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Gallium-Diffused Waveguides in Sapphire

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Abstract

The realisation of Gallium-diffused planar waveguides in sapphire is reported. Their characterisation is discussed along with their potential application for the fabrication and optimisation of active devices in sapphire.

Introduction

In earlier work, titanium was diffused into sapphire to realise channel waveguides and waveguide lasers [1]. Titanium was incorporated into sapphire by diffusion, and the spectroscopy of the diffused region was found to be very similar to that of a high-quality bulk-doped crystal [2]. However, the index elevation, Δn, achieved for titanium concentrations appropriate for the realisation of efficient lasers is low, of order 10^{-4}, resulting in large modal spotsizes and, consequently, limiting minimisation of the pump power threshold. Further, the realisation of active integrated optical circuits with low-loss waveguide bends on a small chip requires a larger index change. In this paper the realisation of gallium-diffused waveguides in sapphire with Δn greater than 5×10^{-3} is reported. Rare-earth diffusion in lithium niobate combined with titanium-diffused waveguides has led to a wide range of multi-functional waveguide laser devices [3]. In a similar way, it is expected that titanium and gallium can be combined in sapphire, as the active and waveguide ion respectively, leading to the fabrication of low-threshold broadly tunable waveguide lasers. The gallium-diffused waveguides presented here exhibit a much smaller mode size than titanium-diffused waveguides in sapphire. This is expected to lead to a much reduced threshold [4] and enable the integration of passive and active circuits.

Diffusion of Gallium in Sapphire

Four samples were prepared to determine the diffusion coefficient of gallium in sapphire. Square samples of side 1 cm were cut from a 0.5mm thick c-cut sapphire wafer, optically polished on one face. Gallium oxide of thickness 50nm was deposited on all samples by thermal evaporation, following which each sample was annealed in argon for between 1 and 4 hours at temperatures between 1400°C and 1600°C. Diffusion profiles were measured by Secondary Ion Mass Spectrometry (SIMS), and the diffusion profile obtained for a sample diffused at 1600°C is shown in Figure 1, from which the diffusion coefficient at this temperature was estimated to be $(3.3\pm0.2)\times10^{-17}$ m^2s^{-1}.

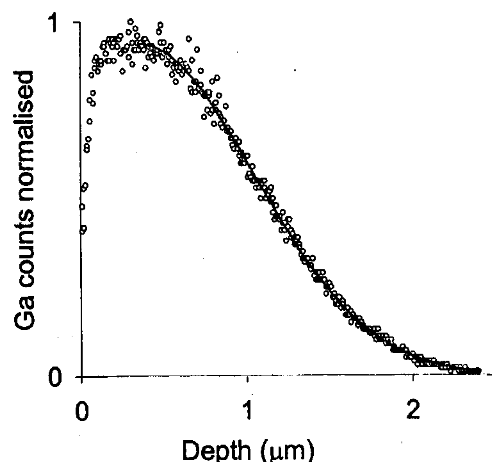

Figure 1. Gallium diffusion profile

Waveguide fabrication

Two sets of waveguide samples were fabricated; the first to establish the effect of increasing diffusion time upon waveguide properties and the second to study the effect of varying gallium oxide source thickness. All diffusions were carried out in an oxygen atmosphere at 1600°C with samples prepared as described above. The first set of four samples to be fabricated were coated with 60±5nm gallium oxide and diffused for 6, 9, 10 and 16 hours. The second set of four samples were coated with 60±5, 90±5, 130±7 and 200±10nm gallium oxide and were all diffused for 16hrs. According to the classical theory of diffusion, the diffusion depth is expected to have a square root dependence with time and from this the diffusion depth of the waveguide samples can be approximated. The samples diffused for 16 hours are expected to have a depth, defined as 1/e of the peak concentration, of 2.8±0.3μm, where the error is estimated by taking into account uncertainties in the Gaussian fit to the diffusion profile.

Waveguide characterisation

a) Mode size against diffusion time

Two parallel ends of each waveguide sample were polished to optical quality to allow end-face coupling of input radiation and near-field intensity profiles to be measured. The modal intensity profiles for samples with 60nm gallium oxide source thickness, diffused for different times, were measured using a Ti:sapphire laser operating at wavelengths between 700nm and 850nm. Light was launched into the waveguide in the TE polarisation by coupling with a microscope objective lens or with a fibre. The light emerging from the waveguide was imaged on CCD camera using a microscope objective lens. The images were stored in a computer and were analysed with the commercial package Vision XL to obtain quantitative data for the mode profiles.

