Spectral variation of the mobility of photoexcited electrons in pure GaAs

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The photoconductivity of pure GaAs during electron heating in a microwave electric field has been studied. A strong dependence of the momentum relaxation time on the wavelength of the exciting light has been observed for the first time.

The cyclotron-resonance method is an effective tool for studying the transport of free carriers in semiconductors. The half-width of the cyclotron-resonance line, ΔH, is related to the momentum relaxation time τ_p by $\Delta H/H_c = \omega\tau_p$, where ω is the frequency of the microwave field, and H_c is the resonant value of the magnetic field. Studies of the cyclotron resonance in the microwave range, under the condition $\hbar\omega < kT$, have made it possible to investigate the scattering mechanism and to determine the carrier mobilities in Ge, Si, and pure GaAs (Refs. 1–3).

In this letter we are reporting a study of the cyclotron resonance (CR) of nonequilibrium hot electrons in pure epitaxial layers of GaAs [the impurity concentration was $N_i < 5\times10^{12}$ cm^{-2}, and the electron mobility was $\mu = 2\times10^6$ cm^2/(V·s) at 1.8 K; Ref. 3] in the 8-mm range at $T = 1.8$ K. The sample was placed in a shorted waveguide section at an antinode of the electric field. The temperature of the electron gas, T_e, could be varied by varying the microwave power level P applied to the waveguide. The sample was also illuminated by the beam from a He–Ne laser with a wavelength of 6328 Å or the light from an incandescent lamp. In the latter case the light was passed through a monochromator, so that the wavelength of the exciting

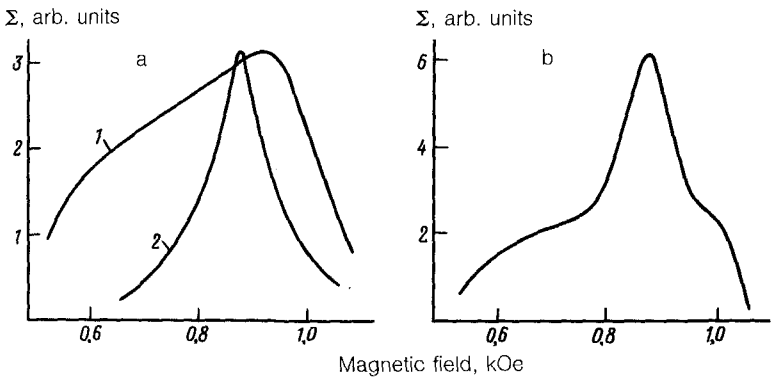

FIG. 1. Cyclotron-resonance lines found (1) during interband excitation and (2) during excitation to the exciton ground state ($P = 2.5$ mW).

light could be varied. The microwave power absorbed by nonequilibrium charge carriers, Σ, was measured. The static magnetic field was directed parallel to the surface of the sample.

Figure 1a shows CR lines under conditions of a pronounced carrier heating, for two wavelengths of the exciting light: Line 1 corresponds to excitation by light with $\lambda_1 = 6328$ Å, and line 2 corresponds to excitation of the exciton ground state at $\lambda_2 = 8182$ Å. In the latter case the free carriers form as the result of an impact ionization of excitons. In the case of pronounced heating, at a microwave power $P \gtrsim P_0$ ($P_0 \approx 0.2$) mW is the threshold power level for the onset of impact ionization of excitons under CR conditions), the shape of the CR line is essentially independent of the excitation wavelength. As the power P is increased, the CR curves measured during excitation by light with wavelengths λ_1 and λ_2 are quite different (Fig. 1a). Under heating conditions, the shape of the CR line during excitation of the exciton ground state (or of the first excited state) changes only slightly, while during interband excitation the half-width of the CR line, ΔH, increases monotonically with increasing T_e. The meaning here is that under heating conditions the momentum relaxation time τ_p depends strongly on the energy of the exciting photon. During simultaneous excitation of the sample by the light from the He–Ne laser, with $\lambda = \lambda_1$, and by light with $\lambda = \lambda_2$, the CR curve shown in Fig. 1b is a superposition of lines 1 and 2 in Fig. 1a. This result shows that during heating by a microwave field the nonequilibrium electrons produced by the intraband light and in the process of impact ionization of the excitons produced by the light are spatially separated. In a weak microwave field, at which the exciton lifetime with respect to impact ionization, τ_{ex}, is much longer than the mean free time of an exciton, ϑ_{ex}, the reasons for this separation are as follows: When the heating is slight ($P \gtrsim P_0$), the excitons produced by light with $\lambda = \lambda_2$ near the surface diffuse into the crystal and are then ionized by hot carriers. As a result, the electrons which appear during impact ionization of the excitons lie in a region with a thickness on the order of the exciton diffusion length $L_{ex} \approx 1.0$ μm (Ref. 4). During interband excitation, on the other hand, the electrons are produced in a thin layer of thickness $L_e \propto 1/$

