A Practical Approach to LWIR Wafer Level Optics For Thermal Imaging Systems

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ABSTRACT

The development and implementation of wafer level packaging for commercial microbolometers has opened the pathway towards full wafer-based thermal imaging systems. The next challenge in development is moving from discrete element LWIR imaging systems to a wafer based optical system, similar to lens assemblies found in cell phone cameras. This paper will compare a typical high volume thermal imaging design manufactured from discrete lens elements to a similar design optimized for manufacture through a wafer based approach. We will explore both performance and cost tradeoffs as well as review the manufacturability of all designs.

Keywords: Precision glass molding, chalcogenide, LWIR, wafer level optics, microbolometer.

1. INTRODUCTION

Wafer Level Optics

Micro lens arrays have been in existence for many years, wafer level optics (WLO) are simply an extreme subset of these types of arrays. WLOs are simply arrays extended to a wafer level scale; this is achieved by increasing the relative aspect ratio of diameter to thickness in order to match the size of the imager wafers and to take advantage of the wafer processing technologies. The development of wafer level optics began in earnest in the mid-2000's to support the development of wafer level cameras for cell phone camera modules. The recent introduction of wafer level packaging for microbolometers has driven interest in wafer level optics for thermal imaging. There are many restrictions on wafer level optics that, to date, have limited their use in almost all but the lowest levels of cell phone imagers[1]. The approach for thermal imaging has similar stumbling blocks and will need careful consideration and development before their general acceptance and inclusion in commercial thermal imagers.

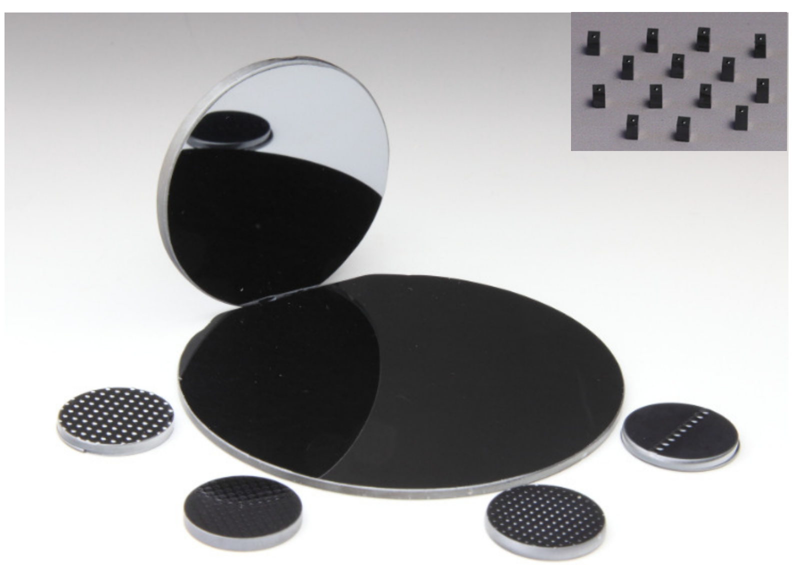

Figure 1. Chalcogenide Wafers, Molded Arrays and Diced Elements
(Photo by Robert Kalinowski, LightPath Technologies)

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2. BACKGROUND

Microbolometers

Uncooled microbolometers are the dominant focal plane array for commercial and high volume thermal imaging applications. These devices were originally developed in the 1980's based on the work of Honeywell and Texas Instruments with the U.S. Department of Defense. Subsequent commercialization and competition in the 1990's and 2000's has led to a rapid decrease the cost of infrared focal plane arrays.[2]

The Cell phone Camera Module (CCM) exhibited the same pattern of cost reduction and high volume application growth through the mid-2000's. Cell phone Camera Modules are in wide production today with volumes in the 100's of millions of units per year. The primary driver for cost reduction was the shrinking of the CCM size by shrinking the pixel size of the sensor without impacting its imaging performance.

Like cell phones, the primary driver for the cost reduction in microbolometers has been the reduction in sensor size and pixel pitch. In 2000, the standard pixel size for uncooled LWIR focal plane arrays was 38 microns. By 2004 the pixel pitch had dropped to 25 microns and in 2009, 17 micron sensors were being introduced. In 2012, DARPA awarded three contracts for the development of a sub $500 thermal imaging camera with 12 micron pixels. Also in 2012, SOFRADIR released a 12 micron IR FPA core.[3] Eventual development in IR FPA will end up with pixels sizes between 5 micron and 7 microns, which represent the diffraction limit for infrared sensors.[4,5] Figure 2 shows the trend for pixel sizes over time.

