Q-factor dependence of angle-resolved transmission spectra in CuCl microcavities

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We have investigated the angle-resolved transmission spectra of the CuCl \( \lambda \)- and \( \lambda/2 \)-microcavities composed of cavity layers sandwiched by distributed Bragg reflectors (DBRs) with various numbers of periods of the DBR layer which affect the degree of confinement of the photons in the microcavity, so-called quality factors (\( Q \) factors). The angle-resolved transmission spectra of the CuCl microcavities drastically change with the \( Q \) factor and the thickness of the cavity layer. The incident angle dependence of the peak energies obtained from the angle-resolved transmission spectra indicates that the cavity polariton modes are observed in the CuCl microcavities, except for the \( \lambda \)-microcavity with 2 periods of the DBR layer. The change of the angle-resolved transmission spectra in the microcavities will result from the difference in the coupling state between the excitons and photons in the microcavities.

1. Introduction
A microcavity which is composed of a cavity layer sandwiched by mirrors with high reflectivity has a property to confine photons in a cavity layer [1]. In a semiconductor microcavity which includes a semiconductor layer in a cavity layer, cavity polaritons are generated in the microcavity when excitons and photons in a cavity layer will strongly interact with each other [2-4]. When the degree of confinement of photons in the microcavities which is referred to as the quality factor (\( Q \) factor) is changed, it is expected that the coupling state between photons and excitons in the semiconductor microcavities will be modified, and then the transmission and reflection spectra of the microcavities will dramatically change with the \( Q \) factor.

In this study, we have investigated the angle-resolved transmission (ART) spectra of the CuCl microcavities that consists of the cavity layers with the thickness of \( \lambda \) (\( \lambda/2 \)) and the distributed Bragg reflectors (DBRs) with various numbers of periods of the DBR layer. Here, we have confirmed that the \( Q \) factor of the CuCl microcavities depends on the number of periods of the DBR layer. It is found that the ART spectra of the microcavities change with the \( Q \) factor and the thickness of the cavity layer. We discuss the change of the ART spectra observed in the microcavities from the viewpoint of the coupling state between the excitons and cavity photons.

2. Experimental Methods
The schematic structure of the fabricated CuCl microcavity is shown in figure 1. The CuCl \( \lambda \)- and \( \lambda/2 \)-microcavities were fabricated on (0001)-Al\( _2 \)O\( _3 \) substrates by using a vacuum deposition method. The cavity layers in the fabricated microcavities are sandwiched between two DBRs. Here, \( \lambda \) is given by \( \lambda_{ex}/n_b \), in which \( \lambda_{ex} \) is the resonant wavelength of the \( Z_3 \) exciton of CuCl and \( n_b \) is the background
The spectral resolution \( \Delta \lambda_{\text{background}} = \lambda_{\text{incident}} + \lambda_{\text{cavity mode}} + \lambda_{\text{exciton}} \times F_{\text{background}} \). Here, \( F_{\text{background}} \) is noted that the following equation is represented by the superposition of Fano functions [5],

\[
T(E) = \sum_{n=1}^{3} F_n(E) + \text{Background} , \quad F_n(E) = A_n \times \left( \frac{E-E_{\text{peak}}}{\gamma_n/2} + q_n \right) + 1.
\]

Here, \( A_n, E_{\text{peak}}, \) and \( \gamma_n \) are the amplitude, the peak energy, and the full width at half maximum (FWHM), respectively. \( q_n \) is asymmetric parameter, so-called Fano parameter. The red solid curves in figure 2 indicate the fitted curves, which are in good agreement with experimental results. The peak energies

**Figure 1.** (a) Schematic structure of the fabricated CuCl microcavity. (b) Schematic diagrams of the spatial distributions of the electric field of the cavity photon (orange curve) and the wave function of the exciton (green curve) in the cavity layers of the CuCl \( \lambda \)- and \( \lambda/2 \)-microcavities.

