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E. Garmire

Optical waveguides in single layers of $Ga_{1-x}Al_xAs$ grown on GaAs substrates*

E. Garmire

California Institute of Technology, Pasadena, California 91109

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Efficient low-loss optical waveguides have been made with the growth of only a single epilayer of $Ga_{1-x}Al_xAs$ on GaAs substrates. The AlAs concentration gradient which is grown by liquid-phase epitaxy using thin gallium melts is the cause of the guiding.

We demonstrate a way to obtain good-quality low-loss waveguides in a single layer of $Ga_{1-x}Al_xAs$ grown on a GaAs substrate. These guides exploit the gradient in aluminum concentration which occurs when the layer is grown by liquid-phase epitaxy using thin melts. The advantages of this technique are several. The use of only one melt and the growth of only a single layer means a simpler growth system with smoother resulting surfaces. The gradation in aluminum concentration reduces the thermally induced stresses and confines the light more closely to the surface, an advantage in several applications. The interest in $Ga_{1-x}Al_xAs$ layers lies in its good lattice match with GaAs and its favorable band gap. Our single layers make useful guides for active and passive elements for integrated optical circuits.

We have grown $Ga_{1-x}Al_xAs$ layers under various conditions of liquid-phase epitaxy, analyzed their light guiding properties at 1.15 μm, and compared these with refractive index profiles deduced from electron microprobe results. We have fabricated layers of thickness $T \approx 4$ μm with large aluminum gradients and have demonstrated optical waveguiding with negligible losses in these layers. We have calculated the aluminum concentration gradients expected during growth and the waveguide losses expected for such layers. The results support our interpretation of the low-loss optical waveguides as the result of the gradient in x due to liquid-phase epitaxy using thin melts.

Let us begin the study of guiding in $Ga_{1-x}Al_xAs$ by considering layers with *uniform* x. A conventional lossless dielectric waveguide requires a layer of increased refractive index, so that the light is confined inside the guide by total internal reflection. However, the refractive index of $Ga_{1-x}Al_xAs$ is less than that of GaAs by about $\Delta n = -0.4x$. This means that we must confine light in a guiding layer of GaAs grown on top of a layer of $Ga_{1-x}Al_xAs$, which acts as an isolation layer separating the guide from the substrate. We have grown such layers, 3 μm thick, for distributed-feedback optically pumped thin-film lasers.[1] Any guided light which penetrates the isolation layer into the substrate radiates away as a loss. The coupling of light from the guide through the isolation layer into the substrate may be determined by the overlap of the guided mode in the substrate with the radiation field. This results in an exponential loss coefficient α for guided light of wavelength λ_0:

$$\alpha \approx \frac{\lambda_0^3 h p^2 \sin^2 hT \exp(-2pd)}{\pi^3 n \Delta n^2 T}, \qquad (1)$$

where T is the guide width, d is the thickness of the isolation layer, and h and p are the transverse propagation vectors inside and outside the guiding layer, respectively. This loss is negligible when $x \approx 0.3$ and the isolation layer and guide thickness are greater than a wavelength.

What happens to light propagating in a single uniform layer of $Ga_{1-x}Al_xAs$ on a GaAs substrate? Although there is no total internal reflection because Δn is negative, light propagating at small angles experiences a large grazing incidence reflection at the dielectric interface, and the layer forms a "leaky" waveguide. The weak component which refracts into the substrate upon each reflection results in a lossy propagation. The exponential loss coefficient is[2]

$$\alpha = \lambda_0^2 / 2(2n\Delta n)^{1/2} n T^3. \qquad (2)$$

We have grown leaky guides with uniform refractive index profiles whose measured losses agree with this value. These guides had $x = 0.6$ and varied in thickness from $t = 4$ μm ($\alpha = 20$ cm^{-1}) to $t = 15$ μm ($\alpha = 0.4$ cm^{-1}). Thicker layers guided with no measurable loss. The loss measurements and observations of guiding were obtained at $\lambda_0 = 1.15$ μm in the same fashion as in earlier publications.[3] Thus 10-μm or thicker single layers of $Ga_{1-x}Al_xAs$ make good low-loss optical waveguides which may be useful for some applications. For most applications, however, thinner guiding layers would be more favorable and require aluminum gradients for low-loss guiding.

