1 May 1998

OPTICS COMMUNICATIONS

ELSEVIER

Optics Communications 150 (1998) 97–100

Potential for size reduction of AlGaAs optical channel waveguide structures fabricated by focused ion beam implantation and oxidation

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Received 27 October 1997; revised 15 January 1998; accepted 20 January 1998

Abstract

Optical channel waveguides formed by focused ion beam (FIB) implantation-induced mixing of AlGaAs multiple quantum well structures and subsequent oxidation of the mixed regions have the potential of significantly reducing the size of integrated photonic waveguide structures. Since FIB implantation is a direct write process characterized by nanoscale precision, we suggest its use for forming channel waveguides having nanoscale (submicrometer) widths. Calculations presented for such channel waveguides show reductions in size by at least an order of magnitude are possible for directional couplers and other structures involving curved channel waveguide sections. Such size reductions would allow the realization of significantly higher levels of device integration than are now currently possible. © 1998 Elsevier Science B.V. All rights reserved.

PACS: 42.82.E
Keywords: Integrated optics; Semiconductor waveguides; Semiconductor superlattices; Ion implantation; Ion beam lithography

1. Introduction

A major reduction in the size of optoelectronic integrated circuits (OEICs) can be achieved by implementing small radius waveguide bends which require strong optical confinement for low loss. This necessitates a high core-cladding index contrast which has typically been achieved by using deeply etched waveguides [1]. Deep etching, however, can lead to high scattering loss and results in non-planar surfaces, which can be detrimental when further processing of an integrated optic chip is required. Strong confinement also implies that single-mode waveguide widths are reduced to the point where the abilities of conventional lithography are strongly taxed. A more subtle effect is the length increase required in evanescent coupling devices such as directional couplers. This limitation can be overcome if the coupling guides could be placed in close proximity with nanometer scale precision. Thus, the ability to pattern photonic waveguide structures with significantly smaller dimensions and higger precision than are found in conventional lithographically fabricated structures is required to achieve a significant reduction in OEIC size, thereby allowing the realization of higher levels of device integration, and consequently enhancing functionality.

Impurity-induced disordering (IID) of superlattice layers by diffusion to define regions of lower effective index has been accomplished [2]. This technique can produce deep disordered regions with a large index contrast, about 1%. However, as the waveguide regions are protected from disordering by a patterned diffusion mask, feature dimensions are limited by standard lithographic techniques. Recently, growth of quality AlGaAs native oxides with re-

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PII S0030-4018(98)00043-1

fractive index $n_{ox} \approx 1.55$ have been demonstrated [3]. Waveguides with high core-cladding index contrast have been formed by oxidizing a cladding region which has been disordered by IID [4]. Low loss transitions with tight bend radii have been fabricated but channel widths were still limited to values greater than one micrometer because of the use of masks and conventional lithography [5].

We have previously demonstrated fabrication of optical channel waveguides in AlGaAs multiple quantum well (MWW) structures utilizing focused ion beam (FIB) implantation to induce quantum well mixing and thus provide optical confinement [6,7]. Because FIB implantation is an inherently direct-write technique, obviating the need for masks and lithography, and since this implantation technique can define patterns with nanoscale precision, its use to fabricate channel waveguide structures such as curved sections, offsets, directional couplers, and Mach-Zehnder interferometers is highly desirable. To date, a drawback of FIB implantation disordering has been the small index contrast value (typically a tenth of a percent) achieved between the waveguide and cladding. This is because only a small number of superlattice layers can be disordered, due to the small implantation penetration depth, and consequently the minimum radius of low loss bends fabricated by this technique is limited.

We are proposing to combine the attributes of high index contrast native oxide clad waveguides with the precision of direct write FIB implantation. Selective oxidation of FIB implanted mixed regions can provide a low index cladding, thereby greatly increasing the core-cladding index contrast in comparison to FIB disordering alone. At the same time, by using FIB, the precision limitations of conventional lithography are avoided. To demonstrate the viability of the FIB implantation-oxidation process, we first consider the theoretical requirements of low loss, single mode, curved optical channel waveguides. We then discuss the example of a directional coupler, and demonstrate that fabrication of nanoscale structures using oxidation of FIB implantation disordered regions has the potential capability of reducing the size of conventional integrated photonic structures by at least an order of magnitude.

