinate system along the external homogeneous magnetic field and assume that the x-axis is in the plane passing through the axis of the crystal and the z-axis, and φ is the angle between them.

The permittivity tensor components ε_{ij} for the uniaxial semiconductor, in which a plane magnetic wave exp $[i(\mathbf{kr} - \nu t)]$ propagates, were determined in [16, 17]. The dependence of permittivity on the frequency in the region of plasmon-phonon interaction can be given, according to [14, 15], as

TABLE 1. Electrophysical Parameters of the 6H-SiC Single Crystal

Sample	n_0, cm^{-3}	ν_p, cm^{-1}		γ_p, cm^{-1}		γ_p, cm^{-1}		$\mu_\parallel$	$\mu_\perp$
		E $\perp C$	**E** $\parallel C$	**E** $\perp C$	**E** $\parallel C$	**E** $\perp C$	**E** $\parallel C$		
PSE-3B	$5\cdot10^{18}$	550	200	620	340	12	12	0.59	4
SiC-1	$6.8\cdot10^{18}$	620	210	700	260	14	14	0.59	4
SiC-2	10^{19}	740	280	830	450	12	12	0.59	4

TABLE 2. Volume Parameters of the 6H-SiC Single Crystal

Direction	ε^0	ε^∞	ν_T, cm^{-1}	ν_L, cm^{-1}
E $\perp C$	9.66	6.52	797	970
E $\parallel C$	10.03	6.7	788	964

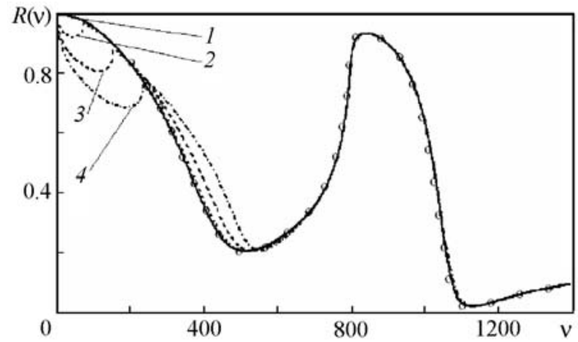

Fig. 2. Reflectance spectra of the 6H-SiC single crystal exposed to the electromagnetic field B: 1–4) calculations at 1 G, 30 kG, 65 kG, and 100 kG, respectively (dots show the experiment, sample PSE-3B). ν, cm^{-1}.

$$\varepsilon^\infty_{\perp,\parallel}(\nu) = \varepsilon^\infty_{\perp,\parallel} + \frac{\varepsilon^\infty_{\perp,\parallel}(\nu^2_{L\perp,\parallel} - \nu^2_{T\perp,\parallel})}{\nu^2_{T\perp,\parallel} - \nu^2 - i\nu\gamma_{f\perp,\parallel}} - \frac{\nu^2_{p\perp,\parallel}\varepsilon^\infty_{\perp,\parallel}}{\nu(\nu + i\gamma_{p\perp,\parallel})} . \tag{1}$$

Let us consider the possible cases of mutual arrangement of vectors **B**, $\mathbf{E}_0$, **k** relative to the optical axis C in a polar optically anisotropic single crystal (Faraday and Voigt configurations (Fig. 1)). Consider the Faraday configuration (see Fig. 1a, b). When the crystal axis is parallel to the magnetic field (Fig. 1a), the refractive index $n_\pm$ is determined by the formulas

$$n^2_\pm = \varepsilon^\infty_\perp(\nu) - \frac{\mu_\perp\nu^2_p}{\nu(\nu \pm \Omega)} , \tag{2}$$

where $\Omega = \frac{eB}{mc}\sqrt{\mu_\perp\mu_{xx}}$, and the tensor components of inverse effective mass μ_{ij} were determined in [16, 17].