Layers grown with uniform aluminum concentration, such as those discussed above, result from liquid-phase epitaxy under near-equilibrium conditions using thick melts. Under many liquid-phase epitaxy growth conditions, however, uniform aluminum concentrations do not in fact result Since the aluminum has a high segregation coefficient, it grows rapidly into the solid phase. If the melt has a finite thickness, a sizable fraction of the aluminum may grow into the crystal, depleting the

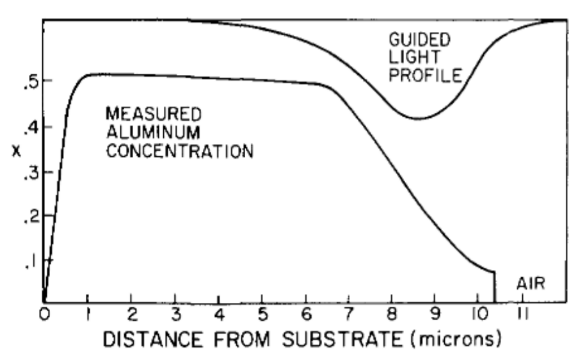

FIG. 1. Measured aluminum concentration profile in a single layer of $Ga_{1-x}Al_xAs$ and resulting guided light profile.

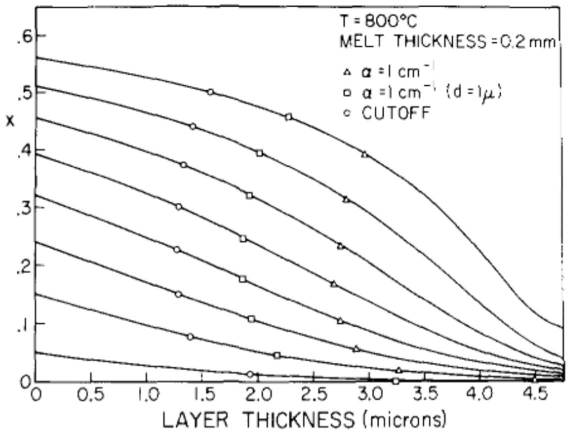

FIG. 2. Calculated aluminum concentration profiles grown at 800 °C by liquid-phase epitaxy from a melt 0.2 mm thick. Squares mark points at which $\alpha = 1\ \text{cm}^{-1}$ when no isolation layer is present. Triangles mark $\alpha = 1\ \text{cm}^{-1}$ for an isolation layer 1 μm thick. Circles mark the lower limit of guiding for triangular profile with infinite isolation layer (waveguide cutoff).

melt of aluminum. This means that the concentration of AlAs decreases and the refractive index increases as the layer grows. The increased refractive index near the surface of the epitaxial layer is just the condition needed for light guiding. We have exploited this concentration gradient to fabricate guides of thickness $T \approx 4$ μm with negligible losses from only a single melt.

We began the growth of a single $Ga_{1-x}Al_xAs$ layer under a thick melt, growing an isolation layer of uniform and high aluminum concentration. Then we partially wiped the substrates clean, growing the rest of the layer with 0.1-mm-thick melt. In this way we obtained isolation layers between 2 and 7 μm thick and guiding regions with a graded aluminum profile between 3 and 8 μm thick. A typical example of an electron microprobe measurement of Al concentration and the resulting guided light profile, drawn to scale, is shown in Fig. 1. Observe that the gradient in aluminum concentration confined light propagation to the region near the surface only. This guide was measured to have a loss of $< 1\ \text{cm}^{-1}$.

