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Selective wet oxidation of AlAs was used to obtain huge birefringence in GaAs/AlAs optical waveguides. A single polarization waveguide was obtained by oxidizing an AlAs layer buried in a GaAs guiding layer. The TM mode is below cutoff due to the high index contrast between the layers. Applications to phase matching in nonlinear optical conversion are envisaged. © *1996 American Institute of Physics.* [S0003-6951(96)01210-6]

Nonlinear frequency conversion in semiconductor optical waveguides is an attractive approach to optical processing and to the realization of compact sources at still unreached wavelengths. Large nonlinear coefficients of semiconductors, possibility of integration with semiconductor lasers, and excellent control and quality of structures make semiconductor-based nonlinear devices potentially very well suited to applications such as wavelength converters in the 1.3–1.5 μm communication window,[1] midinfrared 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 this cubic semiconductor. 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.[5] However, the GaAs/AlAs system ($n \approx 3.5$ and $n \approx 2.9$, respectively, in the near-infrared) presents an index contrast which is not sufficient to compensate for the dispersion. Recently, a wet oxidation technique was developed[6] to selectively convert AlAs into an oxide with refractive index $n \approx 1.6$. 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[7] and vertical cavity surface[8] emitting lasers, leading to threshold currents as low as 8.7 μA,[9] and also to enhance Bragg mirrors' reflectivity and bandwidth.[10] We propose to use this low index oxide to enhance birefringence in a GaAs/AlAs waveguide in order to obtain phase matching between TE and TM modes. As a first demonstration of the huge birefringence obtainable in these structures, we have realized a single polarization waveguide, where the TM mode is well below cutoff at 1.06 μm wavelength due to a thin AlAs layer converted into oxide. We have characterized oxidation by secondary ion mass spectroscopy (SIMS), measured waveguide properties (coupling and losses) of oxidized guides and compared to the unoxidized case.

The sample (see inset in Fig. 1) consists of a multilayer GaAs/AlGaAs/AlAs structure, grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate. The substrate of the waveguide is constituted by a 4 μm thick $Al_{0.2}Ga_{0.8}As$ layer. The core consists of three layers: 0.27 μm of GaAs, 0.1 μm of AlAs, and 0.3 μm of GaAs. The cladding is a 1 μm thick $Al_{0.2}Ga_{0.8}As$ layer. A 100 Å GaAs cap layer is added on the top of the structure. The guide before oxidation supports only TE_0 and TM_0 transverse modes in the near-infrared. Figure 1 shows the calculated effective refractive index in the guide as a function of wavelength, for TE_0 and TM_0 modes before and after oxidation. We assume the oxide refractive index $n(\text{oxide}) = 1.6$ and a 70% reduction of the oxidized layer thickness.[6] The high index contrast between GaAs and the oxidized AlAs layer enhances the birefringence by about a factor of two, so that in the oxidized guide the TM_0 mode is cutoff at a much smaller wavelength than the TE_0 mode.

In order to expose the edge of the AlAs layer for lateral oxidation and to provide lateral optical confinement, a two-step process was used. First, ridge waveguides 4–12 μm wide and 0.67 μm deep were defined by standard photolithography and $SiCl_4$ plasma etching. Then, 100 μm wide and 0.9 μm deep grooves were similarly etched, 10 μm set off from a guide edge. This leaves one side of the AlAs layer exposed for lateral oxidation. The sample was then placed in a furnace at 430 °C, where it was oxidized in a H_2O vapor atmosphere, obtained by passing a N_2 carrier through a H_2O bubbler maintained at 95 °C.[6] The oxidation time was 2 h 30 min. Observation by an optical microscope confirmed that oxidation had proceeded about 20 μm laterally, so that the AlAs layer under the ridge was converted into oxide. To

