Optical Lattices Achieved by Excitons in Periodic Quantum Well Structures

M. Hübner, J. P. Prineas, C. Ell, P. Brick, E. S. Lee, G. Khitrova, H. M. Gibbs, and S. W. Koch*
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721
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Photoluminescence and linear optical response from large-number multiple quantum well structures, with a period in the vicinity of half the exciton resonance wavelength, are dominated by the normal modes of the coupled wells. These show up in multiple linesplitting and a photonic band gap at Bragg resonance. The photonic gap is identified by an enhanced Bragg reflection and a corresponding weak absorption of the optical lattice. The strongly modified light-matter interaction for photons in the photonic gap is also manifest in the *poor* emission from the so-called super-radiant mode after excitation in the free carrier continuum.

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Since the fundamental work by Purcell [1] there has been continuous effort in tailoring the light-matter interaction [2,3]. The most prominent system is an absorber placed at the antinodes of a high finesse cavity, where the well-known "vacuum Rabi splitting" of the normal modes has been observed for atomic [4] and semiconductor [5,6] systems.

Comparable modifications of the light-matter interaction can be achieved by a periodic arrangement of planes of resonant two level atoms in a one-dimensional (1D) optical lattice with a period close to an integer value of half the resonance wavelength [7,8]. There has been continuous progress over the past years in arranging ultracold atoms in periodic light shift potentials to form 1D optical lattices, where the planes of the lattices consist of atoms. Once the specular reflectivity per plane becomes important over the diffusive scattering loss, multiple reflections and interference should make phenomena such as photonic band gaps and photon localization possible [7].

Here, we want to introduce excitons confined in semiconductor quantum wells (QW's) of a periodic quantum well (PQW) structure as a model system for 1D optical lattices. Thus far, several theoretical and experimental studies [9–14] have demonstrated the influence of radiative interwell coupling on the resonant optical response from multiple quantum well structures, especially in the time domain and for a low number of QW's. Coherent optical experiments demonstrate the existence of subradiant exciton modes besides a super-radiant mode in the vicinity of the Bragg resonance. Until now, the predicted splitting of the modes and other signatures of radiative interwell coupling have never been observed in photoluminescence (PL) following excitation in the free carrier continuum.

In this Letter, we present experimental results from PQW structures with a large number N of QW's. The PL shows large radiative mode splitting up to 3.2 meV and a strong dependence of the emission amplitude on the period d. Until now, it has not been clear whether radiative interwell coupling should be observable at all in PL following "incoherent" excitation in the continuum. Surprisingly, the so-called "super-radiant" mode at Bragg resonance has a strongly suppressed emission intensity. This will be explained with our reflection measurements. They show the buildup of the photonic band gap with an increasing number of coupled QW's at Bragg resonance. We further verify experimentally the predicted linear dependence on N of the radiative broadening Γ_0 in Bragg resonance and extract a value of $\Gamma_0 = 27\ \mu$eV half width at half maximum (HWHM) for the single QW (SQW) exciton resonance.

We grew samples with $N = 1$, 10, 30, 60, and 100 under the same molecular beam epitaxy conditions, each containing 8.5-nm thick $In_{0.04}Ga_{0.96}As$ QW's between GaAs barriers. The use of low-In-concentration QW's ensures that the background refractive indices of the well and barrier are nearly identical, thereby eliminating the photonic band gap arising from a distributed-Bragg-mirror-like reflectivity peak [15]. Use of semi-insulating GaAs substrates allows transmission experiments without substrate removal. The drop off of flux with increased radius during growth on a rotating substrate changes the d by 30% to 40% along a radius of the wafer, providing an experimental way to continuously scan d to study normal-mode effects on a single sample.

All samples were antireflection (AR) coated on the front and back of the sample in order to isolate the QW response, i.e., to remove feedback between the vacuum-GaAs interface and the QW structure, which can influence the radiative width [16]. For the cw linear measurements the samples were held at 8 K in a closed cycle helium cryostat. Probe light from a light-emitting diode was monochromatized to a bandpass of 0.035 nm and focused to a 50 μm diameter spot on the sample with an intensity of less than 10^{-5} W/cm^2, i.e., exciting vanishing carrier density. The probe was detected with a photomultiplier using lock-in amplifier techniques.

