High-finesse Al_xO_y/AlGaAs nonabsorbing optical cavity

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We report the measured finesse value of ~390 in nonabsorbing Al_xO_y/AlGaAs cavities. The nonabsorbing cavity consisting of a bottom Al_xO_y/AlGaAs distributed Bragg reflector (DBR), an Al_xO_y spacer layer, and a top Al_xO_y/AlGaAs DBR is prepared by a wet-oxidation process. The measured resonance linewidth agrees well with that of calculation, indicating very small overall losses in the cavity. The wet-oxidation process does not seem to degrade the interface of the epitaxial layers significantly. The lower bound of maximum achievable reflectivity from the Al_xO_y DBR is estimated to be >99.95%, assuming an average interface roughness of about 0.6 nm. The maximum achievable finesse of this type of cavity is expected to be larger than that of the all-epitaxial counterpart assuming the same roughness. © *1998 American Institute of Physics.* [S0003-6951(98)02518-2]

The application of wet oxidation to vertical-cavity surface-emitting lasers has led to significant improvement in the operating characteristics.[1–5] Using low-index Al_xO_y layers, high reflectivity and wide-bandwidth distributed Bragg reflectors (DBRs) are also reported.[6–9] The refractive index and other material properties of Al_xO_y, for application to DBR mirrors, are important parameters and have been investigated by several groups.[6–8,10] However, the ultimate performance of the oxidized DBR has not been studied systematically.[10] We try a nonabsorbing Al_xO_y spacer to minimize the possible absorption loss in the cavity. In this structure, the scattering loss by interface roughness becomes an important limiting factor of the maximum reflectivity of AlGaAs/Al_xO_y DBRs and finesse. In this letter, we optically measure the finesse of vertical resonators having a half-wave nonabsorbing oxide spacer and AlGaAs/Al_xO_y top and bottom DBRs. In the case of an optical resonator having a thin spacer and high-contrast DBR mirrors, the major portion of the energy of the resonance mode is stored in the spacer. Therefore, this structure is also used to precisely measure the change of the optical thickness of the oxide spacer as a function of wet-oxidation time.

The sample was grown on a (100) GaAs substrate with 2° misorientation by metal–organic chemical-vapor deposition (AIXTRON AIX200). $Al_{0.2}Ga_{0.8}As$ is adopted as a high refractive index material of DBR mirrors. Four and 3.5 pairs of $Al_{0.2}Ga_{0.8}As$ (638 Å)/AlAs (1544 Å) are located at the bottom and the top of the structure, respectively. The layers are changed to high-contrast DBR mirrors after wet oxidation. The calculated reflectivities of the top and bottom DBR are 99.35% and 99.55%, respectively. And the oxide layer converted from 3087-Å-thick AlAs between the DBRs is used as a $\lambda/2$ spacer. The cap layer is 100-Å-thick GaAs. All layers are undoped. The sample is wet etched nonselectively by H_2O_2:H_3PO_4:H_2O (1:1:4) to form 50-μm-diam circles and oxidized at 400 °C under 0.5-l/min N_2 flow through 90 °C water. The vertical oxidation profile over the layers is most uniform at a 0.5-l/min N_2 flow rate as compared to the other flow rates (1.0 and 2.0 l/min) in our case. To measure the reflectivity over a small area, our measurement setup is arranged as shown in Fig. 1.

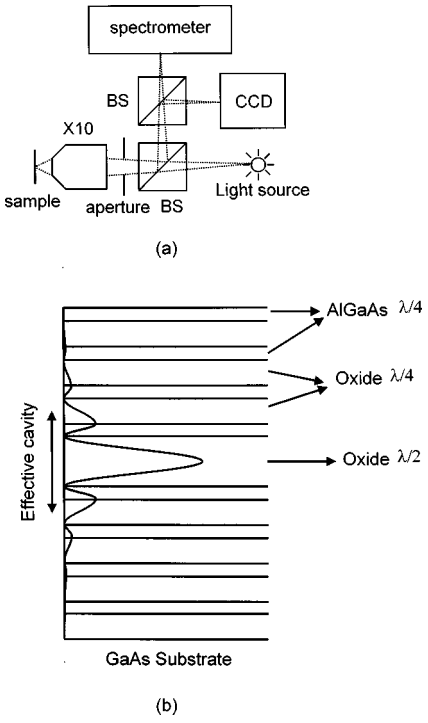

FIG. 1. (a) Setup for reflectivity measurement. The sample and light source are conjugate to each other, also to the image plane on a charge-coupled device and the input slit of the spectrometer. (b) The typical structure of the oxidized sample. The intensity profile is also shown.

