Magneto-optical study of single InAs/GaAs quantum rings

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Abstract—The magneto-optical properties of self-assembled InAs/GaAs quantum rings are investigated by the single ring spectroscopy in this work. The emissions of the single excitons and the biexcition complexes in individual rings are unambiguously indentified by the power dependence of their emission intensity. In magneto-photoluminescence spectra, unlike quantum dots, where the diamagnetic shift of the biexciton emission is smaller than or equal to that of the exciton emission, quantum rings reveal surprisingly large diamagnetic coefficient for biexcitons, about twice as large as that of the single excitons, implying the large spatial extent of biexciton wave function. The magnetic response probes the considerable difference of the electronic structures between excitions and biexciton confined in quantum rings.

Self-assembled quantum dots (QDs) have attracted great interest in the field of photonic devices and quantum computing applications. Recently, a growth process involving partially capping and in-situ annealing has succeeded in transforming InAs QDs into quantum rings (QRs). The detailed morphological evolution and the associated optical properties have been carefully studied by atomic force microscopy (AFM) and conventional photoluminescence (PL) [1]. However, the magneto-optical properties of QRs have yet to be completely studied. So far only the diamagnetic properties of the neutral and the negatively charged excitons have been discussed [2]. In this work, with magnetic field up to 6 T, the diamagnetic shifts and Zeeman splittings of the neutral single excitons and biexcitons are investigated. The diamagnetic energy shift reveals the spatial distribution of the excitonic wave function which in turn provides informations on the QR's confinement potential and the Coulomb interactions.

The QRs used in this study were fabricated by a Varian Gen-II molecular beam epitaxy (MBE) system on a GaAs (001) substrate. Two monolayers of InAs were first deposited at a substrate temperature of 520 ^{o}C to form the precursor QDs. The substrate temperature was then lowered to 490 ^{o}C. A thin GaAs layer of 1.7 nm was next deposited to cover the QD sidewalls, and a growth interruption of 50 seconds was performed for a dewetting process which expels the indium atoms from the center of the QDs to move outwards for the QR formation.[1] The single ring PL studies were achieved in a low-temperature micro-photoluminescence (μ-PL) setup. The PL was excited with a 633 nm He-Ne laser and dispersed by a 750 mm monochromator into a silicon charge coupled device.

The AFM image of the QR on the surface is shown in the inset of fig. 1. The height of the rim including the capped region and the outer diameter are around 3 nm and 70 nm, respectively. The area density of QRs is estimated to be about 1 x 10^{7} cm^{-2}. Figure 1 reveals the conventional PL and the single ring spectra. The conventional PL spectrum shows an emission peak at 1329 meV with a 26 meV line width arising from the size fluctuation of the QRs. In the μ-PL spectrum, there is one sharp emission line at 1320 meV with the narrow line width around 50 μeV which is limited by the resolution of the measurement system.

A series of PL spectra were taken from the single QR over a range of excitation power as shown in Fig. 2. At low excitation powers, one emission line at 1320 meV dominates the spectrum and is associated with the neutral single exciton emission (X). Its intensity increases linearly with excitation power before it saturates. As the excitation power increases, a second emission line at 0.51meV below the X emission peak appears. Fig. 2(b) depicts the integrated intensity of both signals as function of the excitation power. The second line shows a nearly quadratic increase with power and is therefore attributed to the biexciton emission (XX). For seven measured rings, the emission energies of X range from 1320 to 1328 meV, and the biexciton binding energies (defined as E_X - E_{XX}) are estimated to be 0.2 ~ 0.7 meV.

When an external magnetic field is applied along the growth direction, each of X and XX lines shifts and splits into two emission lines with opposite circular polarizations, as presented in Fig. 3. The Zeeman splitting values of X and XX are the same and equal to 120 μeV/T, corresponding to an exciton g-factor of $|g| = 2.1$. The identical splitting of X and XX confirms that the origin of XX is the optical transition of the biexciton into an exciton [3]. Furthermore, the energy shift of the center of the Zeeman doublet, the black solid line in Fig. 3(b), shows the quadratic dependence on magnetic field. This shift is fitted to βB^2, and the average β_X is 6.8 $\mu eV/T^2$, while β_{XX} is 14.8 $\mu ev/T^2$, which is two times more than β_X.

The diamagnetic coefficient is proportional to the square of the radius of the excitonic wave function extension. The biexciton complexes in rings have wider in-plane extension of wave functions. This is different from the case of QDs [3-5], where the extension of the biexciton wave function is smaller than or equal to that of the exciton due to the electron-hole Coulomb attractive force. This striking result in QRs tells us that the Coulomb interactions inside the biexciton complex are much more complicated than that in QDs, where the electrons and holes are strongly confined in the center of QDs. We built up a three-dimensional finite element model based on Hartree approximation. The calculation result agrees reasonably well with our experimental finding. This theoretical study will be published elsewhere.

In brief, single quantum ring spectroscopy was studied. The exciton and the biexciton emission lines were assigned by power-dependent PL. The biexciton emission showed twice larger diamagnetic coefficient than the exciton, implying wider extension of wave functions for the biexciton complexes. The results indicate the novel magneto-optical responses of QRs.

This work was financially supported by the National Science Council under Contract Nos. NSC97-2120-M-009-002, NSC97-2120-M-009-004, and National Nano Device Laboratories.

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Figures:

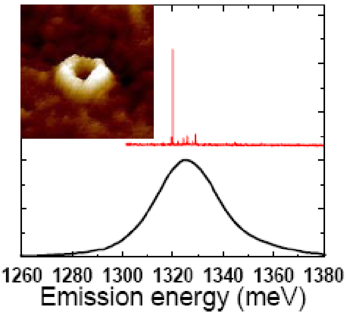

Fig. 1. PL spectra from conventional PL and μ-PL. The inset is the AFM image of the surface QR.

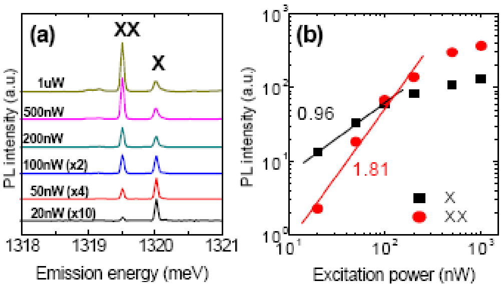

Fig. 2. (a) Power dependent PL spectra of single QR. (b) The integrated intensity versus the excitation power. The straight lines are the fitting results. The slope equals to 0.96 for the exciton (X, square) and 1.81 for the biexcitron (XX, circle)

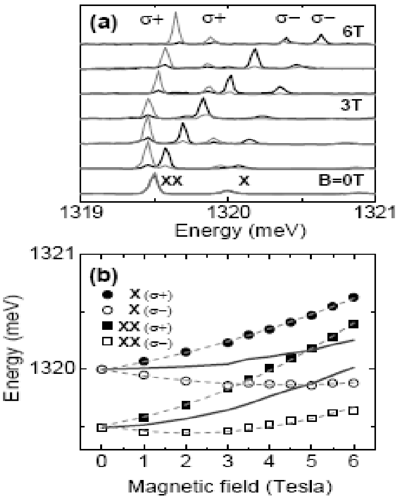

Fig. 3. (a) Magneto-optical spectra of the exciton and the biexciton emissions. (b) Peak positions as a function of the magnetic field. The diamagnetic coefficient of the exciton (biexcition) is 7.1 (14.6) $\mu eV/T^2$.