For pulsed PL excitation studies, the samples were mounted in an open cycle helium cryostat and kept at 4.2 K. All experiments were performed with linearly polarized light from an actively mode-locked Ti:sapphire laser providing picosecond pulses with a spectral width of 1.5 nm. The samples were excited in the free carrier continuum of the QW's slightly above the light-hole exciton at 819 or 827 nm with an average power of 50 μW and a spot diameter of 50 μm. The excitation beam had an external angle of 10° with respect to the normal of the sample surface and, except for the angular dependent measurements, we detected the emission through the substrate in the normal direction with an optical multichannel analyzer detector behind a spectrograph.

The linear optical properties of PQW structures can be well described by a linear dispersion theory (LDT) using a transfer-matrix method [8,10,11,17]. With an excitonic susceptibility determined by a nonradiative broadening γ, the reflectivity of N PQW's at exact Bragg resonance ($d = \lambda_{hh}/2$) is given by [10]

$$R = \frac{(N\Gamma_0)^2}{(\hbar\omega - E_{1s})^2 + (\gamma + N\Gamma_0)^2},$$

where Γ_0 is the radiative HWHM broadening of a SQW and E_{1s} is the resonance energy of the $1s$ heavy-hole (hh) exciton. In a bulk semiconductor, because of its translational invariance leading to total momentum conservation, the light-exciton interaction gives rise to stationary polariton states and to a splitting of the eigenmodes [18]. However, in a QW the translational invariance is broken in the growth direction. Only the in-plane momentum is conserved, and the interaction of the exciton with the continuum of photon modes leads to radiative decay of the exciton in the normal direction. Since the above formula is also valid when $N = 1$, the radiative linewidth of a PQW structure becomes N times broader than the SQW radiative linewidth for perfect coupling. For $d = \lambda_{hh}/2$, the multiple reflections from all N QW's add constructively to give the strong reflectivity and super-radiant broadening of N coupled oscillators. This radiative broadening completely dominates the nonradiative inhomogeneous broadening of 0.56 meV [17] for a large number of QW's. Figure 1(a) shows the measured reflectivity of PQW structures at Bragg resonance for $N = 1, 3, 10, 30, 60$, and 100. The extracted HWHM of the spectra is plotted versus N in Fig. 1(b). For the first time, the linear dependence of the radiative broadening on N predicted by $\Gamma = \gamma + N\Gamma_0$ (valid for AR coated samples [10]) is fairly well verified by the experimental results in Fig. 1(b). The slope of the linear fit in Fig. 1(b) gives a value of $\Gamma_0 = 27$ μeV HWHM, in good agreement with quantum mechanical estimates [19,20].

The spectra in Fig. 1(a) demonstrate the increasing Bragg reflection with the number N of excitonic planes in the optical lattice. Such large effects have not been seen with atoms, because it is very difficult to achieve the 10% single-pass SQW absorption and the confinement/period ratio (here 8 nm/115 nm = 7%) of our PQW's. LDT calculations [17] show that the linear dependence on N starts to saturate for $N \sim 200$ [see dashed line in Fig. 1(a)]. The spectral reflectivity evolves toward the typical stop band characteristic known from distributed Bragg reflectors built of dielectric layers as shown in [8].

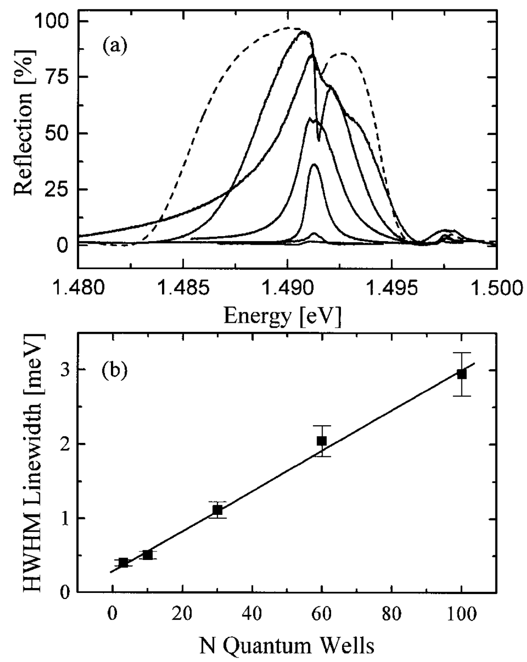

FIG. 1. (a) Measured linear reflectivity spectra at Bragg resonance for the 1, 3, 10, 30, 60, and 100 PQW samples (straight lines). Calculated reflectivity spectrum for a 200 PQW sample (dashed line) [21]. (b) PQW reflectivity FWHM linewidths versus the number of QW's.

