Ultrahigh finesse microcavity with distributed Bragg reflectors

R. P. Stanley, R. Houdré, U. Oesterle, M. Gailhanou, and M. Ilegems
Institut de Micro-et Optoélectronique, Ecole Polytechnique Fédérale de Lausanne, CH1015, Switzerland

(Received 9 March 1994; accepted for publication 8 August 1994)

We have grown a very high finesse microcavity using distributed Bragg reflectors of $Al_xGa_{1-x}As$ and AlAs. The measured Fabry–Pérot mode has a linewidth of 0.84 Å at 930 nm. This implies a finesse in excess of 5500 and an effective (mirror corrected) finesse greater than 1450. Comparison with theoretical calculations for such a structure shows that (i) the growth rates are stable to 0.25% over 14 h and (ii) the internal losses are less than 1 cm^{-1}. © *1994 American Institute of Physics.*

Vertical cavity surface emitting lasers (VCSELs) depend on the high reflectivity of dielectric mirror stacks to overcome the small gain length in such structures. If very-high-*Q* cavities (*Q*: quality factor) are to be attained then the limits for mirror reflectivities need to be accurately determined. This can be done by measuring the finesse of a cavity with two dielectric mirrors. Vertical cavity and microcavity structures have been used in lasers,[1] enhanced photodiodes,[2] light emitting diodes (LEDs),[3] and many types of nonlinear switches.[4,5] In these types of devices, the role of surface roughness, inherent in all growth techniques, has not been precisely investigated. While in edge emitting lasers the main internal loss is scattering from waveguide nonuniformities rather than material purity, the corresponding loss mechanisms in a vertical cavity structure are not clear.

In this letter we address these issues by examining a very high finesse Fabry–Pérot, using GaAs, AlAs, and $Al_xGa_{1-x}As$. These questions were addressed in a previous letter by Jewell some years ago[6] in which the reported record finesses for a Fabry–Pérot (FP), using GaAs, AlAs, and $Al_xGa_{1-x}As$. In this work we have fabricated a similar type of FP structure but with a finesse an order of magnitude greater. Sensitive measurements on this structure provide a new reference standard for surface roughness, material purity, and growth stability.

As shown in Fig. 1, the structure, grown by molecular beam epitaxy consists of a Si-doped GaAs substrate followed by a bottom mirror consisting of 27 pairs of 675 Å $Al_{0.1}Ga_{0.9}As$ and 764 Å AlAs, a 2670 Å GaAs cavity, and a 20 pair top mirror. The $Al_{0.1}Ga_{0.9}As$ is a pseudoalloy of AlAs and GaAs, which allows the use of one Ga and one Al source. The periodicity of the mirrors was measured by x-ray diffraction from the angular position of the satellites close to the GaAs 002 and 004 directions. Measurements were carried out over a 180° spread in azimuth position to counteract the effects of residual substrate misorientation.[7] The peaks have a full width half-maximum (FWHM) of 15 arc sec and show no broadening up to the seventh order implying good crystal quality and little variation in thickness between individual layers. A fit to the x-ray satellite peaks gives a mirror periodicity of 1438.6 Å for the satellites close from GaAs 002 reflection and 1439.9 Å for those close from the GaAs 004 reflection, giving an average period of 1439±1 Å. The Al concentration in (Ga,Al)As pseudoalloy is in the range 9.5%–10% depending on the model used.[8,9]

Figure 2(a) shows a reflectivity spectrum taken at the center of the sample. There is a wide stopband from 880 to 975 nm, with sideband minima to either side. In the middle a sharp FP mode can be seen. The FP mode is shown with greater resolution in Fig. 2(b). The solid line is a Lorentzian with a FWHM of 0.95 Å, when including instrumental resolution this corresponds to a linewidth of 0.84 Å. The spot size and convergence of the beam are very important when measuring such narrow FP resonances as will be discussed below. The minimum reflectivity is 40% while the maximum transmission is 20% implying that 40% is absorbed or scattered by the sample.

The reflectivity spectrum can be calculated theoretically using the known dispersion relations of GaAs, $Al_{0.1}Ga_{0.9}As$ and AlAs,[10] along with a knowledge of the individual layer thicknesses measured by x-ray diffraction. Care was taken to measure the same spot on the sample with both x-ray and optical measurements. The standard method of transfer matrices was used to calculate the reflectivity.[11] The results are shown as the solid line in Fig. 2(a). The only unknown parameter was the position of the FP resonance which could not be measured by x-ray diffraction. The most uncertain parameter is concentration of Al in $Al_xGa_{1-x}As$. The effect of changing the concentration is to shift the position of the stopband and to change its width. The best agreement with measurement is obtained with a value of 9.7% Al which falls in the range 9.5%–10% calculated from the x-ray data.

