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ELECTRIC FIELD EFFECTS ON EXCITONS IN AlGAs QUANTUM WELLS AND THEIR APPLICATIONS TO OPTOELECTRONIC DEVICES

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ABSTRACT

This paper describes our recent work on electric field effects on excitons in AlGaAs/GaAs quantum wells. We discuss the large change of optical absorption at the lasing wavelength of a multiple-quantum-well waveguide induced by the Stark effect, the absorption saturation of excitons controlled by the Stark effect, and the quenching of excitonic luminescence induced by resonance effects of electrons. In addition, the applications of these features to fabricate an optical waveguide modulator monolithically integrated with a multiple-quantum-well laser diode and a voltage-controlled bistable laser are reported.

I - INTRODUCTION

Electric field effects on excitons in semiconductor quantum wells (QWs) have recently attracted much attention due to possible applications in novel photonic devices. In this paper we summarize our recent work in this field. An electric field applied perpendicular to QW layers provides two main effects on excitons, i.e. a Stark shift of the exciton energy and a quenching of the excitonic photoluminescence (PL) intensity. The Stark shift of excitonic absorption peaks is observed at a field as high as 100 kV/cm because the heterojunction potential barriers prevent the field ionization of excitons. Using this effect, an optical modulator and an optical bistable device called self-electrooptic effect device (SEED) were realized. These devices are operated with light transmitted perpendicular to QW layers. We have studied the electric field effects on the transmission of light through multiple-quantum-well (MQW) waveguides, which are suitable for monolithic integration with MQW laser diodes. We have fabricated a MQW waveguide modulator monolithically integrated with a MQW laser diode as well as a voltage-controlled bistable laser. The quenching of excitonic luminescence is induced by two main factors, i.e. the spatial separation of electrons and holes in the wells and the carrier tunneling through the barriers. Both factors have recently been investigated by time-resolved PL measurements. We have studied the field-induced quenching of excitonic PL in AlGaAs/GaAs superlattices using time-

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resolved photocurrent (PC) as well as static PL and PC measurements. The topics presented here include the Stark effect on excitons in AlGaAs/GaAs MQW waveguides at the lasing wavelength of monolithically integrated MQW lasers, the absorption saturation of excitons under an electric field, and the field induced quenching of excitonic PL in Section II, and the applications of these effects to novel optical devices in Section III.

II - ELECTRIC FIELD EFFECTS ON EXCITONS IN QWS

II - 1 Stark Effect in MQW Waveguides

Excitons in QWs exhibit large absorption peaks even at room temperatures due to the confinement effect [12]. The Stark effect has also a strong impact on room-temperature excitons [2] so that it becomes attractive for applications to optoelectronic devices. We have studied the optical properties of AlGaAs/GaAs MQW waveguides, which have similar layer structures as MQW laser diodes. We have found that the laser oscillation of the MQW waveguide occurs at the low-energy side of the excitonic absorption peak obtained for the same MQW waveguide under unexcited conditions [5] because of the band gap shrinkage effect [13], and that the absorption coefficient at the lasing wavelength is much smaller for the MQW waveguide than for the conventional GaAs DH waveguide [5]. The first property suggests that a large excitonic absorption can be induced at the lasing wavelength by applying a voltage to the MQW region. The second feature suggests that MQW waveguides are favorable for integrating passive optical components monolithically with lasers and other passive optical components because of the low transmission loss. These properties are confirmed by PC spectroscopy measurements. In Fig. 1 we show the PC spectra for a p-i-n MQW laser diode structure measured with different bias voltages (Vb). The PC spectrum is a replica of the absorption spectrum for the intrinsic MQW region. The peaks clearly observed on the spectrum for Vb = +1 V are due to the absorption peaks of the heavy hole (hh) exciton and light hole (lh) exciton. These peaks shift to lower energies with decreasing Vb according to the Stark shifts. The lasing wavelength of this diode is indicated by λL, which is about 20 meV below the peak of the hh exciton. The data of the figure show that a large change of absorption can be induced at λL by switching the applied voltage, e.g., from +1 to -1 V. The optical waveguide modulator described in III - 1 utilizes this change of the excitonic absorption.
II - 2 Absorption Saturation of Excitons in Electric Fields

The absorption saturation of excitons is an important property for applications to nonlinear optical devices. Large absorption saturation of excitons in GaAs QWs was reported by Miller et al. and Chemla et al. / 14 / . A four-wave mixing technique revealed that the absorption saturation occurs most strongly at the low-energy side of the hh exciton peak / 14 / . The mechanism of the absorption saturation is attributed to a screening effect of free carriers at room temperature and to the phase-space filling effect in addition to the screening effect at low temperatures / 14 / .

