Motion of electron-hole drops, excitons, and excitonic molecules under the influence of electron wind

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The mechanism whereby electron-hole drops, excitons, and excitonic molecules are dragged by a stream of free electrons and holes is considered. It is proposed to use this phenomenon to investigate excitons and drops, and the experimental results of [1] are interpreted.

Theoretical and experimental investigations of excitons and of excitonic molecules, especially excitonic "matter", [2–5] which is a new phase of electron-hole condensate produced at low temperatures out of large-radius excitons, makes it urgent to investigate new phenomena in which various physical properties of these excitonic formations can be manifest.

It is known that a beam of electrons and holes interacting with a scattering center exerts a force on the center, namely the force of the electron wind.[6] This force causes drift of the scattering center in the lattice. In the simplest model the electron-wind force is given by

$$F_{ew}^{(i)} = \{n_e l_e \sigma_e^{(i)} - n_h l_h \sigma_h^{(i)}\} eE = Z_{ew}^{(i)} E.$$

n_e and n_h are the concentrations of the free electrons and holes, l_e and l_h are the mean free paths, σ_e and σ_h are the cross sections for the scattering of the electrons and holes, and the subscript i labels the excitons ($i=1$) and biexcitons ($i=2$) of the electron-hole drop ($ki=K$), and $Z_{ew}^{(i)}$ is the effective charge of the ith excitonic formation or drop dragged by the electron wind. If the electron-hole drop has a proper Coulomb charge Z_{Coul}, then the total effective charge is $Z_{\mathrm{eff}}^{(d)} = Z_{\mathrm{Coul}}^{(d)} + Z_{ew}^{(d)}$.

The motion of the electron-hole complex in the electric field is determined by the effective mobility $u_{\mathrm{eff}}^{(i)} = (D^{(i)}/kT) Z_{\mathrm{eff}}^{(i)}$ ($D^{(i)}$ is the diffusion coefficient).

We consider a crystal in which continuous generation of electrons and holes maintains a quasistationary state in a system consisting of a gas of free carriers, free excitons, biexcitons, and electron-hole drops.

1. ELECTRON-HOLE DROP MOTION PRODUCED BY ELECTRON WIND

a) To estimate the effective charge of the drop, we assume that the cross sections for the scattering of the electrons and holes by drops of radius R_d are equal to the geometric cross section of the drop $\sigma_e^{(d)} \approx \sigma_h^{(d)} \approx \pi R_d^2$. Then at $n_e = n_h = n$ we have $Z_{ew}^{(d)} = enl_e(1-\gamma)\pi R_d^2$ (where $\gamma = l_h/l_e$). In germanium we have $l_e > l_h$, i.e., $Z_{ew}^{(d)} < 0$ and the drops will be dragged by the electron wind to the anode. Let us estimate the effective charge $Z_{ew}^{(d)}$ for drops with $R_d = 5\times10^{-4}$ cm at a concentration $n = 10^{12}$ to 10^{13} cm^{-3}, assuming $l \approx 10^{-3}$ cm and $\gamma \approx \frac{1}{2}$. The values obtained for $Z_{ew}^{(d)}$ are then $400e$ and $4000e$.

b) We estimate the drop displacement $\Delta x^{(d)}$ and the corresponding shift of the maximum of the recombination radiation under the influence of the electron wind

$$\Delta x^{(d)} = \tau_r^{(d)} M_d^{-1} Z_{ew}^d \, \tau_0^d,$$

where $\tau_p^{(1)}$ is the momentum relaxation time of the drop as a whole, $\tau_0^{(d)}$ is the lifetime of the drop with respect to recombination, M_d is the mass of the drop, and E is the electric field intensity.

At $Z_{ew}^{(d)} = 10^3 e$, $\tau_r^{(d)} = 10^{-7}$ sec,[4] $M_d = 10^8$ electron masses,[1] $\tau_0^{(d)} = 2\times10^{-5}$ sec, and $E = 1$ V/cm, we have $\Delta x^{(d)} = 3\times10^{-2}$ cm. The permissible values of the field are determined by the condition $elQ^{(d)} \approx Q^{(d)}$, where $Q^{(d)}$ is the heat of evaporation of the particle from the drop. Since $Q^{(d)} \approx 1$ meV, we have $E \approx 1$ V/cm at $l \approx 10^{-3}$ cm.

