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Quantum Well Excitonic Polariton and Possibility of Its Device Application

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Excitonic polaritons are observed for the first time in a waveguide incorporating a single GaAs quantum well. Picosecond time-of-flight measurements reveal a decrease in the group velocity of a light pulse (1/1000 of light velocity in the GaAs transparent region) transmitted through the waveguide. The phase coherence length of such an excitonic polariton is found to be drastically increased to about 1 mm. This is achieved by controlling the boundaries of the quantum well and core, resulting in artificial control of the coupling between the exciton and photon fields. Such an extended phase coherence length will make it possible to fabricate new opto-electronic devices using polaritons.

1. INTRODUCTION

In a semiconductor crystal, an electron and a hole may be bound together by the Coulombic interaction to form an exciton. In the spectral region around the excitonic resonance, a photon entering a crystal is changed into an excitonic polariton by linear coupling with the electronic polarization of the exciton.[1] This excitonic polariton has unique properties resulting from the coexistence of an electron, a hole, and light. In this study, we present the first evidence of the existence of the excitonic polariton in a quantum well structure. Possible device applications of the quantum well excitonic polariton are also discussed.

2. QUANTUM WELL EXCITONIC POLARITON[2,3]

A quantum well excitonic polariton will be formed only when light propagates parallel to the quantum well layer, because translational motion of the quantum well exciton is allowed only along the layer. Therefore, we designed a waveguide shown in Fig. 1. A 50-Å GaAs quantum well was sandwiched between 1.8 μm-barrier layers, which were composed of GaAs(30 Å)/AlGaAs(40 Å) superlattices. These layers constituted the core of the waveguide.[4] The cladding was made of GaAs.

Existence of the excitonic polariton should show a considerable reduction of the group velocity, resulting from the coherent coupling of

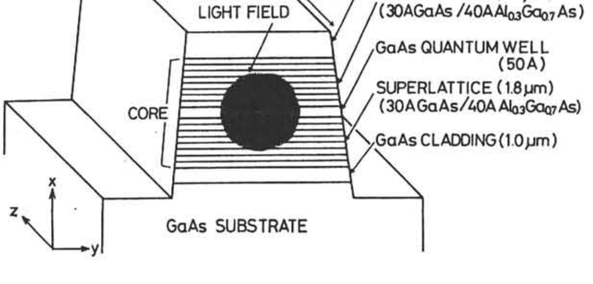

Fig. 1 Structure of a quantum well waveguide.

the exciton and photon. Therefore, we measured the delay time of light transmitted through the quantum well waveguide, because the delay time corresponds to the group velocity.

To obtain information on the excitonic resonance energy of the quantum well waveguide, optical absorption spectra at a temperature of 6 K were taken, as shown in Fig. 2. For TE polarization (parallel to the quantum well), two absorption peaks are observed at photon energies of 1.622 and 1.645 eV. On the other hand, for TM polarization (perpendicular to the quantum well), only one absorption peak is observed at 1.645 eV. Since the absorption peak at 1.622 eV is obtained only for the TE polarization, this peak corresponds to the exciton associated with a heavy-hole (hh).[4] The absorption peak at 1.645 eV is related to a light-hole (lh) exciton because the absorption is stronger in TM polarization than in TE polarization.[4]

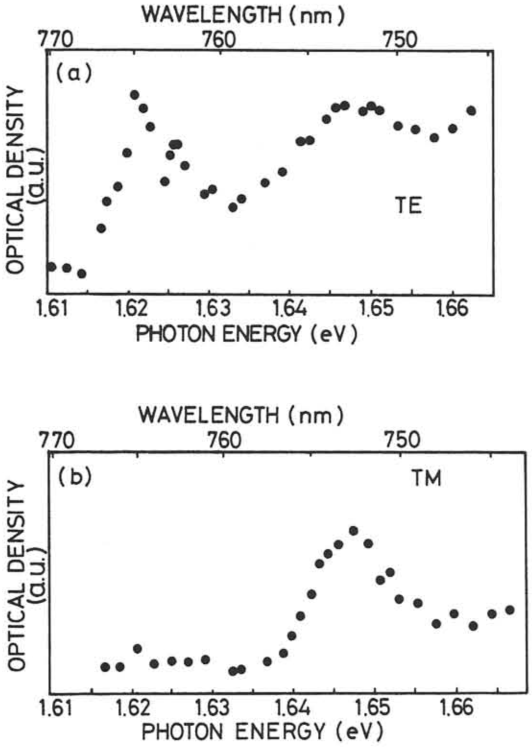

Fig. 2 Optical absorption spectra of a quantum well waveguide measured at 6.0 K. (a) TE polarization, (b) TM polarization.

