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

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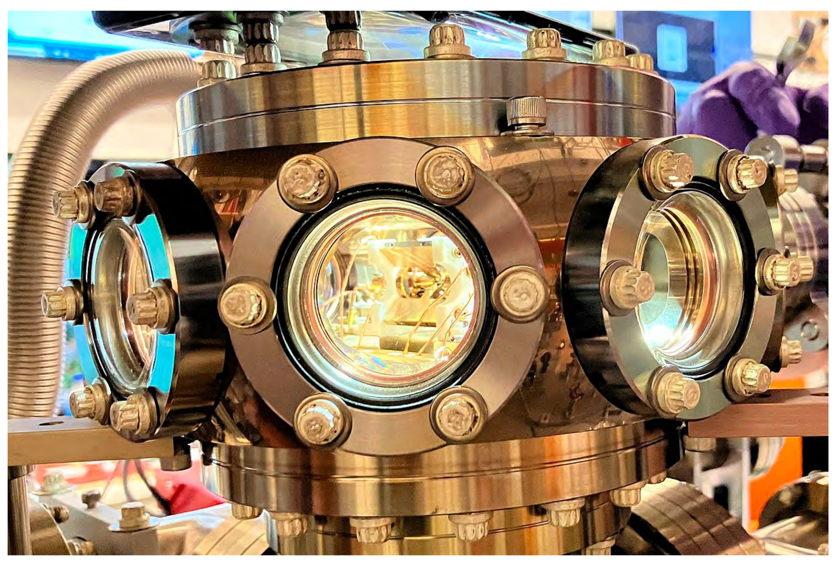
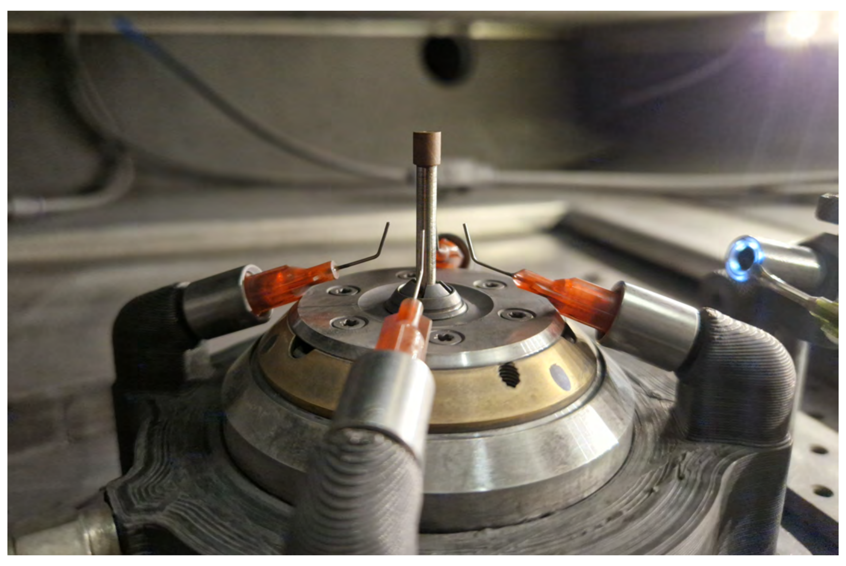


A typical lab-based atom trap system.

Future photonic and quantum technologies (QT) require novel, scalable manufacturing techniques for volume production and commercialization. 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.

Here, we apply an ultra-precision micromilling system with nanometer precision towards rapid prototyping and volume production of components for these applications.

