Acousto-optical analog of the Borman effect in semiconductors

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(Submitted 24 June 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **32**, No. 5, 348–352 (5 September 1980)

The Bragg diffraction of electromagnetic radiation by an absorption grating, which is produced in semiconductors by a high-intensity acoustic wave because of a redistribution of free carriers, is examined. High diffraction efficiency and a large decrease of the total absorption in the medium (Borman effect) are demonstrated.

PACS numbers: 78.20.Hp

As a result of propagation of radiation in a periodic absorbing medium, the absorption can decrease considerably in comparison with its average value in the medium. This decrease occurs due to Bragg diffraction of the radiation when a quasistanding wave with nodes at the absorption maxima of the periodic structure appear as a result of interference of the incident and diffracted waves.[1,2] This effect, initially observed in the propagation of x rays in crystals, is called the Borman effect.[1,3] In this paper we show that an analogous effect occurs in the Bragg diffraction of IR radiation by a high-intensity acoustic wave in a semiconductor.

An acoustic wave propagating in a semiconductor causes a rearrangement of the electron subsystem: free carriers accumulate in the regions with minimum potential energy. At a sufficiently high wave intensity the electrons cannot leave the potential wells. As a result, a periodic system of electron layers, which are separated by nonconducting gaps that move together with the sound wave, appears in the crystal.[4] The light in such a system can be diffracted by a strain wave and by an induced electron-density wave. Acousto-optical diffraction is usually associated with sound modulation

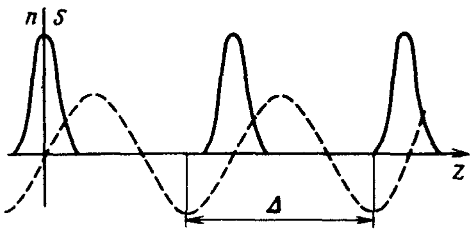

FIG. 1. Distribution of the strain and free carriers in a high-intensity sound wave in a coordinate system moving with the wave (S is the strain and n is the electron density). The solid line represents the free-carrier distribution and the dashed line denotes the strain distribution.

of the refractive index of the medium. However, the modulation of the electron density by a sound wave can form an absorption grating in semiconductors in which the absorption of light in the long-wave region of the spectrum is determined by the free carriers. The scattering of IR radiation by this grating can produce diffraction effects similar to the Borman effect.

We shall examine the propagation of an electromagnetic wave through a semiconductor in which a superlattice of carriers is produced by the action of sound (Fig. 1). The dielectric constant has the form

$$\epsilon(\omega) = \epsilon_0 + \epsilon_0' \frac{\omega_0^2}{\omega(\omega + i\nu)} \frac{n(z, t)}{n_0} . \tag{1}$$

Here $\epsilon_0 = \epsilon_0' + i\epsilon_0''$ is the permittivity of the lattice, $\omega_0 = \sqrt{4\pi e^2 n_0/m^*\epsilon_0'}$ is the plasma frequency, n_0 is the average density of carriers, m^* is the effective mass, ν is the collision frequency, ω is the frequency of the electromagnetic wave, and $n(z, t)$ is the electron distribution in the presence of a sound wave. The electrons are concentrated in layers, whose thickness h, determined by the amplitude of the sound wave, can be made much smaller than the wavelength Λ.[4] The Fourier expansion of the electron density contains a large number of harmonics. For $h \ll \Lambda$ the amplitudes of the harmonics with small numbers l are approximately identical and coincide with the average electron density: $n_l = n_0$.[5]

The electromagnetic wave can be diffracted by each harmonic n_l of the electron

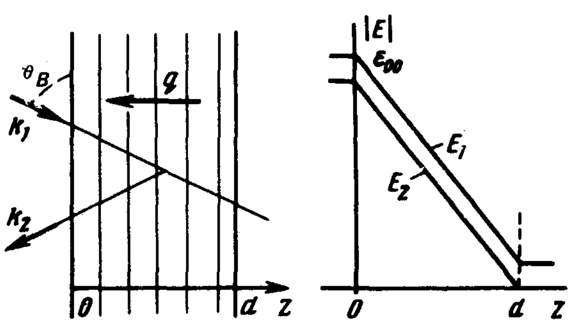

FIG. 2. Diffraction scheme and the distribution of the amplitudes of the transmitted (E_1) and diffracted (E_2) electromagnetic waves for diffraction by an acoustic beam of infinite aperture ($d_0 > d > 1/a_0$).

