Cavity Polaritons in InGaN Microcavities at Room Temperature

T. Tawara,* H. Gotoh, T. Akasaka, N. Kobayashi,† and T. Saitoh‡
NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa, 243-0198, Japan
(Received 5 November 2003; published 25 June 2004)

Cavity polaritons are observed in InGaN quantum well (QW) microcavities at room temperature. High-quality microcavities are fabricated by the wafer-bonding of InGaN QW layers and dielectric distributed Bragg reflectors. The anticrossing behavior of strong exciton-photon coupling is confirmed by vacuum-field Rabi splitting obtained from reflection measurements. This strong coupling is also enhanced by increasing the integrated oscillator strength coupled to the cavity mode. The oscillator strength of InGaN QW excitons is 1 order of magnitude larger than that of GaAs QW excitons.

DOI: 10.1103/PhysRevLett.92.256402 PACS numbers: 71.36.+c, 42.50.–p, 42.55.Sa, 81.05.Je

For the last decade, strong exciton-photon coupling in vertical semiconductor microcavities has been energetically studied with a view to control the properties of both photons and excitons [1–11]. When the exciton state is strongly coupled to the cavity-photon mode, quasiparticles called cavity polaritons are produced with an anticrossing dispersion relation. In recent years, much attention has been directed to the behavior of these cavity polaritons as bosonic particles in the strong coupling regime. One area of interest relates to the Bose-Einstein condensation (BEC) of cavity polaritons [4–11]. These polaritons will condense to their final state with a gain as a result of certain scattering processes, and then coherent light will be emitted from the polaritons in that state. The BEC of the polaritons is expected to yield new scientific fields, such as the coherent manipulation of bosons in a solid state [9], and be applied to a new generation of devices, such as polariton lasers without threshold or population inversion [10,11].

Experimental trials on the BEC of polaritons have already been undertaken using semiconductor microcavities based on CdTe [5] or GaAs [6]. In contrast, it is well known that the excitons in GaN-based semiconductors have a larger oscillator strength [12], faster relaxation rate [13], and larger binding energy than those in GaAs- and CdTe-based semiconductors. In GaN-based microcavities, therefore, we can expect very strong exciton-photon coupling that will achieve the BEC of the polaritons beyond room temperature [10,11]. Several research groups have tried to fabricate GaN-based microcavity structures with monolithically grown GaN/AlGaN distributed Bragg reflectors (DBRs) [14–17]. However, these studies have examined the weak coupling regime, i.e., a conventional lasing regime with population inversion. This may be because the control of the photon and exciton characteristics is insufficient to allow us to reach the strong coupling regime due to surface roughening and cracks that penetrate the whole cavity. These faults are induced by the mismatch between the lattice and the thermal expansion coefficient in monolithically grown GaN/AlGaN DBRs. Very recently, Antonie-Vincent *et al.* observed polaritons in bulk-GaN microcavities without monolithically grown DBRs , but this was still restricted to a low temperature of 5 K [18]. If we are to discuss BEC or the lasing of polaritons in GaN-based microcavities, we must first achieve strong coupling at room temperature by using high-quality microcavities.

In this Letter, we report the observation of cavity polaritons in high-quality InGaN microcavities by reflection measurements. We fabricated the microcavities, which consisted of InGaN quantum well (QW) layers and dielectric DBRs, using the wafer-bonding technique. We observed the anticrossing behavior of strong exciton-photon coupling with a vacuum-field Rabi splitting of 6 meV at room temperature. Moreover, this strong coupling is also enhanced with a Rabi splitting of 17 meV by increasing the integrated oscillator strength coupled to the cavity mode. The estimated oscillator strength of the InGaN QW excitons is 1 order of magnitude larger than that of the GaAs QW excitons.