c) For various reasons, the drops may be charged. According to a theoretical estimate given in[6], in a Ge crystal in which continuous excitation maintains a free-carrier density $n \approx 5\times10^{12}$ cm^{-3} ($T = 2$°K), a drop of radius $R_d = 5\times10^{-4}$ cm can have a Coulomb charge $Z_{\text{Coul}} \approx 500e$. Since the cross section for the Coulomb scattering of electrons and holes by the charged drop is $\sigma_{\text{Coul}}^{(d)} \propto Z_{\text{Coul}}^2$, the Coulomb scattering cross section of a drop with $R_d = 5\times10^{-4}$ cm at $T = 3$°K is $\sigma_{\text{Coul}}^{(d)} \geqslant \pi R_d^2$ already at $Z_{\text{Coul}}^{(d)} \geqslant 10e$. The effective charge produced in the drop by the electron wind is then $Z_{ew}^{(d)} \geqslant 400e$ (for $n = 10^{12}$ cm^{-3} and $l = 10^{-3}$ cm), i.e., $Z_{ew}^{(d)} \gg Z_{\text{Coul}}^{(d)}$.

d) An estimate of the effective charge and of the displacements of the neutral drop and of the effective charge of a charge drop allows us to state that the electron-hole drop drift observed in[1] in an electric field ($Z_{\text{eff}}^{(d)} \approx 100e$, $\Delta x^{(d)} \approx 1.5\times10^{-2}$ cm) is produced for the most part by electron wind.

e) The free-carrier generation is maintained by an external source and it is possible to vary the ratio of the free electrons and holes if, e.g., we ionize the acceptors introduced in a p-Ge crystal. At $n_e/n_h < \gamma$, the dragging of the drops by the holes will predominate, and the charge $Z_{ew}^{(d)}$ will be positive. If $Z_{ew}^{(d)} > Z_{\text{Coul}}^{(d)}$, then the drops move towards the cathode.

2. EXCITON DRAGGING BY ELECTRON WIND

a) Excitons and excitonic molecules are electrically neutral, so that their effective charge is determined entirely by the electron wind. Depending on the ratio $l_e\sigma_e/l_h\sigma_h$, the sign of Z_{ew} can be either positive or negative.

Without a quantitative calculation of the scattering cross sections σ_e and σ_h and without measuring l_e and l_h we cannot predict the sign of Z_{ew}, i.e., the direction of the exciton (biexciton) drift.

We can however, estimate the order of magnitude of $Z_{ew}^{(1)}$ and of the displacements of the excitonic molecules in an external field.

The exciton radius in Ge is $R_{\text{exc}} = 1.4\times10^{-6}$ cm. At such distances, the electron-hole interaction energy is $\epsilon_{\text{Coul}} \approx 1$ meV, so that we expect the cross section for the scattering of free electrons and holes by an exciton at $T < 10$°K to be not less than the geometric cross section, i.e., $\sigma_{\text{exc}}^{(1)} \geqslant \pi R_{\text{exc}}^2$. Putting $\sigma_{e,h}^{(1)} \approx 10^{-11}$ cm^2 we obtain at $n = 10^{12} - 10^{13}$ cm^{-3} and $l \approx 10^{-3}$ cm the value $Z_{ew}^{(1)} \approx (10^{-2}$ to $10^{-1})e$.

The average displacement of the exciton in the electric field is $\Delta x^{(1)} = (\tau_r^{(1)}/m_{\text{exc}})Z_{ew}^{(1)}\tau_g^{(1)}E$, where m_{exc} is the exciton mass, $\tau_r^{(1)}$ is the exciton momentum relaxation time, $\tau_g^{(1)}$ is the exciton free-path time. In the gas phase we have $\tau_g^{(1)} \approx \tau_0^{(1)}$, where $\tau_0^{(1)}$ is the electron-hole recombination time in the exciton. If $Z_{ew}^{(1)} = (10^{-1}$ to $10^{-2})e$, $\tau_r^{(1)} \approx 10^{-9}$ sec, and $\tau_g^{(1)} = 2\times10^{-5}$ sec, then $\Delta x^{(1)} = 10^{-1}$ to 10^{-2} cm, i.e., of the order of the drift displacements of the drop. On the other hand, if the exciton moves in the presence of the drops, then $\tau_g^{(1)} < \tau_0^{(1)}$, and the drift displacements of the excitons may turn out to be smaller than the drop displacements.

b) For biexciton dragging by the electron wind, assuming as a rough estimate that $\sigma^{(2)} \approx \pi R_{\text{biexc}}^2$, then we obtain for $Z_{ew}^{(2)}$ and $\Delta x^{(2)}$ values close to those for the excitons. There are no grounds for assuming, however, that the real quantum-mechanical cross sections $\sigma_{e,h}^{(1)}$ and $\sigma_{e,h}^{(2)}$ will turn out to be close, and it can be presumed that experiment will reveal a significant difference between $\Delta x_{ew}^{(1)}$ and $\Delta x_{ew}^{(2)}$.

c) The study of the drift of electron-hole complexes under the influence of the electron wind uncovers a possibility of measuring the cross section for the scattering of free electrons and holes by excitons, biexcitons, and drops, and offers additional possibilities of studying the mechanism of diffusion and mobility of excitons, biexcitons, and drops, the kinetics of drop formation, and the charges of the drops.

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