In the MQW waveguide under investigation, $\lambda_1$ is located at the low-energy side of the hh exciton peak, where a large absorption saturation is expected. In addition, the magnitude of the excitonic absorption (i.e. the magnitude of the absorption saturation) at $\lambda_1$ can be changed using the Stark effect. Figure 2 shows the photoresponsivity of the p-i-n MQW diode structure as a function of applied voltage ($V_b$) obtained with different excitation densities at 50 K. The photoresponsivity is given by the PC divided by the excitation density. The exciting laser wavelength is fixed just below the absorption peak of the hh exciton under nearly flat band conditions, as schematically shown in the inset. The larger $V_b$ values (left hand side) correspond to the low-energy side of the absorption spectrum since the absorption spectrum shifts to the low-energy side with decreasing $V_b$. The two peaks of the spectra are due to the hh exciton (at larger $V_b$) and lh exciton (at smaller $V_b$). No peak is observed on the photoresponsivity spectrum with white light excitation. When the excitation density is increased from $\sim 1 \text{ W/cm}^2$ to $\sim 1 \text{ kW/cm}^2$, the hh exciton associated peak becomes significantly smaller in intensity due to the absorption saturation. On the other hand, the intensity of the lh exciton associated peak is hardly reduced. This phenomenon is attributed partly to the smaller absorption saturation of lh excitons and partly to the reduction of the carrier lifetime with enhanced electric field. The shifts of the peaks are caused by the field screening due to the photogenerated carriers. A narrowing of the hh exciton associated peak observed at $\sim 100 \text{ W/cm}^2$ is probably due to a kind of feedback mechanism associated with the field screening. In a MQW waveguide with 13-nm wells, the absorption saturation accompanied by the smaller screening effect is achieved with a lower excitation density. The peak observed in the photoresponsivity cannot be compared directly to the peaks of the excitonic spectra because a field induced change of the excitonic absorption spectrum and an enhancement of the magnitude of the PC should be taken into account. Most recently Iwamura et al. have obtained a similar saturation behaviour by optical absorption measurements / 15 / . The saturation behaviour observed here implies...
that the magnitude of the absorption saturation of excitons at an exciting laser wavelength below the hh exciton peak can be changed by the applied voltage. This feature is utilized in the voltage-controlled bistable laser described in Section III-2.

II-3 Resonance Induced Quenching of Excitonic Luminescence

Photoexcited carriers in QWs subject to an electric field generate either PL or PC /11, 16/. At low temperatures the PL at moderate excitation levels is mostly generated by excitonic recombination, and the PC by carriers tunneling through the barriers. The time-resolved PL measured for isolated GaAs QWs at 5 K exhibited an enhancement of the lifetime of excitons at low fields, which is due to the spatial charge separation, and a reduction at high fields, which is due to the tunneling from the inside of the well to the outside of the QW /9, 10/. In superlattices tunneling occurs mostly between the adjacent respective wells. In AlInAs/GaInAs and AlGaAs/GaAs superlattices, an excess PC due to sequential resonant tunneling was observed in static PC-bias voltage characteristics /17, 18/. We have studied the field induced quenching of the excitonic luminescence in AlGaAs/GaAs superlattices incorporated in p-i-n diode structures using time-resolved PC as well as static PL and PC measurements. Figure 3 shows the field dependences of the static PL intensity and of the PC measured under cw excitation condition. The observed PL is associated with hh excitons /11/. The external field, given by (built-in-voltage + applied voltage) divided by total thickness of the intrinsic region, is shown at the lower horizontal axis. Additionally, the calibrated field as evaluated from the Stark shift of the PL emission peak energy is shown at the upper horizontal axis /11/. The discrepancy between calibrated and external fields is due to the field screening by photogenerated carriers under the cw and fairly high (~5 W/cm²) excitation conditions employed here. The PL intensity is strongly quenched at the fields indicated by C and D. In good agreement with these PL quenchings an excess PC appears at the points labeled by c and d, which is caused by the field-induced dissociation of excitons. These PL quenchings are attributed to resonance effects of electrons between the first excited state and the ground state (quenching C) and between the second excited state and the ground state (quenching D) of adjacent wells. The corresponding calibrated fields are well predicted from the calculation of the electron subband levels. The existence of resonance effects is confirmed by the time-resolved PC measurements. When the excitation power density is reduced, the peaks of the PC shift to lower fields because of the smaller field screening. The external fields of the peaks c and d measured with a reduced excitation density down to 0.05 W/cm²...
are 44 and 88 kV/cm, respectively. These values are very close to the calibrated fields of the peaks c and d in the figure. Another small PL quenching indicated by A is possibly due to resonance effects of holes according to the calculation of the hole subband levels. This peak is not discussed further because the resonance effect is not confirmed by time-resolved PC due to the too small PC intensity. An excess PC indicated by b is possibly different from the intrinsic effect because it accompanies no PL quenching.

In Fig. 4 we show the decay time constant $\tau_i$ and the peak value $P_{\text{C, max}}$ of the PC measured after short optical pulse excitation. The exciting pulse has an error-function like time-resolved profile with 200 ps duration. The value of $\tau_i = 60$ ps is the lower limit imposed by the time-resolved fall profile of the exciting pulse. $\tau_i$ exhibits a strong reduction at the external fields of 46 and 85 kV/cm, where the $P_{\text{C, max}}$ exhibits an excess intensity. These two reductions of $\tau_i$ confirm the reduction of the tunneling time induced by resonance effects of electrons between the first two excited states and the ground state as described before. The external fields observed for the reduction of $\tau_i$ are lower than those of the peaks c and d, and they are close to the calibrated fields (see Fig. 3) because the field screening effect is smaller under the excitation conditions of a short pulse and a smaller peak power density ($\sim$ 1 W/cm$^2$).