We used smooth and crack-free GaN-based microcavities to realize a strong coupling regime at room temperature. The microcavities were fabricated using a wafer-bonding technique with a GaN-based QW layer and dielectric DBRs. Figure 1 is a schematic diagram of the fabricated GaN-based microcavities. The 4λ-thick InGaN/AlGaN QW layers were grown directly on n-type 6H-SiC substrates by metalorganic vapor phase epitaxy. The QW consisted of three or ten 5-nm-thick $In_{0.02}Ga_{0.98}N$ barriers and 2.5-nm-thick $In_{0.15}Ga_{0.85}N$ active layers with an $Al_{0.07}Ga_{0.93}N$ buffer layer. The QWs were placed at the antinode position of the resonant optical wave in the cavity. We removed the SiC substrate from the InGaN QW layer with a conventional dry etching technique. We used an optical microscope and a three-dimensional scanning electron microscope to confirm that the QW layers were crack-free and that the surface roughness was less than 1 nm. After removing the SiC substrate, the QW layer was sandwiched between two SiO_2/ZrO_2 DBRs deposited on sapphire substrates using a wafer-bonding technique. Low-threshold lasing by optical pumping has been achieved in such microcavities,

 © 2004 The American Physical Society

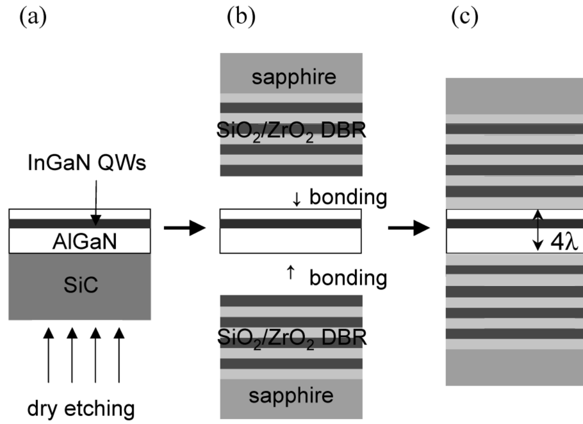

FIG. 1. Schematic diagram of the fabricated InGaN microcavity with dielectric DBRs. (a) The SiC substrate is removed from the InGaN QW layer with a conventional dry etching technique. (b) The InGaN QW layer is sandwiched between two SiO_2/ZrO_2 DBRs deposited on sapphire substrates with a wafer-bonding technique. (c) A smooth and crack-free microcavity is formed.

which act as a vertical-cavity surface-emitting laser [19]. This is direct proof of the existence of high-quality cavities.

We measured the reflection spectra of the fabricated empty cavities at room temperature as shown in Fig. 2. We used a Xe lamp focused with an objective lens as the optical light source, and we limited its effective spot size on the sample surface to about 20 μm by using a pinhole. The light was incident normally on the sample surface. The GaN-based cavities were formed in a wedgelike shape where the energy of the cavity mode varied spatially at a rate of 0.2 meV/μm. The spectra in Fig. 2 were probed at intervals of 200 μm along the sample surface. It can be clearly seen that the cavity resonance position can be controlled linearly. We achieved a cavity quality factor (Q) as high as 400 in this cavity, and this value corresponds to a linewidth (γ_{ph}) of 7 meV.

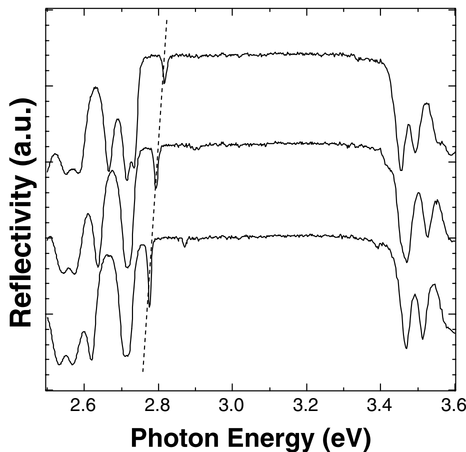

FIG. 2. Reflection spectra of the fabricated cavity in the nonresonant region measured at various positions at room temperature. The dashed line is a guide for the eye. The detuning range in this cavity is 0.2 meV/μm.

Figure 3(a) shows the reflection spectra of the QW microcavities for various degrees of cavity detuning. We observed the appearance and disappearance of splitting at positions around 2.807 eV (dotted line) and these positions varied with the cavity detuning energy $\delta = E_{ph} - E_{ex}$, where E_{ph} is the cavity mode energy and E_{ex} is the InGaN exciton energy. In this case, E_{ex} was assumed to be 2.807 eV. These dip position energies are shown as a function of δ in Fig. 3(b). The anticrossing behavior of the cavity polaritons is clearly shown with a vacuum-field Rabi splitting Ω of 6 meV by the cavity detuning in this figure. The Rabi splitting value reflects the strength of the exciton-photon coupling.

