

# Design, Fabrication, and Measured Performance of Anti-Reflecting Surface Textures in Infrared Transmitting Materials

Douglas S. Hobbs\* and Bruce D. MacLeod

TelAztec LLC, 15 A Street, Burlington, Massachusetts 01803 USA

## ABSTRACT

Rugged infrared transmitting materials have a high refractive index, which leads to large reflection losses. Multi-layer thin-film coatings designed for anti-reflection (AR), exhibit good performance, but have limited bandwidths, narrow acceptance angles, polarization effects, high costs, and short lifetimes in harsh environments. Many aerospace and military applications requiring high optical transmission, durability, survivability, and radiation resistance, are inadequately addressed by thin-film coating technology.

Surface relief microstructures have been shown to be an effective alternative to thin-film AR coatings in many infrared and visible-band applications. These microstructures, etched directly into the window surface and commonly referred to as "Motheye" textures, impart an optical function that minimizes surface reflections without compromising the inherent durability of the window material. Reflection losses are reduced to a minimum for broad-band light incident over a wide angular range. For narrow-band applications such as laser communications, a simpler type of AR surface structure called a sub-wavelength, or "SWS" surface, is used. In general, both the Motheye and SWS surface textures will exhibit the same characteristics as the bulk material with respect to durability, thermal issues, and radiation resistance. The problems associated with thin-film coating adhesion and stress, are thus eliminated by design.

Optical performance data for AR structures fabricated in fused silica, sapphire, Clear ZnS, ZnSe, cadmium zinc telluride (CZT), silicon, and germanium, will be presented.

**Keywords:** Anti-reflection, Motheye, Infrared, Rad-hard, Micro-Structures, sapphire, CLEARTRAN, SWS, ZnSe

## 1. INTRODUCTION

The use of infrared (IR) light in military, industrial, space and commercial applications has expanded significantly in recent years. Laser communication systems, active and passive imaging sensors, industrial cutting, welding, and marking lasers, and a variety of security devices, typically require durable infrared transmitting windows and optics made of materials such as zinc selenide (ZnSe), zinc sulfide (ZnS or Cleartran®), germanium (Ge), sapphire, ALON™, silicon, and gallium arsenide (GaAs). In most applications, the region of the IR light spectrum employed is not absorbed by these materials. However, reflected IR light is a major problem particularly with IR cameras and laser radar. For example, just one surface of a ZnSe window will reflect 17% of the long wave IR (LWIR – 7 to 14 micron wavelength) light incident on-axis, a cadmium zinc telluride (CZT) window reflects 21%, and a Ge window or optic will reflect over 36%. The problem gets worse for IR light incident at higher angles off the normal to the window. Such large reflections produce stray light and can lead to superimposed images that can reduce the contrast or even blind security cameras.

The conventional approach to suppressing reflections from optics and windows is to employ multiple thin layers of dielectric materials deposited onto the external surface of the window or optic. Each deposited layer of material is designed to affect destructive interference for a particular IR wavelength reflecting from the window or optic surface. A great number of thin-film layers are needed to increase the range of wavelengths over which reflections are suppressed. For adequate anti-reflection (AR) over the LWIR range, a typical design would call for as many as 25 layers of material with a total deposited thickness of over 10 microns. In addition, the performance of thin-film AR coatings is limited to applications where the IR light is incident along or near the system axis (normal to the window or optic external surface). For stray light incident off-axis, thin-film coating stacks can produce an increase in reflected light and undesirable polarization effects.

---

\* Correspondence: [DSHobbs@telaztec.com](mailto:DSHobbs@telaztec.com), Voice: 781-229-9905, Fax: 781-229-2195 [www.telaztec.com](http://www.telaztec.com)

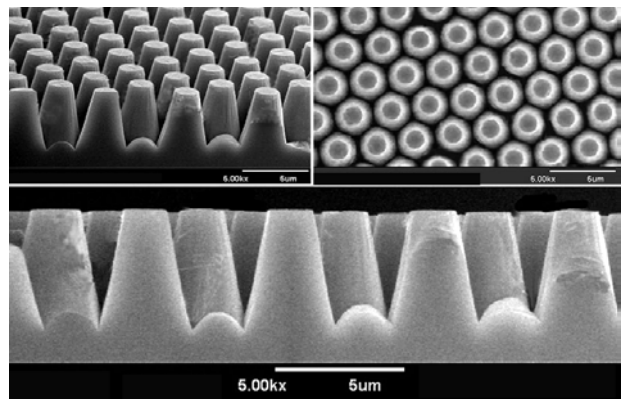
Thin-film AR coatings are typically deposited by high temperature evaporation of the coating materials within a vacuum chamber, a costly process that is problematic for some temperature sensitive materials used in IR cameras. Durability and thermal cycling are a concern with thin-film AR coatings where inherent stress and adhesion problems are found due to dissimilar thermal expansion coefficients of the layer materials. Loss of adhesion from temperature cycling has resulted in catastrophic failure of space-based IR cameras and industrial lasers. Lastly, thin-film AR stacks suffer from degradation and short lifetimes in the presence of solar radiation – mainly high energy protons. However, the use of some types of thin-film material layers to absorb high-energy protons, can impart a degree of protection.

## 2. ENGINEERED SURFACES FOR ANTI-REFLECTION

Surface relief microstructures, commonly known as Motheys textures<sup>[1-4]</sup>, have been shown to be an effective alternative to thin-film AR coatings in many infrared and visible-band applications<sup>[5-8]</sup> where durability, radiation resistance, wide viewing angle, or broad-band performance are critical. These microstructures are built into the surface of the window or optic material, imparting an optical function that minimizes reflections without compromising the inherent properties of the material. An array of pyramidal surface structures provides a gradual change of the refractive index for light propagating from air into the bulk optic material. Reflection losses are reduced to a minimum for broad-band light incident over a wide angular range. In general, these surface relief structures will exhibit similar characteristics as the bulk material with respect to durability, thermal issues, and radiation resistance. The problems associated with thin-film coating adhesion, stress, abrasion resistance and lifetime, are eliminated.

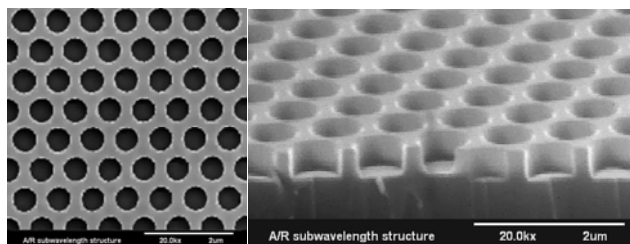
To achieve high performance AR with Motheys surface textures, optical phenomena such as diffraction and scattering must be avoided. This requires that the surface structures be fabricated with a spacing smaller than the shortest wavelength desired. In addition, the height of the surface structures should be sufficient to ensure a slowly varying density change. Motheys textures can be designed to yield reflectance levels of less than one half percent over IR wavelength ranges from 7 to 14 microns, or from 3 to 12 microns, the ranges needed for advanced multi-color IR cameras. In addition, Motheys textures can also be designed and fabricated to suppress the reflection of IR light incident at large angles (45 to 60 degrees or more) with little to no polarization dependence.

As general design guidelines, the relief height of a Motheys texture should exceed 40% of the longest operational wavelength, and the distance between structures should be less than 25 to 30% of the shortest operational wavelength to avoid free-space diffraction losses. A Motheys texture designed to suppress LWIR light reflections from a CZT window used in mercury-cadmium-telluride (HgCdTe) IR cameras, is shown on the right. These micrographs, taken by a scanning electron microscope (SEM), show flat-top, or truncated pyramid structures arranged on a hexagonal, or honeycomb grid pattern. The feature height is 5 micron and the grid spacing is 2.4 micron. This Motheys texture reduces the typical LWIR reflection of 21% for an untreated CZT window, to a level below 1%. Even further



reductions are possible with a more detailed understanding of the design parameters. TelAztec has designed and built Motheys textures for near IR communications, mid-wave IR (MWIR - 3 to 5 micron) windows, LWIR filters, and visible-band prescription eyeglasses, that exceed the performance specifications for the given application.