Figure 2 shows the magnetoreflectance spectra of the 6H-SiC (PSE-3B, Table 1) single crystal. Dots show the experimental reflectance spectra of the 6H-SiC single crystal. Curve 1 gives the calculated $R(\nu)$ with account for the plasmon-phonon interaction and in the absence of the effect of the magnetic field. At a value of the magnetic field of 30 (curve 2), 65 (curve 3), and 100 kG (curve 4) changes in the low-frequency region of the IR magnetoreflectance spectrum 300–600 cm^{-1} were registered. Additional minima with frequencies 44, 113, 186 cm^{-1} that are due to the influence of the strong homogeneous magnetic field on the magnetoreflection coefficient are observed. Analogous results have been obtained for 6H-SiC single crystals with a concentration of free charge carriers of 10^{19} cm^{-3} (SiC-2, Table 1).

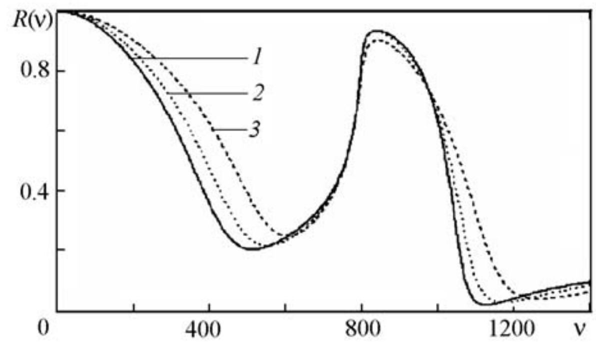

Fig. 3. Reflectance spectra of the 6H-SiC single crystal (calculations have been made in accordance with Tables 1, 2): 1) PSE-3B; 2) SiC-1; 3) SiC-2. ν, cm^{-1}.

These data agree with the experimental investigations of [18], where it was shown that in the case of nonpolarized light propagation along the magnetic field the electric wave vector is always perpendicular to the field and can be decomposed into two equal circularly polarized components with opposite senses of rotation. When the nonpolarized light propagates in the direction perpendicular to the magnetic field, it can be decomposed into two linearly polarized components parallel and perpendicular to the field. The latter component predetermines the splitting of the minimum in the reflectance spectra.

If the crystal axis is perpendicular to the magnetic field (Fig. 1b), then

$$n_{\pm}^2 = \frac{1}{2}\left[\varepsilon_{\parallel}^{\infty}(\nu) + \varepsilon_{\perp}^{\infty}(\nu) - \frac{\nu_p^2(\mu_{\perp} + \mu_{\parallel})}{\nu^2 - \Omega^2}\right] \pm \sqrt{\frac{1}{4}\left[\varepsilon_{\parallel}^{\infty}(\nu) - \varepsilon_{\perp}^{\infty}(\nu) - \frac{\nu_p^2(\mu_{\parallel} - \mu_{\perp})}{\nu^2 - \Omega^2}\right]^2 + \frac{\mu_{\perp}\mu_{\parallel}\Omega^2\nu_p^4}{\nu^2(\nu^2 - \Omega^2)^2}}\,. \tag{3}$$

In this case, the reflectance spectra are analogous to the spectra in Fig. 2, but additional minima show up at frequencies of 15, 41, and 77 cm^{-1}.

Consider the Voigt configuration. Electromagnetic waves propagate here in a uniaxial semiconductor 6H-SiC across a strong homogeneous magnetic field **B** arbitrarily directed with respect to the crystal axis. If the crystal axis is perpendicular to the reflecting surface and $\mathbf{E}_0 \parallel \mathbf{B}$ (Fig. 1c), then the magnetoreflection coefficient is defined as

$$R = \left| \frac{1 - \sqrt{\varepsilon_{\perp}^{\infty}(\nu)\left(1 - \dfrac{\nu_{p\perp}^2}{\nu^2}\right)}}{1 + \sqrt{\varepsilon_{\perp}^{\infty}(\nu)\left(1 - \dfrac{\nu_{p\perp}^2}{\nu^2}\right)}} \right|^2 . \tag{4}$$

Calculations show that at the given orientation the magnetoreflectance spectra of the 6H-SiC monocrystal do not depend on the external magnetic field, and for samples PSE-3B, SiC-1, and SiC-2 they are given in Fig. 3. The data for the calculations are presented in Tables 1, 2.