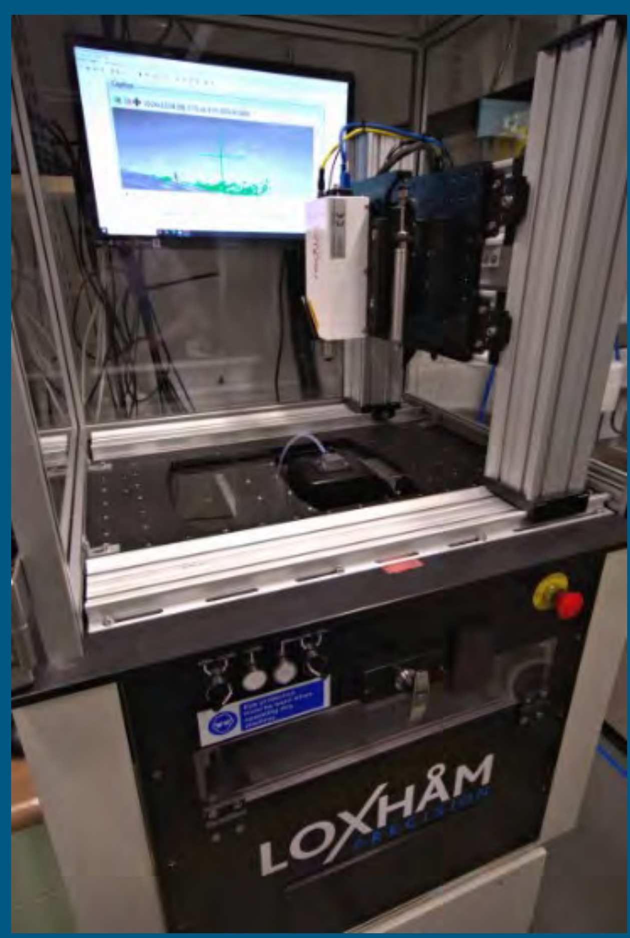


An image of the tool in Loxham machine spindle.

Ultra-precision milling: a complimentary technique to cleanroom fabrication

Cleanroom fabrication techniques such as reactive ion etching (RIE) are excellent for parallel processing of wafers with photolithographic features. However, etching is restricted to crystal planes so features such as circles cannot be achieved, and depths >2mm can be difficult and costly.

Ultra-precision CNC milling with multipoint diamond tools (resin bonded, sintered) is analogous to dicing/grinding operations.Through careful control of tool and machining parameters (feedrate, chip thickness, depth of cut) it is possible to machine in the ductile regime and achieve sub-nm surface roughness without chipping or microcracks [1]. Southampton have demonstrated optical quality machining in brittle materials, including; silica [2]; Ge-on-Si [3]; Si-on-insulator [4]; silicon nitride [5,6]; and facets and ridge waveguides in lithium niobate with 0.29nm surface roughness [7] and multi-Watt power handling (4.5W CW at 1560nm) [8].

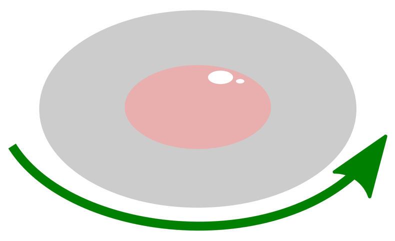


The state-of-the-art 6-axis CNC milling machine from Loxham Precision Ltd operates on air bearing stages, allowing for stable and smooth translation of the axes with nanometer precision in position and velocity feedback. The system operates with an air bearing spindle, capable of up to 200 kRPM.

Benefits include:

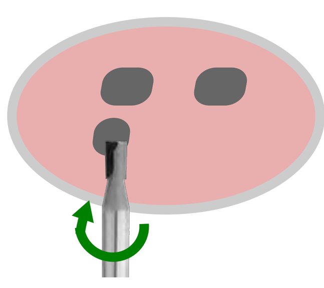
- **Geometries not restricted by crystal planes**
- **3D structures possible (tapers)**
- **Sustainability - No chemicals/cleanroom**
- **Microscope referencing to exisitng features**
- **In-line metrology**
- **Rapid prototyping of individual dies**
- **Wafer scale manufacture**