For narrow-bandwidth applications such as laser communications, a simpler type of AR surface structure called a sub-wavelength, or "SWS" surface, is used. An SWS is a porous texture that reduces the effective refractive index of the material surface, creating the equivalent of a textbook quarter-wave AR treatment at the design wavelength. A typical SWS texture fabricated in the surface of a fused silica window is shown in the SEM micrographs on the right. Holes in the surface of the material are proportioned to create an effective refractive index



equal to the square root of the window material refractive index. With fused silica the effective index created is 1.21, a value that is not attainable with thin-film coating materials. The depth of the holes in the array is set to one quarter of the design wavelength divided by the effective index. Reflection of NIR light from the surface of the SWS textured window was reduced to levels below the stringent requirements of optical fiber telecommunications (-30dB, 0.1%).

### 3. PERFORMANCE MODELING

TelAztec has developed sophisticated computer models to guide the fabrication of, and predict the performance of our Motheye and SWS AR structures. Using a rigorous vector diffraction calculation, our software can predict the spectral reflectance and transmittance of infrared light through a user defined three-dimensional surface texture composed of multiple structured and uniform materials. The model accounts for arbitrary polarization states and light incident angles. Measured data for the optical constants of a library of materials is included. As further demonstrated below and in the Measured AR Performance Section 6, our modeled performance has proven to be a good match to measured AR performance. This ability to predict device behavior and to analyze the impact of fabrication errors is essential to the practical commercialization of surface structure AR technology.

When working with the high refractive index materials required by IR systems, the cross-sectional profile of the structures in the AR surface texture has a significant impact on the AR performance<sup>[6]</sup>. For example, Figure 1 below shows the results of performance modeling of three types of AR textures built into the surface of a silicon window used in a MWIR application. (Note that the model results for GaAs windows are nearly identical). Cross sectional profiles of each modeled structure are shown to scale for two periods (one period is 780nm) of the full texture. The pyramidal and sinusoidal structures protrude from the surface whereas the SWS structures are cylindrical holes in the window surface.

The transmission of normally incident light propagating from an air environment through the surface texture into the bulk window material is predicted. For reference, the model for an untreated flat silicon surface predicts a maximum transmission of 70% into the bulk material. Figure 1 shows that for narrow-band, single wavelength applications, the SWS textures are the best choice due to their ease of fabrication. The highest performance over the widest bandwidth is afforded by the sinusoidal textures. To obtain nearly equivalent AR performance to the sinusoidal profile textures, the pyramidal profile structures need to be fabricated 33% taller.

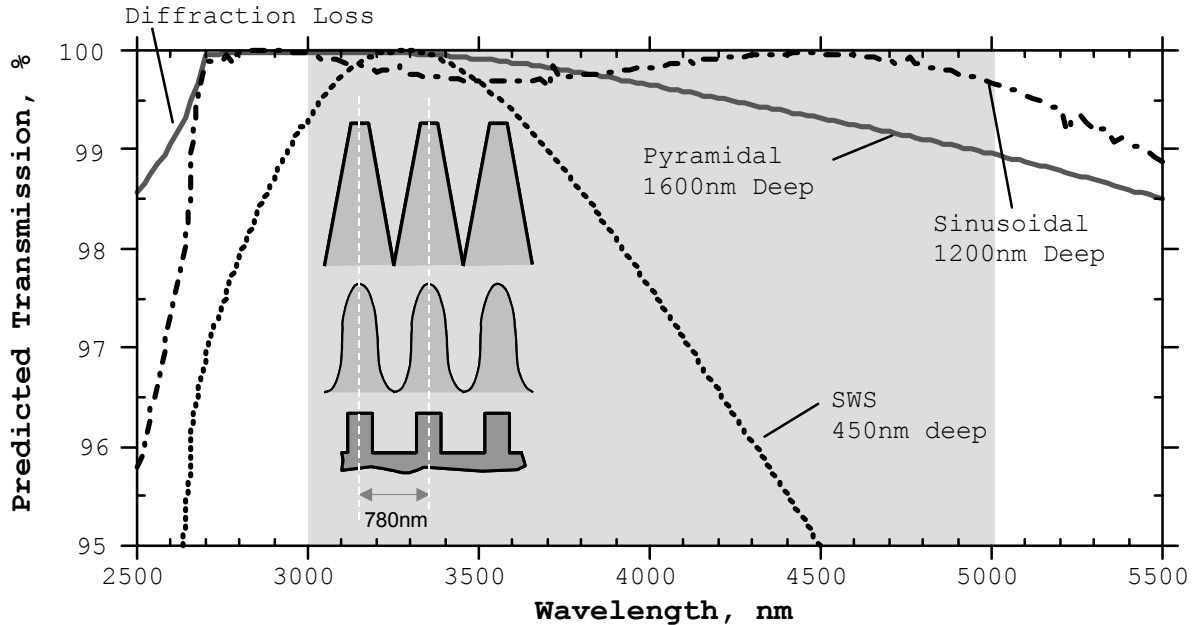


Figure 1: Predicted transmission of MWIR light propagating from air through an AR texture into silicon for various profile structures.

Another factor must be considered when designing AR structures for durability in harsh environments. Figure 2 shows the predicted performance of AR structures fabricated in CZT designed for operation over the LWIR. The predicted AR performance of textures consisting of truncated pyramidal profile cones are compared to textures made up of parabolic

profile holes. Cross sections of each modeled profile are drawn to scale in the figure. Intuition suggests that due to the connected web-like nature of the hole structures, the texture may be more resistant to damage caused by extreme temperature cycling (like that found in space environments). TelAztec is currently investigating this possibility under an ongoing project sponsored by the MDA.

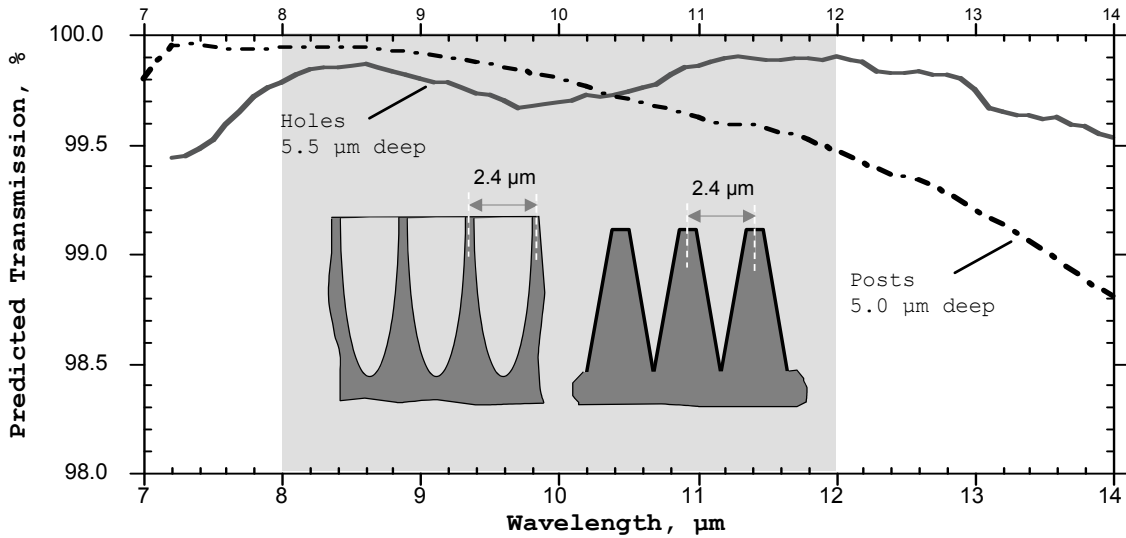


Figure 2: Predicted transmission of LWIR light propagating from air through hole- and cone-type AR textures into CZT.

