Photon-Drag Effect in Intersubband Absorption by a Two-Dimensional Electron Gas

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Intersubband transitions stimulated by a light wave propagating in the plane of a two-dimensional electron gas are accompanied by a "photon-drag" current due to the momentum imparted by the absorbed photons. In a high-mobility electron gas at low temperatures, a peculiar effect is predicted to occur as a result of the difference in the momentum relaxation times in the ground and the excited subbands. This effect permits the implementation of novel far-infrared detectors, as well as a new type of spectroscopy containing information about the momentum-relaxation kinetics in 2D subbands.

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Infrared absorption between quantum-well (QW) subbands was recently demonstrated by West and Eglash[1] in modulation-doped GaAs/AlGaAs superlattice and also by Levine *et al.*[2,3] using conventional doped quantum wells. These dipole transitions are similar in nature to those used previously for intersubband spectroscopy of Si inversion layers[4,5] and other charged-surface states.[6] The purpose of this Letter is to discuss the state of the motion of the QW electrons irradiated by an infrared light propagating parallel to the plane of a QW superlattice (situation quite feasible experimentally, since such superlattices usually form a dielectric waveguide). In general, the intersubband transitions will be accompanied by a measurable "photon-drag" current due to the momentum imparted by the absorbed photons. The frequency dependence of this current contains a wealth of information regarding the momentum-relaxation kinetics in 2D subbands.

The classical (radio-frequency) photon-drag effect in semiconductors was first discussed by Barlow.[7] At low frequencies, the electron current can be pictured in terms of the ordinary Hall effect in crossed electric and magnetic fields of the electromagnetic wave. The quantum photon-drag effect in p-type Ge at optical frequencies was predicted by Kastalsky[8] and observed by himself and co-workers[9] and, independently, by Gibson, Kimmitt, and Walker.[10] In these experiments, the optical absorption was due to electronic transitions between the valence subbands in bulk Ge. The practical utilization of germanium photon-drag detectors was so far limited by their low sensitivity,[8] typically less than 10^{-6} A/W. As will be shown below, the use of a waveguide geometry with the photon-drag current induced in a two-dimensional electron gas (2DEG)—with its high-mobility and high intersubband absorption coefficient—allows one to increase the sensitivity by many orders of magnitude (bringing it into the range ~ 1 A/W), and at the same time observe a novel frequency-dependent effect peculiar to a 2D system.

Consider a transverse-magnetic wave propagating along the waveguide formed by an AlAs/GaAs superlattice and two AlAs cladding layers, cf. Fig. 1. The superlattice core thickness is $D = pd$ and each of the p periods d consists of a d_W-thick QW and a d_B-thick barrier with a duty cycle $r \equiv d_W/d_B$. The superlattice is modulation doped, and each QW contains a 2DEG of areal density n. The fraction of light intensity contained within the core is then given by

$$\Gamma = (2\pi^2 D^2/\lambda_0^2) r \Delta\epsilon, \tag{1}$$

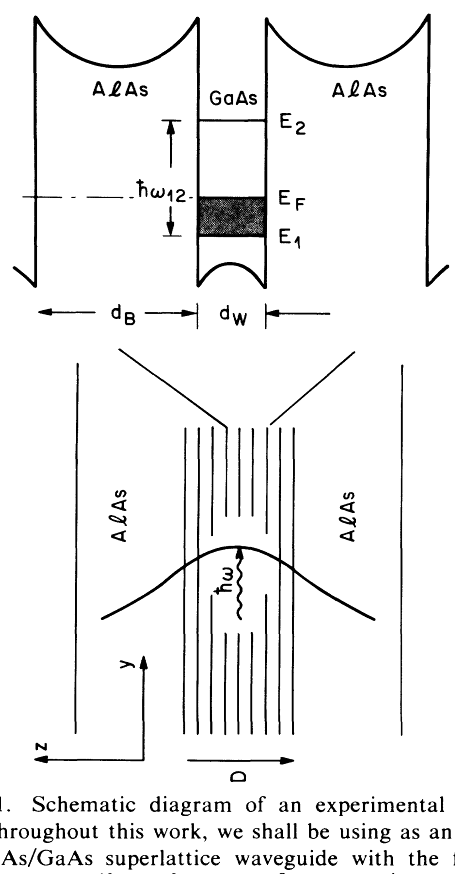

FIG. 1. Schematic diagram of an experimental arrangement. Throughout this work, we shall be using as an example an AlGaAs/GaAs superlattice waveguide with the following parameters: $n = 10^{12}$ cm^{-2}, $d = 150$ Å with $r = \frac{1}{3}$, $D = 0.75$ μm (i.e., $p = 50$ wells).

