AIP Applied Physics Letters

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Citation: Applied Physics Letters **53**, 640 (1988); doi: 10.1063/1.99838
View online: http://dx.doi.org/10.1063/1.99838
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/53/8?ver=pdfcov
Published by the AIP Publishing

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(Received 11 May 1988; accepted for publication 17 June 1988)

We have measured finesse values of at least 160 in (Al,Ga)As Fabry–Perot interference filters grown by molecular beam epitaxy. Losses are low and the finesses are close to predicted values, suggesting that with additional mirror layers much higher finesse should be achievable. This has important implications in the development of resonator-based low-energy photonic logic devices and lasers for information processing and communication. Formulas for calculating the finesse and other parameters such as the effective optical thickness of the cavity in such structures are also given.

The use of molecular beam epitaxy (MBE) to produce single-crystal heterostructure mirrors was first demonstrated in the mid-1970s by van der Ziel and Ilegems.[1] In the last few years there has been renewed interest in these structures for nonlinear optical logic devices and lasers. Many structures have been grown in the $Al_xGa_{1-x}As$ system by metalorganic chemical vapor phase deposition or MBE.[2-7] Mirrors of GaP/GaAsP,[8] (Al,Ga)As/(Ca,Sr)F_2,[9] and InP/InGaAsP[10,11] have also been grown. Structures have been integrated into lasers[2,10] and photodiodes,[8] and micron-sized microresonator optical logic étalons[12] have been demonstrated. The number of efforts currently in progress makes it impractical to attempt a full up-to-date list of references on the subject. When lasers or logic devices are used for information processing, it is usually of critical importance to minimize the optical or electrical energy required to activate them. For resonator devices, this energy is generally inversely proportional to the finesse F. Filters reported to date generally have had F on the order of 10.[4,5] In order to test whether much higher finesse is feasable, we grew two structures with high-reflectivity $AlAs/Al_{0.13}Ga_{0.87}As$ mirrors. One had a half-wave ($\sim 1/8$ μm) spacer of $Al_{0.13}Ga_{0.87}As$ (sample A), while the second had a full-wave ($\sim 1/4$ μm) multiple quantum well (MQW) spacer (sample Q). Both had a design wavelength of 865 nm, and both showed measured values of finesse well over 100. Sample A had finesse of at least 160, while the MQW sample had a measured finesse more than 120 at a wavelength only 150 Å (27 meV) from the band edge. The values are close to those predicted, suggesting that even higher finesse is attainable. Furthermore, measured losses due to absorption and scattering are very low, $\sim 10\%$ on resonance for sample A.

In both cases the MBE growth consisted of a 5000 Å GaAs buffer on a Cr-doped GaAs substrate followed by a 1374 Å $Al_{0.7}Ga_{0.3}As$ etch-stop layer and the filter. Both filters have a symmetric design with each mirror having 14 pairs of 620 Å $Al_{0.13}Ga_{0.87}As$ and 725 Å AlAs layers. The AlAs layers are closest to the spacer, which is 1240 Å $Al_{0.13}Ga_{0.87}As$ for sample A, and 14.5 periods of 75 Å $Al_{0.4}Ga_{0.6}As$ barriers and 100 Å GaAs wells for sample Q. A 580 °C temperature was maintained throughout the growths. The wafer was spun during growth of both mirrors to achieve $\sim 2\%$ thickness uniformity across the entire 2 in. wafer. Spacers were grown without spinning to allow us to investigate variations in tuning within relatively small areas. Reflection high-energy electron diffraction (RHEED) oscillations were monitored just before the growth to calibrate growth rates, resulting in $\sim 2\%$ thickness accuracy. The substrate was ground to ~ 25 μm thickness, then etched to the stop layer in a 100:1 solution of 30% H_2O_2 and NH_4OH, after which the stop layer was removed with concentrated HCl. This last etch is extremely selective,[13] which is important because large variations (>100 Å) in the thicknesses of even the outer mirror layers can cause significant changes in the reflectivity.