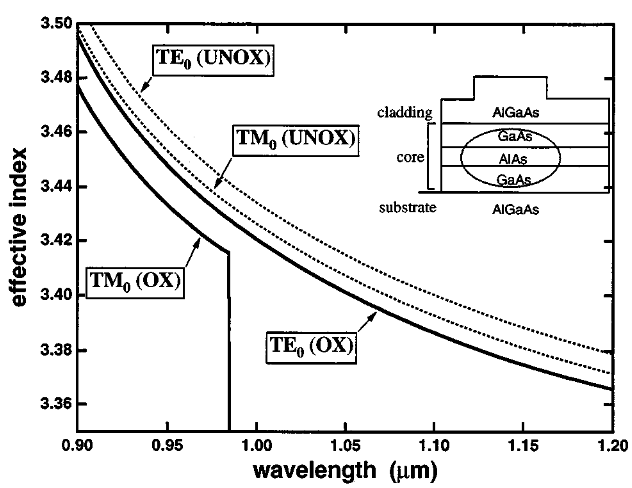

FIG. 1. Effective indices of TE_0 and TM_0 modes in the guide before ("unox") and after ("ox") oxidation. The guide structure is shown in the inset.

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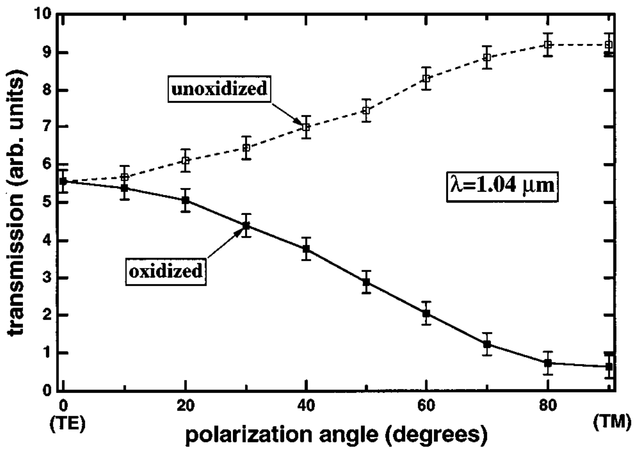

FIG. 2. Transmission in a guide 4 μm wide and 2 mm long as a function of polarization angle at $\lambda=1.04$ μm, before and after oxidation. 0° corresponds to TE mode, 90° to TM mode. Input power is 10 mW.

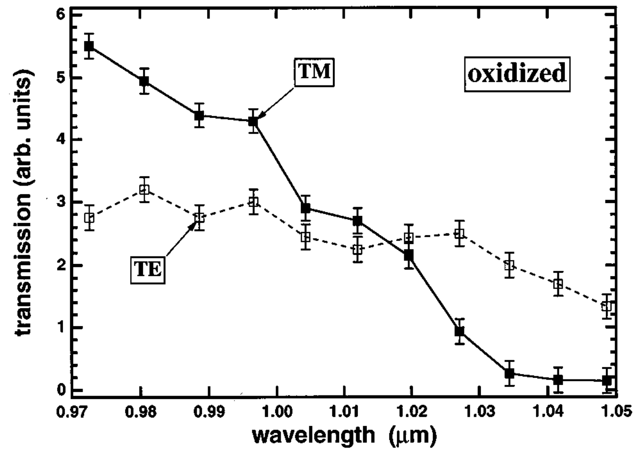

FIG. 3. Transmission in a guide 4 μm wide and 2 mm long as a function of wavelength for TE and TM polarization. Input power is 10 mW.

study the composition of the oxidized layer we performed SIMS measurements on a similar sample having a 0.1 μm AlAs layer embedded between two GaAs layers. After oxidation, an abrupt increase in the oxygen composition and decrease in Al composition are observed in the AlAs layer, while the surrounding GaAs layers remain almost unchanged.