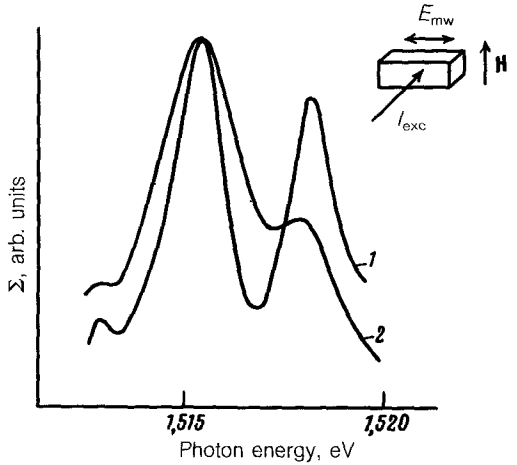

FIG. 2. Microwave photoconductivity spectra in the exciton resonance region. 1—Slight heating of the electrons, $P = 0.35$ mW; 2—pronounced heating of the electrons, $P = 2.3$ mW. The inset shows the experimental geometry.

$\alpha_e \ll L_{ex}$ (α_e is the optical absorption coefficient in the case of interband excitation). In a strong microwave field ($P \gg P_0$) the exciton lifetime decreases sharply and may become comparable to the mean free time. If so, the excitons do not leave the region in which they are produced. At this short lifetime, however, the absorption coefficient for the exciting light, α_{ex}, decreases, and there is an increase in the thickness of the layer in which the excitons are produced and in which the electrons arising from ionization of the excitons are correspondingly produced. During the application of a power $P \sim 3$ mW to the sample under CR conditions, the intensity of the exciton luminescence and thus the exciton lifetime τ_{ex} decrease by a factor of more than 10^3. The time τ_{ex} becomes comparable to the momentum relaxation time $\vartheta_{ex} \sim 10^{-12}$ s (Ref. 5). The effect should be a decrease in the absorption coefficient.

Evidence for a change in the exciton absorption coefficient in pure GaAs in a strong microwave field comes from the shape of the microwave photoconductivity spectra recorded under CR conditions (Fig. 2). It can be seen from Fig. 2 that the width of the exciton lines in the photoconductivity spectrum increases with increasing heating of the carriers (we see two lines, which correspond to the ground state and the first excited state). This result is evidence of a decrease in the absorption coefficient.

The electrons which appear as a result of impact ionization of the excitons and during interband excitation are thus spatially separated in the case of interband excitation. In the former case, the electrons are produced in the interior of the semiconductor, and the half-width of the CR line for them depends only weakly on the strength of the microwave field. In the latter case, all the electrons are in a thin layer near the surface of the sample. If the thickness of this layer is smaller than the Larmor radius R_L (at an electron temperature $T_e = 10$ K we would have $R_L \approx 1.5$ μm), the electrons can collide with the surface of the crystal. This effect will reduce the momentum relaxation time. The broadening of the CR line in this case depends strongly on the heating of the electrons, since the electron Larmor radius and thus the role of scattering by the surface increase with increasing field.

The entire discussion above is valid in the case in which the magnetic field is parallel to the surface of the sample ($\vec{H} \perp \vec{n}$, where $\vec{n}$ is the normal to the surface). In the geometry $\vec{H} \| \vec{n}$, a substantially smaller boradening of the CR line was observed with increasing power of the microwave field. The reason is that in this case the plane of the cyclotron orbit of the electrons was parallel to the surface of the crystal.

A decrease in the exciton absorption coefficient in a static electric field has been observed previously in bulk GaAs (Ref. 5) and also in quantum-well structures.[6] In both cases, however, the lifetime of an exciton state decreased due to field ionization of excitons at electric fields $E > E_0 \approx E_i/a_B = 3 \times 10^3$, where E_i is the exciton binding energy, and a_B is the first Bohr radius of the exciton. Under the same conditions ($E > E_0$), a quenching of exciton luminescence began. The meaning here is that the electron mobility in the samples used in Ref. 5 was exceedingly low, so effects associated with impact ionization were not observed.

In summary, the sharp dependence of the momentum relaxation time of the hot electrons on the energy of the exciting photon found in this study is a consequence of a scattering of carriers by the surface of the crystal and a change in the optical absorption coefficient near an exciton resonance under conditions corresponding to impact ionization of excitions.

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