Transmission and reflection were measured with a 270 mm spectrometer having ~ 2 Å resolution. The full width at half-maximum instrument width (IW) of the transmission peak without subtracting the spectrometer's resolution is ~ 8 Å for the AlGaAs sample (Fig. 1). The free-spectral range (FSR) of the filter is too large to measure directly since either adjacent transmission peak lies outside of the mirrors' reflective region. Furthermore, the FSR cannot be deduced from the spacer thickness. This is because much of the intensity is in the mirror layers, yielding an effective optical thickness of the cavity which is much larger than that of the half-wave spacer.[14] We use thin-film calculations to esti-

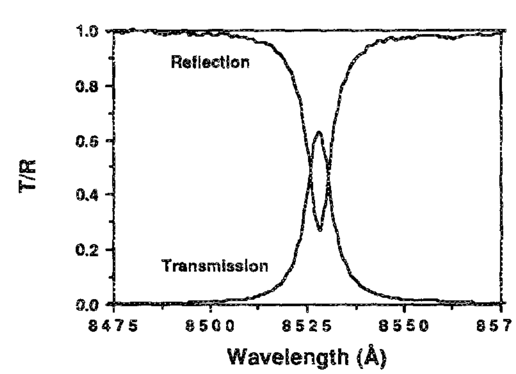

FIG. 1. Transmission and reflection spectra near the resonance of sample A.

mate an effective FSR, however, which in turn yields the finesse. This thin-film program calculates plane wave transmission and reflection of heterostructures, with the complex dielectric constants of $Al_xGa_{1-x}As$ materials determined from the method outlined by Afromowitz.[15] It also gives us the phases of the transmitted and reflected waves. Agreement between the calculations and our measurements is fairly good in instrument width and excellent for the FSR's of other structures having thicker spacers where the FSR can be measured directly. The IW is very sensitive to scattering and impurity absorption losses and to thickness variations, none of which is included in the calculation.

We define a free-spectral range and finesse in terms of parameters evaluated near the cavity resonant wavelength as follows. The condition for a resonance is that the round-trip phase ϕ of a wave inside the cavity be an integer multiple of 2π. Thus a difference of one FSR implies a difference $\Delta\phi$ of 2π radians in the round-trip phase thickness of the filter, which in our case includes dispersion of the materials involved, phase dispersion[14] of the dielectric mirrors, and the spacer of unknown effective thickness. The thin-film calculation implicitly accounts for all of these quantities. We first calculate the phase change on reflection ϕ_1, from one side of the filter which includes one-half of the spacer, then similarly calculate ϕ_2 for the other half. Although it is convenient to choose the midpoint of the spacer as the dividing point, any other point within the spacer yields the same answer. The total round-trip phase is $\phi = \phi_1 + \phi_2$. Then, by evaluating the derivative of ϕ with respect to wavelength λ at the resonance wavelength, we know how much the wavelength would have to change to produce a $\Delta\phi$ of 2π radians. We express the local effective FSR in wavelength units as

$$(\mathrm{FSR})_{\mathrm{loc}} = 2\pi \Big/ \left(\frac{d\phi}{d\lambda}\right). \tag{1}$$

The mirror phase dispersion is fairly constant over a broad region at the center of the high-reflectance zone of quarter-wave stack dielectric mirrors; thus our calculation is not very sensitive to perturbations or small errors in the mirror fabrication. It is worthwhile to note that the real separation of two adjacent resonances calculated in our program is *not* $(\mathrm{FSR})_{\mathrm{loc}}$, whether we use wavelength or frequency units. The difference is due to nonlinear dispersion in the mirrors and in the spacer material which make the measured FSR depend on material and structural properties far from the resonant frequency of interest. Thus we take the position that in structures similar to ours (large FSR and multilayer mirrors), $(\mathrm{FSR})_{\mathrm{loc}}$ is more generally useful than the measured FSR for calculating finesse. In practice, our (purely calculated) finesse values obtained through $(\mathrm{FSR})_{\mathrm{loc}}$ are very close to the standard values of $F = \pi R^{1/2}/(1-R)$, where R is the effective mirror reflectivity. The finesse, being the ratio of the $(\mathrm{FSR})_{\mathrm{loc}}$ to IW, is then

$$F = 2\pi \Big/ \left[(IW)\left(\frac{d\phi}{d\lambda}\right)\right]. \tag{2}$$

For sample Å, Eq. (1) yields $(\mathrm{FSR})_{\mathrm{loc}} = 1134$ Å. The uncorrected IW of 8 Å yields a finesse of 142, while our estimate of the IW corrected for spectrometer resolution of ~ 7 Å gives $F = 162$. The calculation had a 5.3 Å IW and $F = 214$, reasonably close to the measured values. The agreement is much closer if we consider thickness variations over the measured region. In the direction of maximum thickness variation, the transmission peak wavelength shifted about 20 Å over 1 mm travel. Thus we expect about 1 A variation within the ~ 50 μm region that we measured, a significant amount compared to the IW. This implies that in order to achieve very high finesse devices with uniform characteristics over large areas, very strict thickness control will be necessary. Atomic layer epitaxy (ALE),[16-18] still in early experimental stages compared to MBE, seems to be a promising straightforward approach to controlling both uniformity and absolute thickness.