where λ_0 is the vacuum wavelength of the electromagnetic wave and $\Delta\epsilon \equiv \epsilon_{\text{GaAs}} - \epsilon_{\text{AlAs}}$ with $\epsilon_{\text{GaAs}} = 10.88$ and $\epsilon_{\text{AlAs}} = 8.16$ being the relative permittivities of the two materials.[11] The absorption coefficient α can be calculated with the Fermi's "golden rule" for the transition probability per unit time

$$w(\mathbf{k}) = \frac{2\pi}{\hbar^2} e^2 (E/2)^2 |\langle 1|z|2\rangle|^2 \frac{\gamma/\pi}{[\omega - \omega_{12} - \hbar(\mathbf{k}\cdot\mathbf{q})/m]^2 + \gamma^2}, \tag{2}$$

where $\hbar\omega_{12}$ is the intersubband separation, $\mathbf{q}$ is the photon wave vector, m the electron effective mass (assumed, neglecting nonparabolicity, to be the same for all electrons in the 2DEG), E is the electric field amplitude in the direction normal to the QW, and

$$\gamma \equiv 1/2\tau_1 + 1/2\tau_2 \tag{3}$$

is the lifetime contribution to the width of the subband levels $|1\rangle$ and $|2\rangle$.

Let us ignore in first approximation the dependence of w on the electron momentum $\hbar\mathbf{k}$, i.e., neglect in (2) the term $\hbar(\mathbf{k}\cdot\mathbf{q})/m$ which arises from the conservation of energy and 2D quasimomentum during intersubband transitions. In this approximation, $w(\mathbf{k}) \equiv \bar{w}$ and the total transition rate per unit volume equals $n\bar{w}/d$, giving

$$\bar{\alpha} \equiv \alpha[\bar{w}(\omega)] = \frac{ne^2 R_0 f\Gamma}{2m\bar{n}d} \frac{\gamma}{(\Delta\omega)^2 + \gamma^2}, \tag{4}$$

where $f \equiv (2m\omega/\hbar)|\langle 1|z|2\rangle|^2$ is the oscillator strength ($f \approx 1$),[1] $\bar{n}$ is the average refractive index of the material, $\Delta\omega \equiv \omega - \omega_{12}$, and $R_0 \equiv \mu_0 c = 377\ \Omega$ is the vacuum magnetic permeability constant. For $\lambda_0 \approx 10\ \mu$m and the superlattice parameters as in Fig. 1, Eq. (1) gives $\Gamma \approx 0.1$ and with $\gamma = 10^{13}\ \text{s}^{-1}$ (cf. Refs. 1–3) one has $\bar{\alpha} \approx 2\times 10^3\ \text{cm}^{-1}$.

In the above approximation, the entire photon-drag current is carried by electrons in the excited subband, since the cylindrical symmetry of the electron distribution in the lower subband is not distributed by $\bar{w}$ transitions. Each excited electron receives an extra momentum $\hbar q = 2\pi\hbar/\lambda$, which, on the average, relaxes after the time τ_2. The photon-drag current is in the direction of the light propagation and its density J_0 is related to the radiation energy flux S in the waveguide as follows:

$$J_0 = -\frac{e\tau_2}{md}\hbar q n\bar{w} = -\frac{\bar{n}}{c} S\bar{\alpha}\mu_{\text{eff}}, \tag{5}$$

where $\mu_{\text{eff}} \equiv (e/m)\tau_2$ is an effective mobility. A simple way of understanding (5) is to note that $\bar{\alpha}(\bar{n}/c)S$ represents the transferred momentum per unit volume per unit time, i.e., the drag-force density acting on electrons. Since $J_0 \propto \bar{\alpha}$, the spectrum $J_0(\omega)$ contains little additional information over the conventional absorption spectra.[1-6] However, as we shall now see, the photon-drag effect is much richer than that given by (5). The above approximation, although undoubtedly reasonable for calculating $\bar{\alpha}$ (as done, e.g., in Ref. 1), is totally inadequate for estimating the photon-drag current.