In a perfect distributed Bragg reflector (DBR) microcavity the pair of side lobes on each side of the FP resonance are symmetric. In Fig. 2(a) there is a strong asymmetry, with the short wavelength pair having equal intensity while the long wavelength pair have very different intensities. This can be

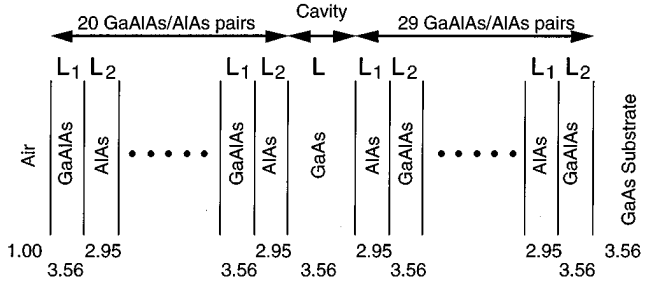

FIG. 1. Schematic of Fabry–Pérot microcavity where the width of the GaAlAs, AlAs, and GaAs layers are L1=675 Å, L2=764 Å, L=2670 Å, respectively.

 0003-6951/94/65(15)/1883/3/$6.00

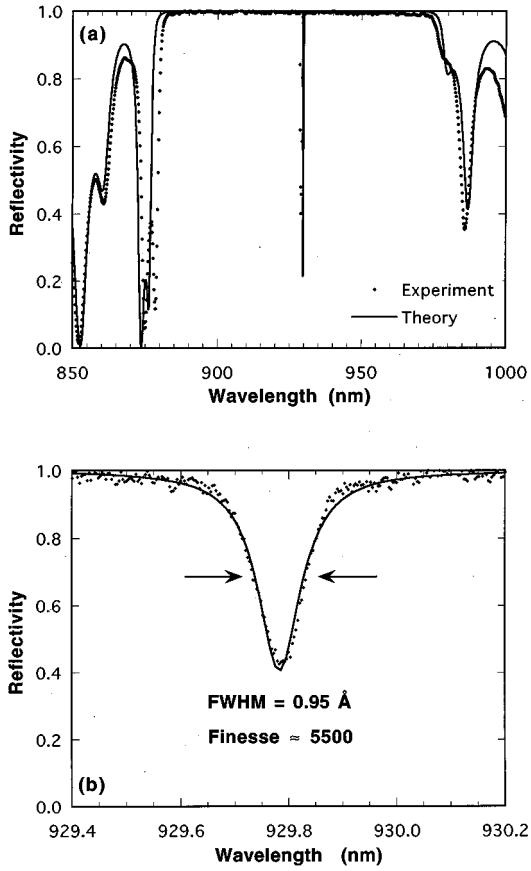

FIG. 2. (a) Reflectivity spectrum of microcavity taken at the center of the wafer; measured curve (dots) and calculated curve (solid line). (b) Detail of Fabry–Pérot mode. The solid line is a Lorentzian with a FWHM of 0.95 Å.

simulated by assuming that the second mirror is thinner than the first mirror and cannot be attributed to uncertainties in the refractive indices which are the same for both mirrors. The agreement with the measured spectra is excellent if the second mirror is assumed to be 0.25% thinner than the first mirror. This small thickness variation is remarkable considering that growth for this sample lasted 28 h, i.e., 14 h from the middle of the first mirror to the middle of the second. The reflectivity spectrum of a DBR Fabry–Pérot is very sensitive to any relative change between the two mirrors because it acts as a differential measurement, where the reflection minima are due to an interplay of both mirrors.

