Polarization Dependence of Excitonic-Polariton Propagation in a GaAs Quantum-Well Waveguide

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Anisotropic propagation of excitonic polaritons in GaAs single-quantum-well waveguide structures is evidenced by means of time-of-flight measurements. This anisotropy suggests that the depolarization effect of two-dimensional excitons enhances the polariton propagation. The observed optical nonlinearity of the group velocity supports the existence of polaritons and reflects the effect of a polariton-polariton interaction on their propagation.

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The coherent coupling between excitons in a semiconductor crystal and the light field gives rise to a propagation of complex quasiparticles called excitonic polaritons (EP's) in the linear regime where the incident light power is far below the onset of exciton-absorption saturation.[1] Based on time-of-flight measurements at liquid-helium temperature, the existence of EP's has been confirmed in bulk semiconductor crystals such as GaAs,[2] CuCl,[3] and CdSe.[4] Large delay times in the propagation of a picosecond laser pulse have been observed in the region resonant with excitonic absorption in these crystals, and have been interpreted as a decrease in the group velocity due to the EP dispersion.

For two-dimensional (2D) excitons in semiconductor quantum wells, the time-of-flight measurements have been performed at low temperature in a geometry where the incident laser beam is perpendicular to the quantum-well layers.[5] An increase in the propagation delay time of a light pulse has been found slightly below the photon energy resonant with the 2D quantum-well excitons. In this geometry, however, 2D excitons have no translational motion, and so the polariton dispersion does not contribute to the observed time delay. By comparison with a theoretical estimate from the hole-burning spectrum, the pulse distortion due to absorption saturation of the excitons has been found to contribute to the time delay.[5]

In the case of light propagating parallel to the quantum well layers, on the other hand, translational motion of 2D excitons is possible. The propagation of quantum-well excitonic polaritons (QWEP's) is thus allowed along this direction. The effect of QWEP's will be stronger than that of EP's in a bulk crystal because of the enhancement of the oscillator strength of 2D excitons.[6] Recently, time-of-flight measurements for 2D excitons in a GaAs single quantum well were performed with a picosecond laser pulse transmitted along the quantum-well layer at low temperature.[7] The data yielded a significant propagation time delay in the exciton-absorption region and suggested a decrease in the group velocity due to formation of QWEP's. The polarization dependence of 2D exciton absorption has been observed for linearly polarized light transmitted parallel to a GaAs quantum well at room temperature.[8] This behavior reflects the optical anisotropy of heavy-hole (hh) and light-hole (lh) excitons in the quantum well. On the other hand, the optical anisotropy of QWEP's has not been observed. Such information is important for understanding the physics of excitonic polaritons in quantum-confined low-dimensional systems.

In this Letter, the polarization dependence of picosecond-laser-pulse propagation along a GaAs single-quantum-well layer is investigated in the photon-energy region resonant with 2D excitons at low temperature. The propagation delay time of the laser pulse reaches a maximum at a photon energy resonant with 2D excitons and shows anisotropic behavior. This anisotropy is much stronger than that of the absorption spectrum. Theoretical considerations for QWEP's predict that QWEP propagation is enhanced due to the depolarization effect with a laser polarization perpendicular to the quantum-well layer.[9] When the incident laser power is increased from the linear regime to a level just above the onset of absorption saturation, the propagation delay time is remarkably decreased, and a small amount of decrease in exciton absorption is simultaneously observed. This power dependence is opposite to that explained in terms of pulse distortion.[5]

To propagate a laser pulse along the quantum-well layer in the time-of-flight measurements, a sample having a waveguide structure was grown by molecular-beam epitaxy on an undoped GaAs substrate. The waveguide core was comprised of a 50-Å GaAs quantum well sandwiched between 1.8-μm superlattice layers. Each superlattice consisted of 250 periods of 30-Å GaAs and 40-Å $Al_{0.3}Ga_{0.7}As$. The cladding of the waveguide was formed by a 1.0-μm GaAs layer. Along the direction perpendicular to the substrate surface, light fields were confined in the core. The structure of the waveguide was a leaky-type waveguide as reported previously.[8] The length of the waveguide was 250 μm.

Time-of-flight measurements were performed using a picosecond dye-laser system and a streak camera.[7] The laser pulses had a 5-ps duration and a 0.85-meV band-

width. The photon energy of the laser was tuned across the absorption region of hh and lh excitons in the quantum well between 1.605 and 1.670 eV. The laser beam was divided into probe and reference beams. The probe beam was focused into the sample mounted in an optical cryostat and cooled to 6 K. The power and delay time of the output probe pulse were compared to the reference pulse, and thus the time-of-flight spectrum was obtained as well as the absorption spectrum. The polarization dependence was measured with two configurations of linear polarization for the incident laser light. In the transverse-electric (TE) polarization, the electric field of the dye-laser pulse was parallel to the quantum-well layer, while for the transverse-magnetic (TM) polarization, the electric field was perpendicular to the quantum-well layer.

