# Mechanical dicing of optical quality facets and waveguides in a silicon nitride platform

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The authors report a ductile dicing process for manufacturing optical-quality facets in a multi-layered silicon nitride platform without the need for polishing. A surface roughness (Sa) of 1.5 nm was achieved. This technique was extended to fabricate ridge waveguides, and the results and characterization are reported.

*Introduction:* Silicon nitride ($SiN_x$) boasts a high refractive index and optical transparency from around 250 nm up to 7 $\mu$m, enabling low-loss planar-integrated devices spanning the UV to the mid-infrared. As a platform, $SiN_x$ benefits from wafer-scale fabrication, complimentary metal-oxide-semiconductor (CMOS) compatible processes, and can be tailored for different applications, including non-linear optical functions [1]. However, as with many integrated photonic platforms, it can be challenging to process facets for end coupling when grating couplers cannot be used. Traditional polishing can prove time-consuming, especially when processing tens to hundreds of photonic devices from a wafer, and also proves challenging to produce precisely placed facets. For laminated structures involving multiple thin layers of different materials, chipping and delamination of the waveguide layers during polishing also result in poor yields.

In recent years, diamond machining, typically using dicing saws, has opened up routes to machine optical quality surfaces in various brittle materials [2, 3]. Machining in the ductile regime allows for plastic-like material removal, resulting in low chipping and low surface roughness in the diced substrate. We have previously demonstrated optical-quality machining in bulk materials such as silica and silicon, and the dicing of ridge waveguides and facets in lithium niobate [4–7]. In this work, we have refined these techniques to dice optical-quality facets in a silicon nitride platform consisting of multiple layers (substrate-oxide-$SiN_x$-capping layer) with no requirement for polishing. We have extended this technique to laterally defined waveguides that demonstrate the precision, preservation of laminated layers, and low surface chipping of the dicing saw technique. Our dicing routine also provides a process to verify the parameters for ductile machining.

*Machining in the ductile regime:* Ductile mode machining removes material via plastic deformation, leaving surfaces with nanometre-scale surface roughness and without cracks or chips. Plastic deformation of a workpiece occurs if the chip size of the removed material is below a critical value, which corresponds to a certain set of machining parameters [8]. Machining parameters to be optimised include the dicing blade grit size, concentration and bond material, blade rotational speed, sample translation speed, depth of cut (DoC) into the sample, and the type and flow of coolant used. If the dicing parameters exceed the material's plastic limit, then machining will occur in the brittle regime. Conversely, if parameters such as translation speed are too slow, then machining will occur in the elastic regime, which can cause rubbing, excessive heating, and accelerated tool wear.

*Optical-quality facet cuts in silicon nitride:* Our $SiN_x$ platform is on a silicon substrate with a 3-$\mu$m $SiO_2$ layer. A 300 nm of nitrogen-rich $SiN_x$ was deposited through plasma-enhanced chemical vapour deposition (PECVD) [9] and then capped with a 1.4-$\mu$m tetraethyl orthosilicate (TEOS) layer. The typical thin layer of $SiN_x$ makes it challenging to precisely determine the surface roughness. A similar structure with a thicker

