Line Broadening of Electron Cyclotron Resonance in Germanium Due to Electron-Exciton Interaction

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A dynamical study of electron-exciton collision process in pure germanium is made by means of millimeter-wave cyclotron resonance combined with a photopulse technique. It is found that carrier recombination occurs primarily via exciton formation and subsequent annihilation process. The exciton lifetime is determined as a function of temperature.

Contribution of electron-exciton interaction to the linewidth of electron cyclotron resonance in pure germanium has been investigated by means of intense photopulses combined with a boxcar-connected delayed gate circuit. It is demonstrated that the cyclotron-resonance linewidth excluding the contribution of electron-phonon interaction consists of two parts, namely, electron-exciton and electron-hole (or carrier-carrier) interactions. Both electron and exciton lifetimes are determined by varying the delay time of the gate. Intensity versus linewidth measurement of the electron resonance signal also definitely supports the existence of exciton contributions to the linewidth.

An ultrahigh-purity germanium crystal lying in a 35-GHz nonresonant waveguide is illuminated with an EG & G FX-108 xenon flash tube at the repetition rate of 25 Hz. Each photopulse has a width of 1 μsec. The opening of the gate is set at 2 μsec. The magnetic field is applied along the ⟨111⟩ direction in the (110) plane and the linewidth of the first electron cyclotron resonance which corresponds to the cyclotron mass of $0.08m_0$ is measured. As the delay time is increased, both intensity and linewidth decrease. Results obtained at 4.2°K are shown in Figs. 1(a) and 1(b). The contribution of electron-phonon scattering to the linewidth is subtracted beforehand.[1] The intensity measurement can also be regarded as a relative carrier-density measurement, and hence the notation n is introduced. The open circles in Fig. 1(a) give the relevant linewidth, or the inverse relaxation time $1/\tau$, due to other than electron-phonon collisions. The variation consists of two branches: The first branch decays fast while the second decays slowly. The closed circles give the intensities of the resonance signals. The slope of the line connecting these circles yields the free carrier lifetime. Figure 1(b) gives the inverse relaxation time as a function of carrier density. Naturally we see a kink again here corresponding to Fig. 1(a). The first branch in Fig. 1(b) is proportional to $n^{1/2}$ while the second is proportional to n^2. The second branch is obtained for shorter delay times

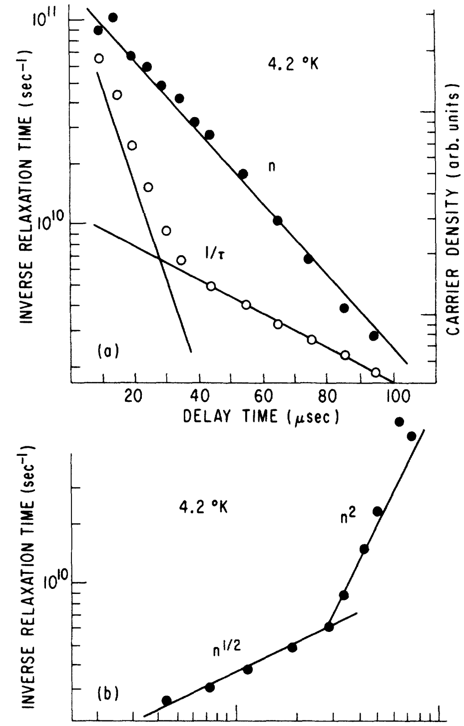

FIG. 1. (a) Contributions of electron-exciton and electron-hole scattering to the collision frequency $1/\tau$ are separable on the time scale. The free-carrier density n, which is proportional to the cyclotron-resonance signal intensity, is also given in arbitrary units as a function of time. (b) Collision frequency as a a function of signal intensity which is denoted by the carrier-density symbol n. The first branch, which is proportional to $n^{1/2}$, corresponds to the second branch in (a) and *vice versa*. The n^2 dependence after the kink shows the bimolecular nature of excitons in the mass-action law.

and hence corresponds to the first branch in Fig. 1(a).

