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Grinding optical-grade features in glass and silicon for compact vacuum cells

Joel M. N. Keen[1], Paul C. Gow[1], Glenn M. Churchill[1], Corin B. E. Gawith[1], James C. Gates[1]

[1]*Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK*

j.keen@soton.ac.uk

Abstract

Centimetre-scale compact vacuum cells, developed for scaling quantum technologies such as quantum-enhanced position, navigation, and timing, bridge the gap between large glass-blown or metallic chambers and single-digit millimetre devices produced by cleanroom micro-fabrication. These cells require vacuum-compatible materials, thermally compatible materials, low outgassing, and a means to introduce and observe light interactions, which are traditionally performed through vacuum chamber ports. The use case is to confine a cloud of atoms in the central cavity of the vacuum cell and observe their interactions. In the past, cleanroom microfabrication has been used to produce compact vacuum cells; however, there are process capability issues when working with wafers thicker than 1-2 mm.

Here, we propose precision grinding to fabricate components for a multi-layered vacuum cell with integrated optics. This enables access for multiple beams and imaging methods; we have demonstrated both reflective mirrors and transparent side wall windows by high precision machining. To enhance process throughput, we use abrasive waterjet machining to rough out through features on the wafer. Dicing saw machining is used afterwards to separate individual cells. Our methods offer a scalable and sustainable approach to producing compact vacuum cells with flexibility in both designed features and sizes which are not readily producible by other methods.

Micro grinding, optical surfaces, ductile grinding, abrasive water jet, compact vacuum cells, quantum technology

1. Introduction

Compact vacuum cells [1] with 3D optical access [2] are of increasing interest for reducing the overall size of quantum sensors, promoting their ongoing commercialisation. These compact vacuum cells are between 5-25 mm in outer dimensions and are developed to enable the scaling of quantum sensors. These have numerous applications in metrology, including measuring position, navigation, and timing, as well as sensing magnetic and gravitational fields. Compact cells bridge the gap between large glass-blown or metallic chambers and sub-millimetre devices produced by cleanroom micro-fabrication.

The materials used in the cell must be both vacuum and thermally compatible. The assembled cell requires low outgassing and optical access windows or mirrors for beams and imaging. The cell is assembled with a reference element which can be activated to create a cloud of atoms in the central cavity of the vacuum cell, for subsequent optical confinement. Our vacuum cell comprises multiple wafer layers anodically bonded together under vacuum.

Deep reactive ion etching is not a viable fabrication route for features deeper than 1-2 mm due to excessive etch time and poor vertical side-wall quality. Although parallel processing can be achieved across a whole wafer, the additional process stages consume some of the parallel efficiency gains. Wet etching can only produce mirror surfaces aligned to crystal planes, rather than a desired angle [3]. Diamond grinding has been successfully used to produce non-optical components for vacuum cells in single-crystal silicon [4]. However, to produce a fully machined optical cell component, the internal sidewalls and facets must be of optical quality in a suitable reflective or transparent material. In our vacuum cells, we machine silicon and borosilicate glass for respective reflection and transparency in the visible range, see Figure 1 for an overview schematic.

2. Methodology

We grind optical surfaces using diamond abrasives with a six-axis air-bearing µ6 machining centre (Loxham Precision Ltd, GB). This process eliminates any need for subsequent polishing. Lower tolerance areas of the wafer are pre- and post-processed using a commercial compact abrasive waterjet (OMAX Corp., US) and a precision dicing saw (Disco Corp., JP) to achieve maximum process throughput. Our methods are compatible with both single-piece and wafer-scale machining for ease of development and batch production. Ductile grinding [5,6] of brittle materials requires a careful selection of machining parameters to produce low roughness surfaces, suitable for optical purposes. Our process is continually under development; however, our current results are achieved with the parameters shown in Table 1.

Table 1 Machining parameters for optical finish grinding in vacuum cells

Material	Tool	Speed m/s	Feed mm/s	Stepover mm
Borosilicate Glass	⌀ 4 mm, D7 Resin Bond	26	0.5	0.025
Silicon (SC)	⌀ 2 mm, D46 Nickel Bond	13	0.5	0.015