2. Theory

Optical channel waveguide widths of a few micrometers have been typical, easing the lithography requirements for defining these structures over long lengths. The largest value of the channel waveguide width for which single mode propagation is maintained, i.e., the single mode width w_{sm}, is given in the effective index approximation as [8]:

$$w_{sm} = \frac{\lambda}{2\left(n_{e2}^2 - n_{e1}^2\right)^{1/2}}, \tag{1}$$

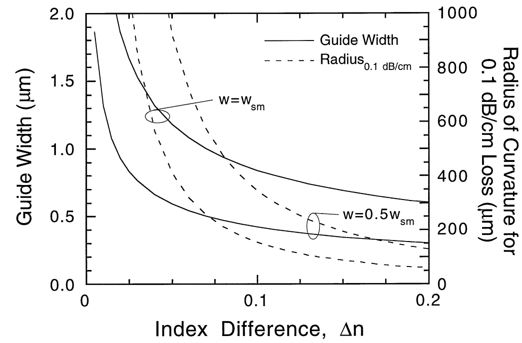

Fig. 1. Variation of single mode channel waveguide width (solid line) and bend radius required for a 0.1 dB/cm bending loss (dashed line) as a function of core-cladding effective index difference, Δn, for the TE_0 mode using $n_{e2} = 3.05$ at an excitation wavelength of $\lambda = 1.3$ μm. The radius of curvature is calculated at each value of Δn using the corresponding single mode channel waveguide width, w_{sm}. Also shown are values of $w_{sm}/2$ and corresponding values of required bend radius.

where n_{e2} is the planar effective refractive index in the channel core region, n_{e1} is the planar effective refractive index in the channel cladding region, and λ is the excitation wavelength.

Variation of single mode width for the TE_0 mode for a representative AlGaAs channel waveguide with $n_{e2} = 3.05$ and $\lambda = 1.3$ μm is shown as the solid curve in Fig. 1, where the effective index difference between the channel core and cladding, Δn, is defined as

$$\Delta n = n_{e2} - n_{e1}. \tag{2}$$

At small values of Δn waveguide single mode widths of a few micrometers are compatible with conventional photolithographic techniques. However, as the value of Δn becomes greater than about 0.1, single mode waveguide widths become substantially less than a micrometer.

Tighter optical confinement, made possible by achieving higher values of Δn, becomes particularly important for curved channel waveguides, where bending loss and changes in the mode field profile are introduced [9], and allows the reduction of bend radius. For a curved symmetrical planar waveguide having a constant radius of curvature R, Marcuse obtained an expression for the exponential power attenuation coefficient due to bending loss [10,11]. Applying this result to channel waveguides and using effective index notation, this attenuation coefficient α_{bend} is

$$\alpha_{bend} = \frac{q^2}{k^3 n_e(1 + qw/2)} \frac{h^2}{n_{e2}^2 - n_{e1}^2} \times \exp(qw)\exp\left(-\frac{2q^3}{3n_e^2k^2}R\right), \tag{3}$$

where

$$q = k\left(n_{\mathrm{e}}^2 - n_{\mathrm{e}1}^2\right)^{1/2}, \quad h = k\left(n_{\mathrm{e}2}^2 - n_{\mathrm{e}}^2\right)^{1/2}, \quad k = 2\pi/\lambda,$$

and n_{e} and w are the channel waveguide effective refractive index and width, respectively. We use Eq. (3) to calculate the channel waveguide radius of curvature required to keep waveguide bending loss to the low value of 0.1 dB/cm as a function of Δn, where the waveguide width is the single mode width at the corresponding value of Δn. This result is plotted as the dashed curve in Fig. 1. By increasing contrast to $\Delta n \approx 0.1$ the required radii are of the order of 100 μm, at least an order of magnitude smaller than for conventional integrated photonic device structures or optoelectronic integrated circuits (OEICs) [1].

There is no lower limit on the channel width but, for a given Δn, the guided mode becomes less confined as the width decreases. Channel widths are often chosen to be slightly smaller than the single mode width in order to maintain single mode operation and minimize bending loss. However, when using a guide width of one half the single mode width, the required radius increases only by approximately a factor of two. To illustrate this, we also show in Fig. 1 values of $w_{\mathrm{sm}}/2$ and the corresponding values of the required radius of curvature for low loss (0.1 dB/cm).

3. Compact directional coupler with nanoscale gap

To illustrate that the FIB implantation-oxidation process can yield sufficiently large values of Δn, consider a 60 period superlattice structure, composed of 5 nm GaAs wells and 5 nm AlAs barriers, on an AlAs lower cladding, at an excitation wavelength of $\lambda = 1.3$ μm. Using effective index calculations, the planar effective index is computed to be $n_{\mathrm{e}2} \approx 3.05$. FIB implantation forms the cladding by disordering the upper superlattice layers. A rapid thermal anneal step selectively mixes these implanted layers resulting in a 250 nm deep region of approximately 50% aluminum concentration. Oxidation of this mixed material changes its index to $n_{\mathrm{ox}} \approx 1.55$, and changes the effective index of the cladding region, providing an index contrast from the unimplanted core of $\Delta n \approx 0.08$. We further assume that some (e.g. 15) of the AlAs layers in the core region will become oxidized through lateral diffusion [3]. Although this reduces the index contrast to $\Delta n \approx 0.05$, this is still a factor of 20 greater than the contrast achieved by FIB induced mixing alone.