The same reasoning also suggests that hole textures may be less susceptible to abrasion due to the impact of sand and rain as found with aircraft and automobile windows. Figure 3 shows the predicted performance of hole- and cone-type Motheye textures fabricated in the surface of a sapphire window. Again the transmission of normally incident light propagating from an air environment through the surface texture into the bulk window material is predicted. The window is designed for very broad-band performance over the NIR to MWIR range. For reference, the model for an untreated flat sapphire surface predicts a maximum average transmission of 92.5% into the bulk material. The models show that hole-type structures must be fabricated with a larger depth than the cone-type structures to obtain nearly equivalent performance (cross sections drawn to scale are also shown in the figure). TelAztec is fabricating both hole- and cone-type structures in sapphire to determine the surface texture configuration with the largest resistance to abrasion damage. The Measured AR Performance Section 6 below lists details of this ongoing work.

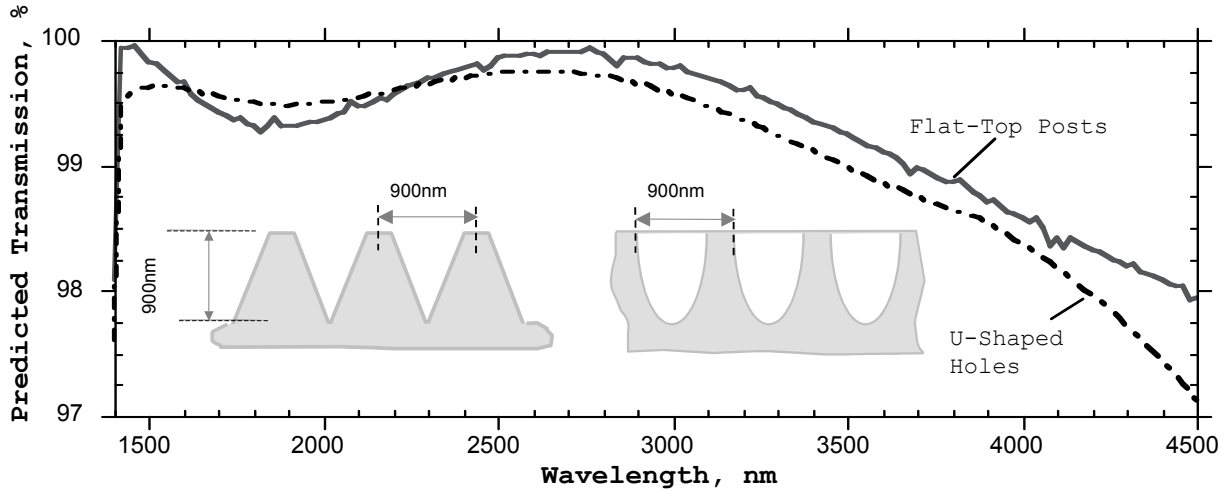


Figure 3: Predicted transmission of NIR to MWIR light propagating through hole- and cone-type textures into sapphire.

Motheye AR textures can be designed to operate over an even wider wavelength range. For example, Figure 4 shows the predicted performance of cone-type structures in ZnSe, ClearTran, and CZT designed to suppress reflections over both the MWIR and LWIR wavelength ranges. As in the previous examples, the transmission of normally incident light propagating from an air environment through the surface texture into the bulk window material is predicted. Cross sections of the truncated sinusoidal profile structures modeled are drawn to scale in the figure. (Hole-type structures would show a similar predicted performance). The spacing of the structures is set to allow free-space diffraction loss only at wavelengths below 3 micron. Note that a depth of just 3 microns is sufficient to suppress reflections below 1% over a 9 micron range spanning 3 to 12 microns.

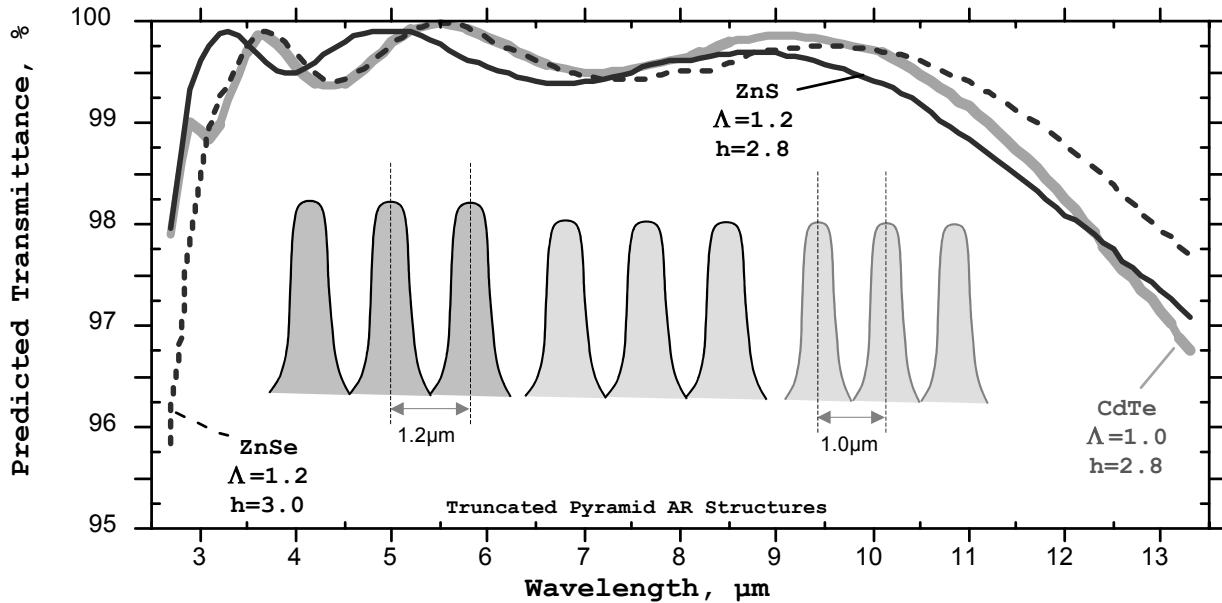


Figure 4: Predicted transmission of MWIR and LWIR light propagating through cone-type textures in CdTe, ZnS & ZnSe.

Many applications require the suppression of reflected light incident at large angles. For example, windows covering aircraft night vision cameras are often mounted at steep angles due to aerodynamic considerations. At these angles, stray reflected light becomes a significant problem. Thin-film AR coatings that operate over wide bandwidths and wide viewing angles do not exist. Motheye AR structures can be designed to meet this demand while simultaneously providing a longer operational lifetime. Figure 5 shows the predicted performance of a cone-type Motheye texture etched in one surface of a sapphire window. The transmission of MWIR light propagating from an air environment through the surface texture into the bulk window material is predicted for angles of incidence (AOI) of  $\pm 30^\circ$ ,  $\pm 45^\circ$  and  $\pm 60^\circ$ . A cross section of the truncated sinusoidal profile structure modeled is drawn to scale in the figure. (Hole-type structures show a similar predicted performance). Depth of the cones was 1.4 micron, and the cone spacing was set at 1.1 micron in the model. For light propagating perpendicular to the window and at angles up to 30 degrees off the normal to the window, reflected light is suppressed to an average level below 1%. No polarization dependence is predicted for light incident at 30 degrees or less. As the AOI increases, the effects of polarization become evident, particularly at the longer wavelengths. (Note that the long-wave absorption in sapphire is not included in the model). The predicted performance at  $45^\circ$  is degraded slightly for S-polarized light at wavelengths beyond 4.5 micron. For P-polarized light incident at  $45^\circ$ , the transmission has been enhanced due to the Brewster angle effect ( $\sim 30^\circ$ ). For an AOI of  $60^\circ$ , the polarization sensitivity is more pronounced with the amount of S-polarized light transmitted reduced to just 94% at 4.5 micron. Additional modifications to the Motheye structure design can improve the long wave performance at the cost of a more difficult fabrication process. For comparison, the transmission of MWIR light into an untreated sapphire window is 92% for light incident from 0 to  $30^\circ$ , 87% for S-polarized light incident at  $45^\circ$ , and just 77% for S-polarized light incident at  $60^\circ$  (the transmission of P-polarized light approaches 100% for AOIs beyond  $30^\circ$ ).