Here we consider the relationship between exciton density and the Rabi splitting value. Ω is given by the relation

$$\Omega = 2\hbar\sqrt{g(f)^2 - \left(\frac{\gamma_{ex} - \gamma_{ph}}{4}\right)^2}, \tag{1}$$

where γ_{ex} (γ_{ph}) is the exciton (photon) linewidth, and $g(f)$ is a coupling factor whose square root is proportional to the exciton oscillator strength f. This coupling factor is given by [20]

$$g(f) = \left[\frac{2\pi}{\varepsilon_r}\frac{1}{4\pi\varepsilon_0}\frac{e^2 N f}{m L_{\rm eff}}\right]^{1/2}, \tag{2}$$

where ε_r, ε_0 is the relative (vacuum) permittivity, $e(m)$ is the electron charge (mass), N is the oscillator density coupled to the cavity mode, and $L_{\rm eff}$ is the effective cavity length. If the linewidth contrast can be assumed to be$\gamma_{ex} - \gamma_{ph} \sim 0$, the coupling factor and Rabi splitting value should be multiplied by a factor $(N)^{1/2}$ as shown in Eqs. (1) and (2). Therefore, we can expect the exciton-photon coupling to be enhanced by the increase in the integrated oscillator strength coupled to the cavity mode.

Figure 4 shows the reflection spectra of microcavities with different numbers of QWs at $\delta = 0$. The Rabi splitting in the 10 QW microcavity increases to 17 meV from a value of 6 meV in the 3 QW microcavity. The solid curves in Fig. 4 are theoretical dispersion curves for the polaritons calculated from the multiple-interference analysis of the DBR Fabry-Pérot interferometer using a transfer matrix for optical propagation. The measured linewidth of the cavity mode γ_{ph} was 7 meV for 3 QW microcavities and 12 meV for 10 QW microcavities. The fitting parameters in this calculation are the Lorentzian homogeneous linewidth of the InGaN exciton γ_{ex} and the peak absorption coefficient α. From the fit with $\alpha = 4 \times 10^5$ cm^{-1} and $\gamma_{ex} = 15$ meV, the theoretical curves well reproduce the experimental result. The α value of 4×10^5 cm^{-1} is of the same order of magnitude as that of the GaN QW excitons [21]. Employing these parameters, we can