A second similarity to CCMs is the development of wafer level packaging. Cell phone cameras were initially produced using common integrated circuit packing techniques including the sensor, a front window and an environmental cavity to protect the sensor. These were all packaged in a separate manufacturing step after the sensor itself was produced. In the late 1990's cell phone camera modules started using wafer level packaging, a process where the sensor, window and its environmental cavity were all produced from wafers.[6] This technology has also been brought to thermal imaging by FLIR in 2011, with the introduction of the Quark IR focal plane array.[7]

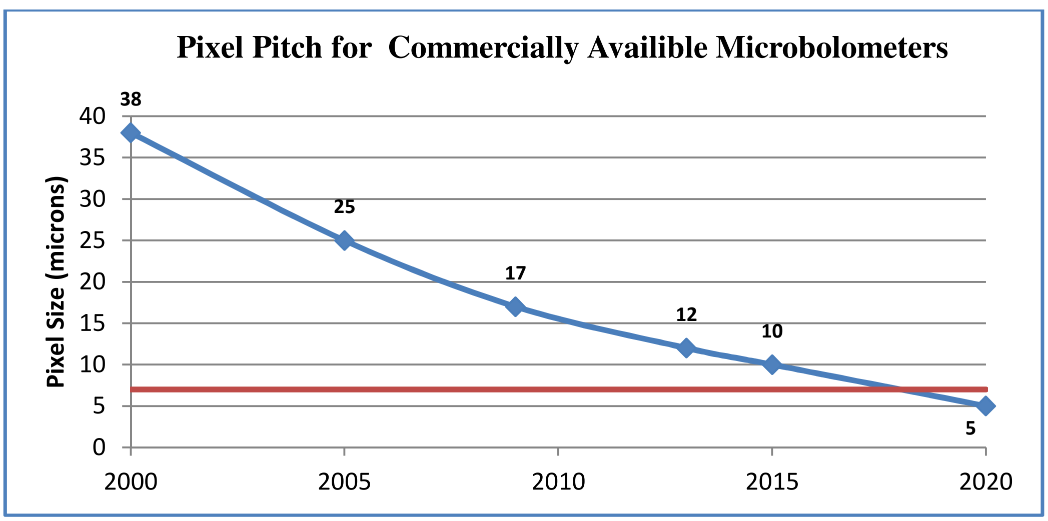

Figure 2 Microbolometer Pixel Pitch Timeline

Wafer Level Manufacturing

The increasing demand for lower cost cell phone camera modules in the mid 2000's led to the development of wafer level cameras (WLCs). WLCs are simply very small digital cameras manufactured at a wafer level. A Wafer level camera has two primary components: an image sensor and the optical component stack. The image sensor is manufactured using wafer level packaging (WLP), where the image sensor is packaged at the wafer level rather than singulated and packaged with subsequent processes. In the original concept of wafer level cameras, the optical components are also manufactured on a wafer level, matching the size of the image sensor wafer. The individual optical components are stacked in combination with spacers and sometimes filters to create a single wafer sized stack consisting of thousands of optics. These wafer level optics (WLO) are then stacked with the image sensor to create the camera. These cameras are then singulated from a single wafer stack, imager and optics to generate thousands of individual cameras.

The wafer level optics used in CCM's can be manufactured using a number of different technologies. The dominant technology however is UV polymer replication on a glass substrate. The technology goes by a number of different names depending on the manufacturer but is essentially the same. The process begins with material selection; a glass substrate and a liquid UV curable resin with specific optical properties selected based on the design. There are limitations on the availability of the resins and substrates, with each manufacturer developing different resins for different optical properties, and glass substrates limited to those available in wafer format. A wafer size array mold is made with thousands of cavities matching the optical prescription of the design.