The propagation delay time of the light pulse obtained by the picosecond time-of-flight measurement at 6.0 K is plotted against the incident photon energy in Fig. 3. The light pulse had a considerably weak power density, i.e., 8.5 x10^{-10} J/cm^2 pulse, which never causes a nonlinear optical effect. For TE polarization, the time delay is 5.3 ps at 1.622 eV resonant to the hh-exciton. However, there is no delay corresponding to the lh-exciton

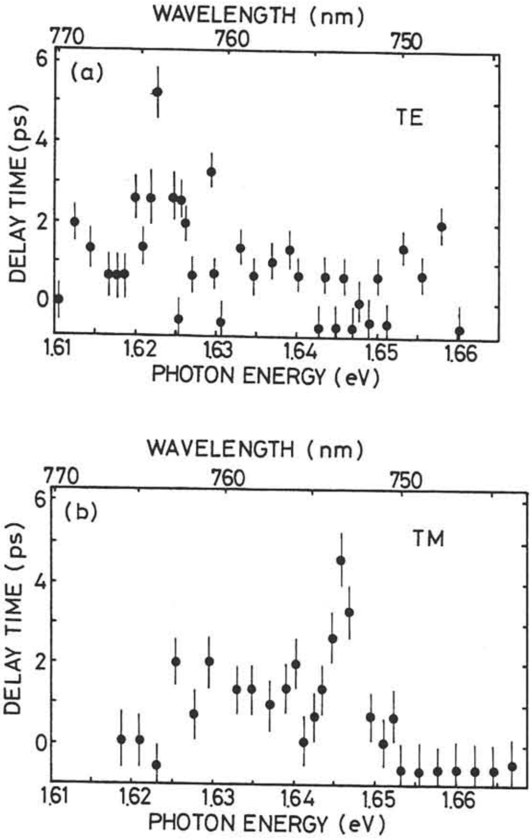

Fig. 3 Propagation delay time of a probe pulse transmitted through a waveguide. The temperature was 6.0 K. (a) TE polarization, (b) TM polarization.

whose absorption is observed at 1.645 eV. For TM polarization, the time delay is 4.6 ps at 1.645 eV.

Since the delay time is inversely proportional to the group velocity, the experimental results show that the group velocity of the light pulse decreases drastically to around the photon energies resonant to the exciton lines. Based on the guided-wave theory,5) numerical calculations show that the group velocities are 3.7×10^4 m/s for the TE polarization hh-exciton and 4.2×10^4 m/s for the TM polarization lh-exciton. This is almost 1/1000 of the light velocity in GaAs transparent regions. A comparable low value has been obtained only for the excitonic polariton in a bulk GaAs crystal at 1.3 K.6) Such a remarkable decrease in group velocity in addition to the coincidence between the photon energies of the absorption and delay time lines, is the first evidence of excitonic polaritons in quantum wells.2)

3. COHERENCE LENGTH7)

This waveguide-type quantum well is particularly advantageous because the coherence length of the polariton propagation can be drastically increased to the order of 1 mm.7) This can be shown as follows. The polariton creation operator A^+ is a linear combination of the photon operator a^+ and the exciton operator b^+,

$$A^+ = \zeta a^+ + \zeta' b^+, \quad (|\zeta|+|\zeta'|=1) \tag{1}$$

where ζ and ζ' are constants determined from the material used to construct the waveguide. Therefore, the polariton eigenstate is a superposition of $|\psi_p\rangle = |\text{one photon}\rangle|\text{no exciton}\rangle$ and $|\psi_{ex}\rangle = |\text{no photon}\rangle|\text{one exciton}\rangle$. An actual eigenstate $|\psi(x)\rangle$ in the waveguide is written as

$$|\psi(x)\rangle = \alpha_p(x)\zeta(x)|\psi_p\rangle + \alpha_{ex}(x)\zeta'(x)|\psi_{ex}\rangle, \tag{2}$$

where x is the axis perpendicular to the quantum well, as shown in Fig. 4. Parameters $\alpha_p(x)$ and $\alpha_{ex}(x)$ are introduced to describe the profiles of the light and exciton in the waveguide. Further, $\zeta(x) = \zeta$ and $\zeta'(x) = \zeta'$ in the quantum well ($|x|<T$), and $\zeta(x) = 1$ and $\zeta'(x) = 0$ in the other region ($|x|>T$). The most important feature of the polariton field derived from the eigenstate $|\psi(x)\rangle$ is the spatial separation of the photon field and exciton field.

