Propagation loss study of very compact GaAs/AlGaAs substrate removed waveguides

JaeHyuk Shin, Yu-Chia Chang and Nadir Dagli*

Electrical and Computer Engineering Department, University of California at Santa Barbara, Santa Barbara, California 93106, USA
**Corresponding author: dagli@ece.ucsb.edu*

Abstract: Very compact GaAs/AlGaAs optical waveguides with propagation loss as low as 0.9 dB/cm at λ=1.55 µm were demonstrated using substrate removal and evaporated Si for index loading. Loss components were identified and minimized through process and waveguide design. Process induced roughness contributed significantly to overall propagation loss. Therefore a low damage process in addition to proper waveguide design is needed for loss minimization.

OCIS codes: (230.7370) Waveguides; (290.5880) Scattering, rough surfaces

References and Links

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1. Introduction

Very compact low loss optical waveguides are essential components for high density and high functionality photonic integrated circuits (PICs). Tight optical confinement due to high index contrast in such waveguides allows the reduction in bend radius without dramatically increasing radiation loss. This helps to increase the integration density. Highly confining optical waveguides can also enhance the performance of individual devices in addition to size reduction. The most common examples of such waveguides are fabricated on Silicon-On-Insulator (SOI) due to high index contrast between SiO_2 and Si [1]. Minimizing propagation loss of such waveguides is desirable. In compact SOI waveguides 0.7 dB/cm loss have been demonstrated [1]. Although SOI technology provide very compact and low loss waveguides, lack of optical gain and linear electro-optic effect in Si limit the performance of components that can be made using such waveguides. Our previous work addressed this issue by forming very compact waveguides in compound semiconductors using substrate removal [8]. These waveguides are very similar to SOI waveguides as far as indices of refraction and dimensions are concerned. They have the added advantage of excellent electro-optic properties of compound semiconductors. Using such waveguides we recently demonstrated highly efficient phase modulators based on current injection [2]. We also fabricated Mach-Zehnder intensity

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modulators with record low V_π values of 0.3 V for 7 mm long electrodes [3]. The propagation loss of these waveguides should be minimized for improved device performance. This paper reports the analysis of the loss components of such waveguides and the approaches taken for loss minimization. This study resulted in submicron thick GaAs/AlGaAs waveguides with propagation loss as low as 0.9±0.4 dB/cm at $\lambda = 1.55$ µm . It is also shown that process induced damage could become a significant loss component and appropriate processing in addition to appropriate design are needed for loss minimization.

2. Optical waveguide design

Figure 1(a) shows the cross sectional schematic of the optical waveguide used. It consists of a GaAs/AlGaAs epilayer removed from its growth substrate and glued onto a transfer substrate using the polymer Benzocyclobutane (BCB). Substrate removal provides a very high vertical index step due to high index of the semiconductor ($n \approx 3.4$) and low index of BCB ($n = 1.53$) and air ($n = 1$). This high index contrast is very similar to that of a SOI waveguide and a submicron epilayer is enough for good optical confinement usually at or above 50% level. Lateral confinement is provided using either a 60 nm $Al_{0.3}Ga_{0.7}As$ or Si layer. Figure 1(b) shows an example of an optical mode for a 1.0 µm wide waveguide with Si loading. The epilayer is grown using molecular beam epitaxy (MBE) and is unintentionally doped. It contains two GaAs quantum wells (QWs). If these QWs are doped, ohmic contacts can be made to them on the sides of the rib away from optical mode and work as buried electrodes that bring external voltages right to the core of the waveguide. This approach is used to fabricate very efficient modulators reported earlier [2-3]. In such waveguides the main loss components are scattering and absorption. At $\lambda = 1.55$ µm absorption is mainly due to free carriers in the QWs if they are doped. In this study doping is not used and we focus on the identification and minimization of scattering loss components.

