# Ultra-precision CNC for the manufacture of components for quantum technologies

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Future photonic and quantum technologies (QT) require novel, scalable manufacturing techniques for volume production and commercialization. Here, we apply an ultra-precision micromilling system with nanometer precision towards rapid prototyping and volume production of components for these applications. We have machined silicon to produce components for atom/ion trap systems with low surface chipping suitable for bonding, as well as apertures and features in materials such as silicon, sapphire, lithium niobate, and glass for electrical feed-throughs, vias, 3D tapers, and electrical shunts. This process surpasses the capabilities of techniques such as reactive ion etching (RIE).

Many QT systems leverage fabrication techniques from the sophisticated field of semiconductor processing, including near-perfect substrate wafers, cleanroom infrastructure, and nanometre-scale lithography and deposition. However, many components such as atom/ion traps used in quantum clocks and sensing, semiconductor quantum components, and nonlinear optical components often include 3-dimensional structures with a complex combination of centimeter-length scales, sub-micron precision, and nanometer roughness that is difficult to achieve with standard semiconductor tools. These applications require the development of novel manufacturing techniques to become commercially viable.

This work uses state-of-the-art ultra-precision machines to fabricate components in various materials (silicon, silica, sapphire) for the photonics and QT industries. Through careful control of tool and machining parameters, it is possible to machine in the ductile regime and achieve sub-nm surface roughness results with no chipping or microcracks [1]. The ductile regime varies for different materials, with brittle materials such as silicon, silica, and sapphire having particularly narrow parameter spaces in which ductile machining can be achieved. Over the last 10 years, our team has demonstrated optical quality machining in various substrate materials, including milling of high-purity silica glass [2], manufacture of ridge waveguides in lithium niobate with 0.29nm surface roughness [3], and machining optical quality facets and waveguides in a layered silicon nitride composite [4].

Here, we will present the manufacture of 3D components for photonic and quantum technologies using a state-of-the-art Loxham Precision µ6 micromilling system. We will discuss the development of 2D arrays of apertures in silicon wafers (Fig.1) as a basis for vias, electrical feedthroughs, and shunts. Such features can be utilized for 3D superconductor qubit lattices for quantum computing, as presented by Spring et. al. [5]. We will also present our work on machining atom trap structures in >2mm thick silicon, both for rapid prototyping of individual dies (fig. 2) and at wafer scale for volume production (fig. 3). This method surpasses what is achievable by techniques such as deep reactive ion etching, and is not limited to producing features along crystal planes.

[1] T.G. Bifano, et.al., (1991): 184-189.
[2] L.G. Carpenter, Precision dicing and micromilling of silica for photonics, PhD Thesis, University of Southampton, 2013.
[3] L.G. Carpenter et al., Elec. Lett. 53(2017) 1672-1674.
[4] P.C. Gow et al., Elec. Lett. 60(2024) e13138.
[5] P.A. Spring et al., Science Advances 8(2022) eabl6698.

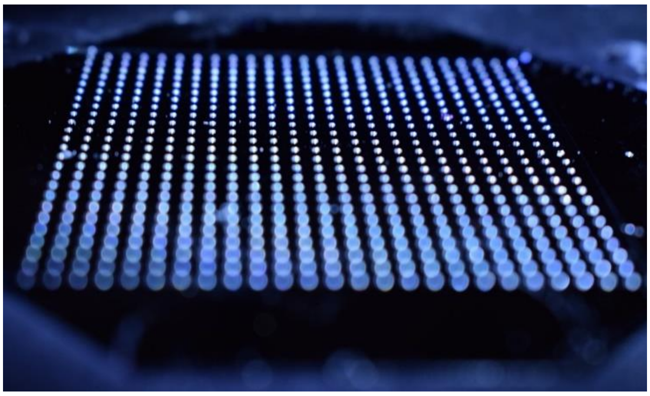

**Figure 1.** 500 micron thick double-side polished silicon wafer with 700 holes milled through.

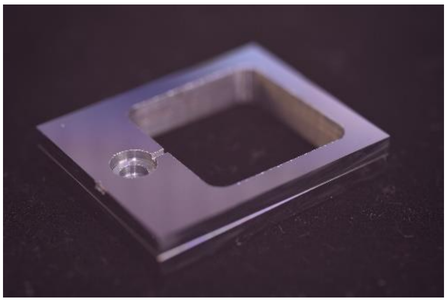

**Figure 2.** Large atom trap structure milled in 4mm thick silicon, surpassing etching capabilities.

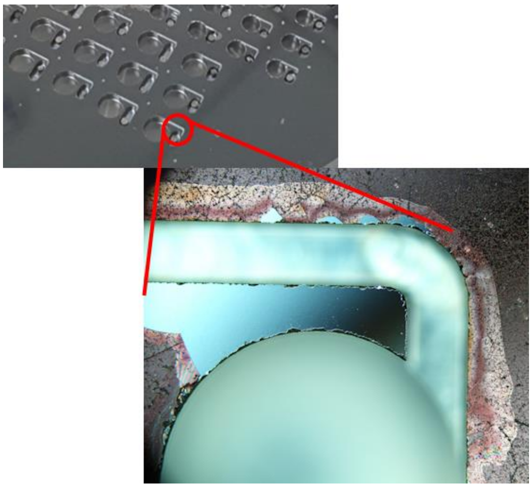

**Figure 3.** 4 inch diameter, 2mm thick silicon wafer with atom trap cells machined. The cells consist of a through hole for optical access, a blind hole for holding the atom source, and a small channel between them for transport of atomic species.