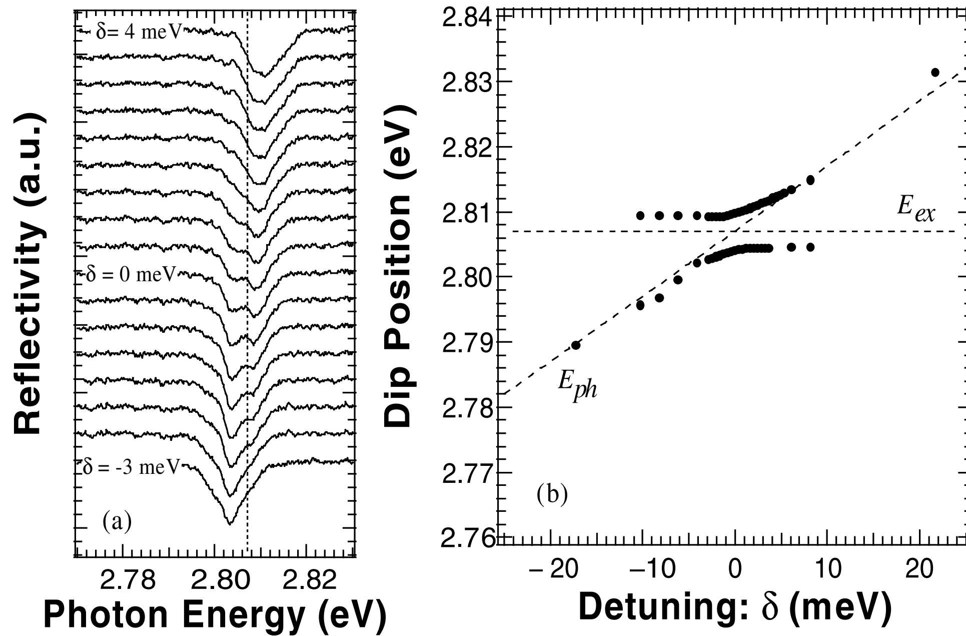

FIG. 3. Reflection spectra of InGaN QW microcavities measured at room temperature for various degrees of cavity detuning $\delta = E_{\mathrm{ph}} - E_{\mathrm{ex}}$. (a) A series of reflection spectra from $\delta = -3$ meV to 4 meV. E_{ex} (dotted line) was assumed to be 2.807 eV. (b) The dip positions in (a) plotted as a function of the detuning energy δ. The dashed lines show E_{ph} and E_{ex}.

deduce an Nf of 2.0×10^{13} cm^{-2} per QW. For reference, the Nf of the GaAs QW microcavities was reported to be 4.8×10^{12} cm^{-2} per QW [22]. The oscillator strength of InGaN QW excitons is 1 order of magnitude larger than that of GaAs QW excitons.

Our InGaN QW has also a photoluminescence linewidth, i.e., the sum total of homogeneous and inhomogeneous linewidth, of about 200 meV in the as-grown samples. With an InGaN QW, it is well known that the

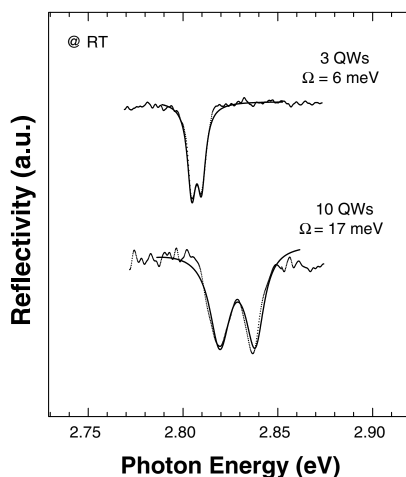

FIG. 4. The reflection spectra of the microcavities with 3 QWs (upper) and 10 QWs (lower) at $\delta = 0$. The solid curves show the theoretical calculations with fitting parameters of $\alpha = 4 \times 10^5$ cm^{-1} and $\gamma_{\mathrm{ex}} = 15$ meV.

In composition fluctuates in the QW plane. The light emission from the InGaN QW originates from the localized excitons in the Inrich regions and this leads to inhomogeneous spectral broadening [23–25]. When the localized excitons in an InGaN QW have discrete energy states such as quantum dots, only those excitons whose energy matches the cavity resonant energy are picked out by the cavity filter effect. Of these localized excitons, only those whose energies are resonant with the cavity mode contribute Rabi splitting. The amount of Rabi splitting is determined by the homogeneous linewidth at the exciton energy [26]. This is generally disadvantageous in regards to strong coupling compared with the situation in a homogeneous QW where all excitons can couple to the cavity mode. In our InGaN QW microcavities, however, the localized excitons with large oscillator strengths at certain discrete energy levels enabled us to observe the Rabi splitting.

We observed cavity polaritons in InGaN microcavities at room temperature. We obtained crack-free microcavities without surface roughening and with a high Q factor by using the wafer-bonding technique. Reflection measurements confirmed the anticrossing behavior of the cavity polaritons with a vacuum-field Rabi splitting of 6 meV. The enhancement of this coupling was also observed with a Rabi splitting of 17 meV by increasing the integrated oscillator strength coupled to the cavity mode. The oscillator strength of the InGaN QW excitons was estimated to be 2.0×10^{13} cm^{-2} per QW, which is 1 order of magnitude larger than that of GaAs QW excitons. The

above results are a first step toward the realization of the BEC of the polariton and its stimulated emission at room temperature.

The authors are grateful to Dr. Toshiki Makimoto, Dr. Yoshiro Hirayama, Dr. Takaaki Mukai, Dr. Hideaki Takayanagi, and Dr. Sunao Ishihara for their encouragement throughout the course of this work.

---

*Email address: tawara@nttbrl.jp
†Present address: Department of Applied Physics and Chemistry, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo, 182-8585, Japan.
‡Present address: Faculty of Engineering, Kansai University, 3-3-35 Yamate-cho, Suita, Osaka, 564-8680, Japan.