We need to define some terms, in order to compare these results with those previously quoted in the literature. Starting with the Airy function,[12]

$$A(x)=1/[1+b\ \sin^2(x)], \tag{1}$$

which has fringes of width Δx and separation 2π, leads to the definition of finesse as

$$F=2\pi/\Delta x. \tag{2}$$

The relationship between phase width and linewidth is just

$$\frac{\Delta\nu}{\nu}=\frac{\Delta\lambda}{\lambda}=\frac{\Delta x}{x_0}, \tag{3}$$

where $x_0=2m\pi$ and m is the order of the fringe. Hence,

$$\frac{\lambda}{\Delta\lambda}=mF. \tag{4}$$

A λ sized cavity is a second-order cavity ($m=2$) so with $\lambda=9300$ Å and $\Delta\lambda=0.84$ Å this gives a finesse of 5530. The usefulness of following this definition is that it is directly related to the resolution of the FP and does not include the free spectral range (FSR) which has no meaning for short cavities with dielectric mirrors, i.e., when the free spectral range is greater than the stopband of the DBR mirror. For ideal mirrors the finesse can be related to the reflectivity of the front and back mirrors in the limit of high reflectivities by

$$F\approx\frac{\pi\sqrt{R}}{1-R}, \tag{5}$$

where $R=r_1r_2$. However, the phase shift of a dielectric mirror means that the cavity is effectively longer than the spacer layer and this increases the finesse over a similar structure with ideal or metallic mirrors. This may be taken into account by using an effective order, m_{eff},

$$m_{\text{eff}}=m+m_0, \tag{6}$$

where m_0 accounts for the penetration into the mirrors. In the high reflectivity limit m_0 (including both mirrors) is given by[13]

$$m_0=n_l/(n_h-n_l), \tag{7}$$

where n_h and n_l are the refractive indices of the high and low refractive index materials in the Bragg mirror. For our sample, $m=2$, $n_h=3.456$, $n_l=2.95$, and $m_{\text{eff}}=7.54$. Noting that $m=1$ corresponds to a $\lambda/2$ cavity, then the effective order gives the effective length of the cavity in units of $\lambda/2$, and $m_0\lambda/4$ is the penetration depth in each of the Bragg mirrors. The reason for using m_{eff} is that many authors quote the finesse in terms of a local free spectral range divided by the linewidth, which is equivalent to using m_{eff} in Eq. (4). If we call this the effective finesse, F_{eff}, then for our cavity $F_{\text{eff}}=1470$, in comparison to values of 160 by Jewell *et al.*[6] who calculated the local FSR, and to values of 700 by Oudar *et al.*[5] who measured the local FSR.

The theoretical linewidth of a FP resonance, calculated both analytically and using the matrix method for multilayer structures, is equal to 0.4 ± 0.1 Å as opposed to the measured linewidth of 0.84 Å. The difference between these values can be attributed to several factors (a) residual absorption or scattering at interfaces; (b) measurement error due to using a convergent probe beam; (c) diffraction losses due to mirror roughness; and (d) cavity width fluctuations. The first possibility, that there may be internal losses, due to either residual absorption or scattering at interfaces, can be calculated by including a distributed loss in the theoretical calculations. The measured linewidth puts an upper limit of 12 cm^{-1} on internal losses. However, this value is much to large to account for the 20% transmission of the FP and substrate. The α measured in similar n-doped substrate is $\approx$12 cm^{-1} at 930 nm. Taking this contribution into account, the corrected reflection, transmission, and absorption in the FP section are

37%, 48%, and 14%, respectively. With these values α lies in the range 0.3–0.9 cm^{-1}, depending on the ratio of the front and back reflectivities used. The smaller value corresponds to the theoretical values of the mirror reflectivities. This internal loss has a negligible contribution to the observed linewidth, as expected from high purity undoped material.

The position of the FP mode changes as a function of angle, so a probe that is not exactly parallel will include a range of angles and will result in a broadening of the FP mode. For example, if the probe beam has a cone of 2.3° then the FP resonance will be broadened significantly from 0.4 to 0.9 Å, although the internal angle in the structure is small. We changed the F number of our lens system until the linewidth of the FP resonance became independent of F number. The lens system was constrained to having F number less than 12, which is a little smaller than this limit and due to diffraction implies a spot size >25 μm. Indeed, as highlighted by Uijara,[14] the size of the FP mode is important in measuring the FP resonance. When the probe spot size is smaller than the FP mode there is poor coupling into the FP mode leading to higher reflectivities and a broader linewidths.

