Excitation of plasma waves during the drift of a two-dimensional electron plasma

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An explanation is proposed for some experiments by Tsui *et al*. and by Hopfel *et al*. in which electromagnetic radiation resulting from the radiative decay of two-dimensional plasmons was observed.

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Electromagnetic emission corresponding to the radiative decay of two-dimensional plasmons has recently been observed experimentally[1,2] in silicon metal–dielectric–semiconductor structures and GaAs-GaAlAs heterojunctions. The emission appears when a constant electric field is applied to give the electrons a drift velocity v_0 on the order of $(1\text{-}4)\times 10^5$ cm/s. The emission is sharply anisotropic, with a maximum corresponding to the drift direction, along the axis of the periodic system of electrodes which determines the momentum **k** of the two-dimensional plasmon. The emission frequency does not depend on the applied field; in accordance with the plasmon dispersion law, this frequency is determined by the momentum k and by the surface charge density N_s. The effect thus cannot be attributed to the occurrence of transition radiation as a charge moves near the lattice of metal electrodes. On the other hand, the drift velocities which are attained are far lower than the phase velocity of the plasmons that are excited ($\omega \sim 10^4$ cm^{-1}), so that Čerenkov emission of plasma waves would also be impossible. The physical nature of the effect thus remains an open question, and we lack a quantitative description of it.

In this letter we wish to propose a theoretical explanation for this effect. We believe that this explanation agrees with the experimental results, at least in terms of the dependence of the emission intensity on the strength and direction of the electric field.

Regardless of the electron velocity, the emission and absorption of plasmons are allowed if these events are accompanied by the scattering of electrons by impurities, phonons, etc. These retarding effects lead to the appearance of a plasmon gas, which is described by a Planck distribution function $n_0(\omega)$ when at thermodynamic equilibrium. The radiative decay of the equilibrium plasmons contributes to the background ("blackbody") emission. The electron drift shifts the plasmon subsystem away from equilibrium. If the nonequlibrium plasmon distribution function $n_{\mathbf{k}}$ is such that the condition $n_{\mathbf{k}} > n_0$ holds in that mode which is "followed" experimentally,[1)] then there will be excess electromagnetic emission at the frequency $\omega(k)$. The intensity of this emission is evidently proportional to $\delta n = n_k - n_0$. We can calculate δn for the case in which the electrons are scattered by impurities; this is the governing mechanism under the experimental conditions of Refs. 1 and 2.

We will begin by writing a kinetic equation for $n_{\mathbf{k}}$:

$$\frac{\partial n_{\mathbf{k}}}{\partial t} = \sum_{\mathbf{p},\mathbf{p}'} W(\mathbf{p},\mathbf{p}',\mathbf{k})\left[(n_{\mathbf{k}}+1) f_{\mathbf{p}}(1-f_{\mathbf{p}'}) - n_{\mathbf{k}} f_{\mathbf{p}'}(1-f_{\mathbf{p}})\right], \tag{1}$$

where f_p is the momentum distribution of the electrons, and $W(\mathbf{p}, \mathbf{p}', \mathbf{k})$ is the probability for the emission of a plasmon with momentum $\mathbf{k}$ upon a transition of an electron from a state $\mathbf{p}$ to a state $\mathbf{p}'$, averaged over the impurity positions. We will evaluate this quantity in the first Born approximation in the electron–impurity interaction. The electron–plasmon interaction operator is given in the two-dimensional case by

$$V = i\,2\pi N_s e^2 \sum_{\mathbf{k}} Q_{\mathbf{k}} e^{i\mathbf{kr}} + \text{c.c.}, \tag{2}$$

where $Q_{\mathbf{k}}$ is the coordinate of the plasma oscillator. Ordinary perturbation theory yields ($h = 1$)

