Gallium-Diffused Waveguides in Sapphire

V.Apostolopoulos, L.M.B.Hickey†, D.A.Sager and J.S. Wilkinson

Optoelectronics Research Centre, University of Southampton,

Highfield, Southampton, Hampshire, SO17 1BJ, UK

Tel: +44 23 8059 3954 Fax: +44 23 8059 3149 E-mail: va@orc.soton.ac.uk

Abstract

The fabrication and characterisation of gallium-diffused planar waveguides in sapphire is reported. Waveguides were fabricated by diffusion of 60nm – 200nm thick films of gallium oxide into c-cut sapphire at 1600°C for times ranging between 6 and 16 hours. Near-field intensity profiles of the guided modes were measured at wavelengths between 488nm and 850nm, and the surface index elevation was estimated to be up to $(0.6\pm0.02)\times10^{-2}$. Potential applications for low-threshold Ti:sapphire waveguide lasers and for optical integrated circuits with passive and active elements in sapphire are discussed.

† Now with: Southampton Photonics Inc., Phi House, Chilworth Science Park, Enterprise Road, Southampton, SO16 7NS, UK.

Titanium-doped sapphire is a well-known laser medium exhibiting a broad emission spectrum, rendering it ideal for short pulse and tunable operation. A Ti:sapphire waveguide laser exhibiting a low threshold could lead to the realization of miniature, tunable or pulsed, laser sources with potential applications in microscopy, spectroscopy and sensing. 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 similar to that of a high-quality bulk-doped crystal [2]. However, the index elevation, Δn, achieved by titanium indiffusion is limited because the concentration must be kept low for the realization of efficient lasers. This results in large modal spotsizes, limiting the minimization of the pump power threshold and making the fabrication of low-loss waveguide bends for compact integrated optical circuits difficult to achieve. In this paper the realisation of gallium-diffused waveguides in sapphire is reported. In an active device, using two different ions to control the waveguide and the gain medium characteristics independently leads to greater design flexibility. Accordingly rare-earth diffusion in lithium niobate combined with titanium-diffused waveguides has led to a wide range of multi-functional waveguide laser devices [3,4,5]. In a similar way it is expected that titanium and gallium may be combined in sapphire, as the active and waveguide ion respectively, leading to the fabrication of low-threshold broadly tunable waveguide lasers.

Prior to waveguide fabrication, the diffusion of gallium into sapphire was characterized using Secondary Ion Mass Spectrometry. 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 the samples by thermal evaporation, following which each sample was annealed in an argon atmosphere. In all the samples after diffusion there was no residue on the surface, indicating that the gallium source was exhausted. The diffusion coefficient was calculated by fitting a Gaussian function to the gallium concentration profile and at 1600°C was estimated to be $(3.3\pm0.2)\times10^{-17}\ m^2s^{-1}$.

Following determination of the diffusion coefficient, 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 for waveguide fabrication were carried out in an oxygen atmosphere, as with argon atmosphere an index change was not detected. Diffusions were performed at 1600°C with samples prepared as described above. The first set of four samples to be fabricated were coated with 60±5nm of gallium oxide and diffused for different durations. The second set of four samples were coated with different gallium oxide thickness and were all diffused for 16hrs. The change of diffusion atmosphere is likely to affect the diffusion coefficient of gallium into sapphire. However the diffusion coefficient of the argon diffused samples was used in order to estimate the diffusion depth, defined as 1/e of the peak concentration, of the waveguide samples. The parameters of the waveguide samples are given in table 1.

Following diffusion, the end-faces of the samples were polished. Light was launched into one end-face of the waveguide by coupling with a microscope objective lens or with a fiber. The modal intensity distribution at the other end-face was imaged onto a CCD camera using a microscope objective lens. The images were stored in a computer and quantitative data for the mode profiles were obtained using the commercial package Vision XL. The response function of the imaging system used was obtained by imaging a photolithographically defined step. The point spread function of the system was deconvolved from the waveguide mode data and the distortion caused by the imaging system was found to be not significant so that mode size measurements presented have not been corrected.