The UV polymer resin is then dispensed into the mold cavities brought into contact with the glass substrate and cured with UV light. This is repeated for the second surface. The process is usually prototype on a much smaller scale to determine the shrinkage associated with the selected resin and surface profile. The master mold can then be compensated for the shrinkage to get the best possible optical performance. The initial molds are very expensive and time consuming to manufacture, whether they are made from a multi-axis diamond turning machines as a single master, or a multi pin, embossing step and repeat process. The mold is then mastered to generate additional sets of tooling. There are a number of references that describe the process in excellent detail.[8,9]

The primary challenges in manufacturing these WLOs are limited material selection, shrinkage, mold manufacturing complexity and accuracy, "z"-height tolerancing and compounded yield issues. The limitations of the current WLO technologies have limited the progression of WLCs beyond the lower pixel formats of CCMs. Conventional CCM technology dominates the larger pixel formats.

A conventional CCM is manufactured using a combination of injection molded and precision glass molded lenses mounted into an injection molded barrel or lens holder.

The future of WLCs will therefore be determined by improvements in the optics manufacturing or by the introduction of novel camera concepts. One such option is the introduction of multi aperture optics which allows the use of a microlens array where a single optic exists in a WLC.[10,11,12] This array within an array concept would allow the use of the existing technologies for WLO for higher pixel cameras. Another option is integrating optical components that are not as limited as the techniques described above, one such option under development is wafer level precision glass molding (WLPGM).

Precision Glass Molding (PGM)

Glass lenses manufactured from precision glass molding (PGM) are used throughout industry. PGM lenses can be found in applications ranging from digital cameras and cell phones camera modules to thermal imagers. The PGM process based on oxide glasses has been around since the early 1940's; molded optics manufactured from chalcogenide glasses are more recent and have gained general acceptance. The manufacturing process is essentially the same for either type of glass. PGM is a high temperature compression molding process in which a piece of glass or preform is heated and then compressed to a final shape. A more detailed overview of the process can be found in Schaub, et al.[13] and the general process can be seen in Figure 3. The molding of precision optics provides a number of advantages, primarily the ability to manufacture precise and complicated optical surfaces in a highly repeatable manner that is readily scaled to high volumes.

PGM has been historically used to manufacture smaller lenses in high volumes by manufacturing of a plurality of lenses on a single substrate. These arrays of lens are then singulated using a dicing saw. The ability to manufacture many lenses in a single process step significantly reduces the processing time per piece. Small form factors that may also be very difficult to mold individually can also be manufactured in this manner. Precision glass molding of these types of arrays has been around almost as long as PGM itself. Wafer level precision glass molding is a further development of this technology.

Wafer Level PGM

It was recognized early on in the development of WLC's that the existing WLO technologies would not be suitable for larger format sensors and higher optical specifications. The optimum solution for WLC is the development of wafer level PGM (WLPGM). An all glass solution that could be precisely manufactured could compete with the traditional camera modules, in fact PGM lenses began appearing in CCMs once pixel formats reached 2MP. The early drive toward WLPGM was started through a European consortium of 20 companies entitled "Production4µ" with the project "WaferLevelOptics"[14,15]. The purpose of this project was to "develop precision glass molding technologies for the replication of micro-optics from glass wafers. The idea is to mold a large number of micro-optics from one glass wafer, stack and link these into optical systems before being cut apart". Production4µ recognized the limitations of the existing WLO technologies and began the development of WLPGM in 2007.

WLPGM is an extreme subset of PGM and an extension of array molding. The primary differences are significantly greater aspect ratios (outside diameter to center thickness), larger diameters and a greater number of individual optical surfaces. The initial approach to wafer level PGM has been 100mm wafers. Assuming a 0.5 mm thickness, the wafer has an aspect ratio of 200:1, most commercial PGM lenses have an average aspect ratio of 2.5:1. Wafer level PGM requires molding significantly larger diameter parts than have been molded in the past, many commercial PGM machines do not even have the capability of pressing a 100mm wafer, let alone 200mm. Much of the early work has been achieved on internally developed machines. One of the primary issues with arrays on such large diameters molded at high temperatures, is shrinkage prediction, mold compensation and differential thermal expansion between the glass and the mold. A number of predictive methods have been established to compensate for the pitch error of the molds.[16,17]

Feedstock availability is also an important consideration, the available moldable glass types need to be available in low cost wafer format. Schott B270, a commonly molded material is readily available but the many of the other moldable glass types would require development.

The other primary issue with WLPGM is mold manufacture. Molds for PGM are made from ceramic or carbide materials due to high processing temperatures. Molding temperatures are always greater than the transition temperature of the glass, (B270, T_g=537℃). These materials can not be diamond turned and must be diamond ground, though lithographic methods could also be used.[18] Diamond grinding of arrays using multi-axis grinding machines is a relatively new technology that is under development.[19] The limited mold life and complexity of the tooling manufacture result in expensive tooling and higher lens cost. Resolution of these issues will be required for WLPGM to penetrate the WLC market. WLPGM remains a promising technology for wafer level cameras.