$$W(\mathbf{p},\mathbf{p}',\mathbf{k}) = \frac{\pi N_i m}{\omega(k)} |u(\mathbf{p}-\mathbf{p}')|^2 \left[\frac{\mathbf{k}}{k}(\mathbf{v}-\mathbf{v}')\right]^2 \delta\left(\frac{p^2-p'^2}{2m} - \omega\right), \tag{3}$$

where N_i is the impurity concentration, $\mathbf{v} \equiv \mathbf{P}/m$, and $u(\mathbf{p}-\mathbf{p}')$ is the Fourier component of the impurity potential. We are ignoring k in the argument of $u(\mathbf{p}-\mathbf{p}')$, and we are also ignoring the terms kv and kv' in comparison with $\omega(k)$. The legitimacy of these simplifications follows from the condition for the existence of plasma waves. Without resolivng the question of the actual electron distribution function, we substitute into (1) the function $f_{\mathbf{p}}$, which describes an electron drift with a given velocity $\mathbf{v}_0$. From the condition for a steady state we then find $n_{\mathbf{k}}$. The simplest approach is to set $f_{\mathbf{p}} = f_0(\mathbf{p} - \mathbf{p}_0)$, where f_0 is the equilibrium distribution function with temperature T, which is generally different from the lattice temperature. It follows from energy conservation that at $T=0$ the frequency of the emitted plasma cannot exceed $2\nu_0 k_F$, where k_F is the Fermi wave number. Estimates reveal $\omega/2v_0 k_F \sim 3-4$ for the experiments of Refs. 1 and 2; i.e., the emission occurs only as a result of the thermal spreading of the Fermi distribution. From Ref. 3 we know that the temperature of the two-dimensional electrons in the Si-SiO_2 system at the electric fields usied in Refs. 1 and 2 is ~15-20 K, and the Fermi energy is $E_F \sim 100$ K. We will therefore evaluate $\delta n_{\mathbf{k}}$ under the assumption $\mathbf{v}_0 k_F \ll \omega, T$.

The part which is linear in p_0 is evidently proportional to $\mathbf{k}\mathbf{p}_0$ and cannot contribute to the emission, since the total number of plasmons of a given frequency $\omega(k)$ does not change. In the next approximation we find

$$\delta n = \frac{p_0^2 p_F^2}{2(mT)^2} e^{-\omega/T}\left(\cos^2 \alpha + \frac{1}{2}\right), \quad E_F \gg T, \quad \omega \gg T$$

$$\delta n = \frac{1}{12} \frac{p_0^2 p_F^2}{m^2 \omega T}\left(\cos^2 \alpha + \frac{1}{2}\right), \quad E_F \gg T, \quad \omega \ll T, \tag{4}$$

where α is the angle between the vector $\mathbf{k}$ and the drift direction. Equations (4) refer to scattering by charged impurities. For short-range impurity centers, the result would differ from (4) by a factor of 3/2. In the nondegenerate case, the two scattering mechanisms lead to the same result:

$$\delta n = \frac{p_0^2}{2m\omega}\left(\cos^2 \alpha + \frac{1}{2}\right). \tag{5}$$

This model thus predicts a quadratic dependence of the emission intensity on the drift velocity, and it has a characteristic anisotropy, described by the factor $\cos^2 \alpha + 1/2$. In the experiments, the emission intensity was measured as a function of the electric field; the dependence was found to be quadratic in the Si-SiO_2 system and nearly linear in the GaAs-GaAlAs system. The later result can also be explained by our theory, if we note that the voltage–current characteristic is nonlinear at low temperatures at the fields used in Refs. 1 and 2.

We note in conclusion that we have considered in the kinetic equation in (1) only the electron mechanism for plasmon relaxation. If all other mechanisms can be described by a phenomenological relaxation time τ_{pl}, then in the limit of low values of p_0, considered here, the quantity δn decreases in modulus, but the dependence on p_0 and on the angle α are still given by Eqs. (4) and (5).

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[1]A periodic system of electrodes serves as a cavity which singles out momenta $k = \pm 2\pi/l$, where l is the period of the structure.

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