Fabrication procedure

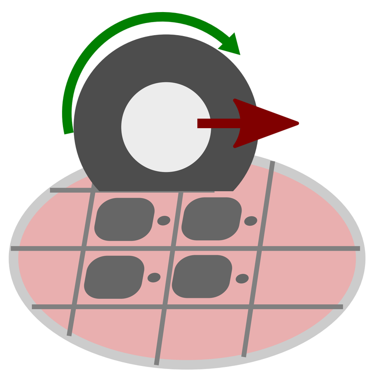


Spin coat protective photoresist on wafer or die

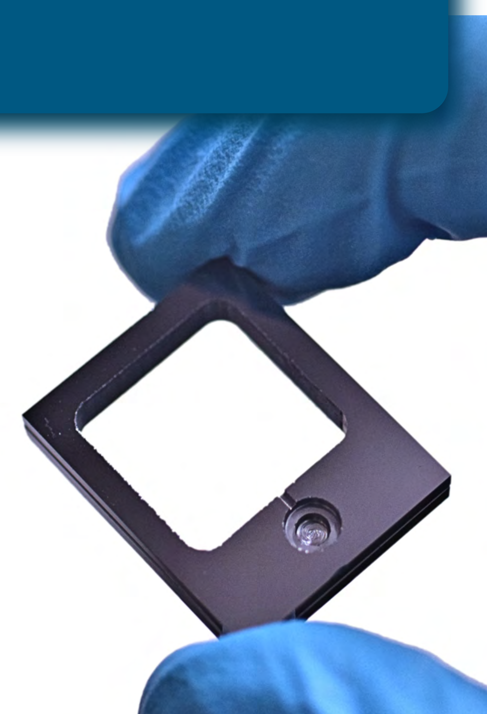
Use of diamond grit grinding pins and polycrystalline diamond fluted tools



Milling of 2D/3D features



Singulation with ultra precision dicing saw

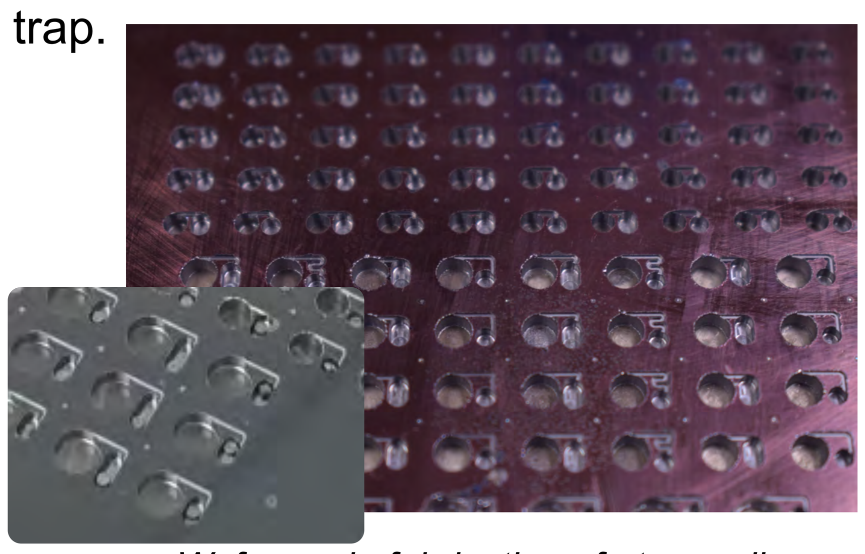


2.5D atom trap structures

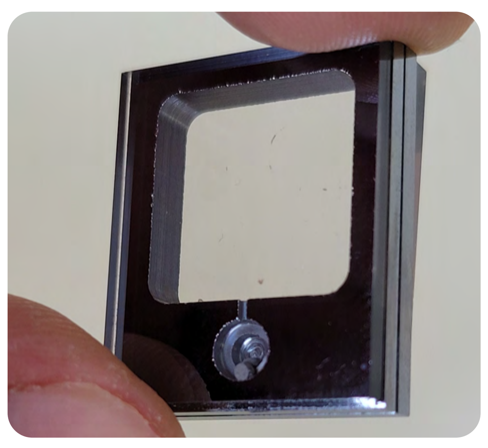
CNC milling allows for rapid prototyping of devices without the cost or development time for masks or photolithographic processes. This can be quickly scaled in volume to wafer-level fabrication.

Here we are developing bespoke geometries for atom traps - the basis for many quantum devices such as; clocks; sensors; GPS; spectroscopy cells. The machining requirements here are low surface chipping/no burrs, to allow for bonding of glass to the surface to form the trap.