The gist of the matter is that the photon-drag current J represents a small net difference between two oppositely directed larger currents: one due to excited electrons in the upper subband, the other to remaining holes in the lower subband. Indeed, consider Fig. 2. If we ignore the level broadening, then the conservation laws of energy and momentum imply that the allowed transitions must obey

$$\hbar\omega + \frac{\hbar^2 k^2}{2m} = \hbar\omega_{12} + \frac{\hbar^2}{2m}(\mathbf{k}+\mathbf{q})^2, \tag{6}$$

i.e., to a good approximation, $\hbar(\mathbf{k}\cdot\mathbf{q})/m = \Delta\omega$. For example, if $\Delta\omega > 0$, then only those electrons whose momentum has a positive component in the direction of $\mathbf{q}$ can make a transition. Thus, in the presence of radiation *both* subbands acquire an electron distribution disturbed from cylindrical symmetry. The next point to note is that the relaxation times in the two subbands can be very different, $\tau_1 \gg \tau_2$, especially at lower temperatures. If we could follow the time evolution of J upon a short infrared pulse with $\Delta\omega > 0$, then we would observe the current to change sign after $\sim\tau_2$, with the magnitude $|J|$ rising, possibly, to a much higher value than the initial current and then decaying after $\sim\tau_1$ (during the time interval $\tau_2 < t < \tau_1$ the characteristic drift velocity in the 2DEG will be of the order of its Fermi velocity, $\hbar k_F/m$, rather than $\hbar q/m$). In a steady state, the resultant current may be directed either along or against the "primary" current, depending on the sign of $\Delta\omega$, and its magnitude can be substantially higher than that given by (5).[12] The effect is, of course, limited by the validity

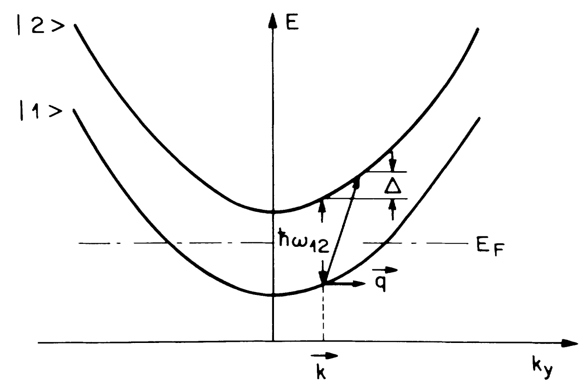

FIG. 2. Intersubband transitions stimulated by an electromagnetic (TM) wave propagating along the plane of a 2DEG in the y direction. The diagram illustrates the selection rule: $k_y > 0$ for $\Delta \equiv \hbar\Delta\omega > 0$. Similarly, $k_y < 0$ for $\Delta < 0$, as follows from the conservation laws for energy and momentum.

of the conservation laws (6), i.e., by the quality factor of the intersubband resonance. In the relaxation-time approximation this limitation is described by the width γ of the Lorentzian line (2).

Quantitatively, the total steady-state current is given by the difference of currents excited within each of the two subbands

$$J=\frac{e\tau_1 f_1}{md}-\frac{e\tau_2 f_2}{md}=\frac{e}{md}[(\tau_1-\tau_1)f_1-\tau_2(f_2-f_1)], \tag{7}$$

where f_i are the rates of momentum transfer in the ith subband per unit area of one 2DEG:

$$f_1=\int\frac{d^2k}{2\pi^2}\hbar k_y w(\mathbf{k})\approx \hbar qn\bar{w}\frac{\pi\hbar n}{m}\frac{\Delta\omega}{(\Delta\omega)^2+\gamma^2}, \tag{8a}$$

$$f_2=\int\frac{d^2k}{2\pi^2}\hbar(k_y+q)w(\mathbf{k})\approx f_1+\hbar qn\bar{w}. \tag{8b}$$