[1] C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. **69**, 3314 (1992).
[2] R. Houdré, R. P. Stanley, U. Oesterle, M. Ilegems, and C. Weisbuch, Phys. Rev. B **49**, 16 761 (1994).
[3] V. Savona, L. C. Andreani, P. Schwendimann, and A. Quattropani, Solid State Commun. **93**, 733 (1995).
[4] A. Imamoglu, R. J. Ram, S. Pau, and Y. Yamamoto, Phys. Rev. A **53**, 4250 (1996).
[5] Le Si Dang, D. Heger, R. André, F. Boeuf, and R. Romestain, Phys. Rev. Lett. **81**, 3920 (1998).
[6] P. Senellart and J. Bloch, Phys. Rev. Lett. **82**, 1233 (1999).
[7] M. Saba, C. Ciuti, J. Bloch, V. Thierry-Mieg, R. André, Le Si Dang, S. Kundermann, A. Mura, G. Bongiovanni, J. L. Staehli, and B. Deveaud, Nature (London) **414**, 731 (2001).
[8] H. Deng, G. Weihs, C. Santori, J. Bloch, and Y. Yamamoto, Science **298**, 199 (2002).
[9] D. Snoke, Science **298**, 1368 (2002).
[10] A. Kavokin, G. Malpuech, and B. Gil, MRS Internet J. Nitride Semicond. Res. **8**, 3 (2003).
[11] G. Malpuech, A. D. Carlo, A. Kavokin, J. J. Baumberg, M. Zamfirescu, and P. Lugli, Appl. Phys. Lett. **81**, 412 (2002).
[12] A. Hoffmann, Mater. Sci. Eng. B **43**, 185 (1997).
[13] Ü. Özgür, M. J. Bergmann, H. C. Casey, Jr., H. O. Everitt, A. C. Abare, S. Keller, and S. P. DenBaars, Appl. Phys. Lett. **77**, 109 (2000).
[14] J. M. Redwing, D. A. S. Loeber, N. G. Anderson, M. A. Tischler, and J. S. Flynn, Appl. Phys. Lett. **69**, 1 (1996).
[15] I. L. Krestnikov, W. V. Lundin, A. V. Sakharov, V. A. Semenov, A. S. Usikov, A. F. Tsatsul'nikov, Zh. I. Alferov, N. N. Ledentsov, A. Hoffmann, and D. Bimberg, Appl. Phys. Lett. **75**, 1192 (1999).
[16] H. Zhou, M. Diagne, E. Makarona, A. V. Nurmikko, J. Han, K. E. Waldrip, and J. J. Figiel, Electron. Lett. **36**, 1777 (2000).
[17] T. Someya, R. Werner, A. Forchel, M. Catalano, R. Cingolani, and Y. Arakawa, Science **285**, 1905 (1999).
[18] N. Antoine-Vincent, F. Natali, D. Byrne, A. Vasson, P. Disseix, J. Leymarie, M. Leroux, F. Semond, and J. Massies, Phys. Rev. B **68**, 153313 (2003).
[19] T. Tawara, H. Gotoh, T. Akasaka, N. Kobayashi, and T. Saitoh, Appl. Phys. Lett. **83**, 830 (2003).
[20] L. C. Andreani, G. Panzarini, and J. M. Gerard, Phys. Rev. B **60**, 13 276 (1999).
[21] A. J. Fischer, W. Shan, J. J. Song, Y. C. Chang, R. Horning, and B. Goldenberg, Appl. Phys. Lett. **71**, 1981 (1997).
[22] R. Houdré, C. Weisbuch, R. P. Stanley, U. Oesterle, P. Pellandini, and M. Ilegems, Phys. Rev. Lett. **73**, 2043 (1994).
[23] Y. Narukawa, Y. Kawakami, S. Fujita, S. Fujita, and S. Nakamura, Phys. Rev. B **55**, R1938 (1997).
[24] Y. Narukawa, Y. Kawakami, S. Fujita, and S. Nakamura, Phys. Rev. B **59**, 10 283 (1999).
[25] S. F. Chichibu, T. Azuhata, T. Sota, T. Mukai, and S. Nakamura, J. Appl. Phys. **88**, 5153 (2000).
[26] R. Houdré, R. P. Stanley, and M. Ilegems, Phys. Rev. A **53**, 2711 (1996).