A 150mm diameter, 2mm thick wafer was produced with variations of an optical atomic trap design in collaboration with INEX Microtechnology. These consisted of; a through aperture for optical coupling to an atomic species; a blind hole for containing a rubidium pellet to release atoms, and a 500 micron diameter via between for transport of atoms.



Wafer scale fabrication of atom cells.
Inset: Bonded cells with rubidium pills.



Bonded cell in 4mm thick Si.

In collaboration with Aquark Technologies, a single die measuring 20 x 25mm was machined in 4mm thick silicon demonstrating the depth capabilities of this technique. This consisted of a large 15x15mm aperture, stepped recess for rubidium pill, and a 500 micron via between. This trap was bonded on both sides for vacuum testing at Aquark Technologies Ltd.

Other work; milling gaskets for anodic bonding in silicon and silica; 3D tapers in lithium niobate; tapered apertures for larger beam acceptance angles.

Examples of milling work in silicon, silica, and lithium niobate.

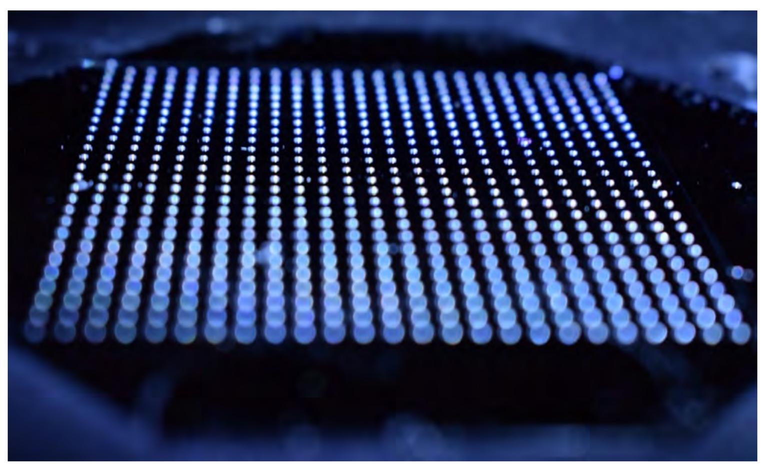
2D aperture arrays

2D arrays of apertures in silicon wafers are used as a basis for vias, electrical feedthroughs, and shunts. Such structures machined in discrete locations and aligned to existing features on the wafer can be utilized for 3D superconductor qubit lattices for quantum computing, as presented by Spring *et al.* [9].

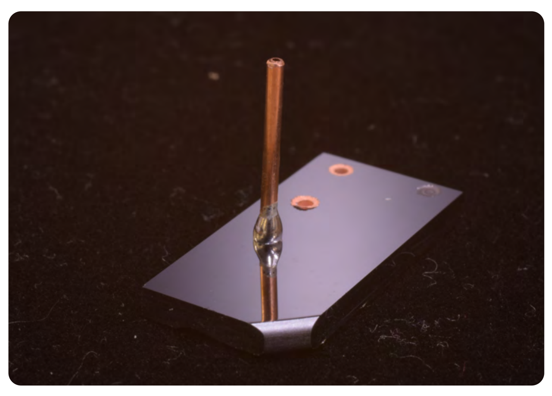
A 150mm diamaeter, 500 micron thick silicon wafer was spin coated with photoresist to protect the surface during machining. An array of 25 x 25 holes were milled using a helical toolpath. The time taken to mill a total of 625 holes was ~4 hours. This time scales with wafer thickness and number of features.

Etching rates are dependant on crystal axes, with an average rate for Si in KOH of ~1 micron per minute. For a 500 micron thick Si wafer this would take ~8 hours, for any number of features scaling only with wafer thickness.

Other work includes milled, plated holes for vacuum feedthroughs.



Above: wafer-scale milling of aperture array.
Below: Plated holes for bonding vacuum feeds.



Conclusions

CNC milling is a viable aproach to processing wafer-based materials for quantum technologies. It is effective for creating 2.5D structures, machining brittle materials, and creating mirror-quality optical finished. It allows for both rapid prototyping and wafer-scale fabrication of components, demonstrating compatibility with cleanroom microfabrication techniques.

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