Low Cost CNC Back Side Sample Preparation for FIB Analysis

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The following article is an overview of an attempt to develop appropriate methods and supporting apparatus for the use of a standard relatively low cost CNC (Computer Numerical Control) mill for back side silicon sample preparation for FIB (Focused Ion Beam) analysis. The effort was successful, resulting in an adjustable stage, a reliable zeroing method, and a recipe for silicon milling and polishing that successfully produced seven FIB appropriate samples, two of which were tested in the FIB and all of which were functional after processing.

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I. INTRODUCTION

FIB (Focused Ion Beam) analysis and machining are common methods in the semiconductor industry for circuit analysis and editing, and in recent years are used in other fields.[1] As the use of FIB techniques inevitably involves etching of the target material, samples must be prepared such that the surface to be etched is extremely smooth (sub-micron smoothness at minimum) and parallel to the circuit.[2]

Traditional methods for sample preparation for FIB analysis require the removal of the bulk silicon from the backside of the device. This denies the user the benefit of the intrinsic heat sink inherent in said bulk silicon, and may introduce etch depth issues due to the bowing of the chip while also being cumbersome and time consuming.[3]

While some silicon milling machines that enable local back side access to the circuit exist, they are often prohibitively expensive and thus not an option for the average user. With the intention of making local back side access for FIB analysis more feasible, a low cost method was developed using a common CNC mill and a variety of readily available milling and polishing materials.

II. APPARATUS

The final milling apparatus consisted of a 3040 CNC mill controlled by a computer running Mach3 and taking several diameters of diamond grit bits, a two axis tilt stage with an aluminum bath containing an insert plate, a removable downwards facing USB camera microscope, and a removable box containing a gel for calibration. For enhanced manual control a Contour Design ShuttleXpress joystick was used. The entirety of the project cost approximately 2000 dollars.

A pneumatic press was used to apply pressure to chips when affixing them to the insert plate for transfer to the stage.

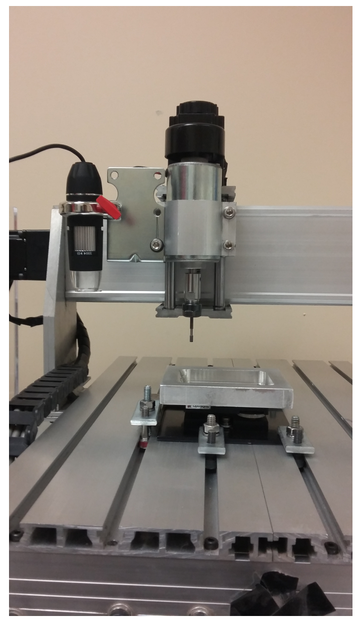

FIG. 1. Milling Apparatus

III. PROCESS

The process of method development was divided into modules based on the process order and availability of materials. The primary components are: control of the CNC mill, development of a stage, silicon milling, and silicon polishing.

A. The Mill

The mill selected was a standard 3040 CNC mill from China (as such, all components were metric), consisting of three stepper motors driving three lead screws. Each lead screw was accompanied by a pair of rails upon which the components ran using linear ball bearings. The mill had previously been modified and as such suffered from some degradation of the lead screws, the screw nuts, and the ball bearings, especially in the z (vertical) axis. The

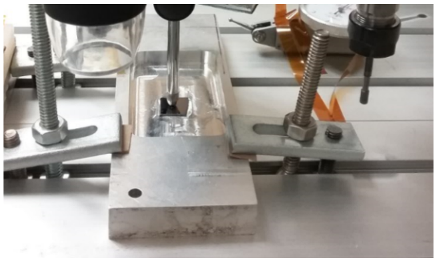

FIG. 2. Initial Bath (Center)

FIG. 3. Left to Right: 6.35 mm, 3.175 mm, and 1 mm Bits

mill was controlled with Mach3, a standard CNC control interface.

For the purposes of carrying out preliminary testing, a basic stage was milled out of aluminum, taking the form of a small bath approximately 8 mm deep, approximately 7.5 by 5.5 cm, and extended at full height on both ends of the bath to allow for clamping and the mounting of any supplementary components. This can be seen in Figure 2, where a sample fixed inside the bath is being probed with a micrometer to establish a z axis offset.

The primary challenges with the mill were functional motor control, axis calibration, and repeatability. The machine was operated through a parallel port, necessitating a non-dedicated graphics card in the control computer, as otherwise interference in the port would result in dropped steps and extremely uneven motor performance. This was easily rectified by acquiring a computer with the requisite hardware.

The axes were calibrated by affixing a digital dial micrometer to each axis in turn and then using the Mach3 calibration system to manually command movement in each axis repeatedly, until values converged.

Repeatability testing was undertaken as part of the silicon milling and polishing modules.

B. Silicon Milling

Considerations when milling silicon include containment, bit selection, axis zeroing, spindle speed, feed rate, and path. Due to the hazardous nature of silicon dust and the production of heat during the milling process, all milling operations were undertaken with the contact point (and the chip in its entirety) submerged in water, contained by the bath on the stage. The mill was also enclosed in a U shaped shield to catch any fragments in the event of the bit shattering.