The strong PL quenching shown in Fig. 3 and the strong reduction of $\tau_i$ shown in Fig. 4 are consistently understood by comparing the excitonic recombination time $\tau_{\text{ex}}$ and the tunneling time $\tau_t$. $\tau_{\text{ex}}$ is 1.5 ns at low fields, which was independently determined by time-resolved PL measurements /11/. The strong reduction of $\tau_i$ means that the $\tau_i$ values measured under resonance conditions are totally determined by the carrier tunneling. These $\tau_i$ ($\sim 1$ ns) values are sufficiently small to quench the excitonic luminescence as compared with $\tau_{\text{ex}}$ which is expected to be enhanced by a factor of two or more at this field (i.e. $\tau_{\text{ex}} > 3$ ns) due to the spatial charge separation effect /9/. In contrast, at the lower fields, where the static PL is almost invariant, $\tau_i$ ($\sim 1$ ns) is comparable to $\tau_{\text{ex}}$ ($\sim 1.5$ ns) so that it is dominated by the excitonic recombination. Our result explains the field induced competition
of excitonic recombination and carrier tunneling in superlattices consistently with respect to their dynamical and static aspects.

III.- APPLICATIONS TO OPTICAL DEVICES

III - 1 Waveguide Modulator Monolithically Integrated with MQW Laser

As described in Section II - 1, MQW waveguides are attractive for optical modulators to be monolithically integrated with MQW laser diodes because of the low loss as well as the large change of the excitonic absorption at the lasing wavelength. Figure 5 schematically shows the monolithic device fabricated in the present work. The modulator and the laser diode are separated by a narrow gap fabricated by reactive ion beam etching. The gap is deep enough to separate the modulator and the laser diode both optically and electrically. From the measured light output versus injection current curve (L-I curve) the absorption loss coefficient of the modulator waveguide is estimated to be $\approx 60 \, \text{cm}^{-1}$ at the lasing wavelength. This value confirms the low loss of the waveguide as described in Section II - 1. Optical modulation of this device is achieved by injecting a constant current into the laser diode and applying a modulation voltage to the modulator. The achieved modulation depth is 7 dB for a driving voltage of 2.3 V, and the cut-off frequency is 0.88 GHz. The cut-off frequency is limited by the RC time constant, which is improved by reducing the device capacitance. We expect a cut-off frequency beyond 10 GHz by reducing the waveguide width as well as insulating the layers under the wiring pads, e.g., by proton implantation.

III - 2 Voltage-Controlled Bistable Laser

Optical bistability is one of the most essential functions for signal processing in an optical computer. A bistable laser is attractive as an active element for the optical bistability. This device which has a region of absorption saturation in the cavity was originally proposed by Lasher / 19 / , and its operation was later demonstrated in bulk InGaAsP / 20 / and GaAs / 21 / DH laser diodes. These bistable lasers probably utilized absorption saturation associated with the band-filling effect. Our bistable laser utilizes the absorption saturation of excitons in QWs, whose magnitude can be changed by the Stark effect. The device has the same waveguide structure as shown in Fig. 5. The difference is that the waveguide is separated into two segments only electrically but not optically. The electrical separation only is realized by Ga focused ion beam implantation instead of reactive ion beam etching. We show the bistable operation by injecting current into one segment A ($I_A$) while applying a voltage to the other segment B ($V_B < \text{built-in-voltage}$). Figure 6 shows the continuously operating L-I curves with different $V_B$ values at 77 K. The hysteresis
loop is observed in the $V_B$ range from 0 to 1.2 V. The width of the loop changes with the applied voltage $V_B$ as shown in Fig. 7. Room-temperature bistable operation of this device is also achieved under pulsed excitation conditions. The lasing wavelength in the bistable operation is at the low-energy side of the exciton absorption peak. More recently, we have obtained cw bistable operation also at room temperature, using a more sophisticated structure (Fig. 8) / 22 / . Inspection of Fig. 7 reveals that the bistability of our device is controlled by an applied voltage $V_B$ smaller than the built-in-voltage so that no current is injected to the segment B. This condition is favorable for low power consumption to control the bistable operation.
IV - CONCLUSION

We have presented several interesting properties of excitons in AlGaAs/GaAs QWs subject to an electric field from the viewpoint of basic physics as well as device application. A large change of optical absorption is induced at the lasing wavelength of a MQW waveguide by the Stark effect. The magnitude of the absorption saturation of excitons is changed by the Stark effect. A strong quenching of excitonic luminescence is induced by resonance effects of electrons. Using these properties we have fabricated novel optical devices, including a waveguide modulator monolithically integrated with a MQW laser diode and a voltage-controlled bistable laser.

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