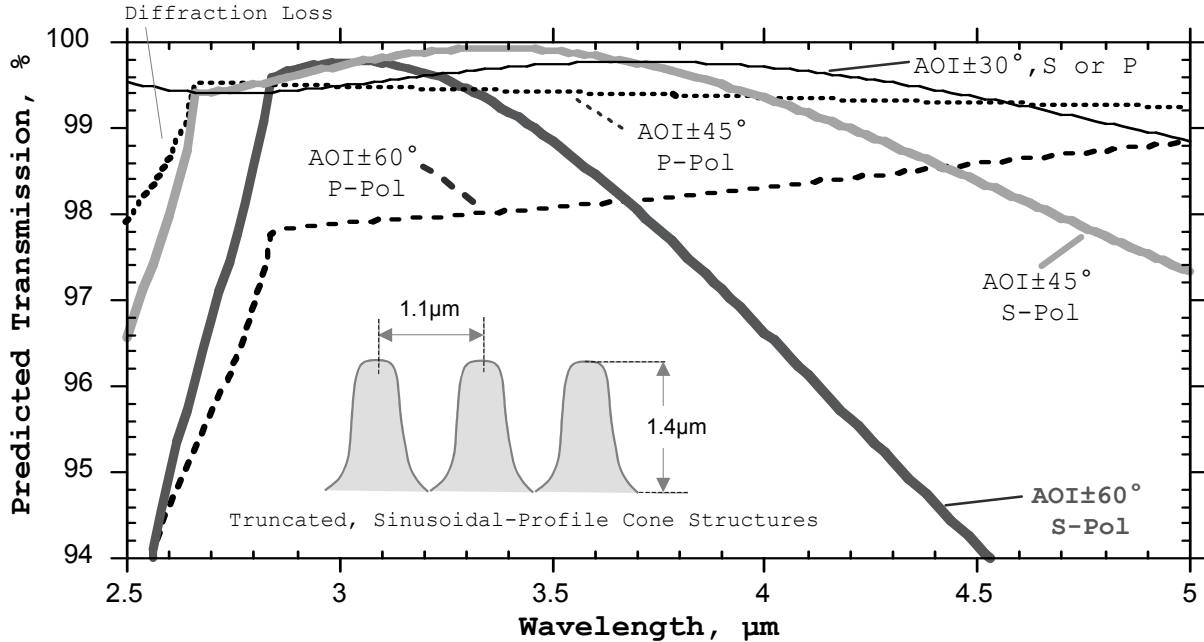


Figure 5: Predicted transmission of MWIR light propagating through cone-type textures in sapphire designed to suppress reflection of light incident at high angles up to 60 degrees off the normal.

#### 4. FABRICATION

Surface relief microstructures designed for high performance AR in the visible or NIR spectral range, are molded directly into plastic or sol-gel glass surfaces using high volume replication of master molds<sup>[12]</sup>. For IR transmitting materials, lower-volume batch processing is used to directly etch the AR structures into the surface of each window or optic. Fabrication is then a two-stage process whereby lithography is used to pattern the microstructure, and conventional etching methods are employed to transfer the patterns into the surface of the final product. (TelAztec provides AR structure fabrication as a service – at costs similar to thin-film coating services).

Figure 6 shows a process flow diagram typical of Motheye fabrication. The process begins with coating a specified substrate with a conventional positive photoresist such as one of the AZ1500 series (steps 1 and 2). Next a non-contact, maskless lithography technique is employed to expose a latent image of the Motheye texture in the photoresist layer (step 3). The structure lithography is completed by a wet development step that delineates the image as a surface relief texture in the photoresist layer (step 3).

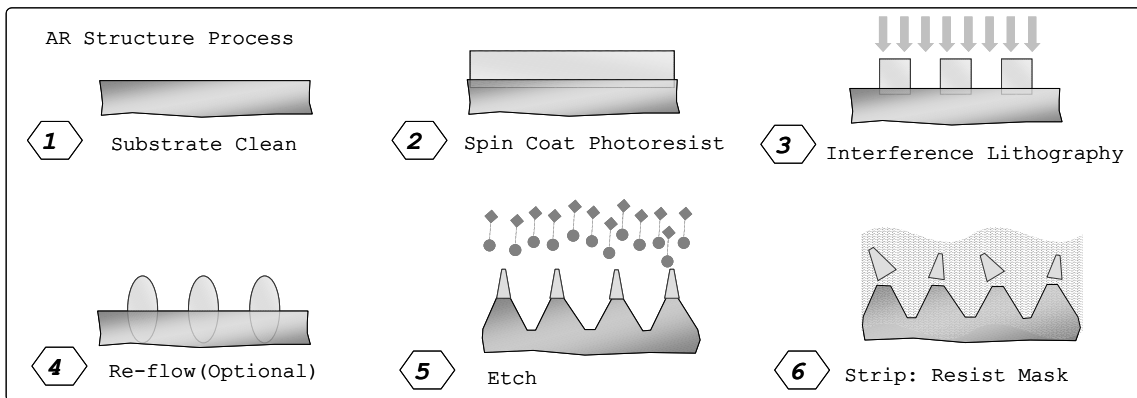
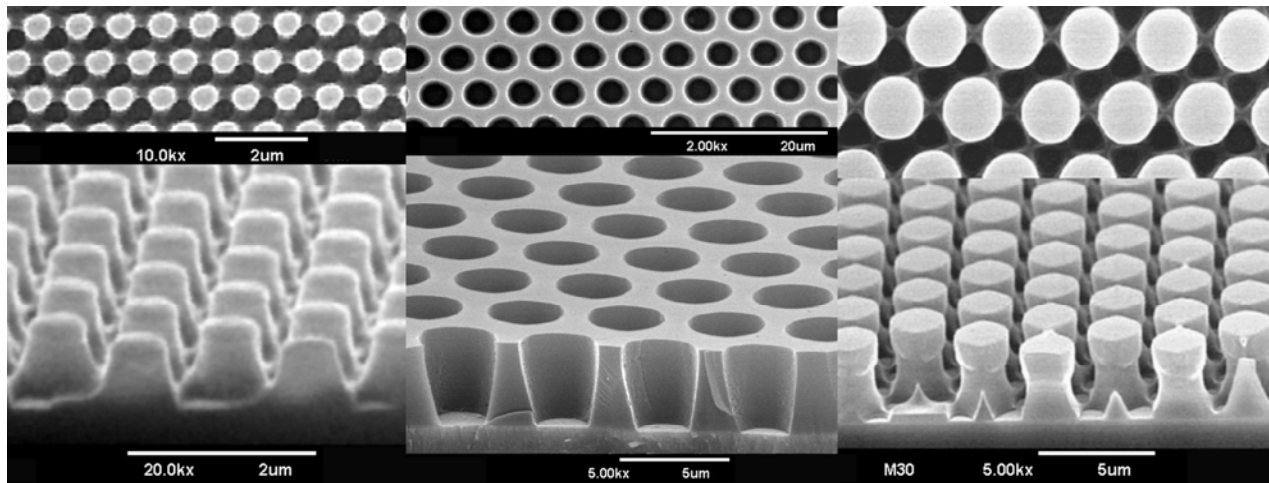
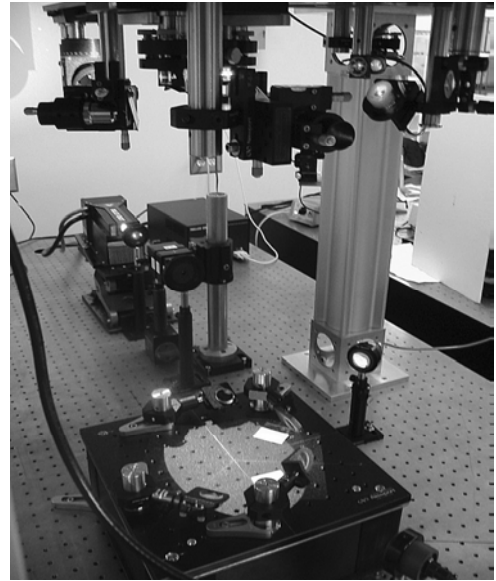


Figure 6: General process flow diagram used in the fabrication of AR microstructures.