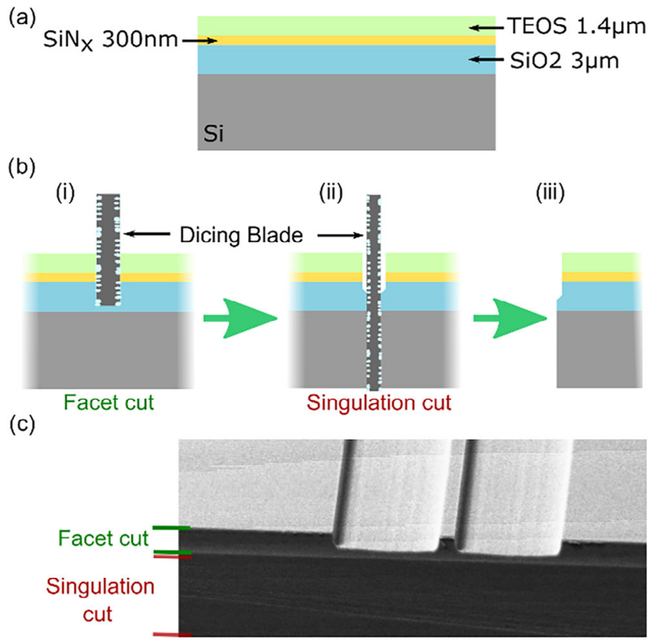


**Fig. 1** *(a) Shows the silicon nitride platform on which the facet cuts were demonstrated. (b) Shows the process for performing the facet cuts, where (i) a ductile 24 $\mu$m deep cut is made; (ii) a thinner blade singulates the dies within the boundaries of the first cut; (iii) the resulting end profile of device. (c) Shows a scanning electron microscope (SEM) image of the resulting cuts*

1.35-$\mu$m layer of $SiN_x$ and no TEOS capping layer was also prepared, to enable surface roughness measurements.

A DISCO DAD3430 dicing saw equipped with an air-bearing slide way and linear position encoders was used to perform all cuts. A resin-bonded blade was used with 6000 grit, equating to a diamond grain size of ~3 $\mu$m. The spindle speed was 15,000 RPM. Before dicing, a thin layer of photopolymer was spun onto the surface of the $SiN_x$ samples to protect from contaminates and reduce surface chipping. A range of material feed rates were explored, with 0.025 mm $s^{-1}$ providing the least chipping and delamination. A decidedly important factor for ductile dicing is the amount of material engagement or DoC. Several lines were diced in the composite with different DoC to observe where delamination or chipping may occur. Delamination was observed for DoC >28 microns; therefore, cuts were maintained at a shallower depth.

Dies were prepared using a two-step dicing process (see Figure 1). First, a 24-$\mu$m deep cut was made to define the optical facet of the structure. Next, a cut with a thinner blade was made at full depth within the boundaries of the first cut to singulate the die and expose the facet. This results in the profile shown in Figure 1b(iii), where there is a >2 micron step between the facet and the singulation cuts. Though these cuts are offset by only microns, there has been no indication of the singulation cut affecting the quality of the diced facet. Figure 1c shows ascanning electron microscope (SEM) image of the surface of the sample, where the clean line of the ductile cut can be seen offset from the chipped profile of the singulation cut.

For an indication of surface roughness resulting from the cut, the sample was measured using a Park Systems atomic force microscope (AFM) (results shown in Figure 2). Analysis of a 1 × 5 $\mu$m area of the $SiN_x$ facet highlighted by the green box in Figure 2 gave a mean roughness (Sa) of 1.5 nm, and root-mean-squared roughness (Sq) of 1.9 nm. The roughness was only analysed in this region as it is the SiNx facet via which light will be coupled into the waveguide.

*Diced silicon nitride waveguides:* Analogous to the work demonstrated in lithium niobate [6], dicing was used to produce ridge waveguides within the $SiN_x$ composite. Ridges were diced 24 $\mu$m deep, with widths ranging from 5 to 15 $\mu$m. Facet and singulation cuts were then performed as discussed previously (Figure 3a). The micrographs of the resulting ridges are shown in Figures 3b to 3d. Delamination was evident in all ridges produced with widths <8 $\mu$m, where the $SiN_x$ layer and the TEOS cap have lost adhesion to the underlying SiO2 layer. This is primarily due