Refractive index of CuCl [2, 3]. In the CuCl \( \lambda \) \( \lambda/2 \)-microcavities, the cavity layer with the thickness of \( \lambda \) \( \lambda/2 \) consisted of a CuCl active layer with thickness of \( \lambda/8 \) sandwiched by AlF\(_3\) spacer layers. The constituent layers of the DBRs were composed of PbCl\(_2\) and AlF\(_3\) with a layer thickness of \( \lambda/4 \), where the thickness of one period of the DBR was \( \lambda/2 \). The \( Q \) factor of the microcavity, which was represented by the ratio of the peak energy to the spectral width of the cavity photon mode, was controlled by changing the number of periods of the DBR [2-4]. The \( Q \) factors of the fabricated microcavities obtained by measuring the cavity photon modes at room temperature are described as annotations in figure 2. The ART spectra were observed at 10 K using a 32-cm single monochromator combined with a charge-coupled device camera and a Xe lamp as the probe light source. The spectral resolution and the angle resolution were approximately 0.4 nm and 2 degree, respectively.

### 3. Experimental results and Discussion

The ART spectra observed in the \( \lambda \)-microcavities with 2, 3 and 5 periods of the DBR layer, and those in the \( \lambda/2 \)-microcavities with 2, 3 and 5 periods are shown in figure 2. In the \( \lambda \)-microcavities with 3 and 5 periods, three peaks are clearly observed. The three peaks are attributed to be the cavity polariton modes, because the peak energies of these peaks depend on the incident angle \( \theta \), which corresponds to the dispersion relation of the cavity polaritons [2-4]. Moreover, the spectral profiles of these peaks change between the symmetric and asymmetric structures with the increase of the incident angle. On the other hand, in the \( \lambda \)-microcavity with 2 periods, two dips near the exciton energies appear on the broad peak of which the peak energy changes with the incident angle. The changes of the spectral profiles between the \( \lambda \)-microcavities with different periods of the DBR layer suggest that the coupling state between the photons and excitons in the cavity layer depends on the \( Q \) factor.

In all the \( \lambda/2 \)-microcavities shown in figures 2(d), (e) and (f), three peaks are obviously observed. It is noted that although the \( Q \) factor of the \( \lambda/2 \)-microcavity with 2 periods is smaller than that of the \( \lambda \)-microcavity with 2 periods, three peaks dependent on the incident angle appear in the \( \lambda/2 \)-microcavity with 2 periods. This result implies that the photons and excitons in the \( \lambda/2 \)-microcavities will be strongly coupled to each other as compared with the \( \lambda \)-microcavities.

Next, we have investigated the incident angle dependence of the peak (dip) energies observed in the microcavities. Since the spectral profiles of the peaks and dips observed in the ART spectra change between the symmetric and asymmetric structures with the incident angle, the ART spectra are fitted by the following equation which is represented by the superposition of Fano functions [5],

\[
T(E) = \sum_{n=1}^{3} F_n(E) + \text{Background} , \quad F_n(E) = A_n \times \left( \frac{E-E_{\text{peak}}}{\gamma_n/2} + q_n \right) + 1.
\]
obtained from the fitting procedure are plotted as a function of incident angle in figure 3. The incident angle dependence of the peak energies in the microcavities except the $\lambda$-microcavity with 2 periods shows the anti-crossing behavior around the $Z_3$ and $Z_{1,2}$ exciton energies of CuCl. In the $\lambda$-microcavity with 2 periods, the dip energies are almost independent on the incident angle, while the peak energy of the broad peak changes with the incident angle. This result indicates that the anti-crossing behavior does not appear in this microcavity; consequently, the dips around the exciton energies will be observed by the weak coupling between the photons and excitons, such as the polaritons observed in CuCl crystals.