The modal intensity profiles for samples 1 to 4 were measured in the TE polarisation using a Ti:sapphire laser operating at wavelengths between 700nm and 850nm. In this experiment the dependence of the mode intensity profiles upon wavelength and diffusion time were observed. Assuming that the source is exhausted for each sample, the same number of gallium ions is supplied

per unit surface area. Figure 1 shows the modal intensity profiles over the range 700nm to 850nm for sample 4. Similar behaviour was observed in the TM polarisation. The resolution of the imaging system is estimated to be about 0.5μm in this wavelength range, which is small compared to the mode size. The mode size was calculated from the numerical data as the separation between the points at which the intensity falls to 1/e of the peak intensity. Figure 2 shows the mode size versus wavelength for samples 2, 3 and 4. Data for sample 1 are not included in Figure 2 as it was very close to cutoff in this range of wavelengths, rendering the mode size difficult to quantify. Figure 2 shows that, for samples 2-4 the modal spotsize increases significantly with wavelength. Samples 3 and 4 guide over the entire wavelength range, while samples 1 and 2 became cut off in this wavelength range. Samples 1 and 2 cutoff at 780±10nm and 800±25nm respectively.

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 and cause 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. In this set of measurements we observed that samples with greater diffusion depths exhibited cutoff at longer wavelengths and had substantially smaller modal spotsizes.

The effect of varying source thickness was then studied using the second set of samples (5-8). This set of measurements was performed using an argon ion laser at 488nm and a He-Ne laser at 633nm. Sample 8, with the thickest source film (200nm), exhibited a surface residue after diffusion, whilst samples 5, 6 and 7 did not. Sample 7 was double-moded at 488nm and sample 8 at both 488 and 633nm. Figure 3 shows the mode size of the fundamental mode, at 633nm and 488nm, as a function of gallium oxide source thickness (60 to 130nm). Sample 8 is not included in the graph as due to surface residue and roughness, it exhibited scattering that affected negatively the mode size.

Assuming that the diffusion coefficient is not significantly concentration dependent, the samples are expected to have similar diffusion depths. As the source thickness is increased, the gallium concentration and thus index elevation, will increase. At a given wavelength, increasing waveguide index results in a reduction of the modal width. At 488nm, which is the typical wavelength used to pump a Ti:sapphire laser, the mode size of sample 7 was 1.4μm, significantly smaller than that obtained for Ti-diffused sapphire waveguides, where the concentration was limited by the maximum titanium concentration required for efficient laser operation [6].

The index change obtained by gallium doping can be estimated from these measurements by comparison with waveguide models. First, a simple homogeneous slab waveguide model was used to make an 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 a first approximation. The thickness of the waveguide core was estimated using the diffusion depths included in table 1. For a slab waveguide of this thickness, the theoretical cutoff wavelengths were found for the fundamental and first-order TE modes, as a function of the index elevation, Δn, above the substrate index.

Sample 1, with source thickness 60nm, exhibited cutoff of the fundamental mode at 780nm, yielding an estimated index elevation, Δn, of $(2.5\pm0.2)\times10^{-3}$. Samples 7 and 8, with source thickness 130nm and 200nm, exhibited cutoff of the first order mode above 488nm and 633nm respectively. The index elevation obtained in these samples was estimated from the model by assuming that the first-order cutoff occurred at 488nm and 633nm, yielding an estimated minimum of index elevation of $(4\pm0.2)\times10^{-3}$ and $(6\pm0.2)\times10^{-3}$ respectively. In order to confirm the validity of the results, a commercial finite difference package, Selene Pro (Kymata Software) was used in a similar way, but assuming an index profile similar to the gallium concentration profiles obtained by SIMS. The peak index increase for sample 1 was found to be 2.4×10^{-3}, in good agreement with the slab model.

The realization 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 has been shown that Ga:sapphire waveguides may be realised with an index increase of $0.6x10^{-2}$, leading to much smaller mode sizes than those obtained with titanium-indiffused sapphire waveguides. The maximum thickness of gallium oxide that can be diffused into sapphire without leaving any residue, for this diffusion time and temperature, 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. Work is now in progress to optimize gallium-diffused channel waveguides that may allow ready integration of active and passive devices for wavelength selection and tuning. In addition, the co-doping of titanium and gallium is being investigated where the gallium diffused waveguide will provide a small mode size leading to a low pump power threshold and the titanium concentration may be flexibly adjusted for low loss and efficient operation.