If in the incident wave the electric field vector $\mathbf{E}_0 \perp \mathbf{B}$ (Fig. 1d), then the expression for the reflection coefficient takes on the form

$$R = \left| \frac{1 - n}{1 + n} \right|^2 , \tag{5}$$

where $n = \sqrt{\dfrac{\varepsilon_{\perp}(\nu)(\nu^2 - \tilde{\nu}_{+}^2)(\nu^2 - \tilde{\nu}_{-}^2)}{\nu^2(\nu^2 - \Omega^2 - \nu_{p\parallel})}}$ is the refractive index of the extraordinary wave; $\tilde{\nu}_{\pm}^2$ is defined by the formulas

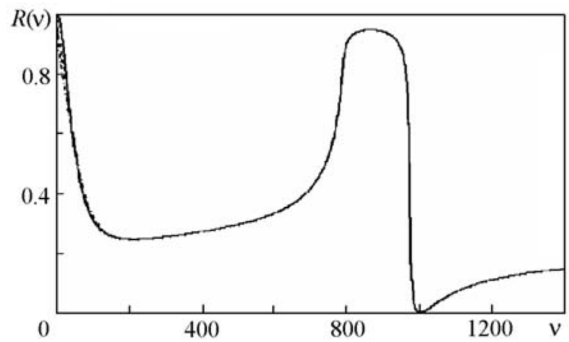

Fig. 4. Reflectance spectra of the 6H-SiC single crystal in the Voigt configuration with a magnetic field B from 1 G to 100 kG at ΔB = 5 kG. ν, cm^{-1}.

$$\tilde{\nu}_{\pm}^2 = \frac{1}{2}\left(\nu_{p\parallel}^2 + \nu_{p\perp}^2 + \Omega^2\right) \pm \left[\Omega^4 + 2\Omega^2\left(\nu_{p\parallel}^2 + \nu_{p\perp}^2\right) + \left(\nu_{p\parallel}^2 - \nu_{p\perp}^2\right)^2\right]^{\frac{1}{2}}.$$

In this case, the magnetoreflectance spectra of the 6H-SiC single crystal are analogous to the spectra in Fig. 2 with additional minima, respectively, at points 20, 39, and 7 cm^{-1}.

Consider the case where the crystal axis C is parallel to the reflecting surface and perpendicular to the magnetic field **B**. If $\mathbf{E}_0 \parallel \mathbf{B}$ (Fig. 1e), then

$$R = \left| \frac{1 - \sqrt{\varepsilon_{\perp}^{\infty}(\nu)\left(1 - \frac{\nu_{p\perp}^2}{\nu^2}\right)}}{1 + \sqrt{\varepsilon_{\perp}^{\infty}(\nu)\left(1 - \frac{\nu_{p\perp}^2}{\nu^2}\right)}} \right|^2 \tag{6}$$

and the reflectance spectra do not depend on the external magnetic field and have the form shown in Fig. 3. If $\mathbf{E}_0$ is polarized along the crystal axis C (see Fig. 1f), then the magnetoreflection coefficient is defined by formula (5) where

$$n = \sqrt{\frac{\varepsilon_{\parallel}^{\infty}(\nu)\,(\nu^2 - \tilde{\nu}_{-}^2)\,(\nu^2 - \tilde{\nu}_{+}^2)}{\nu^2\,(\nu^2 - \Omega^2 - \nu_{p\perp}^2)}}\,,$$

$$\tilde{\nu}_{\pm}^2 = \frac{1}{2}\left(\nu_{p\parallel}^2 + \nu_{p\perp}^2 + \Omega^2\right) \pm \left[\Omega^4 + 2\Omega^2\left(\nu_{p\parallel}^2 + \nu_{p\perp}^2\right) + \left(\nu_{p\parallel}^2 - \nu_{p\perp}^2\right)^2\right]^{\frac{1}{2}}.$$

Figure 4 shows the magnetoreflectance spectra of the 6H-SiC single crystal with a concentration of free charge carriers of $5 \cdot 10^{18}$ cm^{-3} located in a homogeneous magnetic field when the crystal axis C is parallel to the reflecting surface and perpendicular to the magnetic field **B**, with $\mathbf{E}_0$ being polarized along the crystal axis. Scanning was carried out with a magnetic field from 30 to 100 kG at a step of 5 kG. As is seen from Fig. 4, the influence of the magnetic field on the reflectance spectra of the 6H-SiC single crystal at the given orientation of the magnetic field and the optical axis is insignificant.

