ON THE QUESTION OF PHOTOCURRENT FLUCTUATIONS

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ON THE QUESTION OF PHOTOCURRENT FLUCTUATIONS

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Photocurrent fluctuations in the frequency interval $f \div f + B$ can be calculated by the formula [(1)]

$$\overline{i^2} = 2ei_0 B, \qquad i_0 = en. \tag{1}$$

Let us note that formula (1) can be written in the form

$$\overline{\Delta n^2} = 2nB; \tag{1a}$$

it is a consequence of the relation $\overline{\Delta n^2} = n$ [(2)].

Formula (1) was derived under the assumption that the motion of electrons occurs according to the laws of classical mechanics and that the different particles are independent [(3)]. Therefore one should expect that in quantum systems formula (1) is no longer valid and the fluctuations depend on the energy spectrum of the substance and on the method of exciting the current.

Excess noise in semiconductors at low frequencies is well known; its connection with the spectrum has been investigated in [(4)]; in the present note we shall give the opposite example: when at high frequencies the photocurrent fluctuations are half as large as given by formula (1).

Let the photocurrent in an optically thin transparent semiconductor layer be caused by monochromatic radiation of frequency ω_0 such that the frequencies ω_0 and $\omega_0 + 2\pi f$ lie above the red edge of the absorption band, while $\omega_0 - 2\pi f$ lies below it. The spectrum of the semiconductor is shown in Fig. 1; in the absence of illumination there are no electrons in the conduction band. In this case $\omega_0 \gg 2\pi f$; we shall take the temperature of the semiconductor to be zero, which is admissible only under the condition

$$kT/2\pi hf \ll 1. \tag{2}$$

Fig. 1

Figure 1: Fig. 1

Fig. 1

We shall carry out a quantum calculation of the fluctuations of the number of carriers in the conduction band. The carriers formed in the conduction band are removed by a constant field, producing a current.

We are interested in the correlation function $R(t-t') = \overline{\Delta n(t)\Delta n(t')}$; the intensity of the fluctuations is equal to $R(0)$. Let ψ_0 be the wave function of the system in the absence of interaction; S the scattering matrix of the system when the interaction is switched on. Then:

$$\overline{n(t)} = \frac{d}{dt}\langle\psi_0 S^+(t)\hat{n}S(t)\psi_0\rangle; \tag{3}$$

$$R(t-t') = \frac{d^2}{dt\,dt'}\langle\psi_0 S^+(t)\hat{n}S(t)S^+(t')\hat{n}S(t')\psi_0\rangle; \tag{4}$$

$$S = 1 + ik; \qquad k = \frac{e}{hc}\int_{-\infty}^{t}\varphi^+\mathbf{A}\psi\,dV\,dt; \tag{5}$$

$$\hat{n} = \sum_\alpha c_\alpha^+ c_\alpha;$$

φ^+ is the creation operator of an electron in the conduction band; ψ is the annihilation operator of an electron in the valence band; $\mathbf{A}$ is the operator of the electromagnetic field, normalized to the photon flux per second.

It can be shown that, under the assumption made above of the transparency of the semiconductor and at zero temperature, one may use ordinary perturbation theory and take into account only terms quadratic in k, of which only the following are nonzero:

$$\overline{n(t)} = \frac{d}{dt}\langle\psi_0 k^+(t)\hat{n}k(t)\psi_0\rangle,$$

$$R(t-t') = \frac{d^2}{dt\,dt'}\langle\psi_0 k^+(t)\hat{n}k(t')\psi_0\rangle. \tag{6}$$

The fourth-order term, as is easy to verify, in the case of an optically thin semiconductor gives $(\bar{n})^2$.

