Room-temperature normal-mode coupling in a semiconductor microcavity utilizing native-oxide AlAs/GaAs mirrors

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A GaAs/AlAs microcavity containing six InGaAs quantum wells was grown, and the sample was then etched via chemically-assisted ion-beam etching to form 50-μm-diam cylindrical mesas. The formation of native oxides, accomplished by baking the samples at 400 °C in the presence of a pressurized N₂/H₂O vapor line, lowered the refractive index of the AlAs layers to 1.5. The higher refractive index contrast more effectively confined the intracavity field, leading to well-resolved reflectivity dips with an exciton-polariton splitting of 6.72 nm=9.44 meV at room temperature.

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The normal-mode coupling (NMC) or exciton-polariton splitting in semiconductor microcavities first seen by Weisbuch et al.1 has led to a flurry of both linear2-10 and nonlinear11-14 studies. To our knowledge, however, there has been only one observation2 of room-temperature NMC, with barely resolved peaks. We detail the design and fabrication of AlAs native oxide layers in a (DBR) microcavity structure which exhibits well-resolved NMC reflectivity dips. The large splitting may be useful in studying light extraction from room-temperature microcavities using normal-mode coupling.

The motivation to use AlAs native oxides in a microcavity structure comes from the fact that the NMC splitting 2 Ω is proportional to the square root of the inverse confinement length of the cavity mode.1,15 The more the electric field is confined, the larger the splitting. The 1.5 index of the aluminum oxide is much smaller than the 2.9 index of AlAs, resulting in better longitudinal confinement of the field and a larger splitting between the two NMC peaks, 2 Ω. Figure 1 illustrates this principle by plotting the (normalized) intracavity field amplitude, |ε|, for the case of a Fabry–Pérot etalon with a 3λ/2 GaAs spacer using (a) pure GaAs/AlAs mirrors with 28/33 top and bottom mirror layers, respectively (calculated reflectivity R = 99.5%) and (b) native-oxide AlAs/GaAs mirrors using 6/7 top and bottom mirror layers (R = 99.4%). Also plotted as dashed lines are the microcavity index profiles in each case. The horizontal axis in this case represents distance from the center of the cavity spacer, taken as the origin. The indices of refraction at the design wavelength of 940 nm are n_{GaAs} = 3.556, n_{AlAs} = 2.934, and we assumed an index value of 1.5 for the oxidized AlAs layers, consistent with current literature16 and measurements performed at KAIST. Figure 1 shows how increased field confinement is achievable by using mirror layers with a higher index contrast. The field amplitudes in each case were normalized such that each cavity contains the same total energy, and one can clearly see higher |ε| and less penetration of the field beyond the cavity spacer for the case of oxidized mirror layers.

The next step in our design was the characterization of the quantum well (QW) material. The measured absorption spectrum of a molecular beam epitaxy (MBE)-grown sample of 25 85-ÅIn_{x}Ga_{1-x}As(x=0.17) QWs separated by 500 Å GaAs barriers is shown in Fig. 2(a). Kramers–Krönig transformation was applied to it in order to calculate the associated index change (relative to bulk GaAs).17 This allowed us to make a series of transfer-matrix simulations18 incorporating the QW absorption and dispersive index of refraction. Due to the high index of refraction contrast between the GaAs and native-oxide AlAs layers, there was limited flex-

![Figure 1](image-url)
ibility in achieving a wide range of reflectivities based on varying the number of mirror layers. Indeed, after only four layers for the top mirror, the calculated reflectivity was already 96.5%. Our simulations indicated that best resolution for the two NMC peaks occurred for the case of placing three QWs in each of the two central antinodes of a $3\lambda/2$ cavity spacer, as opposed to three QWs in the antinodes of a $\lambda/2$, $1\lambda$, or $2\lambda$ spacer. Note a transfer-matrix simulation of the AlAs/GaAs structure in Fig. 1(a) showed barely resolved NMC, consistent with observations in Ref. 2, further supporting our claim that the improved splitting results from use of the native-oxide AlAs layers.