TelAztec employs a sophisticated patterning method known as interference, or holographic lithography (HL) to record Motheye textures<sup>[10,11]</sup>. A bench-top HL tool is shown on the right. Multiple beams of light are split from a laser source (typically emitting in the blue or violet), expanded and redirected to overlap in a region of space where the resulting interference pattern can be recorded. The platform in the lower part of the photograph is illuminated by three overlapping beams derived from the laser source located at the back edge of the work-bench. An HL system can pattern large field sizes, limited only by the size of the beam that can be created, in a single rapid exposure. Highly uniform Motheye textures have been fabricated over 6-inch diameter windows. A significant advantage to HL patterning is the very large depth of field, on the order of inches, which eliminates depth of focus problems that spherical optics present to conventional lithography equipment such as image projection steppers and contact mask aligners. Figure 7 shows multiple SEM images of various micro-structures recorded in photoresist using an HL system. The left side of the figure shows both elevation and overhead views of a photoresist mask containing post-type structures defined on a silicon window intended for MWIR operation. The structures have a pattern pitch of 780nm and a height of about 650nm. Hole-type structures in a photoresist mask defined on a ClearTran window intended for LWIR operation are shown in the center area of the figure. The holes are about 3 micron deep and spaced on a 2.9 micron grid. Lastly on the right side of the figure, post-type structures in resist on a ZnSe window intended for LWIR operation are shown. These posts are about 2.8 micron high with a grid spacing of 2.4 micron.



**Figure 7: SEM micrographs of various photoresist masks used in the fabrication of AR microstructures.**

Once the Motheye texture has been recorded in the photoresist mask layer, the mask can be optionally reshaped to suit the particular process via plasma etching or re-flow (step 4 in Figure 6). Next the photoresist mask is used to transfer the Motheye texture into the surface of the substrate material using standard dry etching techniques (step 5). If required, removal of the residual photoresist mask material completes the process (step 6). A thorough understanding of the interaction between lithography and etching is essential to fabricating antireflective surface structures, as the finished etched structure will be different than the starting resist profile. This is because the physical and chemical aspects of etching are quite variable for different materials, and process development must account for this.

## 5. CHARACTERIZATION

Surface structure Motheye and SWS AR textures are characterized using SEM analysis, FTIR transmission measurements, and both transmission and reflectance measurements in the NIR using an Agilent optical spectrum analyzer. In addition, precise microstructure pitch and symmetry are configured using diffraction measurements obtained with a fiber-coupled white light spectrometer arranged in the Littrow configuration. Data collected for a variety of AR texture designs is presented next.

## 6. MEASURED AR PERFORMANCE

### 6.1 Fused Silica, SiO<sub>2</sub>, (n = 1.46)

Fused silica is a high purity glass that has extensive use at telecommunication wavelengths. Many communications products require a specific wavelength or narrow wavelength band within the NIR range from 1520 to 1620nm. High performance SWS structures have been designed and fabricated in fused silica targeting specific wavelengths within this spectral region. These AR surfaces were engineered with a symmetric hexagonal grid of holes etched to a specified design depth, effectively mimicking an ideal thin film AR coating, as shown in the SEM images included in Figure 8.

Figure 9 shows both theoretical and experimental data for SWS structures fabricated in fused silica windows targeting lossless performance at 1530nm (a product specification of less than 0.05% reflectance). Four of the windows fabricated are shown in the inset photograph. The measured performance is shown as the solid dark line in the figure (an absorption band of fused silica is seen as the dip in transmission centered around 1390nm). For comparison, the dashed line in the figure shows the predicted performance of an idealized single-layer thin-film AR coating. The thin-film model and measured SWS performance show good agreement, illustrating that SWS structures can be designed to mimic single-layer quarter-wave thin-film coatings – but with a key advantage that SWS structures can be fabricated in any substrate without the material constraints found with thin-film AR coatings. Note that by changing the depth of the SWS structures, the peak performance wavelength can be shifted to meet any target, and that as with quarter-wave thin-film AR coatings, harmonics of the target wavelength can be produced (dual-band AR).

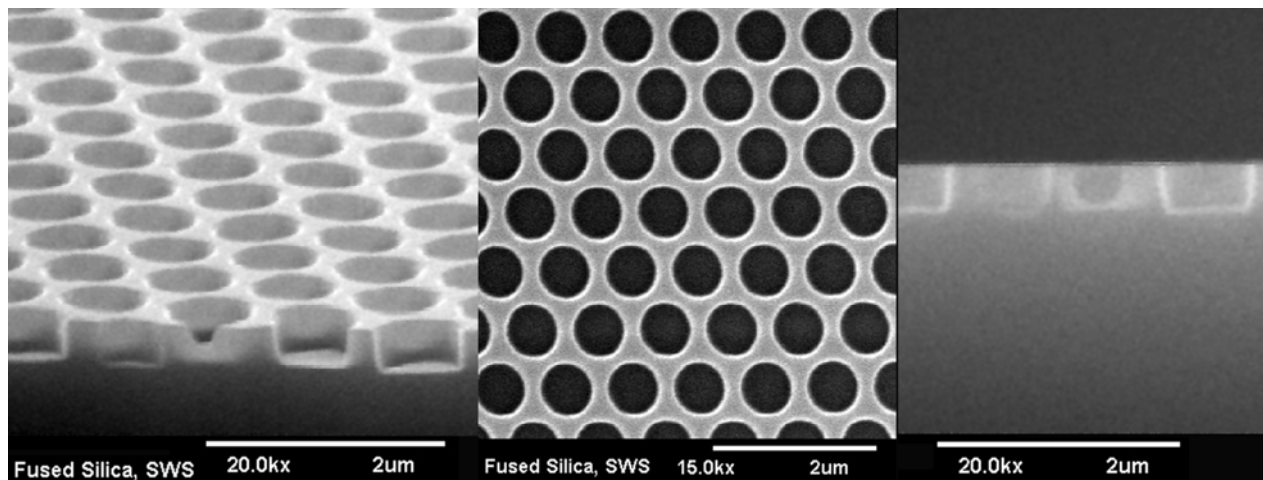


Figure 8: SEM photographs of SWS-type AR textures fabricated in a fused silica window.



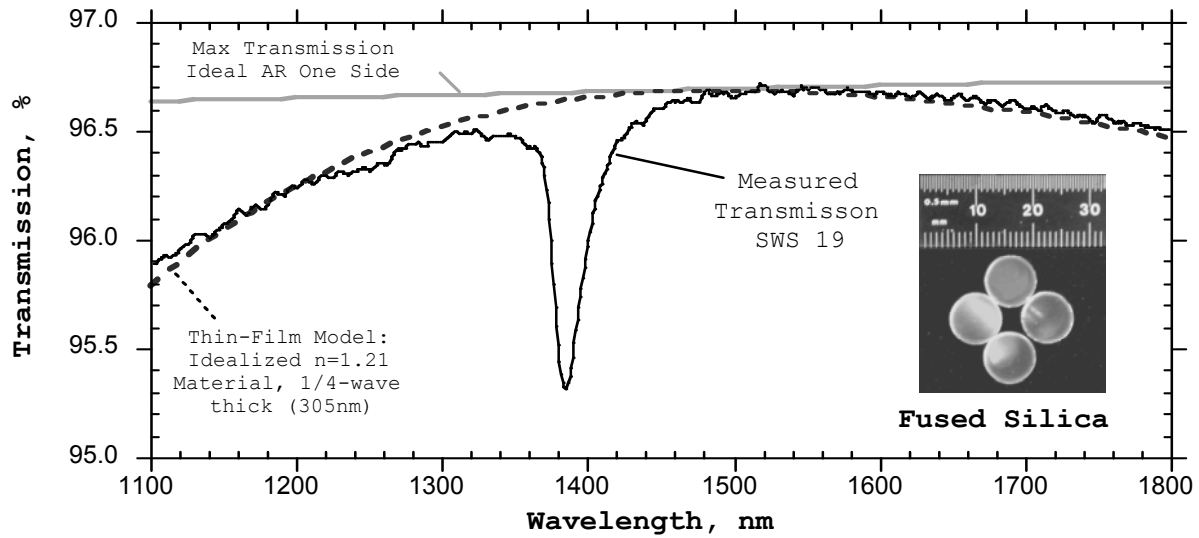


Figure 9: Measured reflectance of SWS AR textures fabricated in a fused silica window.