Let us represent the operators in the form of sums of normalized eigenfunctions $\mathbf{A}_s^0(\mathbf{r})$, $\varphi_\alpha^{0+}(\mathbf{r})$, $\psi_\beta^0(\mathbf{r})$; then

$$k(t)=\sum_{s\alpha\beta}a_s c_\alpha^+ b_\beta \lambda_{s\alpha\beta}\int_{-\infty}^{t} e^{i\Delta_{s\alpha\beta}\tau}\,d\tau, \tag{7}$$

$$\lambda_{s\alpha\beta}=\frac{e}{hc}\int \mathbf{A}_s^0(\mathbf{r})\varphi_\alpha^{0+}(\mathbf{r})\psi_\beta^0(\mathbf{r})\,dV,$$

$$\Delta_{s\alpha\beta}=(1/h)(E_\alpha-E_\beta-h\omega_s),\qquad a_s^+a_s=N_s,$$

$$\varphi^+=\sum_\alpha c_\alpha\varphi_\alpha^{0+}(\mathbf{r}),\qquad \psi=\sum_\beta b_\beta\psi_\beta^0(\mathbf{r}),$$

and the quantities of interest to us in (6) are readily calculated:

$$\bar{n}=\sum_{s\alpha\beta}|\lambda_{s\alpha\beta}|^2N_s\delta(\Delta_{s\alpha\beta}); \tag{8}$$

$$R(t-t')=\sum_{s\alpha\beta}|\lambda_{s\alpha\beta}|^2N_se^{i\Delta_{s\alpha\beta}(t-t')}. \tag{9}$$

It is easy to see that when in (9) the pre-exponential factor does not depend on Δ, then $R(t-t')=\bar{n}\delta(t-t')$. If the light is monochromatic, then in the sum (8) only the term $s=0$ remains and, owing to the presence of the δ-function, only those levels of the valence band contribute to formula (8) for which

$$E_\beta=E_\alpha-h\omega_0,\qquad n=N_0|\lambda_{0\alpha\beta}|^2\rho(E_\alpha-h\omega), \tag{10}$$

where ρ is the density of occupied states. When measuring noise in a band B, we have

$$f\ll\frac{1}{2\pi}|\Delta|\ll f+B, \tag{11}$$

and for the correlation function in this band we obtain

$$R(0)=nB\,\frac{\rho[E_\alpha-h(\omega_0+2\pi f)]+\rho[E_\alpha-h(\omega_0-2\pi f)]}{\rho(E_\alpha-h\omega_0)}.$$

In the selective photoeffect near the red edge, the density of states ρ depends strongly on energy; the intensity of the fluctuations must

vary depending on the form of the energy spectrum at the band edge. In the simplest case of a Fermi distribution at $T\to 0$, when ρ is constant in the valence band and is zero outside the band, for the spectrum shown in Fig. 1 the fluctuations are half as large as follows from the classical formula (1). With a smooth "classical" function ρ, expanding (12) in a series, one easily obtains (1). Therefore the effect of reducing the fluctuations is connected with inequality (2) and is a quantum effect. It is also seen from formula (12) that if ω_0 lies too close to the red boundary, then $\rho(E_a - \hbar\omega_0) \to 0$, and the fluctuations at the same current increase.

The estimates made above assumed that the semiconductor is optically thin and, consequently, that the quantum efficiency is small. Since the correlation of the fluctuations of n is a property of the semiconductor spectrum, and not of its dimensions, one should expect that this property remains also for a large optical thickness; however, the question must be investigated in greater detail.

In conclusion let us discuss the possibility of an experiment in which the noise power is measured at the same photocurrent as a function of the light frequency; the technical difficulties of the experiment are very great. This is connected with the fact that condition (2) is satisfied at ultralow temperatures and in the millimeter range; the fluctuations in the number of photoelectrons determine the photocurrent fluctuations only at small transit times and large constant fields, which can be realized only in a p–n junction. The effect may be strongly distorted because of heating of the junction by light.

If the photocurrent noises are determined by formula (1), then an ideal optical superheterodyne has a noise power $\hbar\omega_0 B$—the same as that of an ideal quantum amplifier[5], but twice as high as the theoretical limit[6]. The quantum depression of the photocurrent noise by a factor of two points to the principal possibility of attaining the minimum theoretical noise limit in reception in the quantum region.

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Note: Figure translations are in progress. See original paper for figures.