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Micro-machining of Monocrystalline Silicon with Improved Edge Quality

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Abstract

This research aims to investigate the feasibility of a novel hybrid manufacturing process, developed to machine monocrystalline silicon with reduced surface defects, such as edge chipping. Edge chipping is commonly observed, when mechanically machined at several hundreds of microns of depth. Hence, the process reduces edge chipping generation by depositing copper as a sacrificial layer onto the silicon's surface. It protects the surface against shock loading contributed by the micro-end-mills during micro-milling by acting as an energy buffer. Full slot micro-milling was performed along the [100] direction on a (001) silicon at 30, 50 and 100 µm of total machining depths. Chemical etching was used to remove the copper after machining. Similar experiment was also performed on an uncoated silicon workpiece for comparison. Scanning electron microscope (SEM) was used to measure the generated edge chipping in terms of length. Measurement was conducted by measuring the average length of the chipped surface along the top SEM image view on each machined slot. Using copper as a sacrificial layer, generation of edge chipping was significantly reduced. Additionally, edge chipping was absent below the total machining depth of 50 µm.

Keywords: Micromachining, Monocrystalline Silicon, Edge Chipping, Hybrid Machining

1. Introduction

Fabrication of monocrystalline silicon, a hard and brittle material, at micro-scale level can be challenging when good machining quality and high accuracy are required. Currently, subtractive techniques such DRIE and wet etching are used. Although they achieve patterned subtraction by lithography process, however, they are only economical for large scale manufacture and are limited to planar structures. Mechanical micro-milling is a maskless technique, which allows direct machining of functional structures on silicon's surface. It is also an economical alternative and helps to bridge the gap of micro/mesoscale components fabrication for prototyping or small batch production.

Edge chipping is generated along the surface edges of the machined profile. It is common when silicon is mechanically machined at hundreds of microns in depth. Functionality of the machined part might be affected, as they cannot be removed in subsequent cutting passes. Hence, this paper investigates the feasibility of a novel hybrid manufacturing process, developed to reduce the generation of edge chipping on silicon during micro-milling.

2. Summary of proposed hybrid manufacturing process

Figure 1 shows the schematic of the hybrid process (Patent Pending). It aims to reduce the generation of edge chipping on silicon by depositing a layer of copper, prior to its main shaping process by mechanical micro-milling (Step 1). Copper was chosen due to its good resistance against fracture and ease of coating by electroplating. It acts as a sacrificial layer and energy buffer for silicon, by protecting the surface against shock loading during tool-silicon contact in micro-milling. Therefore, the use of a sacrificial layer was believed to help in mitigating the issue on brittle fracture and crack propagation in mechanical machining of brittle materials like silicon.

After copper deposition, micro-milling begins on the copper surface and continues into the silicon substrate, until the intended machining depth (Steps 2 and 3). Deposited copper continues to protect the surface edges of silicon, as depicted in Step 3. Upon completion, the electroplated copper was removed by chemical etching to obtain the original silicon workpiece (Steps 4 and 5).

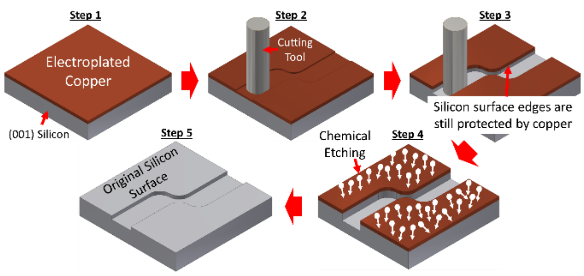

Figure 1. Schematic of Proposed Hybrid Manufacturing Technique. Copper (≈ 90 µm) was electroplated onto a (001) surface silicon (Step 1). Machining begins on the sacrificial layer and continues into the silicon substrate (Steps 2 and 3). Finally, copper was removed using either chemical etching by nitric or hydrofluoric acid (Steps 4 and 5).

3. Experimental Methods

Slot milling was conducted on an ultra-precision three axes micro-milling machine, integrated with an air bearing spindle and 0.5 mm diameter single crystal diamond end-mill with cutting edge radius ≈ 100 nm. Table 1 shows the optimised machining parameters, obtained from the authors' previous research [1-2]. To investigate the behaviour of edge chipping generation at small and large cutting depths, three slots were machined down to a total machining depths, t, of 30, 50 and 100 µm (referenced from the silicon surface) respectively. Similar machining was also conducted on an uncoated silicon workpiece for comparison.

Finally, qualitative characterisation was performed on the final machined surfaces using a table top Hitachi TM3030 scanning electron microscope (SEM). Additionally, an average length of the chipped surface edges, as shown in Figure 2, was measured to quantitatively assess the scale of edge chipping.