### 6.2 Sapphire, ( $n = 1.70$ )

Sapphire is a hard durable optical window material used in infrared applications out to 5.5 microns. Sapphire can withstand large thermal shock loads and mechanical stresses, while providing protection against high velocities, abrasion (sand, rain, hail), and high temperatures. Military applications for sapphire are numerous and include missile domes, MWIR windows, and lightweight transparent armor. The ultimate goal of producing AR structures in sapphire is to replace thin-film AR coatings, which have survivability issues in harsh environmental conditions. It is expected that Motheye textures will maintain their AR function much longer than thin-film coatings in abrasive environments, and thus provide a greater operational lifetime for a window or optic. This expectation of minimal transmission loss for Motheye structures subjected to rain and sand erosion, is a common concept referred to as graceful degradation- the Motheye post structures that are chipped by physical damage remain sub-wavelength and non-scattering, and retain a significant portion of their AR function<sup>[9,13-15]</sup>. With thin-film AR coatings, physical damage and de-lamination often leads to significant scattering losses. Standard rain and sand erosion tests on Motheye AR textures in sapphire will be made this spring.

Motheye AR structures were fabricated in sapphire intended for use in the NIR to MWIR region. Typical etched surface structures, shown in the SEM images of Figure 10, were designed with a blunt tip profile for optimum durability. The pattern period is 780nm and the structure depth achieved to date is 530nm (the goal is 800nm). Transmission measurements given in Figure 11 show an average transmission increase of over 5% in the NIR region at 1550nm (upper chart), but only about 3% in the MWIR region (lower chart). This compares to a maximum transmission increase of about 6.5% as indicated by the solid gray curves in each plot. The measured transmission of a sapphire window (2mm thick) with no AR treatment is also included in each plot.

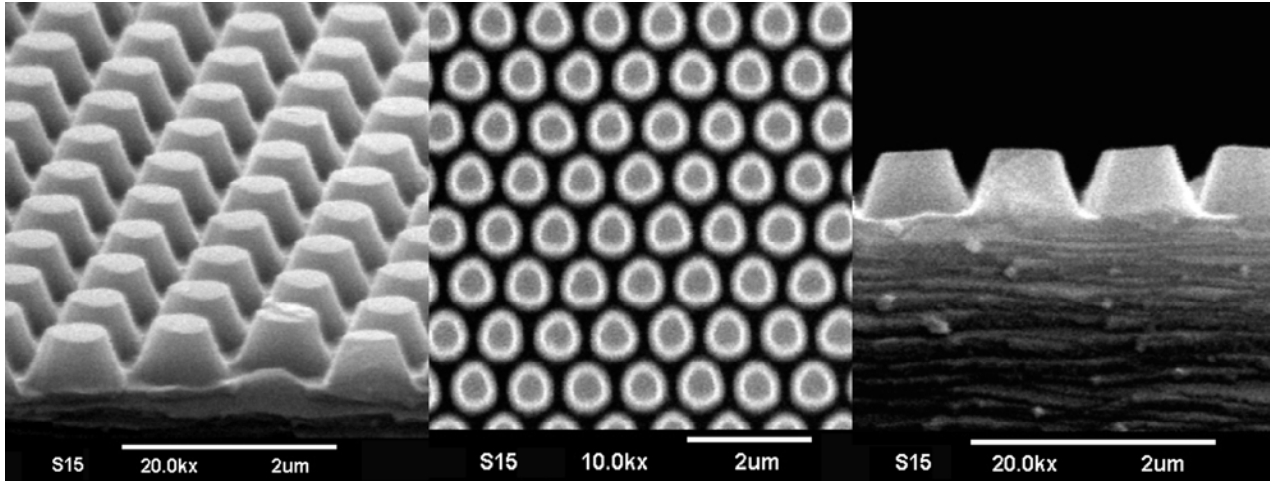


Figure 10: SEM photographs of AR textures fabricated in a sapphire window.

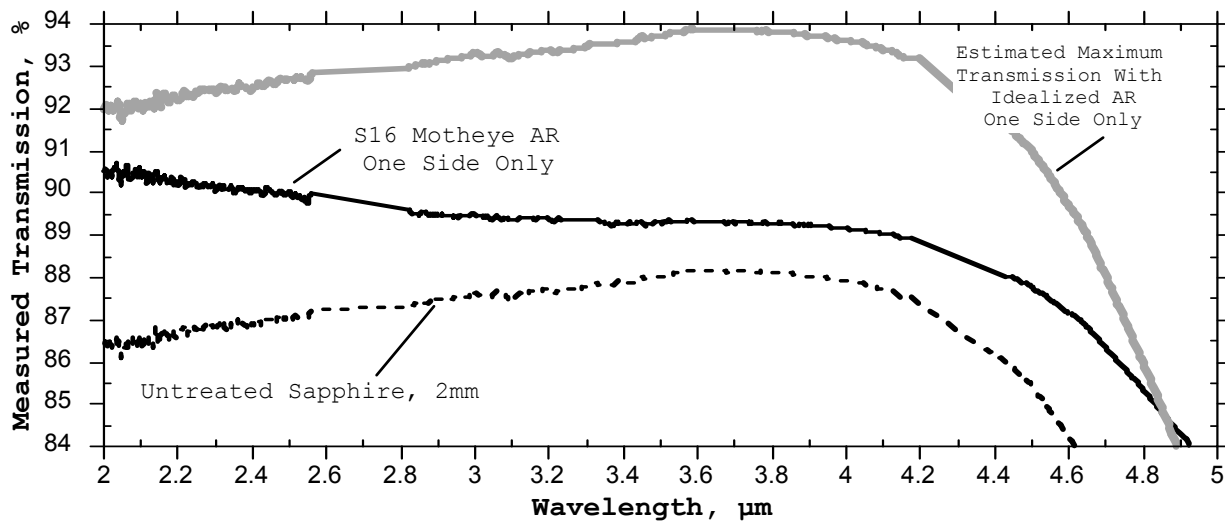
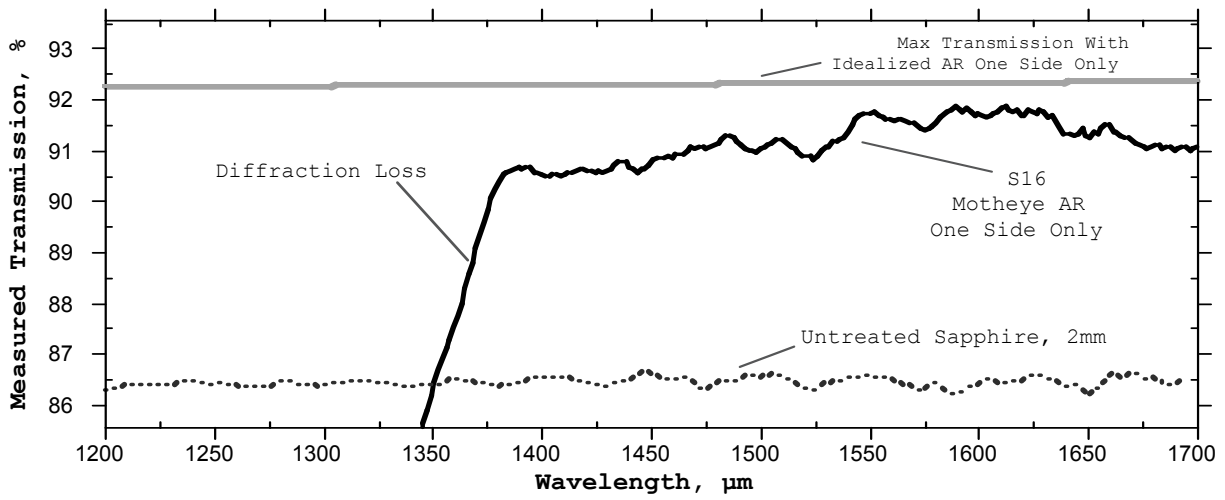


Figure 11: Measured transmission through a sapphire window with a Motheye AR texture fabricated in one surface only.