A complementary behavior to the reflectivity is found in the emission from PQW structures. Figure 2 shows PL spectra of the vertical emission for PQW structures with $N = 30$, 60, and 100 QW's. Spectra are taken from different positions on the samples corresponding to different periods as labeled in Fig. 2. The results in Fig. 2 show obviously that the PL spectra of PQW structures

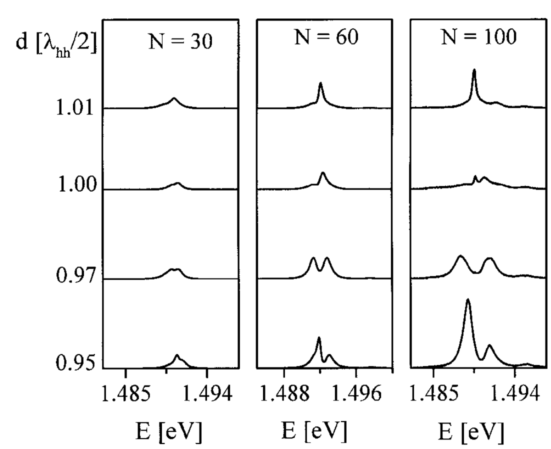

FIG. 2. Time-integrated PL spectra emitted normal to the samples following continuum excitation for the 30, 60, and 100 PQW samples.

with $N \geq 30$ cannot be explained by the radiatively uncoupled incoherent emission of N individual QW's. While for $N = 30$ a close look is still necessary to identify the presence of period-dependent changes in the PL spectra, radiative exciton coupling shows up as large radiative mode splitting, and shifting of the system resonance depending on d for $N = 60$ and 100. The radiative mode splitting for $N = 100$ at $d = 0.98\lambda_{hh}/2$ is 3.2 meV, i.e., much more than the underlying uncoupled inhomogeneous HWHM exciton linewidth in our samples.

The most striking feature of the PL from the PQW structures becomes evident by comparing the PL spectra for all N's at Bragg resonance with the reflectivity spectra in Fig. 1(a). The so-called super-radiant mode is indeed a very *poor* emitter. As surprising as this may be, it is consistent with the reflection data. Ivchenko [10], and later Deutsch [8], pointed out that at Bragg resonance the electromagnetic field adjusts itself in such a way that the QW planes are located in the field nodes. This is forced by the QW refractive index, and this is completely different from the case of a microcavity, where the mirrors determine the field intensity pattern and a QW can be placed anywhere within the standing wave. Here, the poor QW-field overlap results in weak luminescence, analogous to inhibited spontaneous emission of QW's grown in the field nodes of a microcavity.

Note, only the broad, weak background of the spectra at $d = \lambda_{hh}/2$ originates from the super-radiant mode while the remaining small and narrow peaks on top of it can be attributed to a residual coupling of the first subradiant modes to the lightfield. This residual coupling is not allowed in perfect structures with symmetric isolated resonances in the single wells, but it becomes possible if sample disorder (inhomogeneous broadening) or the coupling to higher exciton continuum states is relevant.

Now we want to show that the multiple peaks in PL in Fig. 2 are direct evidence for the eigenmodes of the radiatively coupled structure. Our mode analysis is based on the transfer-matrix approach. As pointed out by Andreani [11], the eigenmodes of the self-consistently coupled light-matter system are given by the N complex roots of the denominator of the transmission coefficient T. The real part of each root determines the eigenenergy [Fig. 3(c)], while the imaginary part gives the radiative broadening [Fig. 3(d)]. At Bragg resonance, all the modes are degenerate, and only the super-radiant mode [dashed line in Figs. 3(c) and 3(d)] couples to the light with a N-times enhanced radiative decay. At periods $d \neq \lambda_{hh}/2$, the remaining N-1 modes split out first with very small (subradiant) radiative broadening. Comparing the 3D-contour plot of the period-dependent PL spectra in Fig. 3(a) with the modes in Fig. 3(c) shows that the measured PL dependence on d resembles quite obviously some of the main features of the mode dispersion in d. And so does the true absorption $A = 1 - R - T$, see Fig. 3(b). Note that, in Fig. 3, a different sample with