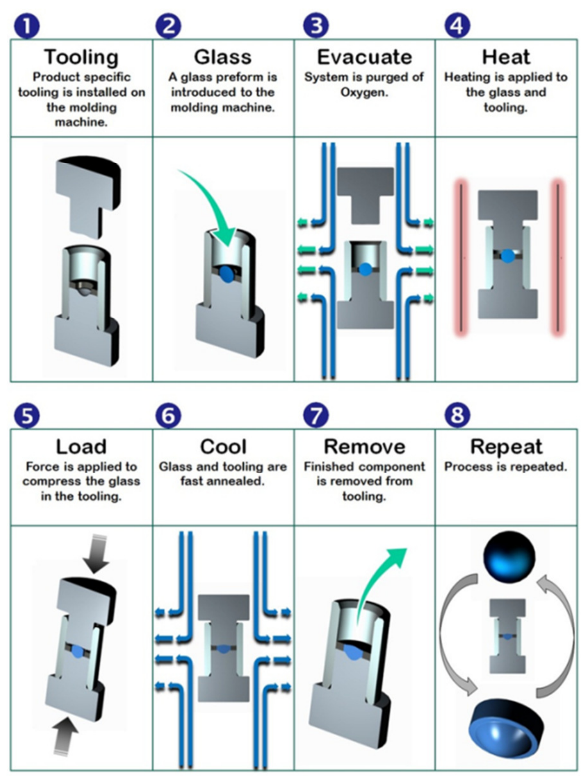

Figure 3 Precision Glass Molding Process

Wafer Level Thermal Optics

The development of wafer level thermal optics is expected to follow a similar path to the developments discussed above. The primary technologies for wafer level thermal optics (WLTO) are lithography based and precision glass molding of chalcogenide arrays. These technologies will need to displace traditional thermal optics that dominate the industry today, similar to the comparison of traditional camera modules optics versus wafer level optics in the visible.

Silicon or Germanium optics manufactured through lithography start with a substrate that is coated with photoresist material. The photoresist is exposed through a mask that defines and creates cylinders of photoresist. These cylinders are melted and form sphere. These spheres are finally processed using inductively couple plasma ion etching (ICP-RIE). The mixture of the etch gasses and oxygen provide control over the final surface and allow production of the aspheric optical surface.

Silicon and Germanium can not be molded due to their crystalline nature, chalcogenide glasses are the only option for precision glass molding for application in LWIR. The commercial development of chalcogenide glasses began in the early 1950's. Amorphous Materials Inc. led the commercial development of chalcogenides in the 1980's, but did not begin molding trials until 2000.[20] Precision glass molding of chalcogenides began as early as 1993[21]. Array molding of chalcogenides has also been achieved by LightPath see Figure 1. The manufacture of wafer level chalcogenide arrays is a new technology driven by the recent interest in wafer level thermal cameras.

The manufacture of wafer level chalcogenide arrays is not as challenging as oxide based glasses due to the much lower processing temperature and the reduction of elements on an array due to the larger pixels and greater pitch of a thermal imager. Fewer optical elements on the same mold reduces tooling complexity and cost. The wafer level optics manufacturing process is not a material efficient process due to the inherent nature of monolithic processing. In order to allow for singulation there is significant area beyond the optically active portion of the lens wafer. This is completely dependent on the wafer level design of the image sensor. This is not an issue for WLO based visible glass or polymer on glass manufacturing techniques as the raw material and wafer substrates are common commodities. IR materials or specifically chalcogenides for molding are not inexpensive in comparison. Any raw material not used specifically for an optical surface adds cost to the lens element. Therefore minimization of the pitch of the wafer is important. A common misconception is that WLC's are assembled and diced as a single process, this was the original goal of WLC, but proved difficult to achieve due to the compounding of yields as the stacks increased. The actual technique currently used is the WLOs are manufactured independently from the sensor and are optimized based on maximizing the output of optics rather than matching the pitch of the corresponding image sensor.[22] This concept is much more appealing to expensive substrates as it results in much higher material efficiencies.