Consider the case of the Voigt configuration where the crystal axis C is parallel to the magnetic field **B**. If $\mathbf{E}_0 \parallel \mathbf{B}$ (see Fig. 1g), then the magnetoreflection coefficient is defined by the formula

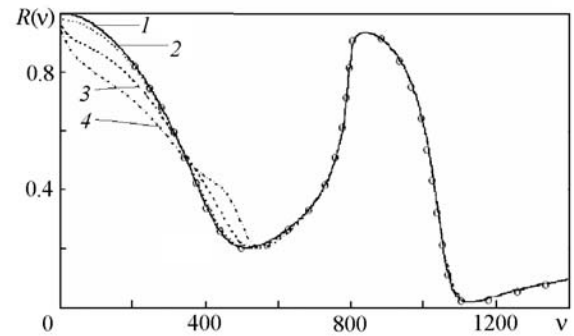

Fig. 5. Reflectance spectra of the 6H-SiC single crystal (n_0 = $5 \cdot 10^{18}$ cm^{-3}) exposed to a uniaxial magnetic field B in the Voigt configuration: 1–4) calculation at B = 1 G, 30 kG, 65 kG, and 100 kG, respectively; dots show the experiment. ν, cm^{-1}.

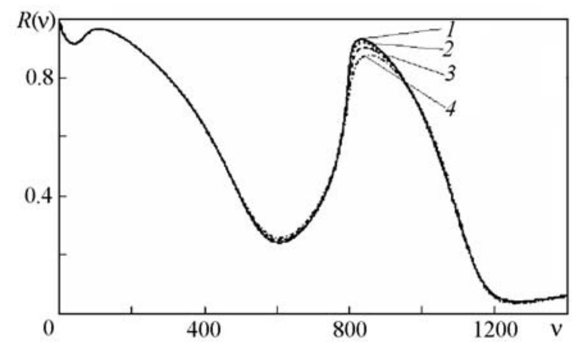

Fig. 6. Reflectance spectrum of the highly doped single crystal (n_0 = 10^{19} cm^{-3}) exposed to a 65 kG magnetic field at various values of the optical phonon attenuation coefficient: 1) γ_f = 11 cm^{-1}; 2) 15; 3) 20; 4) 30. ν, cm^{-1}.

$$R = \left| \frac{1 - \sqrt{\varepsilon_{\parallel}^{\infty}(\nu)\left(1 - \frac{\nu_{p\parallel}^2}{\nu^2}\right)}}{1 + \sqrt{\varepsilon_{\parallel}^{\infty}(\nu)\left(1 - \frac{\nu_{p\parallel}^2}{\nu^2}\right)}} \right|^2 \tag{7}$$

and the reflectance spectra have a form analogous to Fig. 3. In the case where $\mathbf{E}_0 \perp \mathbf{B}$ (Fig. 1h), the expression for the reflection coefficient is analogous to (5), where

$$n^2 = \varepsilon_{\perp}^{\infty}(\nu)\,\frac{(\nu^2 - \nu_+^2)\,(\nu^2 - \nu_-^2)}{\nu^2\,(\nu^2 - \nu_h^2)}\,; \quad \nu_{\pm}^2 = \nu_{p\perp}^2 + \frac{\Omega^2}{2}\left(1 \pm \sqrt{1 + 4\,\frac{\nu_{p\perp}^2}{\Omega^2}}\right); \quad \nu_h^2 = \Omega^2 + \nu_{p\perp}^2\,.$$

At the given orientation of the magnetic field with respect to the crystal axis for the 6H-SiC single crystal (PSE-3B, Table 1), the reflectance spectrum shown in Fig. 5 has been obtained. As is seen, the action of a strong homogeneous field on the given single crystal is followed by marked changes in the magnetoreflection coefficient in a low-frequency IR region down to 540 cm^{-1}, but there appear no additional minima in scanning a magnetic field from 30 to 100 kG.