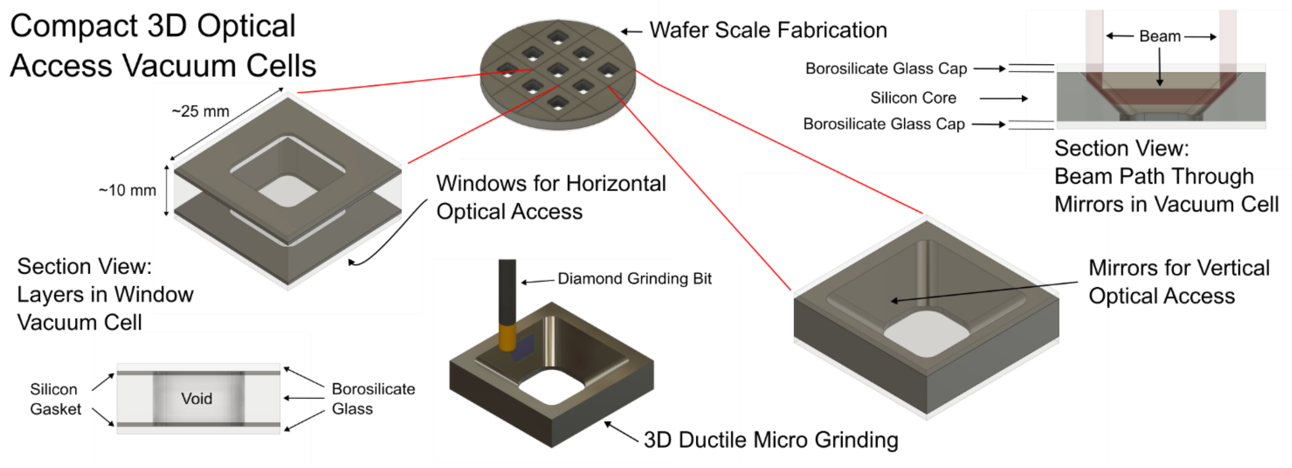

Figure 1. Compact Vacuum Cell Assembly Schematic. Horizontal and vertical beam access is provided by integrated side wall windows and mirrors.

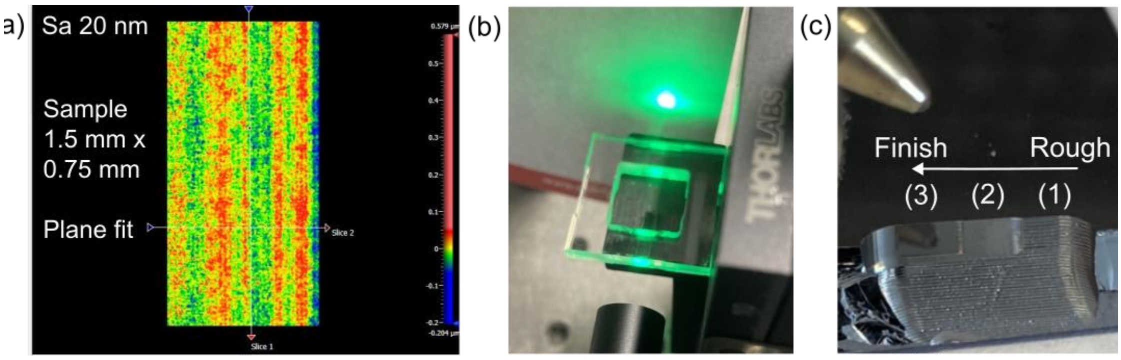

Figure 2. (a) CSI scan of ground area in Borosilicate (Plane fit; 1.5x0.75 mm area) (b) Laser (520 nm) transmission through 4 surfaces in borosilicate (c) Reflection in integrated silicon mirror, rough machined area (1), semi-finish (2), mirror finish with ballpoint reflection (3)

Our earlier work [7] suggests that the feed direction in grinding, i.e. vertical/axial or horizontal/tangential, has a significant effect on the ability to grind an optical surface. We use a parallel toolpath with a small stepover and calculate cusp height to optimise surface roughness. This toolpath can be applied to produce a facet with arbitrary orientation and shape, subject to tool access, providing significant flexibility in design and development.

3. Results and Discussion

The micro-ground optical surfaces were characterised with a Coherence Scanning Interferometer (CSI) (Zygo Corp. US).
As shown in Figure 2, our processes produce surface roughness <20 nm Sa on arbitrarily orientated facets, for mirrors or windows in a range of materials. Our complete ductile grinding process currently takes approximately 150 seconds per mm² of finished surface area. Laser transmission and imaging properties were investigated qualitatively.

The kinematics of the grinding process have a significant influence on the achievable surface roughness. The direction of feed in relation to the grinding tool is a key factor in achieving low nanometric surface roughness, even more so than the diamond grit size. We have demonstrated ductile grinding with minimal chipping or subsurface damage while maintaining productive conditions.

5. Conclusion

In this paper, we present a variety of micro-machining techniques for producing compact vacuum cells with integrated optical surfaces. We also intend to investigate machining parabolic and freeform optics using similar techniques to further reduce the requirements for additional external optical components currently needed to interface with compact vacuum cells.

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