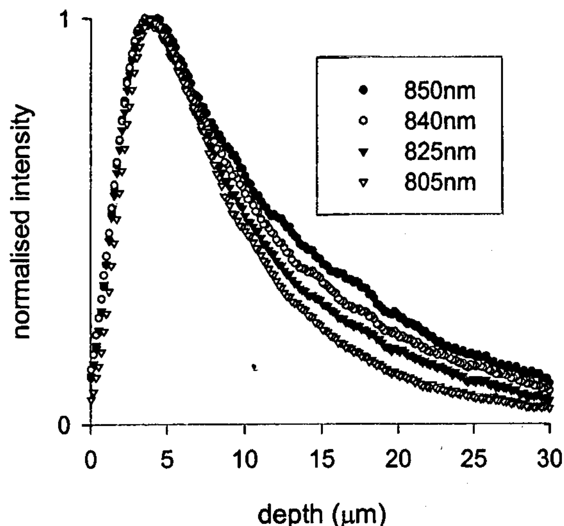

Figure 2 Mode intensity profiles

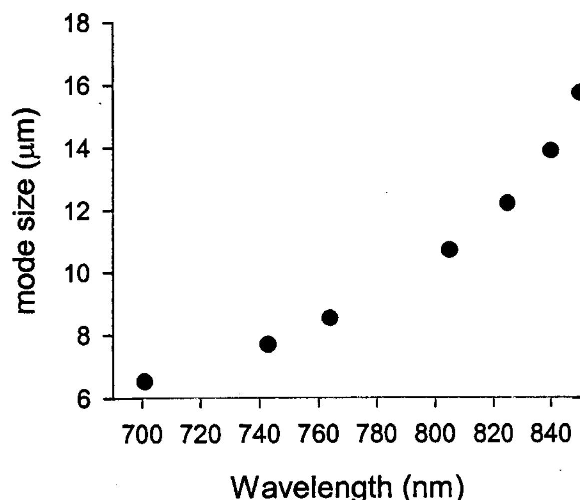

Figure 3 Mode size against wavelength

Assuming that the source is exhausted for each sample, the same number of gallium ions is supplied per unit surface area. Figure 2 shows the mode intensity profiles between 805nm and 850nm for the sample diffused for 16 hours, while Figure 3 shows a plot of the mode size versus wavelength for

this sample over the range 700nm to 850nm. The mode size is calculated from the numerical data as the separation between the points at which the intensity falls to 1/e of the peak intensity. It should be noted that the resolution of the imaging system is estimated to be about 0.5μm in this wavelength range. Figure 3 clearly shows that, for the sample diffused for 16 hours, the mode size increases significantly with wavelength as it approaches cutoff but that it guides over the entire wavelength range. Similar behaviour was observed for the samples diffused for shorter times, except that the sample diffused for 6 hours became cut off at approximately 780nm; the 16 hour sample showed consistently smaller mode sizes over the measured wavelength range.

It is expected that the index elevation of sapphire due to the introduction of gallium will be approximately proportional to the concentration of gallium. Increasing diffusion time will increase diffusion depth while causing the peak concentration to reduce, so that both waveguide depth and Δn are expected to vary. The cutoff wavelength of a waveguide increases with the diffusion depth and with dopant concentration so that, in this experiment, these two parameters are driving the cutoff wavelength in opposite directions.

b) Mode size against gallium oxide source thickness

Having achieved the smallest mode size for waveguides with a 60nm gallium oxide source at 1600°C by diffusion for 16 hours, the effect of varying source thickness was studied using the second set of samples. In this case it was expected that the diffusion depth would remain similar but that the Ga concentration would increase, thereby increasing the Δn. The samples with gallium oxide thickness of 60, 85, 130nm did not show any residue on the surface after the diffusion, indicating that all the gallium had diffused into the sapphire. However, the sample with a source thickness of 200nm gallium oxide showed a residue, indicating that not all the source had diffused into the sapphire. Mode intensity profile measurements were conducted as above but at wavelengths of 633nm and 488nm, using a He-Ne and an argon ion laser respectively. The samples with the 60 and 85nm source thicknesses were monomode at both wavelengths. However the sample with 130nm source thickness was double-moded at 488nm and the sample with 200nm source thickness was double-moded at both wavelengths.

