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Ion Milled Facets for Direct Coupling to Optical Waveguides

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ABSTRACT

Low loss coupling to optical waveguides is one of the on-going challenges with integrated photonics. Edge coupling of fibers or fiber arrays allows for in principle low loss coupling but strongly depends on the optical facet quality. We demonstrate an innovative strategy utilizing ion milling for polishing photonic integrated circuit edge facets for direct optical coupling to waveguides. Specifically, the authors created a 750 µm wide by 130 µm deep polished facet for coupling SM300 fiber to AlN waveguides on Al2O3 substrates; all capped with an index matched, but highly stressed, SiON cladding. Ion milling avoids the lateral shear forces that can delaminate a stressed film, resulting in scattering sites at the tapered edge coupler/facet interface. The authors demonstrate that a mechanical polish produced chipped facets that scattered the light away from the waveguide, thus requiring reprocessing of the chip. After ion milling, the authors coupled light into the waveguides and demonstrate critical coupling into AlN microring resonators between 390 and 395 nm.

Keywords: SiON cladding, AlN waveguides, UV photonics, integrated photonics, taper, waveguide, ion milling

1. INTRODUCTION

Low loss optical coupling into integrated photonics circuits is an ongoing area of research. The coupling into a photonic integrated circuit (PIC) follows two typical paths, grating or edge coupling. Grating couplers suffer from higher insertion loss and spectral selectivity corresponding to the grating design, yet allow for ease of coupling light into waveguides and can be placed anywhere on a photonic chip. The grating dimensions are proportional to the wavelength and waveguide/cladding material properties which may lead to additional fabrication challenges for UV and visible regimes. Edge couplers require individual alignment of each connection, and can only be placed along the periphery of the chip, but can have extremely high coupling efficiency without the spectral selectivity. However, the tapered edge couplers require a facet processing step to reduce loss at the taper/edge interface. In instances where an etched or polished facet can easily be created, the consideration is cost and time. Certain materials do not easily lend themselves to neither plasma nor traditional facet preparation processes and an alternative procedure is necessary. Lack of a reliable facet preparation method for stressed or easily delaminated films is limiting research into novel waveguide material systems. This research demonstrates a technique to allow for a wide variety of optical interfaces to include stressed or etch resistant interfaces to be prepared for direct coupling through an ion milled facet.

The research described in this article demonstrates direct edge coupling to an AlN waveguide with a highly stressed upper cladding. Traditional facet polishing methods may delaminate the cladding, the waveguide, or both thus removing the possibility of direct or free space coupling due to scattering losses at the facet/waveguide interface. Plasma etched facets were unavailable due to the difference in required etch chemistries for the cladding

†The authors would like to note equal contributions from Paul Thomas, John Serafina, and Michael Fanto.
and host substrate. With these constraints ion milling was considered to produce an optical quality facet in this material platform.

Ion milling is commonly used to create flat surfaces for a variety of metrology applications when traditional polishing techniques would damage the target surface. Ion milling has proved useful in the formation of photonic crystal and nonlinear material waveguides,\textsuperscript{7–9} but to the author’s knowledge has not been used for polishing edge facets for direct coupling to PICs. This method is especially useful when traditional polishing or facet preparation are not possible.

2. DESIGN AND FABRICATION

The optical circuits were designed in Klayout to include multiple resonator dimensions, coupling gaps, and waveguide widths (listed in Table 1) with tapered edge couplers terminating in a long uniform width section going to the edge of the chip. This allowed greater coupling tolerance when polishing the last 100 microns of the edge facet. Simulations were performed to optimize the mode matching of the tapered edge couplers and the optical fiber (SM300) connecting to the facet, see Fig. 1, indicating a best case coupling scenario of 60%.

Table 1. By varying widths, diameters, and gaps for the AlN microring resonators the authors should be able to extract $n_{\text{eff}}$, loss, and other values for this material.

| Waveguide Width | Ring Diameter | Resonator Gap |
|-----------------|---------------|---------------|
| 250 nm          | 10 $\mu$m     | 50 $\mu$m     |
| 250 nm          | 10 $\mu$m     | 75 $\mu$m     |
| 250 nm          | 10 $\mu$m     | 100 $\mu$m    |
| 250 nm          | 20 $\mu$m     | 50 $\mu$m     |
| 250 nm          | 20 $\mu$m     | 75 $\mu$m     |
| 250 nm          | 20 $\mu$m     | 100 $\mu$m    |
| 250 nm          | 40 $\mu$m     | 50 $\mu$m     |
| 250 nm          | 40 $\mu$m     | 75 $\mu$m     |
| 250 nm          | 40 $\mu$m     | 100 $\mu$m    |

Figure 1. Simulated ideal mode profile of the SM300 fiber (top) and the tapered edge coupler (bottom). Colormap represents intensity of electric field on log scale (dB).
These designs were then fabricated (see\textsuperscript{10} for specific waveguide fabrication details) in 200 nm of AlN grown on Al\textsubscript{2}O\textsubscript{3} substrates. After waveguide fabrication the samples were coated in photoresist for transport, stripped of photoresist, cleaned, and the low stress SiO\textsubscript{x}N\textsubscript{y} upper cladding was deposited using the Oxford 100 at CNF. Following the deposition of the SiO\textsubscript{x}N\textsubscript{y} upper cladding, the samples were mounted and prepared for standard polishing of the edge facets. The standard polishing was performed on an Allied multiprep polisher by sequentially reducing the grit sizes (30 µm to 0.1 µm) until the polished facet was within the edge coupler taper region, a process that has been successful in prior reports of Si photonics.\textsuperscript{11} The quality of the polish is periodically inspected during each step to address delamination, uneven polishing, and progress. The polishing process left a residue of ground material on the PIC surface that was cleaned off by a 1-2 minute soak in Acetone, followed by a rinse of Methanol or Iso-propanol. The AlN on Sapphire chip was expected to show a polished face without facet defects. However, stress in the SiO\textsubscript{x}N\textsubscript{y} cladding film lead to facet and waveguide damage during polishing as seen in Fig. 3. The result of the standard polishing technique was that neither free space nor fiber coupling solutions were viable to couple with this interface as too much light was scattered away from the waveguide. There was too much damage to the either the facet, waveguide, or cladding to produce an optical quality edge facet. In an effort to gather information from the damaged PICs, the authors decided to ion mill the damaged facet to produce an acceptable interface between the fiber and chip.