For small FSR in a "classical" Fabry–Perot étalon, the FSR in units of wavelength can be expressed in terms of the spacer thickness L, and its refractive index n, as FSR $= \lambda^2/2nL$. For large FSR and cavities in which much of the intensity is in the mirror layers, we can still retain this relation redefined in terms of the "local" FSR and "effective optical thickness," then rearrange to yield the latter:

$$(nL_{\mathrm{eff}}) = \lambda^2 \left(\frac{d\phi}{d\lambda}\right) \Big/ 4\pi. \tag{3}$$

For sample A, $(nL)_{\mathrm{eff}}$ is about 3.3 μm or about seven times the optical thickness of the half-wave spacer. Since the average refractive index n in this region is about 3.2, the filter behaves as though the spacer thickness was slightly more than 1 μm. A decrease in finesse from 214 to 162 can be caused by an additional loss per pass of about 0.0048. The ~ 1 μm effective thickness thus places an upper limit of average absorption in this region at about 0.0048 μm^{-1} or 48 cm^{-1}; however, it is probably lower since the nonflatness can account for much of the degradation in finesse. The calculation showed no appreciable absorption.

The MQW étalon, since it has a thicker spacer, has a smaller $(\mathrm{FSR})_{\mathrm{loc}}$ which we calculate to be 952 Å. There was an additional complication since the refractive index of MQW material is not well characterized. We used $Al_{0.04}Ga_{0.96}As$ in the calculations since it has a band gap close to that of the MQW's in the sample. The transmission and reflection spectra show an uncorrected IW of ~ 8.5 Å on the spectrometer; so the finesse is certainly larger than 110. An IW of 7.5 Å yields $F = 127$. These measurements were taken at a wavelength only 150 Å (27 meV) from the band edge, the region where gating/bistability experiments are usually performed. This region of the wafer had a variation in the transmission peak wavelength of about 36 Å/mm; thus it varies almost 2 Å over the spot diameter. This thickness variation also causes the minimum reflectivity to be rather high at $\sim 40\%$ and the peak transmission to be only $\sim 45\%$.

Using the 7 Å IW estimated for sample A, we have calculated the $1/e$ energy buildup time of the cavity in response to a step function input to be about 0.57 ps. A realistic optical pulse should be ~ 2–3 ps in order to resolve this IW sufficiently. This may be too long for devices to work at very high speeds of 100 Gbits (10 ps cycle times); thus speed considerations may limit F to about 100 in purely (Al,Ga)As resonator devices with high throughput. Higher finesse without increased cavity buildup time could be achieved with thinner mirrors whose components have larger differences in refractive index, such as the (Al,Ga)As/(Ca,Sr)F_2 system[8] or a ZnSe/(Al,Ga)As structure. Combined metal/dielectric mirrors could also be considered,[19] paying careful attention to losses in the metallic layers.

In conclusion, we have demonstrated very high finesse of at least 160 in an MBE-grown AlAs/AlGaAs interference filter. The fairly close agreement of experiment with theory and the low absorption indicate that much higher finesse should be attainable; however, high-yield production will require tight tolerances on uniformity and absolute thickness. ALE might be a suitable approach to achieving them. For high-speed devices, constraints on cavity buildup time are likely to limit F to about 100 unless other materials are used. An F of 100 is still an order of magnitude larger than the finesse for previously demonstrated GaAs microresonators[12]; so a factor ten reduction in their activation energies should be realizable independent of further size reduction or improved materials. This finesse should also be sufficiently high to allow gating operations using a *single* quantum well as the nonlinear medium. It should be possible to construct lasers or modulators for chip-to-chip communication with very low activation energies by taking advantage of such high finesse in microresonators.

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