The WLPGM process is a relatively new development, while many of the development issues are being addressed to make this a viable technology, additional work needs to be completed before commercialization. The primary of which is the development of cost efficient manufacture of chalcogenide wafers. The following section assumes chalcogenide wafers are available at a similar premium to Germanium wafers.

In order to determine what the most practical approach would be to the implementation of wafer level thermal optics or to determine if they in fact make sense for specific design requirements, a projected high volume design is reviewed in the following section.

3. DESIGN OF WAFER LEVEL OPTICS

Design

In order to compare the manufacturing technologies, we have designed lens assemblies for each technology based on projected requirements for the next generation of thermal imaging sensors. The target application is high volume night vision enhancement. These applications are expected to use wafer-level packaged 12µm microbolometers with 320 x 240 pixels within the next few years. The design also assumes a 0.67mm thick window in front of the sensor. The target lens system determined to be typical for this application is an f/1.0 lens assembly that has a field of view of 24 degrees horizontal and 18 degrees in the vertical direction. In addition, the Modulation Transfer Function (MTF) was specified for a pixel size of 12 microns or 41 line pairs per mm. The MTF for this lens assembly was required to meet the following requirements:

Field Position	Required MTF
On Axis	0.45
HFOV	0.25
DFOV	0.18

Based on this optical design, we evaluated the design for manufacture in three different methods.

Manufacturing Method Review

Traditional Thermal Imaging Optics:

The design of this lens assembly would require two molded chalcogenide lenses due to the high volumes expected of any system requiring wafer level manufacturing, diamond turning would not be expected to meet the volumes or price targets of a high volume wafer level thermal camera.[23] The design includes 4 aspheric surfaces on 2 elements; one surface is a hybrid aspheric diffractive surface. The lenses would then be mounted into a 16mm diameter by 11mm long aluminum housing that would be threaded to a camera mount. Clear apertures are 9mm and the overall track height is 12mm. This design concept is typical to current design standards and presents a low cost, low risk option.

Lithographic Methods:

Current state of the art in lithographic methods limit the size and sag height for each lens element. Reported limits for this method would be a diameter of 2 mm - 3 mm and a sag height of 200 microns per surface.[24] Based on these limitations, a comparable optical design would require 3-4 elements plus the necessary spacers. If the design were possible to be manufactured in this way, the final lenses would suffer from poor optical performance due to the sheer number of lens elements causing a drastic loss in transmission and decreased imaging performance due to alignment difficulties. Compounded yielding issues due to the high number of elements would also be expected to reduce yield.

Wafer Level Precision Glass Molding:

The WLPGM design is the same optical design as the traditional design. No spacer is required between the elements; the two wafers can be simply stacked, bonded and diced. The WLTO stack would then be diced to 10mm X 10mm to maximize material usage or 12mm x 12mm (Figure 4) to match the imager wafer. The designs for the PGM and WLPGM versions have the same optical performance as designed. The difference in optical performance shows up in the manufacturing tolerances for alignment. Nominal performance is shown in Figure 4. Figure 5 shows the relative sizes and form factors for the lens assemblies created through PGM and WLPGM.

