Light-induced electron drift in semiconductors

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The appearance of free electron drift in semiconductors is predicted for two-photon transitions (Raman scattering type) between Landau levels. An asymmetry is produced in the electron velocity distribution because of a velocity-selective radiation excitation and a difference in the electron mobilities in different Landau levels. The potential difference produced as a result of the drift, can reach a value of $\sim 10^{-3}$ V under typical conditions.

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The existence of an interesting optomechanical effect—a directed motion (drift) of particles that absorb light in a mixture with a buffer gas—has recently been proved.[1,2] This drift occurs because of a velocity-selective excitation of particles by light (Doppler effect) and a difference in the translational relaxation times in the ground and excited states. As a result, an asymmetrical velocity distribution of absorbing particles, the existence of a drift, is established. The drift can occur in the direction of the radiation wave vector and also opposite to it, depending on the sign of the difference between the radiation frequency and the transition frequency.

This effect, which is very prominent in gases, should find many applications. It would obviously be interesting to look for the analog of this effect in other systems. The electrons in a conduction band in semiconductors have many of the properties characteristic of gases. It turns out that there is a case when the analogy of gas systems, from the viewpoint of the effect being discussed, is nearly total. The case in point is the radiation transition between Landau levels, specifically the two-photon Raman scattering type transitions (Fig. 1). Such transitions are used, for example, in the so-called spin-flip lasers (see, for example, Ref. 3).

The electrons in the m and n states have nearly identical dispersion laws (just as a gas atom in different energy states). Consequently, the lines of the two-photon process in Fig. 1 typify the Doppler effect in its traditional manifestation. The maximum

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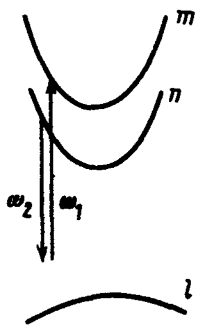

FIG. 1. Diagram of the two-photon transition between the Landau level. l represents the boundary of the valence band.

Doppler broadening occurs when the waves with frequencies ω_1 and ω_2 are propagating in opposite directions and collinearly to the direction of the magnetic field along which the electrons move freely.

Let us assume that in the absence of radiation the free electrons are in the n level. The two-frequency radiation will cause the excitation of the m level, and, because of the Dopper effect, the excitation is velocity-selective in accordance with the resonance condition $\Omega \equiv \omega_1 - \omega_2 - \omega_{mn} = qv$. Here $q = k_{1Z} - k_{2Z}$ is the difference between the projections of the wave vectors in the direction of the magnetic field (Z axis) and v is the velocity of the electrons along the Z axis. If translational relaxation is ignored, then the velocity distribution of the electrons in the n and m levels will have the form shown in Fig. 2. The distribution in the m level and the n level are described by the function $\phi(\Omega - qv)$ that has a maximum at $\Omega = qv$ and a half-width Γ/q, where Γ is the homogeneous half-width of the Raman-scattering line. For clarity, we assume a large Doppler broadening ($\Gamma \ll q\bar{v}$, where $\bar{v}$ is the characteristic thermal velocity of the electrons). For $\Omega \neq 0$ each distribution $N_m(v)$, $N_n(v)$ is highly asymmetrical; however, the total velocity distribution $N(v) = N_m(v) + N_n(v)$ remains asymmetrical in the absence of translational relaxation.

In fact, an active interaction of the electrons with impurities and lattice defects occurs in semiconductors, as a result of which a thermalization of each distribution occurs to some extent (analogously to the action of a buffer gas). The thermalization velocities ν_m and ν_n in the m and n states are different. For example, ν_m and ν_n can differ by severalfold in the transitions with spin reversal, according to the data of Refs.

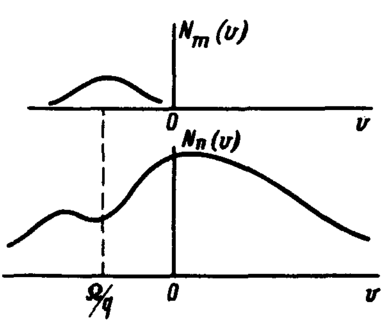

FIG. 2. Characteristic form of the electron velocity distributions in the Landau levels under Doppler broadening conditions.

