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Δn = 0.22 birefringence measurement by surface emitting second harmonic generation in selectively oxidized GaAs/AlAs optical waveguides

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We have measured the birefringence enhancement due to lateral selective oxidation of AlAs in GaAs/AlAs optical waveguides. The birefringence was measured by imaging the surface-emitted second harmonic generated by the nonlinear interaction of counterpropagating TE and TM modes. In a waveguide containing a single AlAs layer the birefringence is enhanced from Δn = 0.017 (before oxidation) to Δn = 0.038 (after oxidation). In an oxidized multilayer GaAs/AlAs waveguide, a birefringence as high as Δn = 0.22 is measured. This birefringence is sufficient to phase-match the difference frequency generation of 3–5 μm infrared radiation from two near-infrared pumps. © 1997 American Institute of Physics. [S0003-6951(97)02044-5]

Nonlinear frequency conversion in semiconductor optical waveguides is an attractive approach to optical processing and to the realization of compact tunable sources at still unreached wavelengths. Large nonlinear coefficients of semiconductors, with the possibility of integration with semiconductor lasers and excellent control and quality of structures, make semiconductor-based nonlinear devices good candidates for applications such as wavelength converters in the 1.3–1.5 μm communication window, 1 mid-infrared sources by difference frequency generation 2 and all-optical processors by cascaded second-order interaction. 3 Whereas the GaAs/AlGaAs system is now recognized as an excellent material for third-order nonlinear optics, 4 its application to second-order nonlinear optics has been limited until now by the problem of phase matching, due to the absence of birefringence in these cubic semiconductors. Although quasi-phase matching by ion beam amorphization or wafer bonding was proposed 5 and recently demonstrated 6,7 for waveguide nonlinear frequency conversion, conversion efficiencies are limited because of high scattering losses. A simple way to achieve phase matching is to use the artificial birefringence induced in the guide by the presence of layers with different indices of refraction. 8 However, the GaAs/AlAs system (n = 3.5 and n = 2.9, respectively, in the near infrared) presents an index contrast which is not sufficient to compensate for the dispersion. Recently, we have proposed 9 to use selective wet oxidation of AlAs to obtain high index contrast, high birefringence GaAs/AlAs oxide multilayers. Wet oxidation was shown 10 to selectively convert AlAs into an oxide with refractive index n = 1.6. The oxidation proceeds laterally into an embedded AlAs layer and preserves the quality of the interfaces. It has been applied to provide current and optical confinement for edge 11 and vertical cavity surface 12 emitting lasers, leading to a dramatic decrease in threshold currents, 13–15 and also to enhance Bragg mirrors’ reflectivity and bandwidth. 16 The index contrast in GaAs/AlAs oxide multilayers is sufficient 9,17 to obtain phase matching in second-order nonlinear interaction between TE and TM modes, both for frequency doubling at 1.5 μm and for difference frequency generation of mid-infrared radiation from near-infrared sources. The effect of oxidation on birefringence was first demonstrated 8 in a single polarization waveguide, where the TM mode was cut off at 1.06 μm wavelength owing to a thin AlAs layer converted into oxide. However, no quantitative determination of birefringence was obtained. In this letter we report direct measurement of birefringence in GaAs/AlAs waveguides before and after oxidation. We show that in a waveguide containing a single AlAs layer the birefringence more than doubles after oxidation. In a multilayer GaAs/AlAs oxidized waveguide we demonstrate a huge birefringence Δn = 0.22. To the best of our knowledge this is the highest birefringence ever reported in a GaAs-based waveguide, and it is sufficient to phase-match the difference frequency generation of 3–5 μm radiation from two near-infrared pumps.