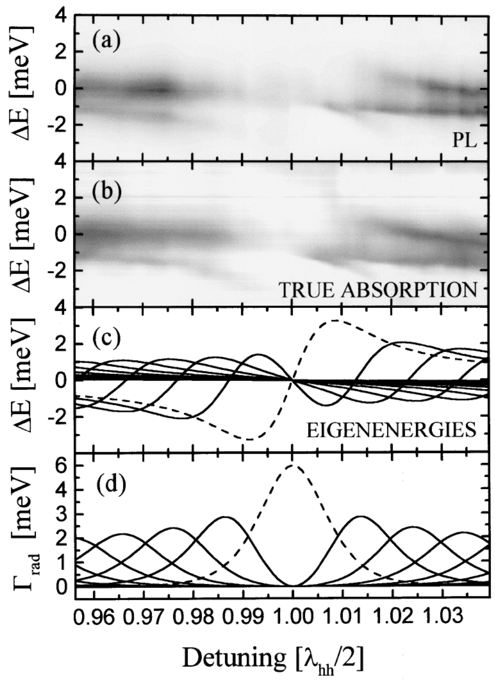

FIG. 3. (a) Measured PL intensity following continuum excitation, and (b) measured true absorption for a 100 PQW sample. (c) Computed energies and (d) radiative broadening of the various eigenmodes with $\Gamma_0 = 27\ \mu$eV.

a slightly smaller mode splitting has been used than in Fig. 2. The lack of emission around Bragg resonance as well as the low absorption can be attributed to the super-radiant mode in Fig. 3(c) (dashed line). On the other hand, a pronounced, peaked emission is observed for already small positive detuning to $d \geq \lambda_{hh}/2$ which can be attributed to the accumulation of subradiant modes at this position. For larger detuning, the PL is always double peaked and coincides with the accumulation of the modes at the two main branches below and above $E_{1s,hh}$ in Fig. 3(c). The splitting in the vicinity of Bragg resonance increases with N (see Fig. 2). Away from Bragg resonance it decreases to its minimum value at $d = \lambda_{hh}/4$ approaching the longitudinal-transfer splitting [11] of bulk in the limit of large N.

Thus far, we have described only the emission in the normal direction. In SQW structures, the occupation of exciton states with finite in-plane momentum due to thermalization results in the emission into different directions given by $\cos(\alpha) = [1 - (k_x/k_0)^2]^{1/2}$, where k_x is the center-of-mass momentum, and k_0 is the photon momentum. To understand the angular dispersion of the coupled modes, depending on the amount of in-plane momentum, consider the relation $d = d_0 \cos(\alpha)$, describing the effective period of the structure into a direction with angle α relative to the growth direction. This means in first approximation that an increase of k_x corresponds to effectively tuning the structure towards smaller periods d, when the period at $\alpha = 0$ is d_0.

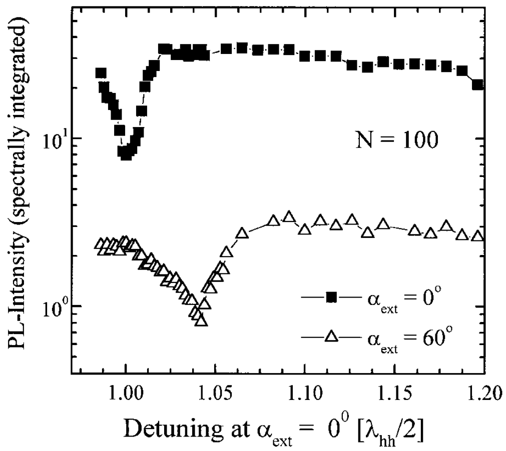

FIG. 4. Spectrally integrated PL intensity as a function of the PQW period d for $\alpha_{\text{ext}} = 0°$ and 60°.

This behavior is observed in angular dependence PL experiments, which have been performed on the $N = 60$ and 100 structures. We find that for detection with increasing α the whole mode pattern dependence upon $d(x)$ simply shifts to positions with larger periods. For the $N = 100$ structure, the experimental results for the time and spectrally integrated PL emitted in the vertical direction and $\alpha_{\text{extern}} = 60°$, respectively, are shown in Fig. 4. It is obvious that the minimum emission at Bragg resonance shifts for $\alpha = 60°$ to larger $d(x)$ at a position where the normal emission almost has a maximum, demonstrating a rather directional emission for the system.

In conclusion, we have demonstrated that, for large numbers of QW's in PQW structures, normal mode coupling polaritonic effects completely alter not only the reflectivity spectra but also the photoluminescence following off-resonant continuum excitation. Clearly, using sufficiently dense sheets of atoms in a one-dimensional optical lattice must give similar results.

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*Permanent address: Physics Department and Material Sciences Center, Philipps-University, 35032 Marburg, Germany.

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[21] The dashed line of Fig. 1(a) shows two kinds of asymmetries. The smaller half-width on the high-energy side stems from the higher excitonic *s* states. The lower reflectivity is a consequence of the slightly asymmetric absorption line of a SQW exhibiting higher absorption on its high-energy tail due to disorder [17].