One may interpret the first branch in Fig. 1(a) to represent the electron-exciton collision frequency. The frequency should then be proportional to the exciton density. From the mass-action law, the exciton density ought to be proportional to the second power of the carrier density. This fact is clearly demonstrated in the second branch in Fig. 1(b). The decay time constant of the first branch in Fig. 1(a) is then considered to give the lifetime of an exciton, nearly 10 μsec at 4.2°K. Temperature dependences of the lifetimes for excitons and electrons thus obtained are given in Fig. 2. Both lifetimes vary nearly inversely to the temperature. If we assume carrier recombination to occur primarily through exciton formation and subsequent annihilation, it is easy to show that the electron lifetime is twice that of the exciton, in fairly close agreement with the observation in Fig. 2. The situation would be different for doped materials.

The variation of the inverse relaxation time in the second branch in Fig. 1(a) is understood to reflect the carrier-carrier interaction as suggested by Kawamura *et al.*[2] Since the lifetime of an exciton is shorter than that of an electron, we observe only this type of interaction some time after the photopulse. The $n^{1/2}$ dependence of the first branch in Fig. 1(b) is also consistent with the theoretical prediction of carrier-carrier interaction.

In order to obtain further conclusive evidence for the presence of electron-exciton interaction, electric-field pulses synchronized with photopulses are applied at 4.2°K with the intention of inducing impact ionization of excitons by accelerated electrons.[3] The pulse height is 500 V/cm with a duration of 3 μsec, and the field pulse is switched on 10 μsec after the photopulse. The observation gate is opened after another lapse of 8 μsec. The result has been a striking enhancement by an order of magnitude of free-carrier cyclotron-resonance signals with considerable plasma shifts in resonance peaks.[2] Such a phenomenon has not been observed either when the applied field is low or when one applies the electric pulse well after the occurence of the kink.

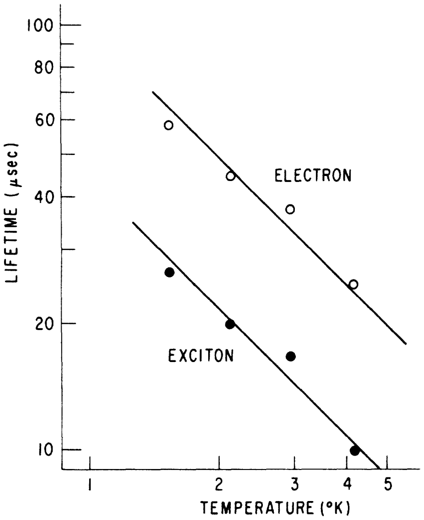

FIG. 2. Electron and exciton lifetimes as a function of temperature. Solid lines indicate a T^{-1} dependence.

Since we do not know the magnitude of electron-exciton collision cross section, it is difficult to estimate the absolute density of excitons at any time. Assuming, just tentatively, that the electron-neutral donor collision formula by Erginsoy[4] also holds for electron-exciton collisions, we obtain, for example, 4.2×10^{14} excitons per cm^3 at 4.2°K right after the photopulse. The effective Bohr radius for an exciton is taken to be ~140 Å from the observed binding energy of 3.2 meV.[5] Even with such a modification of the Bohr radius, use of Erginsoy's formula would still be inadequate. In fact, there is little reason to believe that the electron-exciton collision model is closer to the electron-donor collision model than to the electron-acceptor collision model, and the last of these is found to yield an effect nearly one-tenth as large as that given by Erginsoy's formula.[1] One may also have to take the recoil effect of the exciton into account. Perhaps we are considerably underestimating the exciton concentration. With a little more intense light, accordingly, one might be able to observe an electron-exciton interaction in a condensed phase of the exciton system.[6,7] Such an investigation is now in active preparation.

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