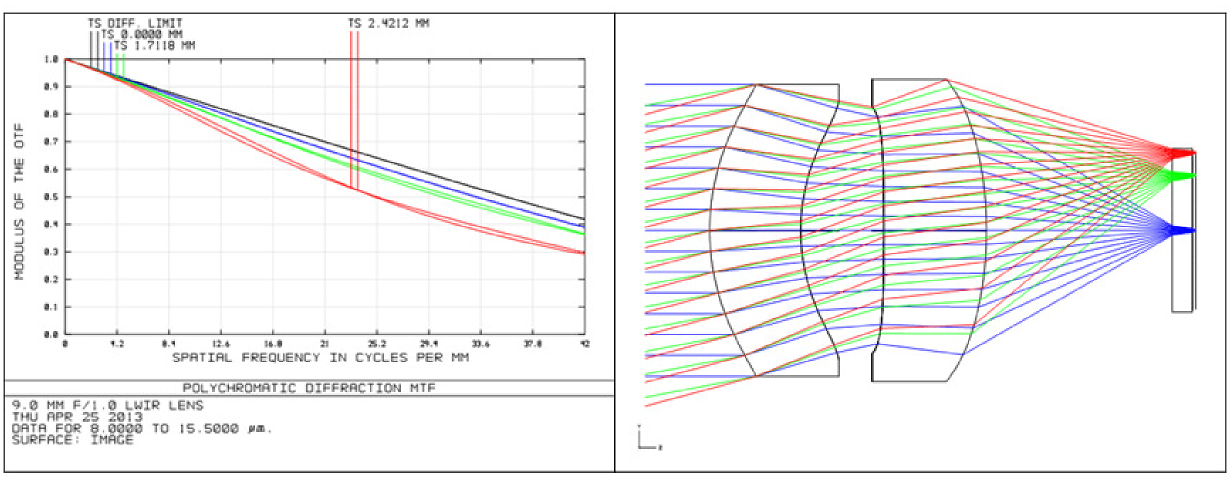

Figure 4 – 2 Element Design for Traditional and WLPGM Approach

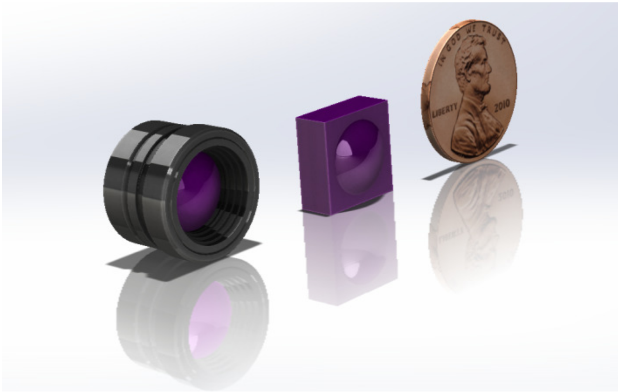

Figure 5 Equivalent Design – Left: Traditional / Right: Wafer Level

4. CONCLUSIONS

Manufacturing Technology Comparison

Based on the target design above and a presumed manufacturing quantity of 50,000 units per year, the cost of a chalcogenide PGM assembly is lower than a wafer based solution. In addition, the optical performance of the PGM version will be superior and will have a higher yield due to the increased alignment issues found in aligning the WLPGM system.

The PGM version will be more cost effective for all clear aperture diameters greater than 3mm, Figure 6. In optical designs using clear apertures under 3mm, the WLPGM option is expected to be more cost effective. The cost of traditional lens assemblies increase at these size due to difficulties in assembly.