A variety of bit sizes (seen in figure 3) were investigated. Larger bits (approximately 0.25 inches or 6.35 mm in diameter) were used to complete surface thinning, and smaller bits (3.175 mm and 1 mm in diameter) were used to mill wells and trenches of various sizes. The larger bits resulted in some splashing of the water and required the construction and application of a small secondary shield enclosing only the bath area. The smallest bits were of poor quality, displaying significant variation bit to bit in terms of edge consistency, length, and grit quality. Some were heavily pitted and considered highly suspect. While some experimentation was carried out, the 1 mm bits were deemed non-viable for immediate use, as most reasonably sized trenches required multiple passes, and due to the degradation and misshapen nature of the bits, would unpredictably contain large peaks where silicon had never been removed.

The optimal bit for trench milling was found to be the 3.175 or 0.125 inch diameter bit, as it could with relative ease produce trenches that even after significant bit degradation had flat zones at the base of 2-3 mm, lending them well to polishing.

Z axis zeroing was initially carried out by affixing a dial micrometer adjacent to the bit, establishing an offset depth, contacting the target with the micrometer, and then sending the bit to the offset depth. While the first test in this manner returned an error of only 10 um, later tests were not so promising, returning deviations of 30-100 um on most replicates, once milling over 400 um and reaching the metals on the other side of a test chip. This was found to be a combination of inaccuracy in the method (it was difficult to establish the offset with the bit, the micrometer slides were occasionally sticky, and the large x, y, and z distances travelled introduced cumulative error), and drop in the z axis due to damaged linear bearings on one of the rails. The intrinsic z axis drop was largely rectified by completely disassembling the machine, cleaning it, and slightly repositioning the rails (easily done due to the lack of self-aligning features in the design). After some testing, the Z axis was zeroed by marking the target with a sharpie line. An approximate Z distance was estimated to be the zero using a tilted camera. The bath was then filled and the bit manually commanded to move to the approximate zero. The mill was then set to milling speed and the bit manually lowered while being rastered back and forth over the line (or the marking over the target point). Using the joystick, the bit could be lowered 10 um at a time, leaving an easily visible score on the line. The bit would then be retracted 10 um, and zeroed. This method produced error on the order of 10-15 um under normal circumstances.

The x and y axes were zeroed by marking a point on the target with a sharpie. The bit would be manually lowered onto the gel and activated to leave a circular mark. The x and y axes would then be zeroed. The camera could then be brought over the gel to establish an offset (the Mach3 interface has a built in crosshairs function). The camera could then be zeroed over the target point and the bit could be brought to the offset, placing it above the target.

While some experimentation was carried out to determine the effect of spindle speed on the process (minimal unless the speed change was extreme), the optimal speed was assumed to be the highest possible speed at which the spindle could reliably run. This was approximately 11 000 rpm. Tests were carried out at 12 000 and 10 000 rpm but the former resulted in often unpredictable speed variation and the latter required reduction of the feed rate (the rate at which the head moves) to run without detrimental effects.

The feed rate with respect to a spindle speed of 11 000 rpm was generally around 1.39 (mm/minute) for multipurpose use. Paths that involved a variety of different depths, cutting angles, and directions could be set to 1.39 globally and work in a reasonably safe and practical manner. The issue with this is that if the angles are too steep, or the script too long, 1.39 can be impractical, resulting in damage or extreme timeframes. After some manual monitoring and on-the-fly modification of the system, speeds of 1 or less on steep descents (100 um down on a distance of greater than 1 mm) and of up to 20 on shallow cuts (surface thinning on the bowed external edges of a chip) were deemed viable for regular use.

Experiments to determine functional zeroing and levelling methods, stage design, mill integrity, usable bits, spindle speeds, feed rates, and material removal rates for both milling and polishing were undertaken in the course of method development.

The stage design was primarily influenced by the necessity of keeping milling operations contained and cooled in a water bath, ease of sample transfer for contact profilometry, ease of multiaxial tilt adjustment for proper contact, and general modularity.

In order to accomplish this, a simple water bath was milled out of aluminum (using a larger CNC mill), and screwed onto a two axis tilt stage. A small plate was then cut from an aluminum sheet. The plate could then easily be mounted inside the bath (with two screws), or removed with acceptable brevity. This allowed the sample to be mounted on the plate inside the mill press (using wax as an adhesive), and be removed from the bath between milling operations for measurement without disruption to the tilt orientation. The stage as a whole was fixed to the deck using the earlier clamps, though modified for better clearance as seen in Figure 1 (the screw ends were cut down to the minimum length required for the nuts).