Under the Born approximation, the scattering probability due to the scattering centers existing in the waveguide is reduced by a factor less than $\int^{T}_{-T} |\alpha^{i}_{ex}(x)|^2 dx \cdot \int^{T}_{-T} |\alpha^{f}_{ex}(x)|^2 dx$ in the case of $\zeta' \Rightarrow 1$ (the exciton fraction is dominant) compared to the bulk uniform medium, where i and f denote the initial state before scattering and the final state after scattering, respectively. Since $\int^{T}_{-T} |\alpha_{ex}(x)|^2 dx$ is 3.3×10^{-2} in the case of the waveguide shown in Fig. 1, the scattering probability is reduced

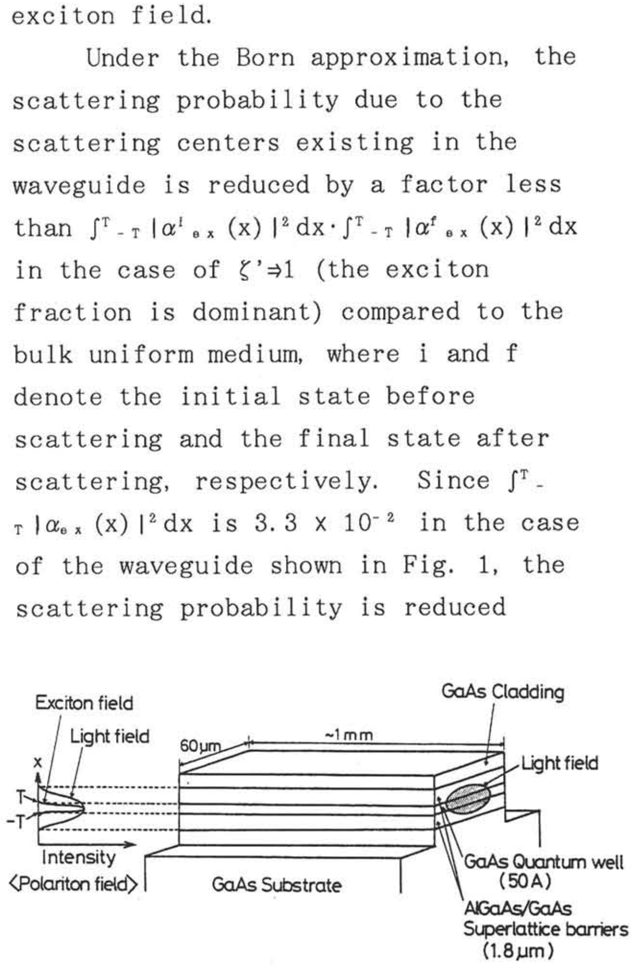

Fig. 4 Profile of the excitonic polariton field in the quantum well waveguide.

approximately to 10^{-3} times that of the polariton propagation in a bulk uniform medium. This leads to a large coherence length reaching 1 mm because the coherence length of a conventional two-dimensional electron propagation is of the order of 1 μm. Furthermore, it should be stressed that by controlling the dimensions of the quantum well and core, the coherence length can be easily controlled. This characteristic results in the artificial control of the coupling between the exciton and light field through the waveguide structure.

4. POSSIBILITY OF DEVICE APPLICATION

Since the excitonic polaritons consist of excitons and light, they exhibit electronic and photonic properties, which can lead to a new generation of opto-electronic devices in future optical network systems. The expected properties are as follows.

1) The propagating speed of the polariton is 2~3 orders of magnitude greater than that of an electron in a conventional wire cable. Therefore, it is possible to increase the switching times over standard electronic devices by using the polariton.

2) Since the polariton has the characteristics of light, it is possible to control the propagating direction along the waveguide without degrading the propagating speed. Further, the direction and speed of the polariton can be easily controlled by electric and magnetic fields, and even by light fields.

For example, an interference device consisting of two joined quantum well waveguides can be fabricated. In this structure, the output light power can be modulated by applying the electric field to one waveguide through the direct interaction between the electron wavefunction and the electric field.

5. SUMMARY

Excitonic polaritons were observed for the first time in a quantum well waveguide. It was also shown that the quantum well excitonic polariton will make possible a new generation of the opto-electronic devices.

6. REFERENCES

1) J. J. Hopfield; Phys. Rev. 112 (1958) 176.

2) K. Ogawa, T. Katsuyama and H. Nakamura; Appl. Phys. Lett. 53 (1988) 1077, also Phys. Rev. Lett. 64 (1990) 796.

3) K. Oimatsu, T. Iida, H. Nishimura, K. Ogawa and T. Katsuyama; J. Luminescence, To be published.

4) J. S. Weiner, D. S. Chemla, D. A. B. Miller, H. A. Haus, A. C. Gossard, W. Wiegmann and C. A. Burrus; Appl. Phys. Lett. 47 (1985) 664.

5) D. Marcuse; Bell System Technical Journal 50 (1971) 1791.

6) R. G. Ulbrich and G. W. Ferenbach; Phys. Rev. Lett. 43 (1979) 963.

7) T. Katsuyama and K. Ogawa; Semicond. Sci. Technol. 5 (1990) 446