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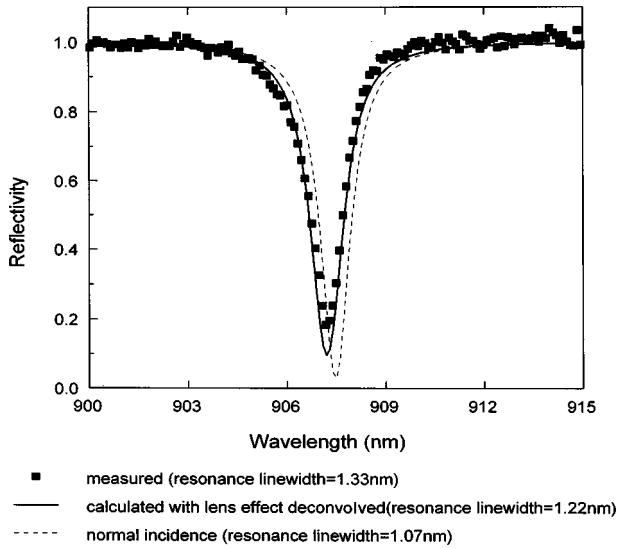

FIG. 2. Comparison of experiment and theory. The diameter of the aperture is 2 mm. The dashed curve is the ideal reflectivity obtained from the normal incidence.

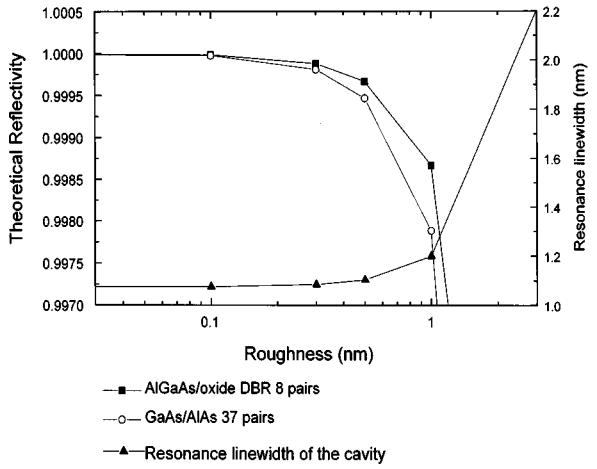

FIG. 3. Reflectivity of the AlGaAs/oxide DBR and GaAs/AlAs DBR and resonant-mode broadening as a function of interface roughness. The GaAs/oxide DBR and GaAs/AlAs DBR have 8 pairs of GaAs/oxide and 37 pairs of GaAs/AlAs, respectively.

The measured and calculated reflectivity of the sample, which is oxidized for 18 min at 400 °C, is shown in Fig. 2. The resonant wavelengths tend to decrease with oxidation time. The calculated resonance linewidth for a normal angle to the sample is 1.07 nm. The measured minimum resonance linewidth is 1.33 nm. The instrument width (the resolution of the spectrometer) is ~ 0.11 nm. Therefore, the actual resonance linewidth of the cavity should be ~ 1.22 nm when the instrument width is deconvolved. This deconvolved resonance linewidth of the oxidized sample is a little bit larger than the calculated one due to the angle effect of the objective lens. When the reflectivity is measured with an objective lens by collecting beams over a finite incident angle, the resonant mode generally shifts to a shorter wavelength resulting in an apparently wider resonance linewidth. To minimize this angular convolution effect, the 2-mm-diam aperture is located in the front of a $10\times$ objective lens (NA $=0.20$). The calculated reflectivity containing the lens effect is shown as a thick solid curve in Fig. 2. When this angular effect is included, the resonance linewidth becomes 1.20 nm from 1.07 nm. This value agrees very well with the deconvolved resonance linewidth (1.22 nm). The result implies that the vertical resonator with AlGaAs/Al_xO_y has a negligible scattering loss in the error limit of our measurement. In the case of the cavity with DBR mirrors, the finesse should be calculated by using the phase penetration depth for cavity length, not by using the energy penetration depth.[11,12] The finesse of the cavity is ~ 390 after instrument-width deconvolution and it becomes ~ 440 after angular deconvolution.