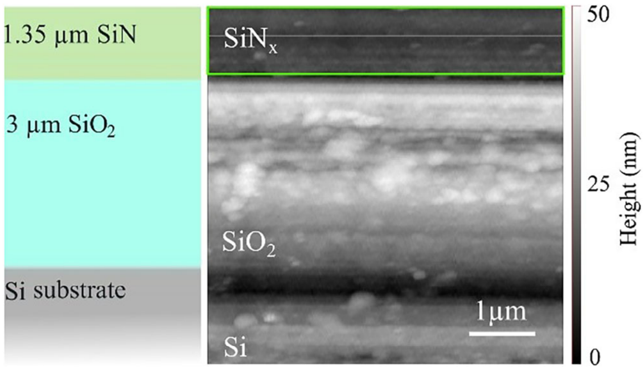


**Fig. 2** *Image showing the structure of the machined sample and the resulting AFM surface profile*

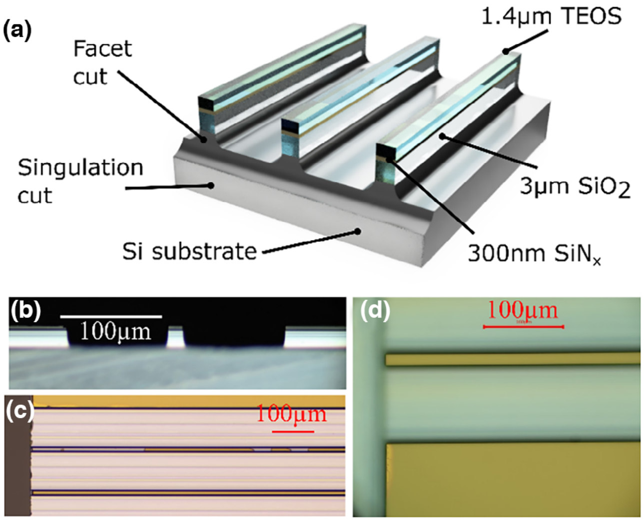


**Fig. 3** *(a) Shows a schematic of the waveguide structure and dicing. (b) Shows a microscope image of the end facet of a diced waveguide. (c) Shows a microscope image of an overhead view, with some delamination occurring in the top ridge. (d) Shows a microscope image of a diced ridge waveguide*

to the reduced contact area between the layers in these thinner ridges. All ridge widths diced >8 $\mu$m showed no delamination. Further control of the dicing and blade parameters may allow for thinner ridges without delamination; however, this was not investigated here.

The optical transmission of a 10 $\mu$m wide, 5 mm long $SiN_x$ waveguide was characterized for different wavelengths. Light was end-coupled via a polarization maintaining (PM) lensed fibre to excite the transverse (TE) mode of the waveguide. The fibre produced a focal spot diameter of 3.5 $\mu$m. The output from the waveguide was coupled back into a matching PM fibre which led to a power sensor. The total insertion loss was measured with wavelength (∼1.52–1.62 $\mu$m) and is shown along with a diagram of the setup in Figure 4. The insertion loss includes waveguide propagation loss as well as coupling losses from the fibres which is significant due to the dimension mismatch between the focal spot and the 10 $\mu$m x 300 nm waveguide facets. Additional losses are present due to multimode behaviour of the waveguide, which is clear from the modal beating evident in Figure 4b. This is caused by the width of the waveguide supporting multimode behaviour. The insertion losses would be improved by reducing the width of the waveguide to allow for single-mode operation, as well as an improved method for optical coupling to the waveguide. In previous work, etched single-mode $SiN_x$ devices with facets prepared through our dicing procedure have shown coupling losses as low as 1.4 dB when inverted taper-based edge couplers were used [10], demonstrating the optical-quality finish of our diced facets. Dicing is not suggested here as an alternative to etching for producing $SiN_x$ photonics circuits, due to limitations in design and feature width. However, this technique allows fine-tuning of dicing parameters to reduce forces and identify the regimes in which delamination does not occur for the generation of the facet cuts. Prior works have shown that lower surface roughness coincides with increased normal stresses [11],

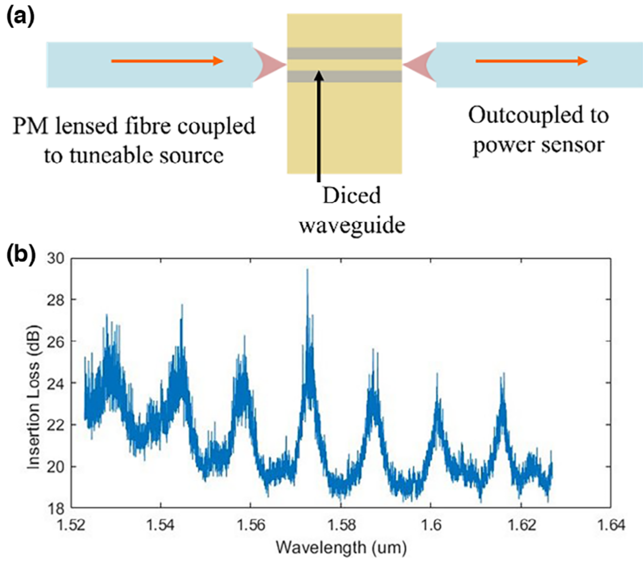


**Fig. 4** *(a) Shows a schematic of the setup used for optical testing of the diced ridge waveguide. (b) Shows the insertion loss of the waveguide as a function of wavelength*

suggesting an effective lower limit to roughness just before delamination occurs.