density. If the wave is incident on the sound beam at an angle θ_{lB}

$$\theta_{lB} = \arc\sin \frac{l}{2} \frac{q}{k},$$

where **k** is the wave vector of the electromagnetic wave and q is the wave vector of the sound, then a Bragg diffraction by the lth harmonic occurs (Fig. 2). The electric field in the perturbed medium is a superposition of two waves– an incident wave 1 and a diffracted wave 2–whose amplitudes E_1 and E_2 contain a slow corrdinate dependence that is defined by the dynamic equations

$$\begin{cases} \dfrac{\mathbf{k}_1}{k_1} \dfrac{\partial E_1}{\partial \mathbf{r}} + (\gamma + a_0) E_1 + a_l E_2 = 0 \\ \\ \dfrac{\mathbf{k}_2}{k_2} \dfrac{\partial E_2}{\partial \mathbf{r}} + (\gamma + a_0) E_2 + a_l E_1 = 0 \end{cases} \tag{2}$$

Here $\gamma = \frac{1}{2}\left(\frac{\epsilon_0''}{\epsilon_0'}\right) k$ is the decrement of an electromagnetic wave, which is not associated with the free carriers, $a_0 = \frac{\omega_0^2}{\nu c}\sqrt{\epsilon_0'}$ is the decrement caused by the free carriers, $a_l = \left(\frac{\omega_0^2}{\nu c}\right)\left(\frac{n_l}{n_0}\right)\sqrt{\epsilon_0'}$ is the coupling coefficient between the waves, which determines the diffraction efficiency, and c is the velocity of light. We assume henceforth that the light absorption is determined by the free carriers ($\gamma/a_0 \ll 1$). In the diffraction by a high-intensity acoustic wave the coupling coefficient a_l is equal to the electron decrement a_0, since $n_l = n_0$.

First we shall examine the effects occurring in the diffraction of electromagnetic radiation in a layer of finite width d, $0 \leqslant z \leqslant d$, by an acoustic wave of infinite aperture (Fig. 2). The electromagnetic wave, which is incident on the layer at an angle θ_{lB}, emerges from the layer through the $z = 0$ plane, after being partially transmitted through the layer and partially diffracted by it, thereby forming a reflected wave. The solution of Eq. (2) shows that the amplitudes of both waves decreases inside the layer and, if the layer thickness is less than the characteristic dimension $d_0 = (\sqrt{2\gamma a_0})^{-1}$, this decrease will be linear:

$$E_1(z) = \epsilon_{00}\left(1 - \frac{a_0 z/\sin\theta_{lB}}{1 + a_0 d/\sin\theta_{lB}}\right) \quad E_2(z') = \epsilon_{00} \frac{a_0(z-d)\sin\theta_{lB}}{1 + a_0 d/\sin\theta_{lB}}; \tag{3}$$

where ϵ_{00} is the amplitude of the incident light. For $d > d_0$ it becomes an exponential distribution:

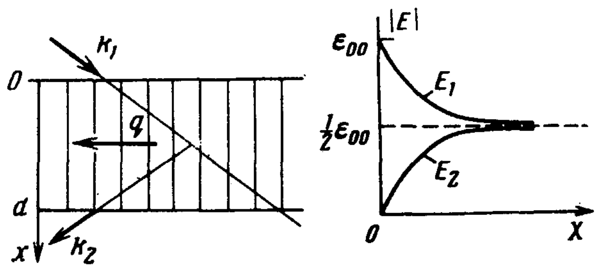

FIG. 3. Diffraction scheme and the distribution of the amplitudes of the transmitted (E_1) and diffracted (E_2) electromagnetic waves for diffraction by an acoustic beam of finite aperture ($\frac{1}{a_0} < d < \frac{1}{\gamma}$).