### 6.3 Zinc Sulfide, ZnS (Cleartran®), ( $n = 2.22$ )

Clear ZnS, known by its trade name of Cleartran®, exhibits low absorption and scatter throughout its broad transmission range from 400nm to 12 microns. Cleartran® is well-suited for multi-spectral applications that require a single aperture for multiple wavelength bands, such as simultaneous infrared and visible imaging, along with target designation. We have fabricated Motheye structures in Cleartran® for use as a durable optical window in the LWIR region. The etched surface structure is shown in Figure 12 and was designed with a blunt tip profile for increased durability. The pattern period is 2.9 microns and the structure has a depth of 3.4 microns. Transmission measurement taken on the sample shows a flat 2% reflectance loss across the 8 to 12 micron region in the LWIR. (Even lower reflectance losses are expected when the structure height reaches 3.8 microns.) Figure 13 shows this transmission measurement over the wavelength range of 7.5 to 12.5 micron. The solid black line is the measured data, the solid gray line is the maximum transmission attainable with zero reflection from one surface, and the dashed line is the transmission of a 2 mm thick Cleartran® window with no AR treatment.

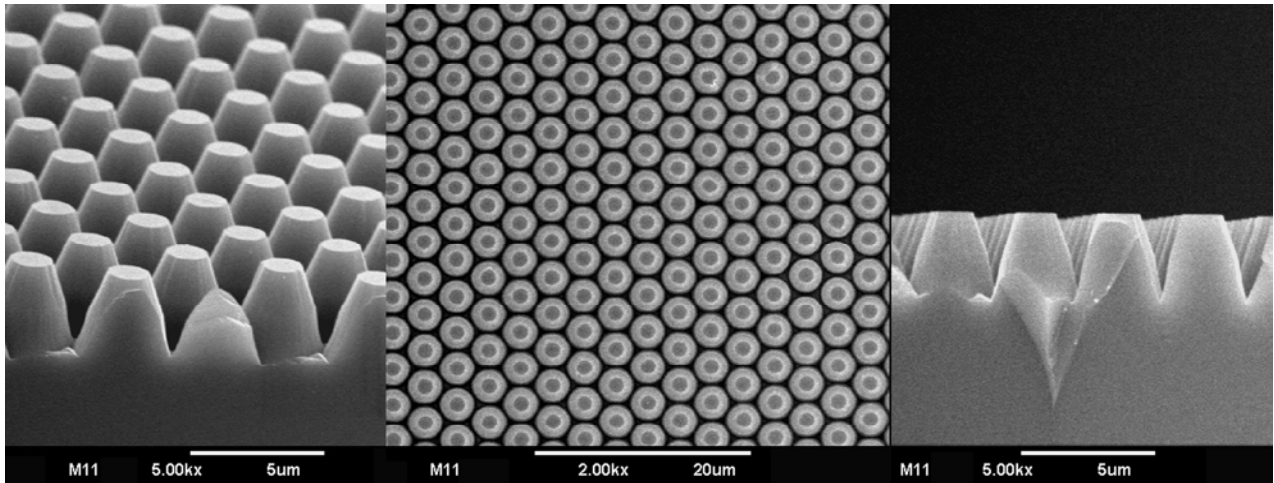


Figure 12: SEM photographs of AR textures fabricated in a Cleartran® window.

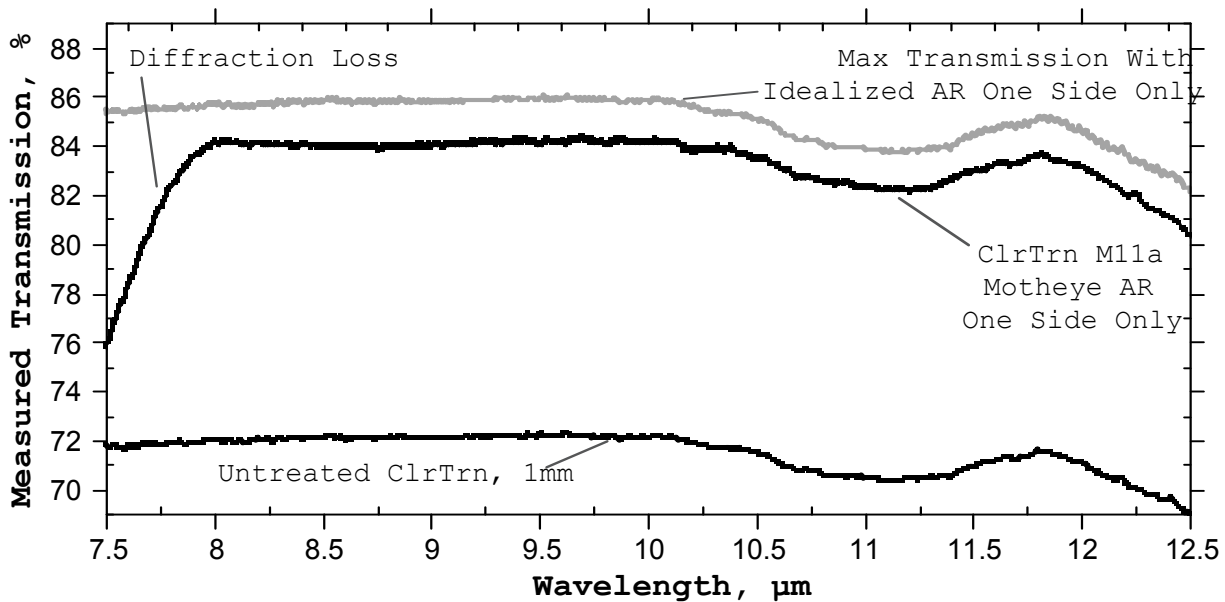


Figure 13: Measured transmission through a Cleartran® window with a Motheye AR texture fabricated in one surface only.

### 6.4 Zinc Selenide, ZnSe, ( $n = 2.43$ )

ZnSe is commonly used for high power CO<sub>2</sub> laser focusing lenses, night vision FLIR applications, and infrared spectroscopy windows. Motheye structures were fabricated in ZnSe windows designed for LWIR imaging applications. Figure 14 shows the hexagonal-grid array of pyramidal structures in the ZnSe surface that comprise the Motheye texture. The texture has a structure spacing of 2.9 micron and structure height of 4.0 microns. Figure 15 shows broadband AR performance from 7 to 14 microns, with an average reflectance loss of less than 0.5% in the 8 to 12 LWIR band. Even higher AR performance could be obtained for single wavelength applications, such as with high power CO<sub>2</sub> laser optics, using an SWS AR structure. ZnSe is also a good candidate for demonstrating very wide-band Motheye AR performance. Work is under way to produce ZnSe Motheye windows capable of AR performance over both the MWIR and LWIR bands using the design of Figure 4 above.