The observed polarization dependence of the excitonic-absorption spectrum in the quantum-well waveguide at 6 K is displayed in Fig. 1. Here the incident power density is 8.5×10^{-10} J/cm^2 for each pulse, which is more than 1 order of magnitude less than that required for the onset of absorption saturation.[5] By assuming an exponential tail for the background part, the excitonic-absorption lines are obtained as the shaded section for each polarization. In TE polarization, two absorption lines are observed. One of the two lines, the one that lies at the lower photon energy, disappears in TM polarization. On the other hand, the other line at the higher photon energy grows larger in TM polarization. This feature is qualitatively consistent with the optical anisotropy of hh and lh excitons.[8] The line at the lower photon energy corresponds to a hh exciton. The line at the higher photon energy is due to a lh exciton. The anisotropy of the lh exciton is weaker than that expected. This weakness is due to polarization rotation by the correlation between lh excitons in TE and TM polarization.[10]

The absorption coefficient of the waveguide at the photon energy of the hh exciton absorption was measured as $\alpha_0 = 190$ cm^{-1} in the linear regime. The coefficient α_0 is indicated in each part of Fig. 1. Subtracting the background, the coefficient $\alpha_{\text{hh-ex}}$ for the hh exciton is 170 cm^{-1}. The value of $\alpha_{\text{hh-ex}}$ is about 85% of that estimated for the room-temperature exciton absorption in GaAs quantum wells.[8] This decrease in the coefficient reflects the coherent propagation of the light pulse.

The time-of-flight spectrum in the exciton-absorption region at 6 K is plotted for both polarizations in Fig. 2. The delay time in TE polarization reaches a maximum at a photon energy which is almost resonant with the hh exciton absorption. The delay time is measured relative to the time of flight of a probe pulse at a photon energy far below the exciton absorption. The dispersion curves of EP's change drastically from photonlike to excitonlike and vice versa in the energy region of the exciton absorption.[1] In general, the polariton group velocity is obtained from the curvature of EP dispersion curves. So, this gives a considerable change in the polariton group velocity. The observed peak in the delay time is caused by a decrease of the group velocity of the QWEP's associated with the hh exciton. The observed time delay can be explained by a theoretical model based on the disper-

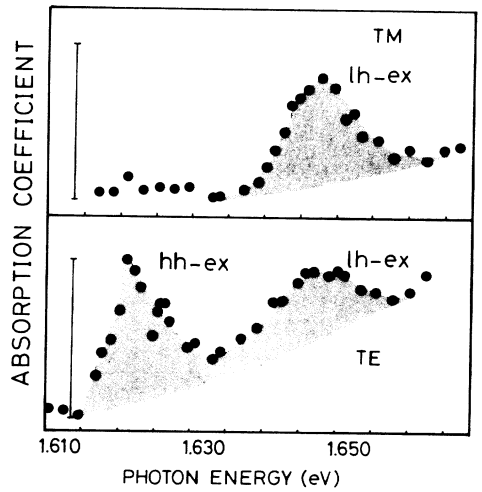

FIG. 1. Absorption spectrum of 2D excitons in a GaAs single-quantum-well waveguide in TE (lower) and TM (upper) polarizations at 6 K. Shaded areas correspond to the 2D exciton absorption for each spectrum. The labels hh-ex and lh-ex denote heavy-hole exciton and light-hole exciton, respectively. Each vertical bar indicates the absorption coefficient $\alpha_0 = 190$ cm^{-1}.

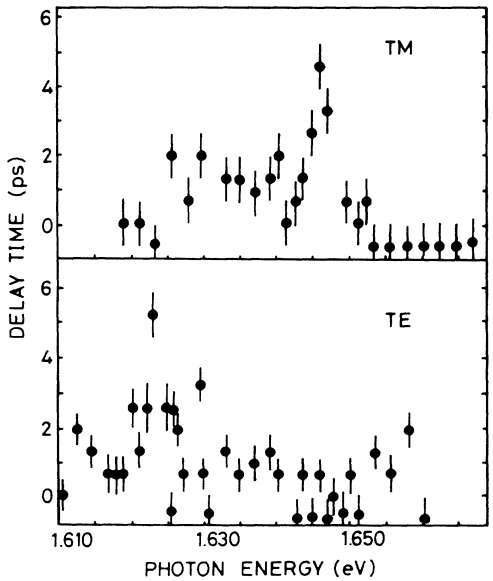

FIG. 2. Delay time of probe pulse transmitted from the waveguide sample at 6 K. The lower part corresponds to delay-time spectra obtained in TE polarization, and the upper part, in TM polarization.

sion relations of the QWEP's in the waveguide. Details of the model will be presented elsewhere.

