Quantum nature of the reflection of an exciton from the surface of an electron-hole drop

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The small values of the sticking fraction for the impact of an exciton on the surface of an electron-hole drop are shown to be attributable to above-barrier quantum reflection of the exciton from the surface of a drop.

At low temperatures and very high levels of excitation of a semiconductor, the system of nonequilibrium carriers in Ge and Si separates into electron-hole drops (EHD) and a gaseous phase consisting of free excitons (FE) and free carriers.[1] The important parameter, which describes the interaction of the FE gas with the EHD is the sticking fraction for the impact of an exciton on the surface of a drop ξ. Hammond and Silver[2] and Voison *et al.*[3] estimated ξ to be ~ 0.05, for Si, whereas Milyaev and Sanina[4] and Sanina[5] found ξ to be ~ 0.1–0.2 for Ge. We will show that this low value is apparently a consequence of above-barrier quantum reflection of the exciton from the surface of an EHD and that it cannot be attributed to the phonon wind, as done in Refs. 2 and 3.

To explain theoretically the mechanism for the formation of EHD in Si, it was necessary to assume in Refs. 2 and 3 that the sticking fraction ξ in Si is very small: ξ

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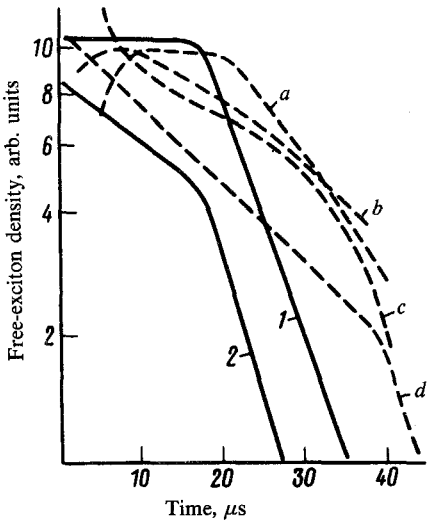

FIG. 1. Kinetics of the density of free excitons in germanium at $T \sim 4$ K. The experimental curves *a*, *b*, *c*, and *d* are taken from Refs. 8–11, respectively. Curves 1 and 2 of $n(t)$ were computed from Eq. (1) with $\xi = 1(1)$ and $\xi = 0.1(2)$.

~ 0.05. The mechanism for the formation of EHD in Ge was satisfactorily described by assuming that $\xi \sim 1$.[1,6] We note, however, that the kinetics of formation of the liquid phase in Ge is virtually insensitive to variation in ξ over a wide range ($0.01 < \xi < 1$), because (see Ref. 7) the lifetime of carriers in an EHD in Ge is much longer than in Si. On the other hand, the transient characteristics of the decay of the EHD–FE system in Ge depend strongly on the value of ξ.

Figure 1 shows the decay curves for the density of FE at a temperature of ~ 4 K after pulsed laser excitation. The curves *a*, *b*, and *c* show the decrease in the luminescence signal of the FE with time (the 0.714-eV line).[8–10] The curve *d* was obtained from an analysis of the cyclotron resonance spectra recorded with a different time delay between the laser pulses.[11]

The time dependences of the density of the FE gas, $n(t)$, and of the average carrier density in the liquid phase, $N(t)$, in the course of the decay are described by

$$\begin{cases} \dfrac{dn}{dt} = -\dfrac{n}{\tau_{ex}} - \Gamma(n - n_T) \\ \dfrac{dN}{dt} = -\dfrac{N}{\tau_0} + \Gamma(n - n_T), \end{cases} \tag{1}$$

where τ_{ex} and τ_0 are the lifetimes of FE and carriers in the EHD, respectively; n_T is the thermodynamic equilibrium density of FE; $\Gamma = \xi 4\pi R^2 N_d V_T$ is the rate of capture of excitons by a drop; R is the radius of the EHD; n_d is their number per cm^3 of the sample; and V_T is the average thermal velocity of FE. It turns out that if $\xi = 1$ and the other parameters in (1) vary within limits that are reasonable for Ge, the numerical solutions of (1) for $n(t)$ are virtually independent of time in the initial stage

of decay of the system (curve 1 in Fig. 1). Slowly decaying dependences (curve 2), which are characteristic for all experimental results presented here, can be obtained only when $\xi = 0.1$.

By making use of the analogy between the electrostatic forces and the forces arising when an exciton absorbs nonequilibrium phonons,[12] it is easy to show that the phonon wind has a large effect on the flow of excitons to the EHD only at the lowest temperatures ($T < 0.1$ K for Si and $T = 0.01$ K for Ge), but it cannot explain the small values of ξ in Si and Ge.

The estimate $\xi = 1$, proposed in the preceding studies without allowance for the phonon wind, was based on the classical picture of the descent of an exciton into a potential well—the EHD. However, the classical analysis is applicable only if the de Broglie wavelength satisfies

$$\lambda = \hbar/p \ll a, \tag{2}$$

where p is the momentum of the particle; a is the smallest scale of inhomogeneities of the potential, which in our case is defined as the length of the transitional region from the EHD to the "excitonic atmosphere" and which (see Ref. 1) is approximately $a_{ex} = \epsilon\hbar^2/2\mu e^2$ (the exciton radius); m_e and m_h are the effective masses of the electron and hole; and $\mu = m_e m_h/(m_e + m_h)$ is the reduced mass. In the entire range of temperatures at which EHD exist ($kT \ll E_{ex} = \hbar^2/2\mu a_{ex}^2$), the condition (2) is not satisfied:

$$\frac{\lambda}{a_{ex}} \sim \sqrt{\frac{\mu}{m_e + m_h}} \sqrt{\frac{E_{ex}}{kT}} \gg 1. \tag{3}$$

Estimate (3) and, therefore, the quantum nature of the reflection of excitons from the surface of the EHD are a direct consequence of the relation $m_e \sim m_h$.

Although we do not know the general solution of the quantum problem of scattering of FE, i.e., of a bound state of two particles in an external potential field, we can show that when the kinetic energy of the complex as a whole, E_c, approaches zero, we have simultaneously $\xi \to 0$. This is a standard situation for problems which can be reduced to one-dimensional problems when $\xi \sim \sqrt{E_c}$. By assuming that the energy dependence is similar in nature in the case of reflection of FE, we can roughly estimate

$$\xi \sim \sqrt{kT/E_{ex}},$$

where E_{ex} is the only energy scale in the EHD–free carrier system. For $E_{ex} \sim 100$ K and $T \sim 4$ K, we obtain $\xi \sim 0.2$.

The value $\xi \sim 0.1$ obtained experimentally in Ge and Si can thus be explained by the quantum reflection of excitons from EHD. In addition to the well-known quantum oscillations of luminescence of EHD in strong magnetic fields,[1] the kinetics of recombination of free excitons in the presence of drops is a vivid experimental manifestation of the influence of quantum-mechanical effects on the behavior of a macroscopic system.

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