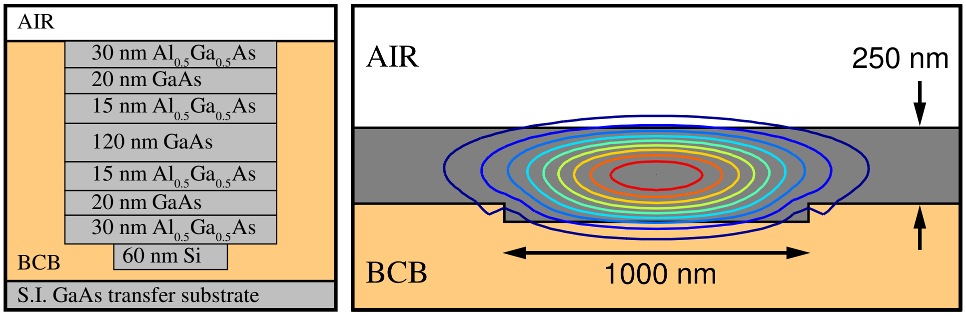

Fig. 1. (a) Cross sectional schematic of the substrate removed waveguide (not to scale) and (b) fundamental TE mode power profile of 1.0 µm wide waveguide with Si loading.

To estimate scattering loss due to surface roughness, we adapt the 2D analysis reported in [6] to 3D waveguides. This allows us to estimate the loss of an interface as

$$\alpha_i = \Gamma_i \left(n_{ci}^2 - n_{si}^2\right)^2 \frac{k_0^3}{8\pi n_{ci}} S_i \qquad (1)$$

A factor of 1/2 was included in (1) to consider only one interface at a time. n_{ci} and n_{si} are the refractive indices of the core and clad material, k_0 is the free space wave number. For example, n_{ci} and n_{si} of interface 1 shown in the inset of Fig. 3(a) are those of Si and BCB respectively. $\Gamma_i = \int \left|U\right|^2 dl_i$ is the overlap of the normalized optical power with an interface where U is the normalized optical mode field distribution. The integration is taken along the length of the interface. S_i is the integrated spectral density function detailed in [6].

Calculations indicate that for L_c less than 50 nm, $S_i \simeq 5.42\sigma^2 L_c$ where σ and L_c are the rms roughness and autocorrelation length of the interface. Then the loss coefficient for an interface is proportional to $\alpha_i \propto \Gamma_i \sigma^2 L_c$. Hence we have two handles to minimize scattering loss. One is to improve the growth, lithography and etching processes to reduce σ and L_c. If we can eliminate etching, σ and L_c directly correlate with lithographic quality and as grown interface quality. Otherwise very smooth etching condition or some way of smoothing an etched surface should be found. Hence high quality lithography and growth are essential for loss reduction. In addition we have control over Γ_i by changing the waveguide design and minimizing the overlap of the optical mode with the interfaces. This is not easy to do in a high index contrast structure shown in Fig. 1(a). A fair amount of power approaching 11 % resides outside the semiconductor for the waveguides discussed in this paper. In addition, for TE modes the main optical electric field component is perpendicular to the rib sidewalls. Due to boundary condition $\varepsilon_{SC} E_{SC} = \varepsilon_{BCB} E_{BCB}$ at the Si/BCB sidewall $E_{BCB} \approx 5E_{SC}$ since $\varepsilon_{SC} \approx 5\varepsilon_{BCB}$. Hence field strength at the Si/BCB interface on the BCB side is enhanced and a significant fraction of the optical power overlaps with the semiconductor sidewalls. This overlap can be reduced by increasing the optical confinement which requires increasing the rib width. The maximum rib width would be limited to single mode operation.