To derive the group velocity of QWEP's in the waveguide, it should be noted that QWEP's propagate as guided waves. The strength of the polariton coupling is determined by the filling factor[8] which corresponds to the overlap between the exciton wave function and the light field. The optical constants of QWEP's, such as the absorption coefficient and group velocity, must be divided by the filling factor for comparison with those of bulk EP's. From standard waveguide theory,[11] it can be shown that the mode profile of the light field is close to Gaussian and so the filling factor is estimated to be 7.8×10^{-4}. The QWEP group velocity associated with the hh exciton is observed to be 3.7×10^{4} m/s which is almost $\frac{1}{2300}$ of the velocity of light in GaAs. In bulk GaAs, the polariton group velocity has been reported to be about $\frac{1}{600}$ of the velocity of light at 1.3 K.[2] The observed decrease in the group velocity of QWEP's is due to the influence of confinement on the oscillator strength compared to the case of EP's in bulk material.

The time delay due to the lh-exciton-associated QWEP is almost zero in TE polarization. This is probably because the TE component of the lh-exciton oscillator strength is almost a quarter that of the hh exciton. In TM polarization, however, a significant increase in the delay time is observed at a photon energy resonant with the lh-exciton absorption. The maximum delay time is larger than that expected from the ratio of lh-exciton oscillator strengths in TE and TM polarizations. The polariton group velocity associated with the TM lh exciton is 4.2×10^{4} m/s. The light fields extend beyond the narrow quantum-well layer while the exciton wave function has an almost δ-functional distribution in the waveguide space in TM polarization, and so the physical situation for QWEP propagation in TM polarization is very different from that in TE polarization.

Theoretical estimates suggest that the dispersion relation of QWEP's is strongly modified on account of the existence of depolarization fields by the excitons in the TM configuration.[9] The depolarization energy shift of QWEP's is expected from the theory[9] to be $12(a_{ex}/L_W)\Delta_{LT}$, where, a_{ex}, L_W, and Δ_{LT} represent the Bohr radius of bulk exciton, the width of the quantum well, and the longitudinal-transverse splitting of the bulk EP, respectively. In the present sample, $L_W=50$ Å, and the estimated depolarization shift is more than 2 meV using the values[12] $a_{ex}=136$ Å and $\Delta_{LT}=0.086$ meV. In the absorption spectrum in Fig. 1, the shift is not apparent. The reason is believed to be due to mixing between TE and TM polarizations.[10] The depolarization effect also shifts the bottom of the parabolic dispersion of the lh exciton from the Γ point to a point with $k\neq0$, and the QWEP group velocity becomes slower. This effect on the group velocity is much larger than that on the energy shift, and qualitatively explains the observed enhancement of the group-velocity decrease in TM polarization.

It may be argued that the decrease in the group velocity is due to a change in the refractive index. However, an anomalous dispersion occurs in the spectral region of the exciton resonance, which will cause an increase or at most a negligible decrease in the group velocity.[5] Thus, the influence of the refractive index on the observed pulse delay is not considered significant.

When the incident power density is increased to 2.1×10^{-8} J/cm^2 for each pulse, a drastic change of the pulse delay time is found in the spectral region of the exciton absorption. This power density is just above the onset of the absorption saturation.[5] Figure 3 shows an example of the power dependence of the absorption spectrum and the time of flight for the QWEP associated with the hh exciton in TE polarization. The intensity of the hh-exciton-absorption line decreases when the laser power increases. The amount of this saturation is approximately 20% of the intensity of the line measured in the linear regime. However, the pulse propagation delay time is decreased to half that in the linear regime; thus, the group velocity increases by a factor of 2. Such a tendency is quite opposite to that of saturation absorption. According to the relation, $v_g \propto 1/-\Delta\alpha_{ex}$, which applies to absorption saturation,[5] the light group velocity v_g should decrease as the amount of the saturation

