Resonant emission of electron-hole drops at plasma frequency

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It is shown that resonant emission of electron-hole drops (EHD) in germanium at the plasma-oscillation frequency can be due to radiative decay of surface plasmons. It is assumed that the plasmons are excited by fast electrons (holes) which result from Auger recombination of carriers in EHD.

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Vavilov *et al.*[1] were the first to report observation of resonant emission of electromagnetic waves by optically excited germanium in the far infrared. Since the maximum of this radiation is near the plasma frequency, it was connected with plasma oscillations of the EHD.[2] The plasmon excitation mechanism, however, remained unexplained.

It was shown in[3] that the possible carrier recombination channel in EHD in germanium is the Auger process, wherein fast electrons (holes), with energy on the order of the width of the forbidden band E_g, are ejected from the drop. The latter excite effectively the plasmons,[4] which subsequently can decay with emission of light. The mechanism whereby photons are emitted by surface plasmons in EHD is analogous to the well known phenomenon of electromagnetic-wave radiation at plasma frequency from thin foils[5] or minute spherical particles[6] bombarded by fast electrons. In a spherical electron-hole drop, surface plasmons can be excited and electromagnetic waves are emitted at frequencies

$$\omega_l^2 = \omega_p^2 l/(2l + 1), \qquad l = 1, 2, 3, \ldots, \tag{1}$$

in the band $\omega_p/\sqrt{3} \leq \omega \leq \omega_p/\sqrt{2}$, where ω_p is the plasma frequency of the electron-hole liquid.

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A calculation of the spectral dependence of the intensity of the resonant emission of the EHD was carried out in analogy with[6] for a dipole ($l=1$) surface plasmon of frequency $\omega_1=\omega_p/\sqrt{3}$ in the Born approximation. The differential cross section for the complete process of photon emission by an electron that is ejected from the drop is equal to

$$\frac{d\sigma}{dk} = 36\frac{Re^2c}{\hbar\omega_1}\left(\frac{\omega}{\omega_1}\right)\frac{\left(\frac{1}{2}\right)\gamma_R}{(\omega-\omega_1)^2+\gamma_T^2/4}K_1\left(\frac{\omega_1 R}{v}\right), \tag{2}$$

where

$$\gamma_R = \frac{2}{3}\frac{\omega_1^4 R^3}{c^3} \tag{3}$$

is the rate of radiative decay of the surface plasmon[6]; γ_T is the total rate of plasmon decay; c, k, and ω are the velocity, wave vector, and frequency of the electromagnetic radiation; $\hbar$ is Planck's constant; R is the radius of the drop, v is the velocity of the Auger electron, and e is the electron charge.

Since $\omega_1 R/v \gg 1$ for Auger electrons in semiconductors, we assume in (2) $K_1(a)=\int_1^\infty [j_1^2(ax)/x^3]\,dx \cong 1/8a^2+O(a^{-3})$, where $j_1(x)$ is a spherical Bessel function. It follows from (2) that the spectral distribution of the radiation intensity near the maximum has a Lorentz shape, and the differential cross section at resonance is equal to

$$\frac{d\sigma}{dk} = 6\frac{e^2R^2}{\hbar\omega_1}\left(\frac{\omega_1}{\gamma_T}\right)^2\left(\frac{v}{c}\right)^2. \tag{4}$$

The cross section of the considered process can be connected with the spectral emission density by the formula

$$\frac{dW}{dk} = \frac{Nn_0R}{3\tau}E_g\frac{d\sigma}{dk}, \tag{5}$$

where $Nn_0R/3\tau$ is the density of the energy flux connected with the Auger electrons; N is the total number of the EHD in the volume of the sample; n_0 is the carrier density in the EHD; τ is the lifetime of the carriers relative to Auger recombination.

The spectral density of the EHD emission in germanium at resonance $\omega=\omega_1$, determined in experiment,[2] was of the order of $\sim 10^{-9}$ W/cm^2 (at $(\omega_1/\gamma)_{exp}=2-3$. For estimates, assuming a sample dimension $1\times1\times0.1$ cm, $R\cong10^{-4}$ cm, $N\cong3\times10^8$, $n_0=2\times10^{17}$ cm^{-3}, $\tau=4\times10^{-5}$ sec, $v=10^8$ cm/sec, $E_g=0.7$ eV, and $\omega_1=1.4\times10^{13}$ sec^{-1} (these EHD-system parameters should be expected under the conditions of the experiment of[2]) we obtain $(dW/dk)_{theor}=10^{-9}$ W/cm^2 at $(\omega_1/\gamma_T)\cong4$.

Thus, the proposed mechanism explains the spectral position and the integrated intensity of the EHD resonant emission line in germanium in the far infrared. We note that the EHD emission intensity at the plasma frequency in silicon is expected to be $\sim10^2-10^3$ times larger, and the radiation maximum should lie in the region $\omega_1\sim5\times10^{13}$ sec^{-1}.

We note in conclusion that the foregoing analysis is valid if the mean free path λ of the fast electron $\lambda\gg R$ ($\lambda\cong3\times10^{-4}$ cm for Ge). At $\lambda\lesssim R$, the probability of exciting surface plasmons decreases, but the probability of their radiative decay increases in proportion to R^3 (3), as a result of which one can hope the mechanism in question to remain effective also at $R\gtrsim\lambda$.

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