We used end-fire coupling to study the guide transmission as a function of polarization and wavelength. The beam coming from a continuous wave Ti:sapphire laser is chopped, passed through a $\lambda/2$ plate, and then focused by a 40× microscope objective onto the edge of the waveguide. The typical power incident on the sample is 10 mW. The field at the exit facet is imaged either on a CCD camera or on a silicon photodiode. The corresponding optical power is then measured using standard lock-in detection techniques. The guides exhibit one or more lateral modes, depending on the width. All measurements have been performed on single mode guides. Figure 2 shows the transmission of a 4 μm wide and 2 mm long guide as a function of polarization ($\alpha=0°\rightarrow$TE, $\alpha=90°\rightarrow$TM) at $\lambda=1.04$ μm and for constant input power, before and after oxidation. The two curves are normalized to the same value for TE polarization. In the unoxidized guide the output power is higher in the TM polarization, corresponding to lower losses for the TM mode. In contrast, in the oxidized guide there is no more TM mode, as expected from the enhanced index contrast (the small signal measured in the TM polarization is due to the planar mode propagating in the unoxidized part of the structure). To confirm that the absence of the TM signal is related to refractive index change and not to increased losses, we measured the TE and TM transmission for different wavelengths. The variation of the output power in the oxidized guide as a function of wavelength is reported in Fig. 3 for the two polarizations. The input power was kept constant and the coupling conditions reoptimized for each wavelength. While the TE power is roughly constant with wavelength, apart from small Fabry–Perot fringes, the TM power decreases steeply with increasing wavelength, the corresponding mode being completely below cutoff at $\lambda=1.04$ μm. The cutoff appears to take place at a somewhat greater wavelength than the value $\lambda=0.98$ μm calculated above. This can be due to incomplete oxidation of the AlAs layer or to a slight error in the layer thicknesses.

Losses in the waveguides were measured using the Fabry–Perot fringes method.[11] Instead of changing the effective index in the guide by varying the sample temperature, the wavelength of the incident beam was continuously varied and the transmission in the guide deducted from the resulting fringes in the output signal. Typical losses in guides with freshly cleaved edges were in the range of 15 db/cm at $\lambda=0.98$ μm, both for oxidized and unoxidized guides. In our case the Fabry–Perot fringes method tends to overestimate losses, since oxidation of AlAs at guide facets exposed to air reduces the facet reflectivity and thus the fringe amplitude. Reduction of this amplitude with time was observed, whereas the average transmitted power remained constant. This effect is more important for the unoxidized guides, so we expect losses in the unoxidized guide to be somewhat lower than the measured value. Losses in our guides are high due to scattering at ridge edges and at interfaces between layers. These interfaces presented a characteristic anisotropic residual roughness typical of thick $Al_{0.2}Ga_{0.8}As$ layers grown under these conditions. The fact that losses are not significantly increased after oxidation confirms that the oxidation process preserves the quality of interfaces and does not create scattering centers, as confirmed by preliminary high resolution transmission electron microscopy observations.

Let us now discuss some applications of oxidized guides. The birefringence in our sample is about 0.02 at $\lambda=0.9$ μm. This value is limited by the presence of the AlGaAs cladding, which was added to the structure to reduce losses. In a similar guide with no such cladding the birefringence is as high as 0.1. It can be made even higher by stacking many AlAs-oxide layers. We have calculated that a guide with two oxidized layers would allow phase matching for difference frequency generation of 8 μm radiation from two orthogonally polarized 0.9 μm and 1.06 μm pumps. Moreover, second harmonic generation from 1.5 μm pumps can be phase matched using an AlGaAs/oxide multilayer. Phase matching of these nonlinear conversion processes in a material with such high nonlinear coefficients as GaAs would represent a major advance in the field of guided wave nonlinear optics. Moreover, oxidation can prove useful whenever one is willing to engineer the shape of the field in the guide, for instance to optimize mode overlap or to severely confine the field in the core layer. Also, an oxidized AlAs layer less than 1 μm thick can replace several microns of AlGaAs as a guide substrate. In all these cases, use of a low index layer embedded in the structure adds a degree of freedom in the design of the guide.

In conclusion, we have demonstrated the use of selective oxidation of an AlAs layer in a GaAs/AlGaAs guide to increase the birefringence. The guide was designed so that after oxidation the TM mode was pushed below cutoff at $\lambda=1.04$ μm by the high index contrast between the layers. This was confirmed by measuring the TE and TM transmissions at different wavelengths. Measured losses were high due to the interface scattering by the residual roughness of the sample. Applications to phase matching in nonlinear optical conversion were suggested.

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