Birefringence in GaAs-based waveguides can be conveniently measured 18 by monitoring the second harmonic (SH) fringes created along the guide by the nonlinear interaction 19 of counterpropagating TE and TM modes. When TE and TM fields are simultaneously injected into a GaAs waveguide, they interact with the beams reflected at the exit facet, giving a SH polarization 20

\[ P_{2ω} = 2e_0 \lambda^{(2)}_{xyc}(A^+e^{-jβ_{TE}z} + A^-e^{+jβ_{TE}z}) \]

× \[ (A^+_{TM}e^{-jβ_{TM}z} + A^-_{TM}e^{+jβ_{TM}z}) e^{2jωt} \]

\[ = 4e_0 \lambda^{(2)}_{xyc}rA^+_{TE}A^-_{TM} \cos[(β_{TE} - β_{TM})z] e^{2jωt} + \ldots \]

(1)

where \(A^+, A^-\) are the incident and reflected field amplitudes, \(λ^{(2)}_{xyc}\) is the GaAs second-order susceptibility \((x,y,z\) being the crystallographic axes), and \(r = A^-/A^+\) is the reflection coefficient at the exit facet. Only the mixed terms were retained. This SH polarization [see Fig. 1(a)] radiates two plane waves at a small angle \(θ\) to the surface normal. The angle \(θ\) is imposed by the phase-matching condition in the guide plane: \(sin θ = λ_{2ω}(β_{TE} - β_{TM})/2π\). By imaging the near-field pattern of the SH field along the guide on a charge-coupled device (CCD), the period of the fringes in the square of the nonlinear polarization (1) can be measured, and hence the difference in the propagation constants of TE and TM modes is

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The birefringence was first measured by end-fire coupling a 1.06 mm laser beam into the device. The sample was grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate, and consists of: GaAs substrate/1000 nm Al\textsubscript{0.5}Ga\textsubscript{0.5}As/150 nm GaAs/200 nm AlAs/272 nm GaAs/272 nm Al\textsubscript{0.5}Ga\textsubscript{0.5}As. The light is confined in the waveguide core (272-nm-thick GaAs layer), sandwiched between the Al\textsubscript{0.5}Ga\textsubscript{0.5}As upper cladding and the AlAs lower cladding to be oxidized. Due to its low oxide index the thin oxide layer is very effective in confining the optical mode. The 1000-nm-thick Al\textsubscript{0.5}Ga\textsubscript{0.5}As cladding layer was added to minimize radiation losses, and it was separated from the AlAs-oxide layer by a GaAs layer to protect it against oxidation. Assuming an oxide refractive index $n$(oxide) = 1.6 and a 20% reduction of the oxidized layer thickness, the birefringence at $\lambda = 1.06 \mu m$: $\Delta n = n_{TE} - n_{TM} = 0.0196$ (before oxidation) and $\Delta n = 0.0372$ (after oxidation).

To expose the edge of the AlAs layers for lateral oxidation and to provide lateral optical confinement, a two-step process was used, as discussed in Ref. 9. First, 3-μm-wide, 0.055-μm-deep ridge waveguides were defined by standard photolithography and SiCl\textsubscript{4} plasma etching. Then, 15-μm-wide, 0.75-μm-deep ridges were etched, centered on the waveguides. This leaves the AlAs layers exposed for lateral oxidation. The sample was then placed in a furnace at 430 °C, where it was oxidized in a H\textsubscript{2}O vapor atmosphere, obtained by passing a N\textsubscript{2} carrier through a H\textsubscript{2}O bubbler maintained at 95 °C. The oxidation time was 1 h 10 min. The birefringence was first measured by end-fire coupling a mode-locked Nd:YAG laser (100 ps, 100 MHz, $\lambda = 1.06 \mu m$) in the waveguide and imaging the surface-enhanced second harmonic generation (SESHG) near-field pattern through a 60 mm lens on a CCD, as described above. The input beam was polarized at 45° and the average power measured at waveguide exit was $P_{av} \approx 1 mW$. Figure 1(b) shows the SH fringes, in the unoxidized (upper part) and oxidized (lower part) waveguides. Waveguide lengths are $L = 0.8$ and 1.08 mm, respectively. By counting the number of fringes, we deduce the fringe period: 30.8 μm (unoxidized) and 13.8 μm (oxidized). The corresponding measured birefringence is: $\Delta n$(UNOX) = $(1.7 \pm 0.1) \times 10^{-2}$ and $\Delta n$(OX) = $(3.8 \pm 0.1) \times 10^{-2}$. The measured values compare well with the calculation. The small discrepancy for the unoxidized guide is probably due to imperfect knowledge of AlAs bulk index.