Figure and Table Captions

Figure 1. Modal intensity profiles of sample 4 against wavelength.

Figure 2. Modal spotsize for samples 2-4 against wavelength.

Figure 3. Modal spotsize for samples 5-7 against diffusion source thickness at 488 and 633nm.

Table 1. Diffusion parameters for waveguide samples

References

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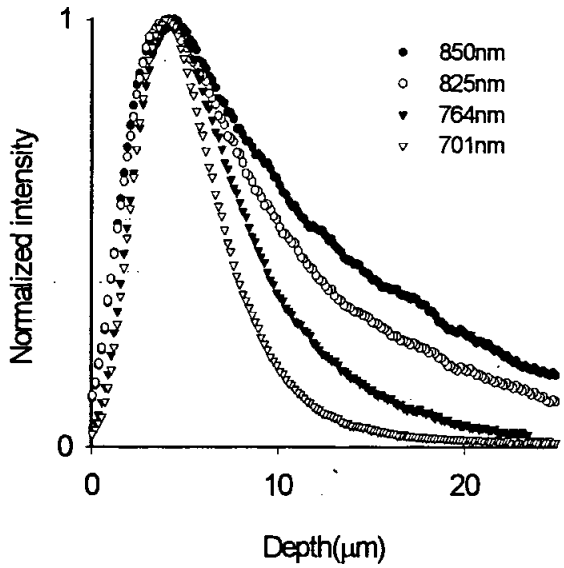
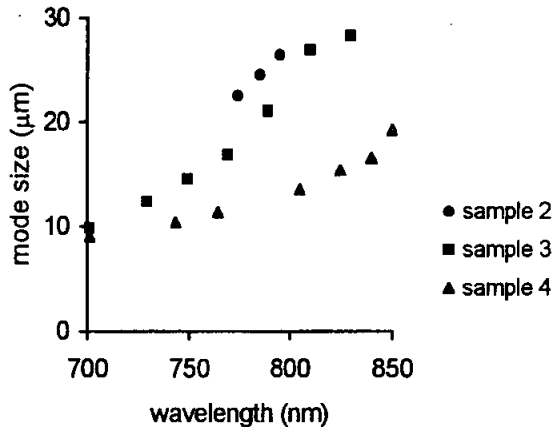
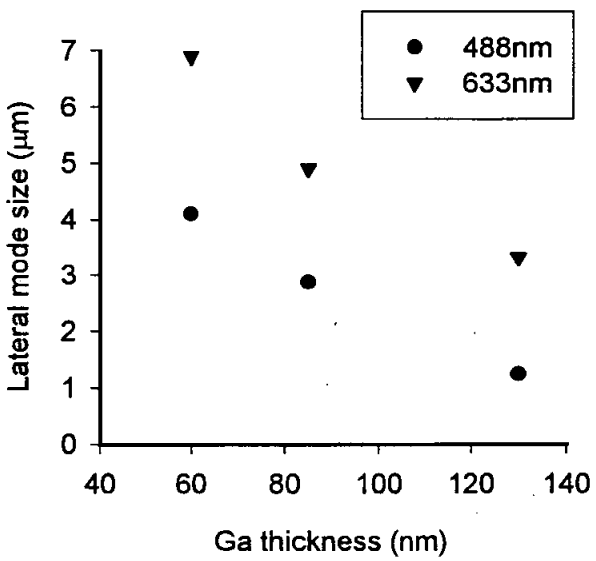

1
0
Normalized intensity
0
10
20
Depth(μm)
850nm
825nm
764nm
701nm


30
20
10
0
mode size (μm)
700
750
800
850
wavelength (nm)
sample 2
sample 3
sample 4


488nm
633nm
Lateral mode size (μm)
0
1
2
3
4
5
6
7
40
60
80
100
120
140
Ga thickness (nm)

Sample number	Time (hrs)	Thickness (nm)	Depth (μm)
1	6	60±5	1.7±0.3
2	9	60±5	2.1±0.3
3	10	60±5	2.2±0.3
4	16	60±5	2.8±0.3
5	16	60±5	2.8±0.3
6	16	90±5	2.8±0.3
7	16	130±7	2.8±0.3
8	16	200±10	2.8±0.3