Table 1. Machining Parameters for the Feasibility Study

Feed per Tooth	Cutting Speed	Depth of Cut	Orientation	Cutting Lubricant
0.15 µm/tooth	78.54 m/min	10 µm	[100]	No

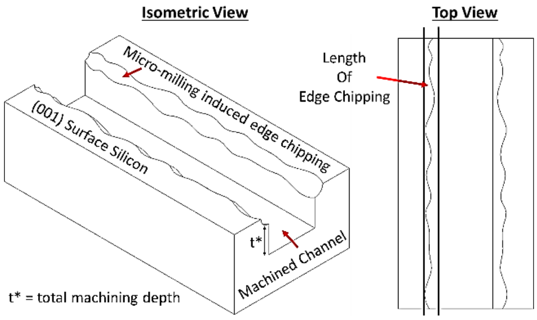

Figure 2. Schematic of the Edge Chipping Measurement. Average chipping length was measured on the chipped surface edges along each machined slot using the SEM imagery (Top View).

4. Results and Discussion

Figures 3 and 4 show the SEM imageries and measured length of edge chipping for the machined slots on both copper coated and uncoated silicon workpiece. Per Figure 3b, no visible edge chipping was observed on the copper coated silicon at both t = 30 and 50 µm. This phenomenon was also evident in the interface layer between the copper and silicon, as shown in Figure 3a, prior to copper removal. In terms of copper coated silicon, the generation of edge chipping was believed to have begun beyond t = 50 µm. This is because, even though the newly formed chips were dust away by the constant supply of compress air, advancement of the cutting tool into the silicon substrate at higher cutting depths might affect the chips expulsion process. Hence, a “build-up-edge” effect might occur, leading to possible chip adhesion on the diamond micro-end-mill and eventually tool wear.

Furthermore, the scale of edge chipping was significantly reduced with the assistance of copper, when compared to the uncoated silicon workpiece, as shown in Figures 3b and 3c. Such phenomenon was also shown in Figure 4, whereby the highest edge chipping generated on the copper coated silicon was ≈ 124 µm at t = 100 µm, when compared to the uncoated silicon of ≈ 168 µm. Controversially, insignificant differences in the chipping length were observed between the up-milling (Fig. 4a) and down-milling (Fig. 4b) sides of the copper coated silicon. Choong et al. 2016 [1] shows that smaller edge chipping was achieved when machined along the up-milling side. However, such effect was believed to have taken the advantage of the sacrificial layer, thus reducing the defects generated on the silicon surface. Use of a sacrificial layer also allows greater flexibility in planning the machining path.

To further justify the advantage of the sacrificial layer, Figure 3a also shows that edge chipping does occur at the entrance of each machined slot. No doubt, the copper was electroplated onto the whole silicon surface. However, the electroplated copper around the slot’s entrance region will be removed once the cutting tool advances into the silicon substrate. Hence, no protection was embedded to that region from the subsequent cutting passes.

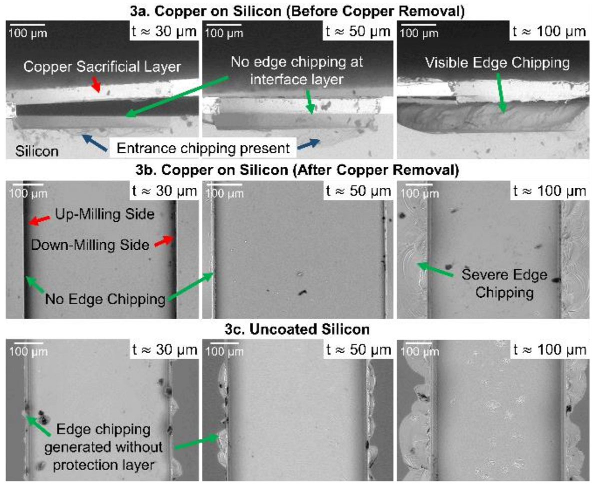

Figure 3. SEM Microscopy: Copper coated silicon (a) before removal, (b) after removal and (c) Uncoated silicon. Edge chipping was absent below t = 50 µm, when machined by the proposed process.

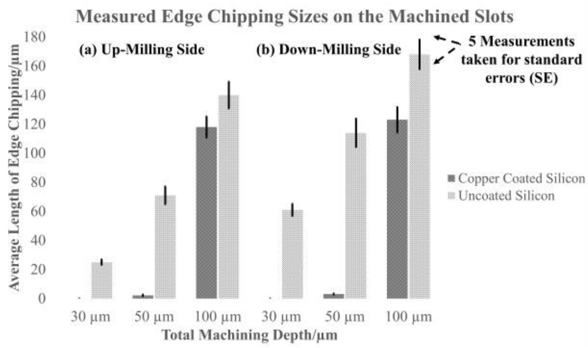

Figure 4. Measured Length of Edge Chipping: (a) Up-Milling and (b) Down-milling Sides. Measured chipping lengths for copper coated silicon at t = 30, 50 and 100 µm shows insignificant differences. This allows greater flexibility in planning of the machining path.

5. Conclusions

In conclusion, feasibility investigation on the proposed hybrid manufacturing technique was conducted. Absence of edge chipping below t = 50 µm was observed. This was made possible with the introduction of a sacrificial layer, such as copper, to protect the surface of brittle material from shock loading during machining. In addition, the measured chipping length indicates insignificant differences between chipping on the up and down-milling sides of the machined slot. Hence, it justifies the feasibility and capability of the proposed hybrid process. In addition, this process also provides flexibility to employ down-milling, if necessary, while not sacrificing the final machining quality. Further optimizations to this process will be conducted in the later stages of this research.

Acknowledgement

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Reference

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