In Fig. 2 we show the far-field images of the SH emission from the unoxidized and oxidized waveguides. The images were taken by placing the CCD in the focal plane of an f = 20 mm lens. The SH images in this case are the Fourier transforms of the near-field images shown in Fig. 1(b). In the direction orthogonal to the lines (which corresponds to the propagation direction) the SH intensity shows the delta function dependence corresponding to the Fourier transform of the intensity dependence in Eq. (1), whereas along the lines the diffraction due to ridge lateral confinement is observed. The ratio of the distance between the two lines in the oxidized and unoxidized case is equal to the ratio of the birefringences in the small angle limit. The birefringence ratio deduced in this way agrees within the experimental error to the values measured in the near-field image.

Next the birefringence in multilayer oxidized waveguides was studied. To maximize the birefringence, a five-layer Al\textsubscript{0.1}Ga\textsubscript{0.9}As/oxide waveguide core was sandwiched between two oxide cladding layers. In this way the optical mode is squeezed between the low index cladding layers and is forced to propagate in the high index contrast, high birefringence core. The sample was grown by molecular beam epitaxy and consists of: GaAs (100) semi-insulating substrate/1500 nm, Al\textsubscript{0.7}Ga\textsubscript{0.3}As/200 nm, Al\textsubscript{0.5}Ga\textsubscript{0.5}As/270 nm, Al\textsubscript{0.7}Ga\textsubscript{0.3}As/20 nm GaAs, Al\textsubscript{0.5}Ga\textsubscript{0.5}As/270 nm, Al\textsubscript{0.1}Ga\textsubscript{0.9}As/62.5 nm, Al\textsubscript{0.5}Ga\textsubscript{0.5}As/300 nm, Al\textsubscript{0.1}Ga\textsubscript{0.9}As/25 nm, AlAs/270 nm, Al\textsubscript{0.1}Ga\textsubscript{0.9}As/62.5 nm, Al\textsubscript{0.5}Ga\textsubscript{0.5}As/270 nm, Al\textsubscript{0.5}Ga\textsubscript{0.5}As/20 nm GaAs. The 200 and 62.5 nm AlAs–oxide layers act as field confining cladding layers, whereas the Al\textsubscript{0.5}Ga\textsubscript{0.5}As layers were added to minimize radiation losses. By the same type of two step processing described above, 3-μm-wide ridge waveguides were defined on the top of 100-μm-wide, 2.6-μm-deep ridges, 17 μm aside from the ridge edge. The AlAs layers were oxidized at 400 °C for 3 h in a water vapor atmosphere. Figure 3 shows a scanning
almost an order of magnitude larger than which was reported. This produced the surface roughness observed in the oxidized sample. The birefringence enhancement due to oxidation should be compared with the one observed in Fig. 2. From the angular distance between the two lines due to oxidation should be compared with the one observed previously in GaAs-based waveguides. It is sufficient for achieving phase matching for the difference frequency generation of 3–5 μm radiation from two near-infrared pumps. Losses in the multilayer oxidized waveguides were measured to be in the 20 dB/cm range at λ = 1.06 μm. However, these losses are related rather to waveguide structure processing than to intrinsic oxide absorption. Indeed, they are essentially due to scattering on the etched ridge sides. By growing a thick cladding layer at the waveguide surface, the waveguided mode has a low overlap with the surface, and scattering losses are lower. Thanks to this, we are currently working with oxidized waveguides which show 8 dB/cm loss. We were able to demonstrate a difference frequency generation of 4 μm radiation in these guides. These results with experimental characterizations of infrared losses (which will be published elsewhere), are beyond the scope of this letter.

In conclusion, we have measured the birefringence in oxidized GaAs/AlAs optical waveguides. The birefringence was deduced by measuring the fringe period and the emission angle in the surface-emitted second harmonic generated by counterpropagating TE and TM modes. Oxidation results in a birefringence enhancement of more than a factor of 2 in a single-oxide layer waveguide and a factor of 17 in a multilayer waveguide. This proves that birefringence in selectively oxidized GaAs/AlAs multilayers can be used for phase-matching in nonlinear frequency conversion.

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