It is known that molecular beam epitaxial (MBE) growth leads to interface roughness on the order of a few monolayers. Davies[15] has shown that for a surface with microroughness the distribution of heights alone is sufficient for calculating its reflecting and scattering properties. Given a Gaussian distribution of heights $p(z)=\exp(-z^2/2\sigma^2)$, where $\sigma \ll \lambda$ then an ideal mirror of reflectivity R_0 has its reflectivity reduced to,

$$R=R_0 \exp[-(4\pi\sigma/\lambda)^2 \cos^2 \theta], \tag{8}$$

where θ is the angle of incidence. A linewidth of 0.9 Å implies that the FWHM of the height distribution is $\approx$50 Å. One can conclude that microroughness is a relatively unimportant scattering mechanism at normal incidence in comparison to large scale roughness. Furthermore, if this calculation is extended to scattering at each interface then monolayer scale roughness causes negligible losses due to the small relative refractive index change between the layers of the Bragg mirrors.

Finally, large scale variations must be considered. The effective finesse of our cavity indicates that average cavity width fluctuations across the diameter of the probe spot are less than 0.5 Å which implies that the mirrors are both very flat and highly parallel (to $\lambda/10^4$). Growth conditions mean that the sample is thicker in the middle than at the edges. The narrowest linewidth was measured in the very center of the sample where sample variations are minimal. To either side of this region the cavity linewidth rapidly increases by 50% to 1.5 Å implying that the difference in theoretical and measured linewidths is due to the very slight curvature of the sample.

In conclusion, we have grown and measured a DBR Fabry–Pérot microcavity with a linewidth of 0.84 Å at 930 nm. This implies a finesse in excess of 5500 and an effective finesse greater than 1450. Limiting requirements for such a high finesse imply several factors. First, the optical wave sees a much flatter interface than, e.g., electrons. Second, for accurate measurements correct coupling to the FP mode is important. Thus F number requirements limit practical increases in finesse which would lead to very large mode sizes. Third, internal losses (<1 cm^{-1}), are not a limiting factor in undoped structures. Fourth, the stability of the growth is better than 0.25% over 14 h. Finally, the current limits for the finesse depend on the flatness of the samples which at $\lambda/10^4$ are already extremely flat. As pointed out by Jewell[6] for many types of device effective finesses of 100–500 are not only adequate but desirable for short photon lifetimes. However, for bistable devices higher finesse leads to lower switching powers.

This work was supported under a joint Thomson-CSF (France) and EPFL (Switzerland) program and by the Swiss Priority Program for Optics.

[1] G. P. Agarwal and N. K. Dutta, *Semiconductor Lasers* (Van Nostrand Reinhold, New York, 1993), p. 472.
[2] K. Kishino, M. S. Unlü, J.-I. Chyi, J. Reed, L. Arsenault, and H. Morkoc, IEEE J. Quantum Electron. **QE-27**, 2025 (1991).
[3] N. E. J. Hunt, E. F. Schubert, R. F. Kopf, D. L. Sivco, A. Y. Cho, and G. J. Zydzik, Appl. Phys. Lett. **63**, 2600 (1993).
[4] D. Pellat, R. Azoulay, G. Leroux, L. Dugrand, Y. Raffle, R. Kuszelewicz, and J. L. Oudar, Appl. Phys. Lett. **62**, 2489 (1993).
[5] J. L. Oudar, R. Kuszelewicz, B. Sfez, D. Pellat, and R. Azoulay, Superlatt. Microstruct. **12**, 89 (1992).
[6] J. L. Jewell, Y. H. Lee, and S. L. McCall, Appl. Phys. Lett. **53**, 640 (1988).
[7] M. Gailhanou, J. F. Carlin, and U. Oesterle, J. Cryst. Growth **140**, 205 (1994).
[8] B. K. Tanner, A. G. Turnbill, C. R. Stanley, A. H. Kean, and M. McElhinney, Appl. Phys. Lett. **59**, 2272 (1991).
[9] M. S. Goorsky, T. F. Kuech, M. A. Tischler, and R. M. Potemski, Appl. Phys. Lett. **59**, 2269 (1991).
[10] S. Adachi, in *Properties of Gallium Arsenide*, 2nd ed. (INSPEC, London, 1990), p. 125; D. E. Aspnes, in *Properties of Aluminium Gallium Arsenide* (INSPEC, London, 1993), p. 157.
[11] H. A. MacLeod, *Thin-Film Optical Filters* (Hilger, Bristol, 1986), p. 32.
[12] If both front and back mirrors have the same reflectivity R, than $b=4R/(1-R)^2$.
[13] Derived from formulas 7.15 and 7.22 of Ref. 11.
[14] K. Ujihara, Jpn. J. Appl. Phys. **30**, L901 (1991).
[15] H. Davies, IEE Proc. Part 3, **101**, 209 (1954).