![Figure 2](image-url)

Figure 2. Layout of the variety of waveguide structures and dimensions, drawn in Klayout, on chip with tapers aligned to edges for traditional edge polishing for direct fiber coupling.

The chips were cleaned in acetone followed by methanol and then mounted with wax on metal chucks for the ion mill. Once mounted the facets were prepared using a JEOL IB-09010CP cross-section polisher and aligned such that 40 µm to 60 µm of the chip edge containing the edge tapers was exposed for milling. An accelerating bias of 6.5 keV, with 6 to 7 sccm of Ar gas, for 3 hours was sufficient to polish a facet region 1 mm wide to at least 70 µm deep to accommodate a bare SM300 fiber (125 µm diameter). After ion milling the chips were removed, soaked in acetone of 1 - 2 minutes to remove mounting wax, cleaned with methanol and iso-propanol, and then inspected on a Keyence microscopy system at 20X to 2000X optical zoom.

When compared to Fig. 3 left, Fig. 3 right exhibits minimal defects at the waveguide/facet interface since the ion milling does not place additional pressures on the film/surface interface that may cause delamination, chipping, and cracking. The inspected chips were then mounted to a vacuum chuck to test for optical coupling.

### 3. EXPERIMENTAL SETUP AND RESULTS

The testbed consisted of a frequency doubled continuous wave (CW) Ti:Sapphire (M2 Solstice w ECD-X) for generating 369nm and 390nm. Each respective crystal (369 and 390) crystal in the ECD-X had a tuning of 2nm but needed to be changed and realigned for each of the two wavelength regimes. The output of the doubler was free space coupled into an SM300 optical fiber to allow for ease of monitoring the system. The SM300 fiber connected to a second SM300 fiber which was routed to a 3 axis fiber stage terminating in a cleaved fiber end to couple to the chip, see Fig 5. The exit waveguide was fiber coupled as the input waveguide was and terminated
Figure 3. (a) 2000X optical micrograph of chipped facet from traditional polishing. Notably the cladding and waveguide often delaminate together which disallows direct and free space coupling. (b) 2000x micrograph of the same optical chip with an ion milled facet suitable for fiber or freespace coupling.

Figure 4. 200X optical micrograph of ion milled facet. (Inset) Waveguides array along top edge.

in power meter (Thorlabs S120VC) to monitor coupling. A secondary confirmation came from a microscope mounted UV sensitive camera (pcO Pixelfly USB) above the chip.

The ion milled facet showed very little surface roughness with no chipping and scattering was minimal compared to a the scattering observed in the UV regime from a traditionally polished edge. After coupling was achieved, the first qualification was to measure coupling efficiency to the waveguide. Maximum theoretical coupling efficiency of the AlN waveguide to fiber interface was found to be 0.1% based on the comparisons of the mode field dimensions between the waveguide and fiber, see Fig. 6. This low coupling efficiency was not intentional but due to the initial standard polishing of the chip where the damage was great enough from the chipping/delamination that the tapered edge couplers were completely damaged/removed. This meant that the
designed adiabatic mode transition region from the mode field of the optical fiber to the waveguide was missing. Thus the resulting coupling efficiency was not optimal. This result will be improved on waveguides which include the tapered couplers to transition between fiber and waveguide modes, refer back to Fig. 1 (where the waveguide tapers were mode matched to the SM300 optical fiber).

Accepting the lower coupling efficiency into the waveguides, the waveguide and ring resonator were easily excited by the input mode. Fig. 7 clearly demonstrates the coupling between the SM300 fiber and the AlN waveguide. This was more than optimal since prior to the ion milling coupling to the waveguide could not be achieved.

Additionally, this technique could be used to reclaim and test samples that are otherwise lost like Fig. 4. This process may be able to correct singular defect regions if properly tuned and calibrated.
Figure 6. Simulated ideal mode profile of the SM300 fiber (top) and the untapered waveguide (bottom). Colormap represents intensity of electric field on log scale (dB).

Figure 7. Transmission plot from direct fiber coupling to the AlN PIC showing resonances from 391 to 394 nm.

4. CONCLUSION

Ion milling provides an additional method for preparing edge facets for edge coupling to PICs beyond the traditional polishing and plasma processes. In situations where the cladding or waveguide may readily delaminate, due to high stress, brittleness, or chemical sensitivity, ion milling provides a method for direct coupling to a PIC that would otherwise not survive the polishing process. In this research the authors have demonstrating the
collection of meaningful data from devices that were otherwise deemed unusable due to damage from other polishing means. The authors have demonstrated that ion milled facets are a consistent and viable processing solution for preparing chip facets for direct coupling, producing facets that rival traditional polishing processes. The authors expect this process could be expanded to other difficult to prepare materials such as lithium niobate, potassium titanyl phosphate, air clad waveguides, or high stress films\textsuperscript{12} that resist traditional facet polishing techniques.

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