In [13], the influence of anisotropy of plasmon-phonon perturbations on the reflection coefficient of 6H-SiC with no influence of the magnetic field was investigated. It was shown that in doped 6H-SiC plasma oscillations (plasmons), whose energy at typical concentrations of free carriers $n_0 = 10^{14}$–10^{18} cm^{-3} is small enough (of the order of 10^{-2} eV), are excited. The properties of these low-frequency plasmons have much in common with the ideal electron gas plasma. Longitudinal plasma oscillations interact actively with longitudinal optical phonons of a polar crystal generating mixed plasmon-phonon excitations in the bulk of the 6H-SiC monocrystal. The plasmon-phonon interaction without the influence of the magnetic field on the single crystal was revealed in investigating the optical reflectance spectra in the region of the band of residual rays.

Figure 6 shows the magnetoreflectance spectra of a doped single crystal under the action of a strong uniaxial magnetic field parallel to the 6H-SiC semiconductor surface, with the crystal axis *C* perpendicular to the reflecting surface and $\mathbf{E}_0 \perp \mathbf{B}$. No influence of the external homogeneous magnetic field on the refection coefficient of the 6H-SiC monocrystal in the region of residual rays is observed (Fig. 6). In the above-mentioned region, the reflection coefficient varies only due to the anisotropy of plasmon-phonon excitations (in the region of residual rays the reflectance spectrum in the presence of the effect of the magnetic field on the 6H-SiC single crystal is similar to the reflectance spectrum without magnetic field). Analogous results have been obtained for any orientation of the magnetic field and of the optical axis of the crystal.

Conclusions From the investigations made it may be concluded that in the case of the action on the 6H-SiC single crystal of a uniaxial magnetic field of up to 100 kG, in the IR reflectance spectra at certain orientations oscillations of the reflection coefficient in the low-frequency spectral region are observed. However, if the electromagnetic wave propagates in a uniaxial 6H-SiC semiconductor across a strong homogeneous magnetic field **B** (Voigt configuration), then in the cases of Fig. 1c, e, g the reflection coefficients do not depend on the action on them of a magnetic field and the reflectance spectra have the character described in the present paper.

At orientations of Fig. 1a, b, and d, maximum changes in the reflectance spectra are observed, which is due to the decomposition of the polarized light into two linearly polarized components — parallel and perpendicular to the field — and the latter component is responsible for the splitting of the minima in the reflectance spectra.

NOTATION

B, external magnetic field induction; **B**, external magnetic field induction vector; *C*, optical axis of the crystal; *c*, velocity of light in free space; *e*, free carrier charge; **E**, electric vector of radiation; $\mathbf{E}_0$, electric field strength vector of the incident electromagnetic wave; **k**, wave vector; *m*, free electron mass; *n*, refractive index; n_0, concentration of free charge carriers; *R*, reflection coefficient; **r**, radius vector drawn to the considered point of the field; *t*, time; *x*, *y*, *z*, axes of the rectangular coordinate system; $\gamma_{\mathrm{f}\perp,\parallel}$, $\gamma_{\mathrm{p}\perp,\parallel}$, attenuation coefficients of the optical phonon and plasmons across and along the crystal axis; ε_{ij}, permittivity tensor; $\varepsilon^0_{\perp,\parallel}$, static permittivity across and along the crystal axis; $\varepsilon^\infty_{\perp,\parallel}$, principal values of the high-frequency permittivity across and along the crystal axis; λ, wavelength; $\mu_{i,j}$, dimensionless tensor of inverse effective mass; $\mu_{\perp,\parallel}$, principal values of the dimensionless tensor of inverse effective mass across and along the crystal axis; ν, frequency; ν_h, hybrid frequency; $\nu_{\mathrm{L}\perp,\parallel}$, $\nu_{\mathrm{T}\perp,\parallel}$, frequencies of the longitudinal and transverse optical phonons across and along the crystal axis, respectively; $\nu_{\mathrm{p}\perp,\parallel}$, plasma resonance frequency across and along the crystal axis; φ, angle between the optical axis of the crystal and the *z* axis; Ω, cyclotron frequency. Subscripts: h, hybrid; p, plasmon; f, phonon; L, T, longitudinal and transverse optical phonons.