3. Device fabrication

In the initial studies we used patterning and etching of a 60 nm thick $Al_{0.3}Ga_{0.7}As$ layer on top of $Al_{0.5}Ga_{0.5}As$ layer for waveguide definition. The patterning was done using an i-line projection aligner. Figure 2(a) shows the top view of such a waveguide. In this case there is significant sidewall roughness varying between 20 nm and 25 nm. The roughness was due to difficulties both in lithography and etching. Standing wave formation within the photoresist in the i-line stepper created excessive line width variation and poor sidewall definition. Due to the shallow etch depth and etch uniformity requirements, dry etching good quality waveguides was difficult and selective wet etching in citric acid:H_2O_2 was used. This resulted in non-uniform etching of the $Al_{0.3}Ga_{0.7}As$ index loading layer. For waveguides fabricated on SOI wafers, one could perform an oxidation to smoothen the sidewalls [4]. However, this is difficult for GaAs/AlGaAs waveguides. To eliminate these difficulties we used electron beam lithography to improve pattern definition and eliminated the etching altogether. Fabrication of the optical waveguides started with blanket etching the original 60 nm $Al_{0.3}Ga_{0.7}As$ index loading layer in citric acid:H_2O_2 (6:1). Waveguides with width between 1.0 μm and 2.2 μm were written with a JEOL JBX-5DII(U) electron beam lithography system on a photoresist ZEP520. After e-beam evaporating 60 nm thick Si, the patterns were lifted off by immersing the sample in a photoresist stripper 1165. Figure 2(b) shows the top view of such a waveguide. In this case 60 nm lifted off Si layer provides the index loading rather than 60 nm etched $Al_{0.3}Ga_{0.7}As$ layer. The improvement in the sidewall quality is obvious and rms sidewall roughness was reduced to 4 nm. Liftoff has an added benefit that dimensions can be accurately controlled when compared to wet etching. Cross sectional profiles showing the details of the sidewalls and the BCB/semiconductor interface are also shown in Fig. 2(c) and (d). As seen AlGaAs sidewall is sloped due to selective chemical etch used in its fabrication whereas Si sidewall is more vertical. The BCB/semiconductor interface is free of voids. Once the waveguides are defined a mesa etch was performed to isolate individual waveguides. The sample was then bonded upside down to a transfer substrate with BCB and the epitaxial growth substrate was removed.

Two samples were fabricated this way. The only difference between these two samples was the time used for Si liftoff in 1165. The first sample was left in 1165 overnight while the second sample was taken out after 30 minutes. The immersion time in 1165 had a significant effect on propagation loss as will be discussed in the next section. Even though just a 30

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minute immersion results in some good devices yield improves significantly if immersion time increases. This is the reason why an overnight immersion was used initially.

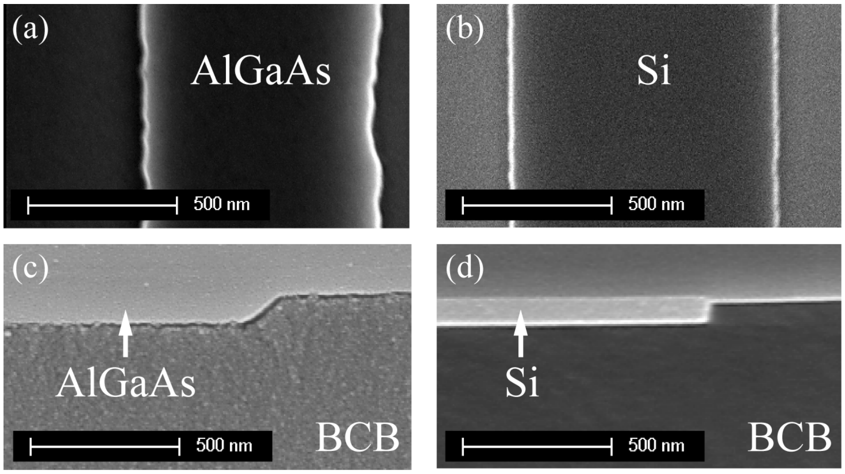

Fig. 2. Top down SEM view of optical waveguide fabricated by (a) etching $Al_{0.3}Ga_{0.7}As$ defined by stepper ($\sigma = 20$ nm) and (b) lifting off Si defined by electron beam lithography ($\sigma = 4$ nm). (c) and (d) shows the cross sectional SEM view for each case.

4. Experimental results and discussion

Measurements were made by coupling the output of a tunable laser into the waveguides with a lensed fiber. Output light from the waveguides were collimated with a microscope objective and projected to a photodetector. Single mode operation was confirmed by checking if the transmission as a function of wavelength fit well to the expected Airy function shape. For waveguides wider than 1.8 μm, multi-mode behavior was observed. For these waveguides measurements were made within the wavelength range where the transmission fitted well to the Airy function dependence [7].

The propagation loss can be found by measuring the ratio of maximum to minimum transmission, $K_T = T_{\max} / T_{\min}$ of waveguides with different lengths and fitting them to the equation below.

$$\alpha_{tot}(dB) = \alpha L - 10\log R = 10\log\left(\frac{\sqrt{K_T}+1}{\sqrt{K_T}-1}\right) \qquad (2)$$

R is the facet reflectivity and L is the length of the waveguide. After each cleave, the facets were inspected under an optical microscope. Only the waveguides with clean facets were measured.