Light propagation in these guides is technically leaky since the substrate has the highest refractive index. However, the relative increase in refractive index near the surface confines most of the light to the guiding region, and only that which penetrates into the substrate will radiate as a loss. We calculate the loss for such a guide in a fashion analogous to Eq. (1). The triangular refractive index profile causes a light distribution inside the guide which is an Airy function[4] $E(x) \simeq \text{Ai}(\Delta z/T - \zeta)$. Here z is the distance into the crystal from the air interface, Δ is a guide parameter given by $\Delta^3 = \delta n^2 (2\pi T/\lambda_0)^2$ (where δn^2 is the height of the triangular index profile), and ζ is related to the propagation vector β by $\zeta\Delta^2/t^2 = (n^2 + \delta n^2)(2\pi/\lambda)^2 - \beta^2$. By calculating the overlap of the exponential tail of the guided mode with the radiation modes in the substrate, of increased refractive index Δn^2, we obtain the exponential loss coefficient

$$\alpha = \frac{4\lambda_0 \sigma \delta n^2 \gamma\, \text{Ai}^2(\gamma)}{\pi n \Delta n^2 T} \exp\left(-2\sqrt{\gamma}\, \frac{\Delta}{T}\, d\right), \qquad (3)$$

where $\sigma^2 = \Delta n^2 (2\pi/\lambda_0)^2 - \gamma\Delta^2/T^2$ and $\gamma = \Delta - \zeta$. From this equation the loss of any triangular guide can be calculated. For the guide shown in Fig. 1 ($\delta n^2 = 1.1$, $T = 4$ μm), the guide parameters are $\Delta = 23$ and $\gamma = 21$, and Eq. (3) gives negligible loss even when $d = 0$. Thus the losses of a 4-μm guide with aluminum gradient are so low that an isolation layer is not needed to make a good guide.

We shall now verify our assertion that this large aluminum concentration gradient can be expected from liquid-phase epitaxy. We have calculated the expected growth profile for different melt thicknesses using the previously determined thermodynamic properties of the ternary melt.[5] The calculations assume equilibrium growth conditions, in which the temperature uniquely determines the relative concentrations of gallium, aluminum, and arsenic in the melt, as well as the fraction x of AlAs grown. The change in concentrations which occurs from the growth out of a finite melt of a layer of thickness dz results in a new equlibrium temperature and in a new value $x - dx$. The iteration of this procedure determines the aluminum concentration profile.

We have performed this analysis by computer for a number of initial growth conditions. Typical results are shown in Fig. 2. This assumes a melt 0.2 mm thick and an initial growth temperature of 800 °C. From the relation between aluminum concentration and relative refractive index, these aluminum concentration profiles represent refractive index profiles which can be seen to be roughly triangular. Using Eq. (3), we can determine the loss of any thickness guide. We have marked with triangles on the graph the points where $\alpha = 1\ \text{cm}^{-1}$; any guides thicker than those will have negligible loss.

The introduction of an isolation layer of thickness d, such as we grew in our experiments, will lower the losses still further, allowing thinner guides to be used. The squares in Fig. 2 represent the points at which $\alpha = 1\ \text{cm}^{-1}$ for a 1-μm isolation layer. Thicker isolation layers will allow even thinner guides to be used with negligible loss until a thickness corresponding to the circles is reached, which represents waveguide cutoff for the triangular guide. Guides thinner than this will not confine light at all. These numerical results verify the usefulness of the thin-melt technique for growing ~2-μm guides with reasonable melt thicknesses.

We have demonstrated experimentally and theoretically a method for producing waveguides in a single layer of $Ga_{1-x}Al_xAs$ with refractive index gradients due to the aluminum depletion during growth from thin melts. We expect this technique to be a useful tool for building planar optical circuits. Finally, we suggest that these techniques may be extended to other liquid-phase-epitaxial systems.

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