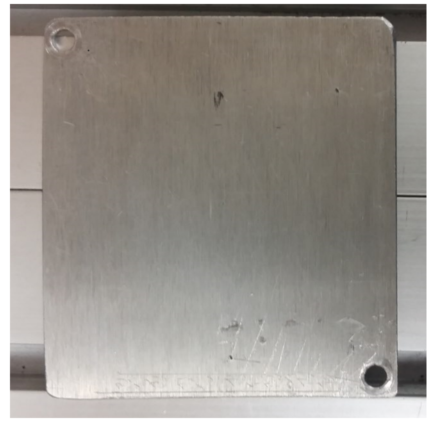

FIG. 4. Insert Plate from Bath

FIG. 5. Felt Bobs for Polishing

C. Silicon Polishing

Polishing was carried out using a variety of different implements and patterns. Testing began using felt bobs and diamond grit paste. The first attempts used small diameter "hard" felt bobs, a series of pastes (15 um, 6 um, 3 um, 1 um, 0.5 um, and 0.1 um colloidal silica) and a circular pattern at the bottom of circular wells. This approach proved to be ineffective. The felt bobs disintegrated when used with the colloidal silica, and deformed during general use, contributing to an eventual convexity centered at the base of each well, worsening with each consecutive pass.

A wooden dowel was combined with water and a small amount of the 0.1 um colloid in a attempt to remedy this issue with the superior stiffness of the wood. While the dowel produced an unexpectedly smooth surface texture (on the order of 5 um), it was ultimately unsuccessful as

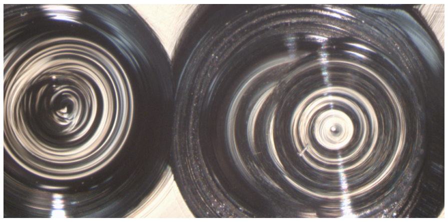

FIG. 6. Surface After Dowel Polishing

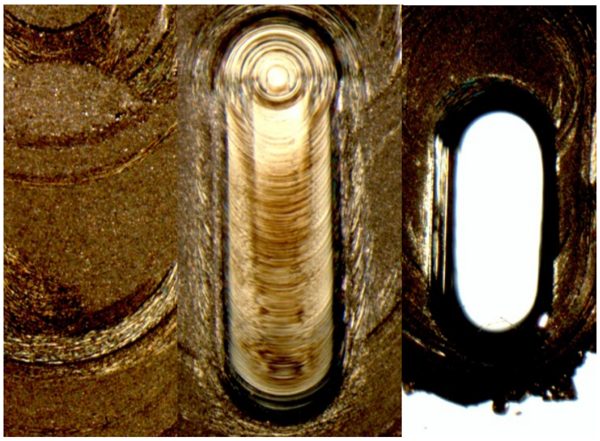

FIG. 7. Unpolished, After 15 um, and Fully Polished

it left deep grooves in the surface and slightly worsened the convexity (see figure 6).

After some experimentation, polishing a linear segment of a trench (be it a circular or linear trench) with a truncated felt bob (the tips lacked rigidity) was found to be optimal, as it significantly reduced the likelihood of unintentional convexities, and also reduced the likelihood of the felt bob colliding with the walls of the trench or well. Additionally, the method was reduced to only three different pastes (15 um, 3 um, and 1 um), greatly streamlining the process and cutting the polishing time (including the un-mounting and washing of the sample between grit sizes) down to approximately 45 minutes.

The 15 um run was found to be invaluable in removing the large scale surface defects produced in the milling process. The final polishing process consisted of one pass (being a single "back and forth" motion) using the 15 um paste, 3 passes using the 3 um paste, and 6 passes using the 1 um paste. This had the added advantage of being modular in Mach3, as the pass process can be implemented as a loop, making mid-process modifications or further processing easy to implement. The final surfaces exhibited textures in the ten nanometer range, while the overall surface gradient was found to be on the order of several hundred nanometers over several millimeters.

IV. CONCLUSIONS

The use of a standard, relatively low cost CNC mill for FIB sample preparation is a viable method. While some challenges exist in terms of appropriate setup and calibration, developing both the methods and apparatus is realizable and, in this case, produced two samples with FIB editable surfaces that, once tested for post-process functionality, were found to be successful. An additional five samples were prepared and, while not edited with the FIB, were also found to be functional after the milling and polishing process. The process itself can produce surfaces with sub-micron smoothness, and can mill samples with a deviation of 15 um.

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Notes and References

[1] Kedar Narayan and Sriram Subramaniam. Focused ion beams in biology. *Nature Methods*, 12(11):1021–1031, November 2015. ISSN 1548-7091. doi:10.1038/nmeth.3623. URL `http://www.nature.com/nmeth/journal/v12/n11/full/nmeth.3623.html?foxtrotcallback=true`.

[2] Chun-Cheng Tsao, E. LeRoy, S. Saha, L. Ansorge, and M. E. Potter. Reliability of ultra thinning of flip chips for through-silicon analyses. In *2002 IEEE International Reliability Physics Symposium. Proceedings. 40th Annual (Cat. No.02CH37320)*, pages 198–204, 2002. doi:10.1109/RELPHY.2002.996636.

[3] P. Perdu, R. Desplats, and F. Beaudoin. *Comparative study of sample preparation techniques for backside analysis.* Asm International, Materials Park, 2000. ISBN 978-0-87170-701-7. WOS:000175459100024.