The propagation loss of the waveguides fabricated using i-line projection aligner and $Al_{0.3}Ga_{0.7}As$ etching was about 21 dB/cm. Excessive rms sidewall roughness observed in Fig. 2(a) was the main reason. Such high loss made this fabrication technique impractical. The open and crossed squares in Fig. 3(b) show the measured propagation loss as a function of waveguide width for the waveguides fabricated with e-beam lithography and Si liftoff. The two sets of measurements were from devices fabricated from the identical MBE wafer using the identical fabrication steps except for the time of immersion in 1165 for Si liftoff. Single mode behavior was observed for waveguides as wide as 1.78 μm. For the first sample shown in open squares an overnight immersion in 1165 was used. For this sample the propagation loss was 12 dB/cm at 1.0 μm and reduced to 4.3 dB/cm for 1.78 μm wide waveguides. For the second sample shown in crossed squares immersion in 1165 was only 30 minutes. For this sample loss dropped significantly. The propagation loss was on average 0.9±0.4 dB/cm over a

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wide waveguide width range making such waveguides very attractive for device applications. The measurement result also suggested that the sample surface may have undergone some roughening when immersed in 1165.

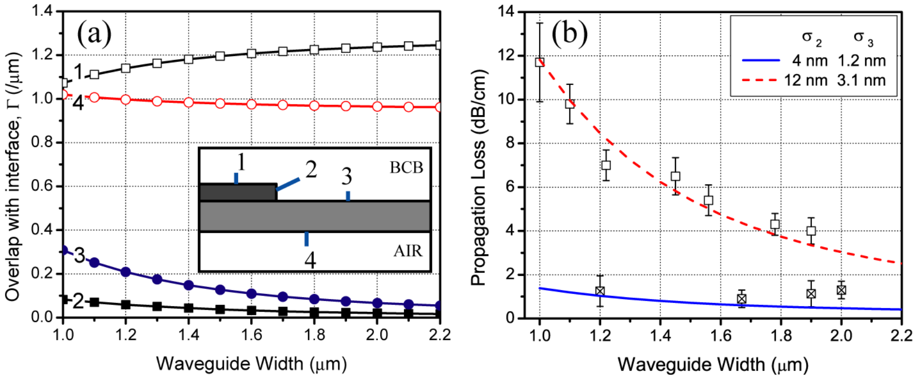

Fig.3. (a) Calculated optical power overlap with interfaces, and (b) calculated and measured propagation loss as a function of waveguide width. Open and crossed squares are measurements for long and short immersion time in the photoresist stripper 1165. Dashed and solid curves are calculations for each case with σ values in the legend.

In order to understand this loss behavior and estimate the loss contribution of the interfaces σ and L_c were measured for each interface. Atomic force microscope (AFM) measurements were used on horizontal interfaces and SEM measurements and image analysis were used on sidewalls. The results are summarized in Table 1 for the interfaces identified in the inset of Fig. 3(a). This table also shows the σ and L_c obtained from AFM measurement on an as grown MBE surface. Interfaces 1 and 4 are almost as good as MBE grown interfaces and are atomically smooth. There are several σ and L_c values given for interface 3. The first one is for the top $Al_{0.5}Ga_{0.5}As$ surface after 60 nm thick $Al_{0.3}Ga_{0.7}As$ was removed using the citric acid:H_2O_2 selective etch. Particles 25 – 35 nm in diameter which are believed to be Al rich clusters are scattered across the top $Al_{0.5}Ga_{0.5}As$ surface after this etch, slightly increasing roughness. These Al rich cluster alone do not contribute significantly to the scattering loss since σ is still less than 1 nm and is very close to that of the bottom $Al_{0.5}Ga_{0.5}As$ interface. However, further processing of this surface increased the roughness significantly. To liftoff Si, the sample was immersed in a photoresist stripper 1165 overnight. The stripper is known to be safe for most semiconductor materials but previous experience suggested that it does etch AlGaAs if only by a small amount. After an overnight bath in 1165, σ increased from 0.9 nm to 3.1 nm. This increase in σ would increase scattering loss from the top $Al_{0.5}Ga_{0.5}As$ by 12 times. Decreasing the immersion time in 1165 to 30 minutes reduced σ to 1.2 nm. Hence the resulting increase in scattering loss would be less than twice of the unprocessed surface.

Table 1. Measured Root Mean Square Roughness σ and Autocorrelation Length L_c of Surfaces shown in Fig. 3(a).