4 and 5 for the change in electron mobility due to spin reversal. We assume that $\nu_n > \nu_m$, i.e., the $N_n(v)$ distribution is thermalized faster. The total distribution $N(v)$, therefore, acquires an asymmetry matching the asymmetry of $N_m(v)$. In other words, there is a directed electron motion (drift) in the form of an electric current. The drift velocity u is described by the equation

$$u = \frac{\nu_n - \nu_m}{\nu_n} \frac{1}{\Gamma_m + \nu_m} P \frac{\langle v \phi(\Omega - qv) \rangle}{\langle \phi(\Omega - qv) \rangle} . \tag{1}$$

Here Γ_m is the spontaneous and collisional quenching rate of the m level and P is the probability (per unit time) of the $n \to m$ transition due to radiation; the angle brackets denote an averaging over velocities with a uniform distribution.

A light-induced electron drift leads to the establishment of a potential difference V across the ends of the test specimen, which is determined from the relation

$$V = uL / \mu , \tag{2}$$

where L is the sample length in the direction of the magnetic field, and μ is the electron mobility (we are analyzing an n-type semiconductor).

We shall estimate the value that V can attain. We choose a sample length L of the order of the distance l_F, within which a significant decrease occurs in the intensity of the radiation with frequency ω_1, and l_F can be determined from the relation

$$S \equiv \frac{c}{8\pi} |E_1|^2 = \hbar\omega_1 N P l_F , \tag{3}$$

where N is the electron density and S is the energy-flux density. Thus, we obtain the following estimate for the potential difference:

$$V \sim \frac{\nu_n - \nu_m}{\nu_n} \frac{S\bar{v}}{\hbar\omega_1 N\mu(\Gamma_m + \nu_m)} \frac{\langle \frac{v}{\bar{v}} \phi(\Omega - qv) \rangle}{\langle \phi(\Omega - qv) \rangle} . \tag{4}$$

The last factor in this expression can reach a value of the order of unity. Thus, we have in the case of predominant Doppler broadening

$$\frac{\langle \frac{v}{\bar{v}} \phi(\Omega - qv) \rangle}{\langle \phi(\Omega - qv) \rangle} \sim \frac{\Omega}{q\bar{v}} ; \quad (\Omega \lesssim q\bar{v}) . \tag{5}$$

We substitute in Eq. (4) the values that are typical of the indium antimonide crystal—a typical material for obtaining spin-flip lasing through excitation by CO-laser radiation. For $T = 4$ K we have $v \sim 10^7$ cm/sec (for an effective electron mass[6] of $\sim 1.5 \times 10^{-29}$ g), $\mu \sim 10^6$ cm^2/V sec (Ref. 6); ν_n, $\nu_m \sim 10^{11}$ sec^{-1} (the collision frequency is calculated from the values of the mobility and effective mass), $N \sim 10^{14}$ cm^{-3}, $|\nu_n - \nu_m|/\nu_n \sim 1$, $\Gamma_m \ll \nu_m$. For a CO-laser radiation power of ~ 1 W ($\lambda = 5.3 \times 10^{-4}$ cm) and a sample cross-sectional area of $\sim 10^{-2}$ cm^2 we obtain, according to (4),

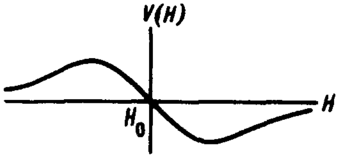

FIG. 3. Qualitative dependence of the potential difference on the magnetic field intensity. The value $H = H_0$ corresponds to the resonance condition ($\Omega = 0$).

$$V \sim 10^{-3}\ \mathrm{V}. \qquad (6)$$

Thus, the light-induced electron-drift effect can be easily observed experimentally. We note that the potential difference changes sign when Ω changes sign. Since the frequency of the $m - n$ transition is proportional to the magnetiy-field intensity H, the H dependence of the potential difference has the characteristic form shown in Fig. 3. On the basis of this specific dependence it is easy to isolate the light-induced electron drift effect in a background of other effects, in particular, in a background of the known photon-drag effect of electrons due to transfer of the photon momentum to the electrons (see, for example, Ref. 7 and the literature cited therein). Note that the effect discussed above predominates quantitatively over the drag effect. We can show that the corresponding drift velocities correlate with both the electron thermal momentum $m\bar{v}$ and the photon momentum $\hbar q$. We obtain $m\bar{v}/\hbar q \sim 10$ for the parameters given above, i.e., the light-induced drift effect can be an order of magnitude stronger than the photon drag of electrons (we ignored the latter effect in the calculations).

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