Fig. 1 shows that this large value of Δn can greatly reduce the spatial extent of various photonic waveguide structures by allowing smaller radius bends. However, large values of Δn often lead to significantly increased lengths for directional couplers, so that a savings in overall space may not be achieved [12]. This problem can be avoided for directional couplers by using nanoscale gaps between coupling channels, gaps which can be accurately defined by FIB. For example, Fig. 2 shows the results of a beam propagation method simulation [13] of a directional coupler, using $n_{\mathrm{e}2} = 3.05$, $\Delta n = 0.05$, a channel width of 0.6 μm, and a coupler gap of 0.6 μm. Nearly 100% coupling is achieved in a coupling length of only 60 μm, a value more than an order of magnitude smaller than for directional couplers in conventional OEICs. Both this result and the results shown in Fig. 1 are strong quantitative indications that, by using FIB implantation and subsequent selective oxidation resulting in nanoscale channel widths and gaps, considerable potential exists for significantly increasing the level of photonic integration.

The precision afforded by the FIB direct write process could also improve performance in another way. The throughout loss indicated in Fig. 2 of about 0.15 dB is primarily caused by transition loss as the optic field traverses regions of varying curvature, and not by bending loss induced by the high curvature. Offsets can alleviate this problem to some extent by improving mode match across discontinuous waveguide segments [9,14]. However, even raised cosine bends, which are becoming more common and have no discontinuous changes in radius of curvature, still suffer transition loss during curvature change due to non-adiabatic transformation of the extremely distorted modes. The results of a recent theoretical study that showed asymmetrically tailored transverse and longitudinal waveguide index profiles could reduce bending loss, could also be used to reduce this type of transition loss [15]. The precision afforded by direct write FIB

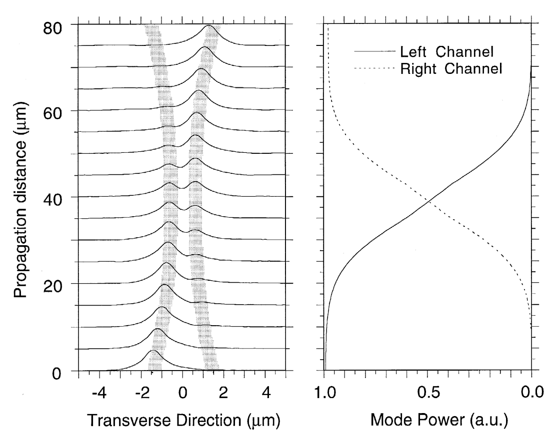

Fig. 2. Compact directional coupler beam propagation simulation: (a) Field profiles along the directional coupler (the shaded regions correspond to the location of the channel waveguides), (b) mode power as a function of propagation distance. Channel waveguide width of 0.6 μm, coupler gap of 0.6 μm, core index, $n_{\mathrm{e}2} = 3.05$, $\Delta n = 0.05$, and excitation wavelength $\lambda = 1.3$ μm.

implantation would allow the definition of the required asymmetric waveguide index profiles, enabling a further reduction of bend radii and lowering transition loss.

4. Conclusion

In summary, we have considered the potential for reducing the size of photonic waveguide structures by utilizing channel waveguides with AlGaAs native oxide claddings formed with submicrometer precision by direct write FIB implantation of AlGaAs superlattice structures. To date, the size of channel structures formed by self-aligned IID and oxidation have been limited to values greater than one micrometer because of the use of masks and conventional lithography [5]. Use of FIB direct writing would overcome this limitation and thus could lead to an additional significant reduction in size of photonic waveguide structures.

FIB implantation disordering allows the mixed regions to be defined with submicrometer accuracy and, by selectively oxidizing these regions in an effectively self-aligned manner, the large values of Δn needed to form channels with strong optical confinement can be achieved while maintaining a planar structure. The strong optical confinement of these waveguides allows the fabrication of low loss, small radius bends, but also requires submicrometer widths to achieve single mode operation. A beam propagation method simulation of a directional coupler formed with such waveguides yielded a coupling length of 60 μm, a coupling length that is more than an order of magnitude smaller than for conventional present-day OEICs. Although the coupling gap of 0.6 μm would be difficult to achieve using conventional lithography, it is well within the range of precision for FIB implantation. Furthermore, the ability of FIB implantation to tailor both transverse and longitudinal waveguide index profiles could further improve component performance. These results indicate that, by using nanoscale channel waveguides formed using FIB implantation processing, there exists significant potential for reducing the size of photonic device structures, achieving a corresponding increase in OEIC density and functionality, and improving overall waveguide performance.

Acknowledgements

This research has been supported in part by the National Science Foundation, Air Force Research Laboratory Materials Directorate, and the Army Research Office.

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