Ultra-precision diamond micro-grinding of integrated mirrors in silicon for quantum atomic technologies

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

The main body of a microfabricated atom trap or vapor cell is typically fabricated in silicon or glass. Etching is suitable for thinner substrates, with materials >2mm thick requiring alternative techniques such as waterjet cutting [1] or multilayer stacked fabrication [2]. With fabrication moving to thicker substrates, there is also interest in improving optical access to the trap. One method is by using a transparent substrate to couple through the sides of the cell, requiring optical quality internal sidewalls, which can be achieved through moulding [3]. Alternatively, the addition of mirrors within the cell can aid optical coupling, though the angles of these are limited to crystal planes when etching [4].

Over the last 10 years, our team has demonstrated optical quality machining in various substrate materials, including milling of high-purity silica glass [5], manufacture of ridge waveguides in lithium niobate with 0.29nm surface roughness [6], and machining optical quality facets and waveguides in a layered silicon nitride composite [7]. This work applies a state-of-the-art ultra-precision micro milling system with nanometre precision (Loxham Precision Ltd. µ6 micro turn/mill machine, Fig. 1c) towards producing components for the QT industry. Using diamond grain micro grinding tools (Fig. 1a) and carefully controlled machining parameters, it is possible to machine thick, brittle materials such as silicon in a rapid and scalable way, whilst achieving nanometre surface roughness through ductile material removal [8]. This method surpasses what is achievable by techniques such as deep reactive ion etching, is not limited to producing features along crystal planes, and does not require a cleanroom.

We will present our work on the fabrication of vacuum cell and atom trap components in up to 6mm thick silicon wafers, with low surface chipping suitable for anodic bonding (Fig.1b), as well as apertures for optical interaction, and vias for transport of atomic species. We will also present ductile machining of silicon to produce optical-grade mirrors internal to the atom trap frames, allowing for in/out-coupling of light for interaction with trapped atom clouds (Fig.2). Machining is not restricted to crystal planes like etching; therefore, mirrored geometries can be produced at any angle. We will also show how this wafer-based machining technique is complementary to cleanroom processing, as well as its suitability for both rapid prototyping and scaling towards volume production.

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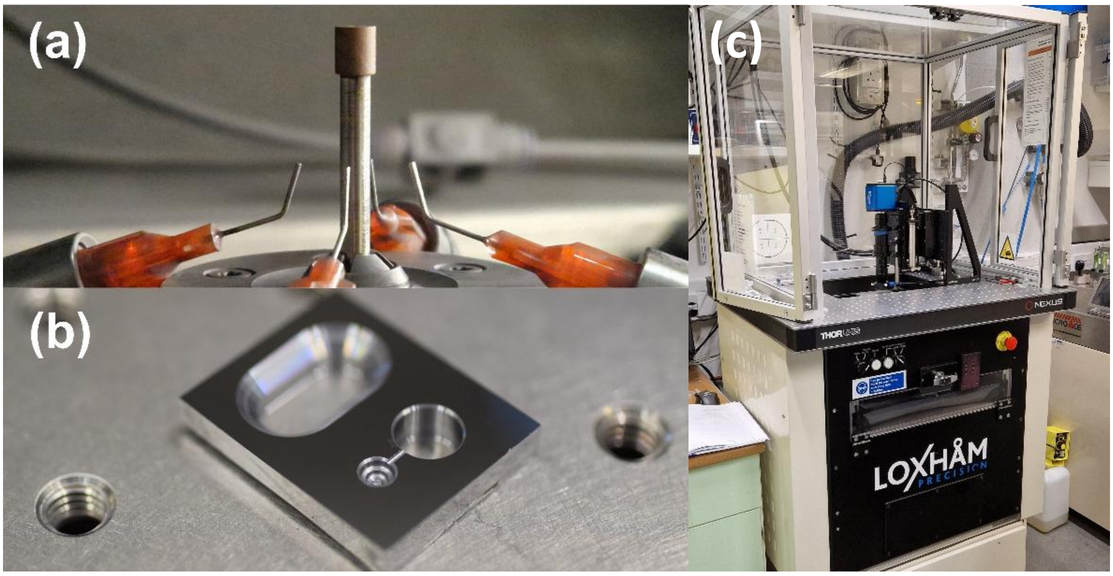

Figure 1. (a) shows a 4mm diameter diamond tool mounted in the air bearing spindle of the Loxham system. (b) shows an example of an atomic vapour cell design in silicon, featuring tapered sidewalls for optical access, main aperture, recess for material source, and a 500-micron channel. (c) shows an image of the Loxham Precision Ltd. μ6 micro turn/mill machine

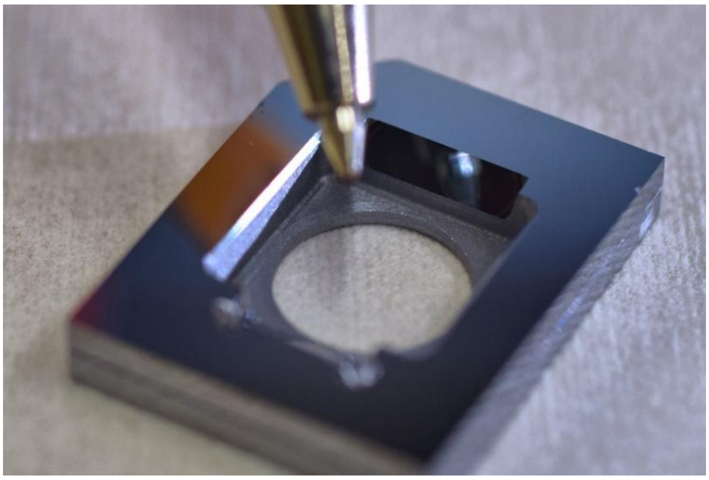

Figure 2. A 4 mm-thick machined silicon atom trap cell. The cell comprises a 15x15mm chamber and a through hole for optical access. Shown is the reflection from mirrors machined at an angle of 45 degrees into the silicon to allow light coupling into the cell for atomic interactions.