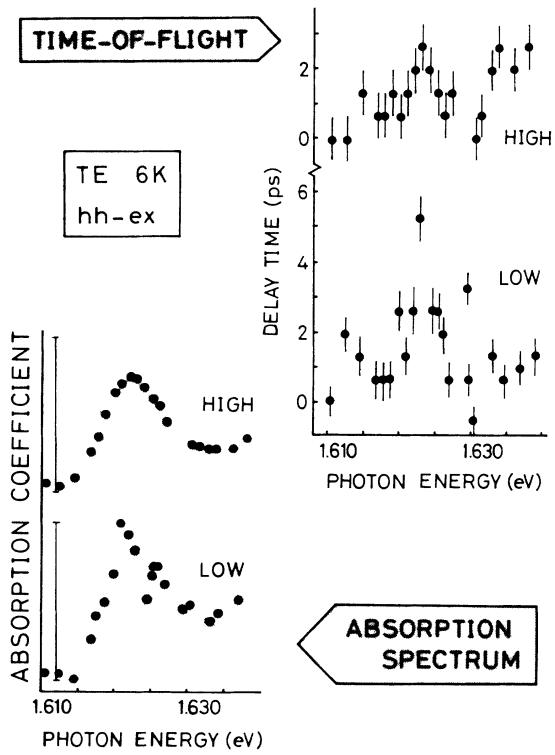

FIG. 3. Power dependences of the absorption spectrum and the delay time due to QWEP propagation for the hh exciton in TE polarization at 6 K. Incident power density for the index LOW is 8.5×10^{-10} J/cm^{2}pulse, and that for the index HIGH is 2.1×10^{-8} J/cm^{2}pulse. Vertical bars are for indicating α_0 as in Fig. 1.

($-\Delta\alpha_{ex}$) increases. The observed increase in the group velocity is caused not by saturation but by nonlinearity of the QWEP's. The higher incident power generates a larger QWEP population. Because of an interaction between QWEP's, scattering of QWEP's becomes large when the population is increased. The scattering weakens the coupling between the exciton and the photon, and the QWEP dispersion becomes more photonlike. Similar nonlinearity is observed for QWEP's associated with the lh exciton.

In conclusion, experimental observations of excitonic polaritons in a GaAs single-quantum-well waveguide have been made by time-of-flight measurements. The polariton group velocity associated with the heavy-hole exciton is 3.7×10^4 m/s, while that associated with the light-hole exciton is 4.2×10^4 m/s. The polariton effect is significantly enhanced in the configuration of incident polarization perpendicular to the quantum well. The polariton group velocity has been found to increase with incident power because of polariton scattering.

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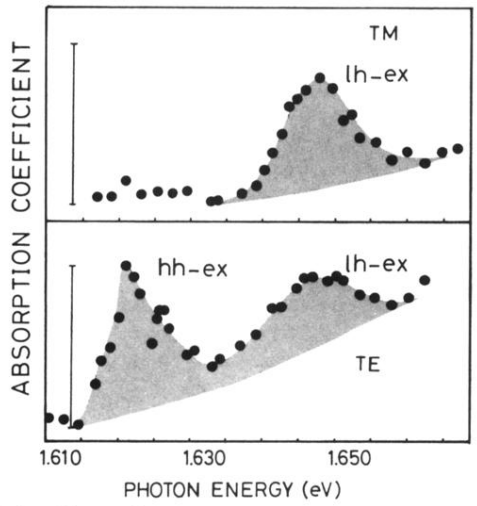

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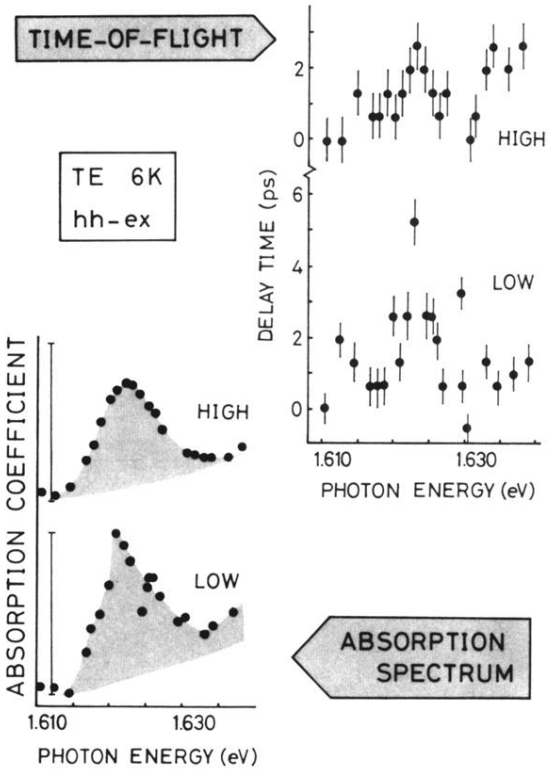

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