Finally, we discuss the coupling constant between the photons and excitons in the microcavities. In order to estimate the coupling constants, the incident angle dependence is fitted by using the following effective Hamiltonian $H$ [2-4],

$$
H = \begin{pmatrix}
E_{\text{cav}}(\theta) & \Omega_3 / 2 & \Omega_{3,2} / 2 \\
\Omega_3 / 2 & E_{Z_3} & 0 \\
\Omega_{3,2} / 2 & 0 & E_{Z_{1,2}}
\end{pmatrix}, \quad E_{\text{cav}}(\theta) = E_{\text{ph}} \left( 1 - \frac{\sin^2 \theta}{n_{\text{eff}}^2} \right) \frac{1}{2}.
$$

(2)

Here, $E_{\text{cav}}$ is the peak energy of the cavity photon mode which depends on the incident angle, and $E_{\text{ph}}$ is the cavity photon energy at the normal incidence. $n_{\text{eff}}$ is the effective refractive index in the cavity layer.

**Figure 2.** Transmission spectra of the CuCl $\lambda$-microcavities with 2 periods of the DBR layer (a), 3 periods (b), and 5 periods (c), and those of the CuCl $\lambda/2$-microcavities with 2 periods (d), 3 periods (e) and 5 periods (f) at various incident angles of the probe light. The black dotted curves indicate the experimental results and the blue dotted curves show the transmission spectra multiplied by appropriate constants. The red solid curves show the fitted curves. The vertical dashed lines indicate the $Z_3$ and $Z_{1,2}$ exciton energies of CuCl. $\theta$ is the incident angle of the probe light. LPB, MPB and UPB indicate the lower, middle, and upper polariton branches, respectively.
Figure 3. Incident angle dependence of the peak energies in the CuCl $\lambda$-microcavities with 2 periods (a) and 3 periods (b) and that in the CuCl $\lambda/2$-microcavities with 2 periods (c) and 3 periods (d). The solid curves indicate the fitted curves by using the effective Hamiltonian. The horizontal dashed-dotted lines indicate the $Z_1$ and $Z_{1,2}$ exciton energies of CuCl. The dashed curves show the dispersion relation of the cavity photon.

$\Omega_3$ ($\Omega_{1,2}$) is the coupling constants between the cavity photon and the $Z_3$ ($Z_{1,2}$) exciton. $E_{Z3}$ and $E_{Z1,2}$ are the $Z_3$ and $Z_{1,2}$ exciton energies, respectively. The solid curves in figure 3 indicate the fitted curves which well reproduce the incident angle dependence of the peak energies. From the fitting procedure, the coupling constants of $\Omega_3$ and $\Omega_{1,2}$ in the $\lambda/2$-microcavities are estimated to be approximately 50 and 95 meV, respectively, while those in the $\lambda$-microcavities except the $\lambda$-microcavity with 2 periods are approximately 45 and 85 meV, respectively. In the $\lambda$-microcavity with 2 periods, the coupling constants of $\Omega_3$ and $\Omega_{1,2}$ are less than approximately 40 meV. Although these values obtained in this microcavity show no characteristic of the strong coupling state, we consider that the observation of the dips around the exciton energies will be due to the weak coupling between the photons and excitons. Moreover, it is noted that the coupling constants of the $\lambda/2$-microcavities are slightly larger than those of the $\lambda$-microcavities. Assuming that the coupling constant will originate from the degree of overlap between the spatial distribution of the electric fields of the cavity photons in the cavity layers and the wave functions of the excitons with various principal quantum numbers ($n \geq 1$) in the active layers as shown in figure 1(b), we have calculated the overlap integral between the electric field of the cavity photon and the wave functions of the excitons. The calculated results indicate that the values of the overlap integral in the $\lambda/2$-microcavities are larger than those in $\lambda$-microcavities, which is consistent with the characteristics of the coupling constants obtained in the $\lambda/2$- and $\lambda$-microcavities.

4. Conclusion

We have investigated the ART spectra of the CuCl $\lambda$- and $\lambda/2$-microcavities with various periods of the DBR layer. The ART spectra of the microcavities change with the $Q$ factor and the thickness of the cavity layer. The cavity polariton modes are observed in the ART spectra of the microcavities, except for the $\lambda$-microcavity with 2 periods. The incident angle dependence of the peak energies observed in the microcavities indicates that the CuCl microcavities except the $\lambda$-microcavity with 2 periods express the strong coupling state between the photons and excitons.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP16H04003.

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