The sample design that was grown and oxidized consisted of 6 top/7 bottom layers of native-oxide AlAs/GaAs mirror layers, with a $3\lambda/2$ GaAs spacer. Three In$_{x}$Ga$_{1-x}$As ($x=0.17$) QWs were grown at each of the two intracavity field antinodes. The wells were separated by 100 Å GaAs barriers. In preparation for oxidation, the samples were first etched to the GaAs substrate layer using chemically-assisted ion-beam etching (CAIBE) to form cylindrical mesas approximately 50 μm in diameter, and separated by center-to-center distances of approximately 110 μm. Oxidation was at 400 °C for approximately 20 min using a pressurized N$_2$ line with H$_2$O vapor. The use of mesas helped to ensure uniform oxidation, and an array of mesas was necessary to allow us to tune the cavity resonance into and out of resonance with the QW exciton peak at 940 nm, utilizing the variation in thickness across the sample. It is worth noting that there is a corresponding shrinkage in the thickness of the oxidized AlAs, the final layers being about 95% of their original thickness. It was therefore important to include both the shrinkage factor and the index change in the preoxidation design simulations. Figure 2(b) shows the growth and corresponding fit via the transfer-matrix program of a preoxidized sample measured in reflection. This measurement was taken at growth center, the thickest part of the sample, which was intentionally fabricated to put the Fabry–Pérot transmission peak at a wavelength longer than the QW resonance. This allowed us to scan outward and bring the cavity and QW material into resonance with each other. Figure 2(c) shows the corresponding post-oxidation prediction using $n_{oxide} = 1.5$ and a 95% shrinkage factor. We also performed a series of reflectivity measurements along a radius from growth center, and were able to fit the data at each scan position. By then computing a post-oxidation simulation for each of these points, we could roughly determine where on the sample we would expect to see NMC, and then be careful to include this area as one of our etched mesas. Figure 3(a) shows a comparison of the predicted splitting (dashed) to the experimentally observed splitting in reflectivity. As not every point along the radius was measured and fit, the prediction curve in Fig. 3(a) was found by simply scaling down all of the fit values from the nearest measured point to bring the predicted Fabry–Pérot peak into resonance with the QW resonance. We found the observed splitting-to-linewidth ratio to be 6.72 nm/6.1 nm = 1.1, when using the wider, short-wavelength reflectivity dip. The modeling also indicated $R=0.8673$ and $T=0.0025$ at the lower reflectivity dip/higher transmission peak, so that the absorption is approximately one minus the reflectivity$^2$ and hence has the same splitting. A comparison with the predicted splitting spectrum shows very good agreement, except that the experimental resonance was shifted to higher energy. This was due to the fact that as we tuned out from growth center on the sample, all layers became thinner, including the QW layer. As the QW became thinner, its resonance shifted to higher energies, if only slightly as shown. The transfer matrix, on the other hand, assumed constant resonance energies for each quantum well, and hence the coupling remained centered about 940 nm.

Finally, in Fig. 3(b), we show an AC diagram as we scanned along a radius from growth center and tracked the reflectivity dips. The ability to easily resolve the two peaks

![Image](https://example.com/image.png)
will prove extremely helpful for both time- and angle-resolved studies at room temperature.

In conclusion, we have successfully designed and fabricated a microcavity sample exhibiting well-resolved NMC splitting using a combination of MBE growth and etching for AlAs oxidation at 400 °C. We have also demonstrated the usefulness of a transfer-matrix simulation in the design and preoxidation characterization of such samples to better aid in predicting their post-oxidation behavior.

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35 A. Macleod, Thin-Film Optical Filters, 2nd ed. (MacMillan, New York, 1986).
36 This technique was performed at KAIST; identical NMC was seen on an adjacent piece of the sample processed at CoreTek.