INTRODUCTION

Single crystal diamond turning of "soft semiconductors", such as germanium in the ductile mode, has been established [2] and has many uses for infrared devices. The goal of this work is to enable multi-axis contour machining of zinc selenide and germanium to generate freeform surfaces. The practical goal which has driven the research is the manufacture and testing of an Alvarez lens for the infrared regime. We believe this will be the first Alvarez lens, an optical device with many potential uses. The project has: (1) involves the design of small scale milling tools with negative rake angles that had not previously been available and tested in these materials; (2) testing to determine if ductile mode milling is possible and under what conditions; (3) determination of milling parameters necessary for producing surface finish and quality of freeform optics suitable for use in the infrared. While we have focused on germanium and zinc selenide for this project, the general results and approach are expected to be broadly applicable to other materials as well.

Alvarez Lens

The Alvarez lens was invented in 1967 by Luis Alvarez [1]. It is a two-element lens, composed of two cubic phase plates, with the capability of variable focal length through lateral shifts. Each cubic phase plate is composed of a flat surface on one side and a surface defined by a cubic equation on the other side (Eq. (1)).

\[ z(x, y) = 0.0012 ( \frac{1}{3}x^3 + xy^2 ) + 2.5 \]  

(1)

When assembled, the two cubic surfaces are inverted with respect to each other and aligned along the z-axis so that at each point the total thickness of the material along z is constant. Thus, if aligned in the x-y plane, and the assembly acts as a plate of constant thickness with infinite focal length in z. When the plates are laterally shifted in the x-y plane, by an equal amount in opposite directions, a composite spherical surface is created from the combination of the shifted cubic surfaces. The composite spherical surface changes by varying the amount of lateral shift in the x-y plane, changing the focal length of the system. The Alvarez lens system is shown below in Figure 1.

![FIGURE 1. Orientation of the Alvarez lens cubic phase plates when aligned (left) and shifted (right).](image)

Stated again, the goal of this work is to manufacture and test such a device in germanium, and later in zinc selenide, by diamond milling the freeform aspheric optical surfaces.

MACHINING TESTS

In order to manufacture the Alvarez lens design, it is necessary to understand the contour milling behavior of each material. To that end, a set of cutting experiments were designed and carried out using both turning (rotating part, stationary tool, no cut interruption, two axis motion) and milling configurations (rotating tool, interrupted cutting, three-five axes of motion). All cutting tests reported were completed using a spray mist of mineral oil for coolant. The materials for all cases were 27.5 mm diameter, single crystal germanium wafers and 30 mm diameter zinc selenide wafers. Prior to all experiments, these wafers were mounted to the C-axis with a vacuum chuck and turned on one side at the least aggressive of the parameter sets listed below to produce a planar optical surface perpendicular to the C-axis of the machine. The purpose of the turning experiments, which have been reported elsewhere in the literature for germanium [2-6], was to help in the tool design
and choice of parameters for the contour milling operations.

**Turning Experiments**

**Turning Setup**

Based upon previous work in literature [2-6], a set of turning parameters intended to span the ductile and brittle modes of machining were developed and used for both materials. Surface speed was held constant at 1 m/s, while depths of cut varied between 1 μm and 10 μm for both materials and the feed rate was varied between 0.3 micrometers per spindle revolution (μm/rev) and 10 μm/rev. Twelve bands were cut into each type of material using multiple combinations of the aforementioned parameters. Single crystal diamond tools, having nose radii of approximately 1 mm and a -25° rake angle were used.

**Turning Results**

Turning experiments in germanium and zinc selenide show that, consistent with existing literature, both materials can be machined in the ductile regime using a negative rake, single crystal diamond tool. Curiously, zinc selenide seemed to behave more favorably in the ductile regime and produced superior surface finishes below 0.5 nm R_a, that correspond quite well with theoretical prediction based on geometry alone.

**Milling Experiments**

**Milling Setup**

For the milling experiments, 11 square patches were raster milled using linear cutting movements directed toward the center of the wafer, with a constant step-over of 4 μm perpendicular to the radius of the wafer. The first set of patches (patches 2-7) maintained a constant feed rate (15 mm/min) with varying depths of cut (0.001-0.015 mm) at a constant spindle speed of 50,000 rpm and thus a constant cutting (surface) speed. The second set of patches (8-11) maintained a constant depth of cut (0.002 mm) with varying feed rates (50-500 mm/min). Cuts were completed using single flute, single crystal diamond milling tools, with 1 mm nose radii and 0° rake angle and -45° rake angle. Figure 2 shows the machining setup.

**Milling Results**

Milling tests showed that both germanium and zinc selenide can be milled with a zero rake angle tool, as has been reported by Davis et al.[7]. After milling with a zero rake tool, the surface finish was limited to approximately 20 nm R_a. But milling with a negative rake tool, better surface finishes were produced than those produced using a zero rake tool by approximately 25%. The disadvantage of using a negative rake angle micro-endmill is that the surface errors (since the tool projection is elliptical) are not as easily understood and compensated for as those produced from using a zero rake angle tool. For this reason, a zero rake angle micro-endmill was used for the fabrication of the prototype germanium optic.