REFERENCES

1. S. A. Dembovskii, E. A. Chechetkina, and S. A. Kozyukhin, Anomalous influence of weak magnetic fields on diamagnetic glassy semiconductors, *Pis'ma Zh. Éksp. Teor. Fiz.*, **41**, Issue 2, 74–76 (1985).
2. R. C. Johnson, R. E. Merrifield, P. Avakian, and R. B. Flippen, Effects of magnetic fields on the mutual annihilation of triplet excitons in molecular crystals, *Phys. Rev. Lett.*, **19**, No. 6, 285–287 (1967).
3. H. Hayashi, B. Sakaguchi, and H. Abe, Magnetic field effects on dynamic behavior of excited molecules, *Physica*, **B164**, 217–221 (1990).
4. E. L. Frankevich, I. A. Sokolik, D. I. Kadyrov, and V. M. Kobryanskii, Influence of a weak magnetic field on the conductivity of polyacetylene films, *Pis'ma Zh. Éksp. Teor. Fiz.*, **36**, Issue 11, 401–403 (1982).

5. E. L. Frankevich, A. I. Pristupa, and V. M. Kobryanskii, A new effect of a magnetic-resonant change in the resistance of an organic semiconductor: weakly doped polyacetylene, *Pis'ma Zh. Éksp. Teor. Fiz.*, **40**, Issue 1, 13–15 (1984).
6. R. H. Tarkhanyan and A. G. Nassiopoulou, Generation of guided terahertz electromagnetic waves in semiconductor superlattices, *J. Phys.: Conf. Ser.*, **10**, No. 5, 19–22 (2005).
7. R. H. Tarkhanyan and D. G. Niarchos, Effective negative refractive index in ferromagnet-semiconductor superlattices, *Opt. Expr.*, **14**, No. 12, 5433–5444 (2006).
8. R. H. Tarkhanyan and N. K. Uzunoglu, Propagation of electromagnetic waves on the lateral surface a ferrite/semiconductor superlattice at quantum Hall-effect conditions, *Prog. Electromagn. Res.*, **29**, 321–335 (2000).
9. B. M. Darinskii and V. N. Feklin, Spin effects in nonmagnetic crystals in a magnetic field, *Fiz. Tverd. Tela*, **48**, Issue 9, 1614–1616 (2006).
10. Yu. I. Golovin, Magnetoplasticity of solids (Review), *Fiz. Tverd. Tela*, **46**, Issue 5, 769–803 (2004).
11. A. F. Kravets, Yu. I. Dzhezherya, V. G. Kravets, and E. S. Klimuk, Characteristic features of the infrared radiation reflection by crystalline dielectrics in a magnetic field, *Zh. Éksp. Teor. Fiz.*, **126**, No. 6, 1362–1366 (2004).
12. E. F. Venger, A. V. Melnichuk, L. Ju. Melnichuk, and Ju. A. Pasechnik, Anisotropy of the ZnO single crystal reflectivity in the region of residual rays, *Phys. Status Solidi* (b), **188**, No. 2, 823–831 (1995).
13. E. F. Venger, A. I. Ievtushenko, L. Yu. Melnichuk, and O. V. Melnichuk, Investigation of ZnO single crystals subjected to high uniform magnetic field in IR spectral range, *Semicond. Phys. Quant. Electron. Optoelectron.*, **11**, No. 1, 6–10 (2008).
14. E. F. Venger, A. V. Mel'nichuk, and Yu. A. Pasechnik, *Spectroscopy of Residual Rays* [in Russian], Naukova Dumka, Kiev (2001).
15. A. V. Mel'nichuk and Yu. A. Pasechnik, Anisotropy of the effective masses of electrons in silicon carbide, *Fiz. Tverd. Tela*, **34**, No. 2, 423–428 (1992).
16. R. H. Tarkhanyan and N. K. Uzunoglu, *Radiowaves and Polaritons in Anisotropic Media*, John Wiley & Sons Inc., Weinheim (2006).
17. L. É. Gurevich and R. G. Tarkhanyan, Electromagnetic waves in uniaxial conducting crystals in a magnetic field, *Fiz. Tekh. Poluprovodn.*, No. 4, 703–709 (1972).
18. I. M. Tsidil'kovskii, *Electrons and Holes in Semiconductors* [in Russian], Nauka, Moscow (1972).