An imperfect interface causes scattering and lowers reflectivity rather than that of an ideal interface. The reflectivity at a rough interface is expressed as follows:[13]

$$R_s = R_0 \exp(-(4\pi\sigma n/\lambda)^2).$$

n is the refractive index of the incident medium, R_0 is reflectivity of the perfect interface, and σ is the root-mean-square fluctuation from the average interface. For reflectivity calculation of a multilayer, a modified transfer matrix is used.[14] The maximum reflectivity converges to a limiting value in spite of the increasing number of pairs of DBR whenever there exist scattering losses at interfaces. In Fig. 3, the reflectivities of GaAs/Al_xO_y and GaAs/AlAs DBR mirrors are compared for various interface roughnesses. The GaAs/Al_xO_y DBR and GaAs/AlAs DBR have 8 and 37 pairs, respectively. These numbers of pairs of DBRs are selected to give the same initial reflectivity of 99.9997% for both mirrors. In order to achieve reflectivity above 99.9% from this ideal mirror, the interface roughness of the AlGaAs/oxide DBR should be less than ~ 0.8 nm as shown in Fig. 3. On the other hand, to achieve the same 99.9% reflectivity from the GaAs/AlAs DBR mirrors, the equivalent interface roughness should be ~ 0.6 nm. Because of the high contrast of the refractive indices, the penetration depth of the GaAs/oxide DBR mirror is much smaller than that of the GaAs/AlAs DBR. Therefore, photons pass through a smaller number of rough interfaces and the overall scattering loss becomes smaller. Our calculation shows that the GaAs/oxide DBR is generally less sensitive to the interface roughness than the GaAs/AlAs DBR.

As shown in Fig. 3, the interface roughness of 0.6 nm results in the resonant-mode broadening of 0.05 nm, corresponding to the measurement error of 0.05 nm for our $\lambda/2$ cavity. However, since our maximum measurement error is less than 0.05 nm, the corresponding interface roughness of 0.6 nm sets the upper bound that can occur during the wet-oxidation process. With this upper bound of interface roughness, the limiting value of reflectivity for the AlGaAs/oxide DBR becomes $>99.95\%$. The corresponding finesse is 6280 for the cavity consisting of an oxide spacer and 8 pairs of AlGaAs/oxide DBR mirrors.

The resonant wavelength position fluctuates over a mesa as shown in Fig. 4. This spreading is attributed to the overall optical thickness variation of the oxide layer over a circular mesa. For example, the variation of ~ 1 nm in the resonant wavelength corresponds to the relative thickness variation of $\sim 0.1\%$ or the absolute thickness variation of ~ 0.3 nm in the oxide layers. Since the spatial resolution of our setup is $\sim 8\ \mu$m, the measured reflectivity is, in fact, the spatial average over this area. The values of the resonance linewidth spread between 1.3 and 2.2 nm over various samples. Since

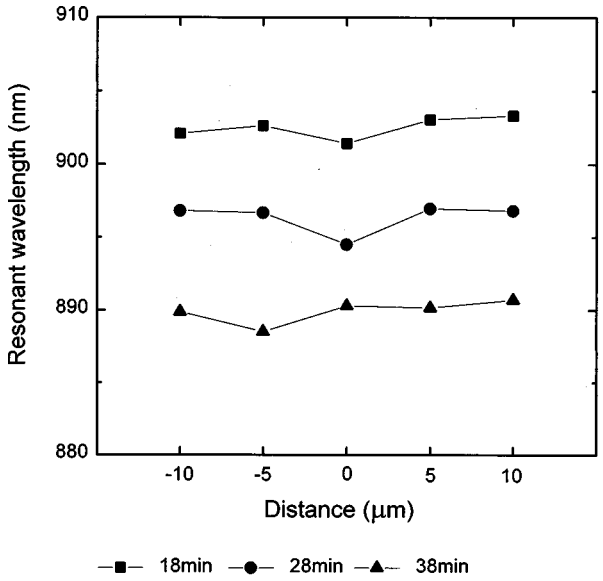

FIG. 4. Resonant wavelength variation over a mesa. The origin is taken at the center of the mesa. The resonant wavelength decreases with oxidation time.

the interface itself was reported to be very smooth from the transmission electron microscope data,[10] this spreading of the resonance linewidth can be attributed to the optical thickness variation and spatial average effects.

In summary, a high-finesse value is obtained from a nonabsorbing Al_xO_y/AlGaAs cavity and the maximum achievable finesse value is projected from the loss analysis. The scattering loss is studied from the analyses of the line shape of the cavity. The measured resonance linewidth of the resonant mode agrees well with the calculated result, implying an interface roughness of less than 0.6 nm. According to our calculation based on the measurement, the GaAs/Al_xO_y DBR is expected to have a higher limiting reflectivity than the corresponding GaAs/AlAs DBR because of the high refractive index contrast of the AlGaAs/oxide DBR.

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