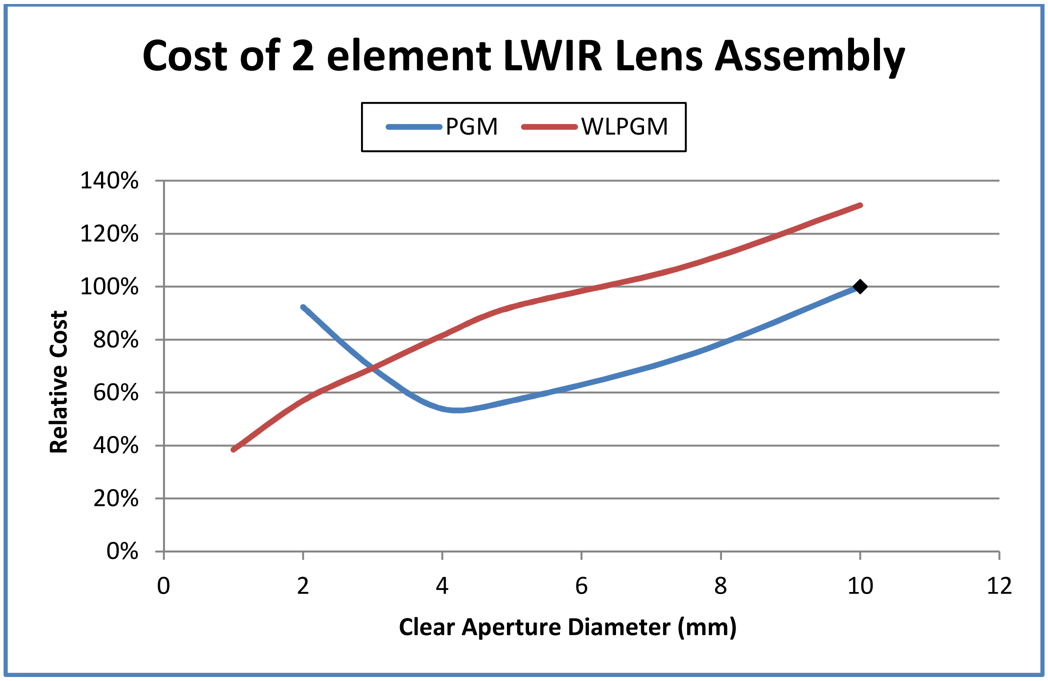

Figure 6 Cost Comparison of ManufacturingTechnologies

For optical designs with clear aperture smaller than 3 mm, we must compare WLPGM to lithographic techniques utilizing silicon as an optical material. As noted above, these methods are restricted to smaller lens systems and have restrictions on the diameter and sag heights of the individual lens elements. We are assuming that an acceptable optical design can be manufactured from silicon that meets these design requirements. Manufacturability will be dependent on finding a vendor willing to accept such a design. Wafer-level silicon lenses will be at the low end of production volumes when compared to other semiconductor products and will most likely be performed on the smallest wafer scale possible for highest yield in the final assembly. Contracting a vendor to produce these lenses is by no mean guaranteed for the lowest cost. Vendors may not be willing to invest in 'low volume' production in the 10,000 – 100,000 units as is typical for high volume LWIR systems.

Based on these assumptions, if a lens system is manufacturable both technically and commercially viable for a fabrication house, the cost of the silicon will be significantly less than a WLPGM. The cost drivers that account for the difference in these two methods are 1) the fabrication cost for the chalcogenide wafer substrate and 2) the lens alignment and testing and 3) the WLPGM mold manufacturing capabilities.

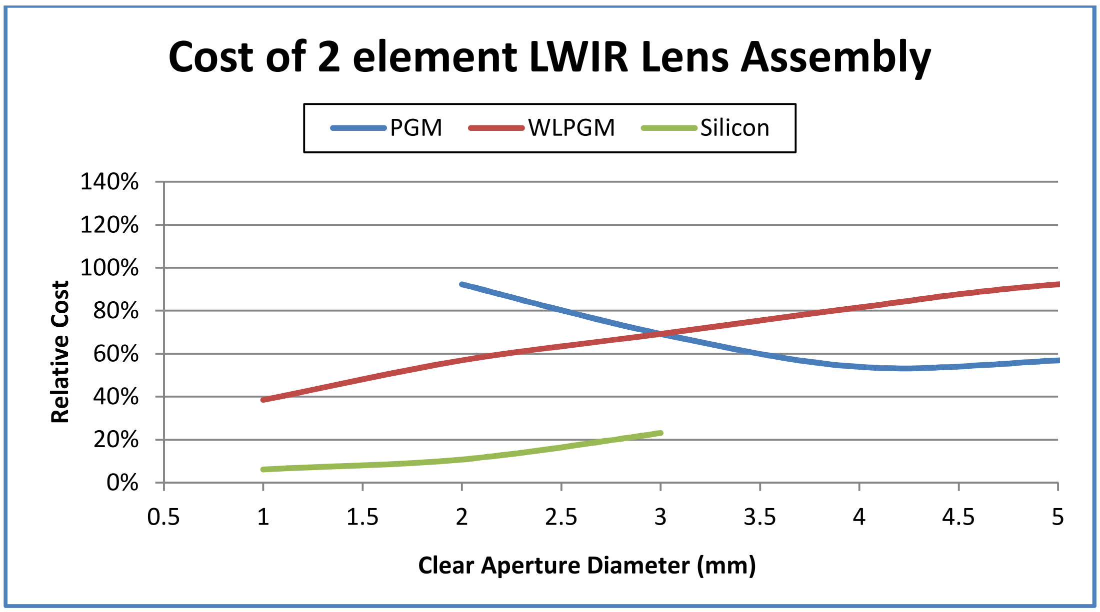

Figure 7 Cost Comparison of 2 Element LWIR Lens Assembly based on Clear Aperture

For current optical designers, chalcogenide WLPGM may not be the most cost effective option at high production volume, but may present the design flexibility and a mid-volume manufacturing option that is required in specific circumstances. Applications of LWIR systems already exist for lens systems that can take advantage of WLPGM. These would include imaging optics for small imaging sensors and thermopiles, such as an 80x60 microbolometer with 25 micron pixels, used for temperature measurements and more compact collimating lenses for quantum cascade lasers.

Future development work at LightPath will be focused on reducing the cost of WLPGM using chalcogenides and offering more design flexibility than infrared wafer-level optics products using silicon.

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