$$E_1(z) \approx E_2(z) \approx \epsilon_{00} \exp(-z/d_0). \tag{4}$$

It follows from an analysis of Eqs. (3) and (4) that the acousto-optical diffraction effects are important at $a_0 d > 1$. In this case the radiation penetrates the layer to a depth $z \sim d_0 \sim (\sin\theta_{lB})/\sqrt{2\gamma a_0}$. This value is much greater than the penetration depth of electromagnetic radiation in an acoustically unperturbed medium $z \sim (\sin\theta_{lB})/a_0$, which is determined by the electron absorption it it. Nonetheless, there is no absorption in the medium, since $E_2(z=0) = -\epsilon_{00}$, and the incident radiation is almost totally reflected from the layer. As a result of interfering with each other, the incident and diffracted waves produce a quasi-standing wave

$$E(\mathbf{r}, t) = 2E_1(z)\sin(k_x x - \omega t)\sin qz. \tag{5}$$

Its nodes occur in the region of electron layers and there is no absorption of the electromagnetic energy.

Let us assume that the electromagnetic radiation passes through a sound beam of finite width d ($0 \leqslant x \leqslant d$) that is propagating along the z axis (Fig. 3). As a result of Bragg diffraction, two wave come out through the $x = d$ plane: the incident wave and the diffracted wave. The amplitude distributions of these waves have the form

$$E_1(x) = \frac{1}{2}\epsilon_{00}\exp\left(\frac{-\gamma x}{\cos\theta_{lB}}\right)\left(1 + \exp\left(\frac{-2a_0 x}{\cos\theta_{lB}}\right)\right);$$

$$E_2(x) = -\frac{1}{2}\epsilon_{00}\exp\left(\frac{-\gamma x}{\cos\theta_{lB}}\right)\left(1 - \exp\left(\frac{-2a_0 x}{\cos\theta_{lB}}\right)\right). \tag{6}$$

At $x < (\cos\theta_{lB})/a_0$ the absorption is determined by the electrons; at $x > (\cos\theta_{lB})/a_0$ it is not determined by electronic mechanisms, since the incident and diffracted waves interfere in this region and produce a quasi-standing wave (5). At

$(\cos\theta_{IB})/a_0 < d < (\cos\theta_{IB})/\gamma$ the intensity of the radiation leaving the sound beam is equal to one-half the intensity I_{00} of the incident radiation, regardless of the thickness of the sound beam; this energy is equally distributed between the transmitted and the deflected waves: $I_1 = I_2 = \frac{1}{4}I_{00}$.

We give estimates for a piezosemiconductor. To retain the electrons trapped by the electric field of the sound wave, the depth $e\phi = 2\beta e\Lambda / \epsilon_0' S$ (β is the piezoelectric modulus, S is the strain amplitude, and Λ is the sound wavelength) of the potential well must be greater than the thermal energy kT: $e\phi / kT > 1$. In addition, the electric field $E_{\rm el.stat} = \dfrac{2\pi e n_0}{\epsilon_0'}\Lambda$, which is produced as a result of the formation of electronic layers due to separation of charges, must be compensated for by the electric field of the wave $E_{\sim} = \dfrac{2\pi\beta}{\epsilon_0'}S$. For a transverse, wave in tellurium ($\beta = 3\times 10^5$ cgs units, $v_s = 10^5$ cm/sec, and $n_0 = 10^{14}$ cm^{-3}) with a frequency $f = 17$ MHz, it is necessary to generate sound fluxes $P \sim 40$ W/cm^2 in order to produce an effective absorption grating. An interaction length of a few centimeters is required to observe the above-described acousto-optical diffraction effects for IR radiation with a wavelength of 337 μm.

The diffraction effects indicated above can also occur in formation of a periodic, spatial absorbing medium, such as that for infrared quenching of photoconductivity.

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Translated by Eugene R. Heath
Edited by S. J. Amoretty