**ALVAREZ LENS**

**Alvarez Lens Tests Setup**

Through preliminary turning and milling tests, parameters to create this complex contoured surface were determined. A single crystal, zero rake angle micro-endmill from Contour was used to raster mill all the optical components of the Alvarez lens. A feed of 300 nm/rev, surface speed of 50,000 rpm, and a step-over of 4 μm was used for each cubic phase plate. Each plate was machined in one process to reduce thermal errors, tool location errors, and any possible control loop errors.

**Alvarez Lens Results**

For the first cubic phase plate (Figure 3), manufactured in germanium, surface roughness analysis and surface measurements were taken.
to help determine the achieved surface finish and the actual machined surface.


**Surface Finish Analysis and Results**

Quantitative surface roughness measurements were taken across the surface of the first cubic phase plate. Nine different locations across the optic surface were measured in order to obtain an accurate average measurement of the surface roughness. To aid in eliminating error due to the surface curvature and stage tilt, fourth and lower order terms were removed in the measurement analysis. After examination in the scanning white light interferometer (SWLI), an average surface finish of 14 nm $R_a$ or 17 nm RMS was achieved; where $R_a$ values of approximately 2 nm were achieved along the tool feed paths. Average peak-to-valley was measured to be 122 nm, due primarily to the tool step-over.

From the SWLI data (Figure 4), it can be seen that the center of the optic contained the best surface finish (9 nm $R_a$) and that the surface roughness increases gradually at the outer edges of the optic (16 nm $R_a$).

**Surface Measurement Analysis and Results**

Once the Alvarez optic surface was machined and measured in the SWLI, the surface was then measured using a Leitz CMM to verify the contour of the surface. Four hundred data points were measured across the optic surface, in a 10 mm x 10 mm grid pattern, evenly spaced by 0.5 mm. Measurements were taken using a 3 mm ruby sphere probe. The collected data was imported into MATLAB for comparison with the theoretical surface equation (Eq. 1).

![Germanium Alvarez lens surface roughness data: 200x magnification with 4th order removed.](image)

**FIGURE 4.** Germanium Alvarez lens surface roughness data: 200x magnification with 4th order removed.

From the SWLI data (Figure 4), it can be seen that the center of the optic contained the best surface finish (9 nm $R_a$) and that the surface roughness increases gradually at the outer edges of the optic (16 nm $R_a$).

**FIGURE 5.** Germanium Alvarez cubic phase plate: Theoretical vs. Actual Surface.

Seen above in Figure 5, the "dotted" surface is the MATLAB generated surface fit to the CMM data. The solid surface was generated using the theoretical surface equation. Visually the two surfaces contain the same contour, having only variations on the order of 10 microns at the outer extremities of the part mostly due to a slight rotation between the measured data and the mathematical curve. MATLAB generated the following fit (Eq. 2) to the experimentally measured data.

$$z(x,y) = 0.0004056x^3 + 0.00119xy^2 + 2.4$$  (2)

Comparing Eq. 1 and Eq. 2, the coefficient for $x^3$ should theoretically be 0.0004, and it was measured to be 0.0004056, an error of 5.6 x 10^{-6}. The $xy^2$ coefficient was measured to be 0.00119 when it theoretically should have been 0.0012 an error of 1.0 x 10^{-5}. Finally, the standard error (root mean squared error) for this surface fit is 0.9999. These errors are small enough to not affect the overall focusing capability of the Alvarez optic, but may affect the comparison of measured and theoretical change.
in focal length as a function of shift; the behavior of the optic and will be reported in a later publication.

The second cubic phase plate has also been manufactured and the Alvarez optic is being assembled for testing.

CONCLUSIONS
A basic understanding of the machinability of germanium and zinc selenide has been gained through fundamental research and many trials of experimental machining and given us the knowledge needed for producing contoured surfaces, such as an Alvarez lens. A complete Alvarez lens has been machined in germanium, with an overall surface finish of approximately 14 nm $R_a$, where the machined surface contained minimal errors, on the order of $10^{-3}$, when compared to the theoretical surface. Actual surface errors at particular locations on the optic surface are being examined. It may be that the machined surface is better than the capability of the CMM. Eventually the goal is to measure the surface on the machine with an LVDT and develop an algorithm for a surface correction program that generates a corrected toolpath while the optic remains on the machine.

The final stages of the project consist of testing the Alvarez lens setup to verify that it has the ability to produce variable focal lengths as a function of lateral shifts in the x-y plane. Once it is verified that the Alvarez lens operates as expected, another set of cubic phase plates will be manufactured in the second material, zinc selenide. While we have focused on germanium and zinc selenide for this project, the general results and approach that were discovered are expected to be applicable to many other materials as well.

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REFERENCES