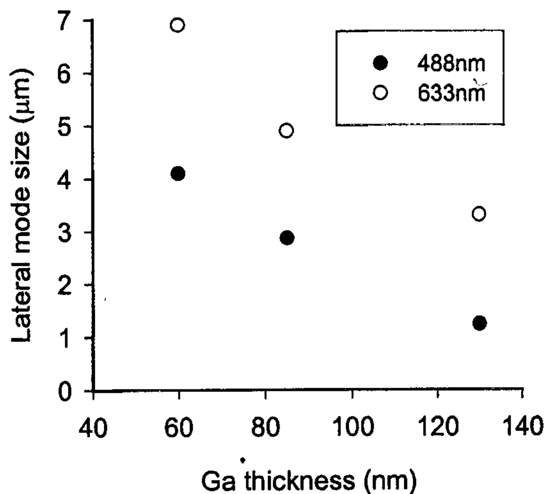

Figure 4. Mode size against source thickness

Figure 4 shows the mode size of the fundamental mode at 633nm and 488nm as a function of gallium oxide source thickness for samples with source thickness between 60 and 130nm. The mode size measurements have not been corrected for the finite resolution of the imaging system, so that they represent overestimates. It is clear that the mode size reduces with source thickness, and that a much smaller mode size has been obtained than that reported to date for titanium diffused waveguides in sapphire [5]. As mentioned above, it is expected that the index change is

approximately proportional to the concentration of the dopant. Therefore as the source film thickness is increased it is expected that the index change will also be increased, resulting in a reduction of mode size for sufficiently shallow waveguides. Figure 4 confirms this expectation and the process yielded the anticipated small mode waists. Furthermore, for this time and temperature, the maximum thickness of gallium oxide source which caused no residue to be left on the sample surface may was found to be between 130 and 200nm. For these conditions, using a source thickness below approximately 150nm is expected to yield low-loss waveguides with maximum surface index elevation.

Estimation of index increase due to gallium indiffusion

A simple homogeneous slab waveguide model was used to make a first estimate of the index increase caused by gallium diffusion into sapphire. While the refractive index profile of a diffused waveguide is not a step function, the slab waveguide model may be used as an approximation. The thickness of the waveguide core was estimated using the diffusion coefficient found above and the diffusion time, making allowance for the offset of the peak concentration from the sample surface. The theoretical modal effective indices for the TE polarisation were found as a function of wavelength and the index elevation, Δn, above the substrate index. The index increase was estimated by comparison with the fundamental mode cutoff wavelength of 780nm for the 6 hour sample, and the minimum refractive index increase was estimated for the 16 hour samples with 130nm and 200nm gallium oxide source from the knowledge that the former was double-moded at 488nm and the latter was double-moded at 633nm. The index changes for the three samples were estimated to be $(2.5\pm0.2)\times10^{-3}$, $(4\pm0.2)\times10^{-3}$ and $(6\pm0.2)\times10^{-3}$ respectively. In order to confirm the validity of the results a commercial BPM package, Selene Pro (Kymata Software) was used in a similar way, but using an index profile similar to the concentration profile shown in Figure 1. In this case the peak index increase for the 6 hour diffused sample was found to be 2.4×10^{-3}. Although only data for TE polarised light are presented here, the TM polarisation yielded similar results.

Conclusions

The realisation of gallium-diffused planar waveguides in sapphire has been demonstrated. A range of gallium oxide source thicknesses and diffusion times at 1600°C have been studied, and the diffusion coefficient and modal characteristics have been determined. It was shown that Ga:sapphire waveguides may be realised with a significant index increase (0.6×10^{-2}), leading to much smaller mode sizes than those obtained with titanium-indiffused sapphire waveguides. Work is now in progress to optimize gallium-diffused channel waveguides which, in combination with titanium co-diffused regions, are expected to lead to low-threshold broadly tunable waveguide lasers.

References

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