No	σ (nm)	L_c (nm)	Description
0	0.32	14	as grown MBE
1	0.57	10	Si surface
2	4.00	50	Si sidewall
3	0.93	23	top $Al_{0.5}Ga_{0.5}As$ after $Al_{0.3}Ga_{0.3}As$ removal
	1.20	35	top $Al_{0.5}Ga_{0.5}As$ after 30 minute in 1165
	3.10	45	top $Al_{0.5}Ga_{0.5}As$ after overnight in 1165
4	0.62	25	bottom $Al_{0.5}Ga_{0.5}As$

Figure 3(a) shows the fraction of optical power overlap with each interface Γ_i from optical modes found with commercial software. The overlap is highest for the bottom and top

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interfaces since the length along which the optical mode overlaps with these interfaces are much longer when compared with others. The top Si surface labeled 1 in Fig. 3(a) has the highest overlap since Si has the highest refractive index and pulls the optical mode towards itself. The overlap factor for interfaces 1 and 4 does not change much with waveguide width. The overlap factor with interfaces labeled 2 and 3 decreases as waveguide widens since the fundamental mode becomes more confined laterally and less energy resides on the sidewalls and outside the rib.

Figure 3(b) also shows the calculated propagation loss using the formulas provided earlier. According to these calculations the maximum loss contribution from the evaporated Si surface and bottom $Al_{0.5}Ga_{0.5}As$ labeled 1 and 4 in the inset of Fig. 3(a) were less than 0.1 dB/cm. Calculations for the sample fabricated with shorter 1165 immersion shown as the solid curve agrees well with measurements. For the longer 1165 immersion sample, we find that we need to increase the rms roughness of interface 2 from 4 nm to 12 nm to accurately predict the measured loss coefficient. Loss prediction with $\sigma_2 = 12$ nm is in very good agreement with the data as seen in Fig. 3(b). The main reason for this artificial increase in rms roughness is the additional surface roughening near the edge of the Si layer during liftoff due to pitting on the top $Al_{0.5}Ga_{0.5}As$. While the edge may look fine under top inspection there could be a lot of voids and pits under the edge which contributes to scattering. Given these results, it is reasonable to conclude that significant portion of the loss originates from scattering due to the roughness introduced by pitting of $Al_{0.5}Ga_{0.5}As$ in 1165. We could reduce the fabrication induced roughness by using a photoresist that requires less aggressive chemicals for liftoff, such as acetone, or modify the epilayer structure. AFM measurements showed that the surface roughness of the original epilayer which was capped with 5 nm thick GaAs to prevent oxidation of the $Al_{0.3}Ga_{0.7}As$ layer underneath remains unchanged after an 8 hour bath 1165. Hence, utilizing an epilayer with 5nm – 10nm thick GaAs cap layer directly on top of the $Al_{0.5}Ga_{0.5}As$ layer could prevent pitting. Doing so would reduce the surface roughness and associated scattering.

5. Conclusions

In this paper, the propagation loss of very compact waveguides formed by substrate removal was studied. The loss dependence on the waveguide dimensions and interface roughness was also studied by modifying an existing theory. Main loss component is identified as the roughness of the sidewalls. Waveguides fabricated using an optical aligner and chemical etching had excessive sidewall roughness and loss coefficients were higher than 20 dB/cm. Switching to electron beam lithography and Si evaporation to form index loading both improved the quality of the lithography and eliminated etching altogether. Hence scattering loss due to etching related surface roughness is reduced significantly. This allowed us to reduce the scattering loss from 21 dB/cm to 5.5 dB/cm for 1.6 μm wide waveguides. However, the decrease in loss was not as large as what was expected from surface roughness measurements. We found out that additional roughness was introduced to the sidewalls of the waveguide during fabrication due to process induced damage. Pitting of the $Al_{0.5}Ga_{0.5}As$ layer on which Si is evaporated during liftoff contributed a significant amount to scattering loss. By reducing the immersion time in Si liftoff to minimize surface roughening, we were able to demonstrate waveguides with propagation loss as low as 0.9±0.4 dB/cm. Therefore quality of the lithography and low damage processing are very important to reduce the propagation loss. This reduction in the propagation loss makes this type of optical waveguides a good candidate for building highly efficient devices such as GaAs/AlGaAs electro-optic modulators.

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