Evaluation of the integrals in (8) has been done to second order in the small parameter q/k_F. The result can be conveniently expressed in terms of the quantum efficiency of the drag-effect detector,

$$\eta\equiv\frac{J/e}{S/\hbar\omega}=-\frac{2\pi\hbar\bar{\alpha}}{\lambda m}\left[\tau_2-\frac{\pi\hbar n(\tau_1-\tau_2)}{2\gamma m}\frac{2\gamma\Delta\omega}{(\Delta\omega)^2+\gamma^2}\right]. \tag{9}$$

The first term in the brackets corresponds to the primary drag current (5), whereas the second (which may be denoted by τ_1^{eff}) describes the novel enhanced effect resulting from the drag force (8a) and the difference in the relaxation times for the two subbands. Relative importance of the two terms depends on the frequency, the second term being maximized at $\Delta\omega\approx\gamma$ (at which point $\bar{\alpha}$ is reduced by a factor of 2 from its value at $\Delta\omega=0$). The maximum ratio $[\tau_1^{\text{eff}}/\tau_2]_{\max}\approx\pi\hbar n\tau_1/m\equiv E_F\tau_1/\hbar$ can substantially exceed unity (E_F is the 2DEG Fermi energy).

Varying the frequency of incident radiation in a narrow range near the intersubband resonance ω_{12} and measuring the photon-drag current $J(\omega)$, one obtains valuable information on the momentum-relaxation kinetics in 2D subbands. The predicted spectral curve is given by (9) or, for $\tau_1\gg\tau_2$, by

$$J(\omega)=J_0(\omega)\left[1-\frac{E_F\tau_1}{\hbar}\frac{2\gamma\Delta\omega}{(\Delta\omega)^2+\gamma^2}\right], \tag{10}$$

with J_0 given by (5). It is worth noting that the additional information is provided entirely by the enhanced effect, since $J_0(\omega)$ mimics the intersubband absorption spectra and depends only on $\tau_2\approx(2\gamma)^{-1}$, whereas the enhanced photon-drag current spectrum is modulated by τ_1. It may also be possible to probe the drug-current response at a fixed frequency, but varying carrier concentration.

Let us estimate the detector sensitivity for the exemplary structure of Fig. 1 at temperatures well below the Debye temperature Θ, say at $T=77$ K. In this case, τ_2 is limited mainly by optical phonon emission and τ_1 by impurity scattering. Taking $\tau_2\sim7\times10^{-13}$ s, and $\tau_1\sim10\tau_2$, we find $[\tau_1^{\text{eff}}/\tau_2]_{\max}\sim300$ and $\eta\sim6\%$. This corresponds to a sensitivity $J/S=1.24[\lambda_0/(1\ \mu\text{m})]\eta\approx0.7$ A/W for $\lambda_0=10\ \mu$m. This estimate should be compared with the thermal noise in the detector. In an ideal close-circuit current-measurement arrangement, the root-mean-square noise current in a bandwidth Δf is given by the Nyquist formula, $I_{\text{noise}}=(4kT\Delta f/R)^{1/2}$, where the resistance R in the detector is given by $R^{-1}=e(pn)\mu\xi$ with $\mu=e\tau_1/m$ and ξ being a geometrical factor. In the above example, taking $R\sim10\ \Omega$ and $\Delta f\sim1$ GHz, I find $I_{\text{noise}}\sim6\times10^{-7}$ A, which implies that in order to beat the noise in a detector with a 1-GHz response, I must couple into the waveguide at least 1 μW of infrared power.

In summary, I have considered the photon-drag effect in intersubband absorption of polarized infrared radiation by a two-dimensional electron gas. In addition to the usual drag current—present in the absorption of light by *any* conductor—the intersubband absorption in a high-mobility 2DEG system is shown to give rise to a much enhanced frequency-dependent effect due to the difference in the momentum relaxation times in the ground and the excited subbands. The maximum enhancement factor, $E_F\tau_1/\hbar$, is given by the ratio of the 2DEG Fermi energy to the collision-broadened width of ground-subband levels. The photon-drag effect permits a new type of spectroscopy containing additional information compared with that contained in conventional absorption spectra in the same wavelength range. It also permits the implementation of novel infrared and far-infrared high-speed detectors.

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