*Conclusion:* Here, we have shown optical-quality facets in $SiN_x$ produced with a mechanical dicing saw. A surface roughness of 1.5 nm Sa and 1.9 nm Sq was achieved in a PECVD grown nitrogen-rich $SiN_x$ layer. This technique was extended towards dicing ridge waveguides within the composite structure. The propagation losses in the machined waveguides were measured over a range of wavelengths, and multimode behaviour was observed. This technique is primarily useful for identifying the optimal dicing regime in composite materials for creating optical quality cuts while reducing delamination. However, optimisation of dicing parameters to enable narrow waveguides, alongside extension of this technique to other materials and platforms, will be the subject of future work.

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*Data availability statement:* All data supporting this study are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D2908.



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## References


1 Blumenthal, D.J., Heideman, R., Geuzebroek, D., Leinse, A., Roeloffzen, C.: Silicon nitride in silicon photonics. *Proc. IEEE* **106**(12), 2209–2231 (2018)

2 Yasui, H.: Ductile-mode ultra-smoothness grinding of fine ceramics with coarse-grain-size diamond wheels. In: *Handbook of Advanced Ceramics Machining*, CRC Press, pp. 43–68 (2006)

3 Courjal, N., Guichardaz, B., Ulliac, G., Rauch, J.Y., Sadani, B., Lu, H.H., Bernal, M.P.: High aspect ratio lithium niobate ridge waveguides fabricated by optical grade dicing. *J. Phys. D Appl. Phys.* **44**(30), 305101 (2011)

4 Carpenter, L.G., Rogers, H.L., Cooper, P.A., Holmes, C., Gates, J.C., Smith, P.G.: Low optical-loss facet preparation for silica-on-silicon photonics using the ductile dicing regime. *J. Phys. D Appl. Phys.* **46**(47), 475103 (2013)

5 Carpenter, L.G., Cooper, P.A., Holmes, C., Gawith, C.B., Gates, J.C., Smith, P.G.: Nanoscale roughness micromilled silica evanescent refractometer. *Opt. Express* **23**(2), 1005–1014 (2015)

6 Carpenter, L.G., Berry, S.A., Gawith, C.B.E.: Ductile dicing of LiNbO3 ridge waveguide facets to achieve 0.29 nm surface roughness in single process step. *Electron. Lett.* **53**(25), 1672–1674 (2017)

7 Carpenter, L.G., Berry, S.A., Gray, A.C., Gates, J.C., Smith, P.G., Gawith, C.B.: CW demonstration of SHG spectral narrowing in a PPLN waveguide generating 2.5 W at 780 nm. *Opt. Express* **28**(15), 21382–21390 (2020)

8 Bifano, T.G., Dow, T.A., Scattergood, R.O.: Ductile-regime grinding: A new technology for machining brittle materials. *ASME. J. Eng. Ind.* **113**(2), 184–189 (1991)

9 Bucio, T.D., Khokhar, A.Z., Lacava, C., Stankovic, S., Mashanovich, G.Z., Petropoulos, P., Gardes, F.Y.: Material and optical properties of low-temperature NH3-free PECVD SiNx layers for photonic applications. *J. Phys. D Appl. Phys.* **50**(2), 025106 (2016)

10 Vitali, V., Domínguez Bucio, T., Liu, H., et al.: Fully-integrated and broadband Si-rich silicon nitride wavelength converter based on Bragg scattering intermodal four-wave mixing. *Photonics Res.* (2023). https://doi.org/10.1364/PRJ.506691

11 Rowe, W.B.: *Principles of Modern Grinding Technology*. William Andrew (2013)