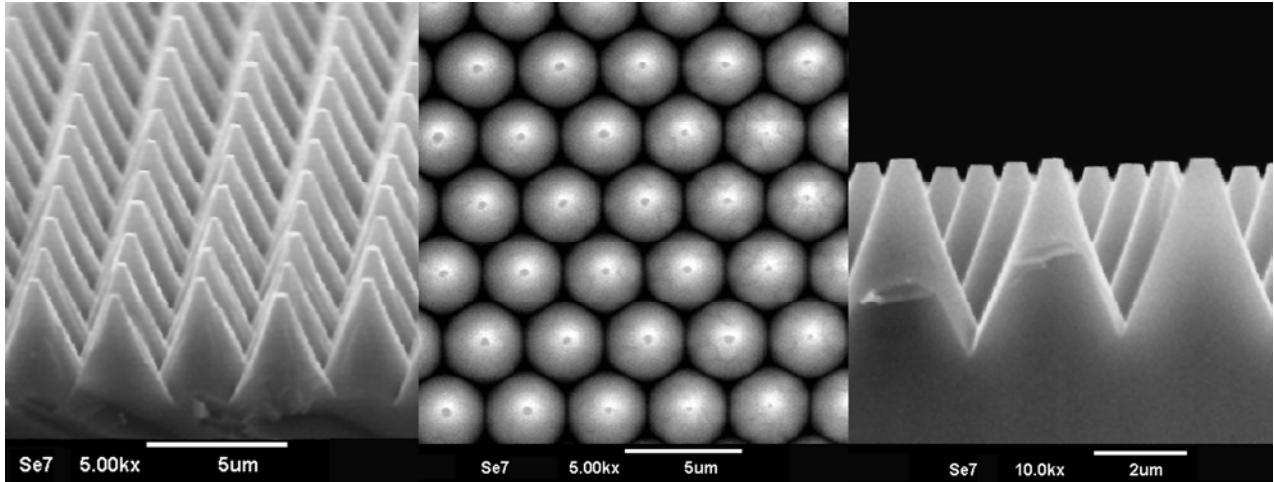


Figure 14: SEM photographs of AR textures fabricated in a ZnSe window.

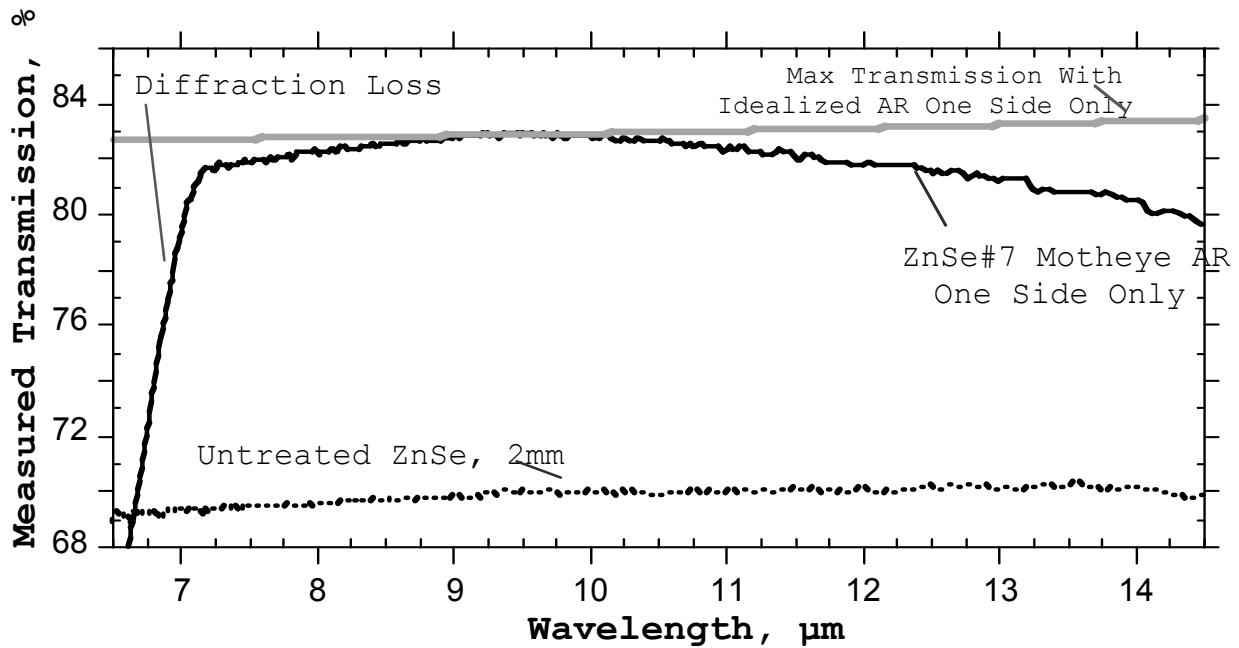


Figure 15: Measured transmission through a ZnSe window with a Motheye AR texture fabricated in one surface only.

### 6.5 Cadmium Zinc Telluride, CZT, ( $n = 2.67$ )

Cadmium Zinc Telluride (CZT) has been the substrate of choice for the epitaxial growth of HgCdTe, a critical detector material for a wide range of infrared applications. HgCdTe detectors are typically used in a backside-illuminated configuration where the detector array is bump bonded onto silicon readout circuitry. This requires the incident infrared flux to pass thru the transparent but highly reflective CZT substrate. AR treatments are required on the CZT backside to minimize signal loss and crosstalk. We have designed and fabricated Motheye AR surfaces in CZT substrates for broadband LWIR imaging applications.

A Motheye structure was designed and fabricated with a structure spacing of 2.4 microns and structure height of 4.0 micron depth into a CZT substrate for operation in the 7.5 to 13 micron range. Again, the etched surface structure, as shown in the SEM images of Figure 16, was designed with a blunt tip profile for increased durability. Transmission measurements, shown in Figure 17 show minimal loss of incident radiation at the Motheye surface, with an average loss of 1% across the broad 8 to 13 micron band in the LWIR, a significant improvement over the 21% loss for an untreated surface.

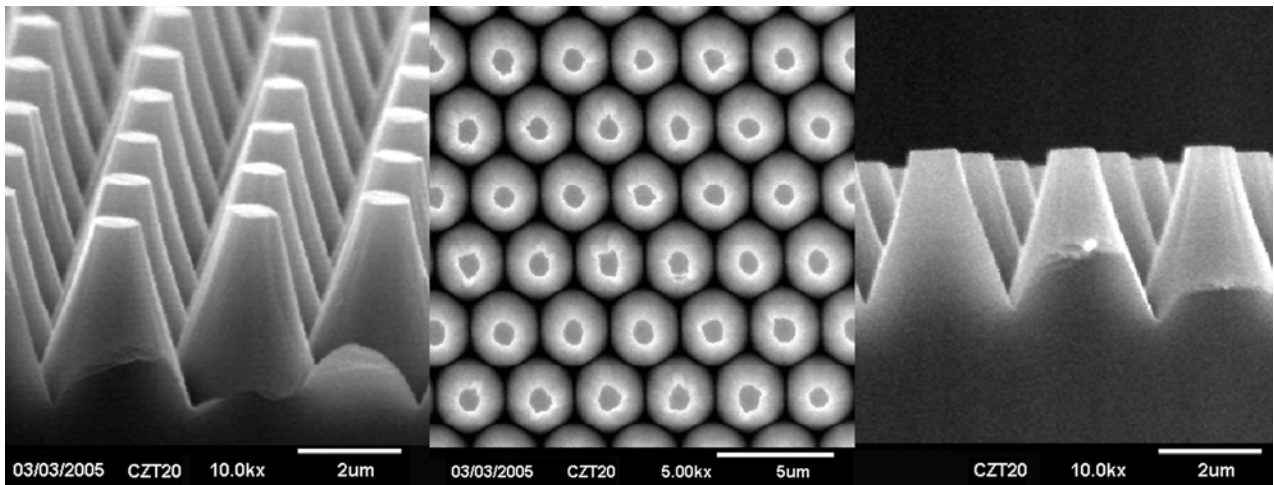


Figure 16: SEM photographs of AR textures fabricated in a CZT window.

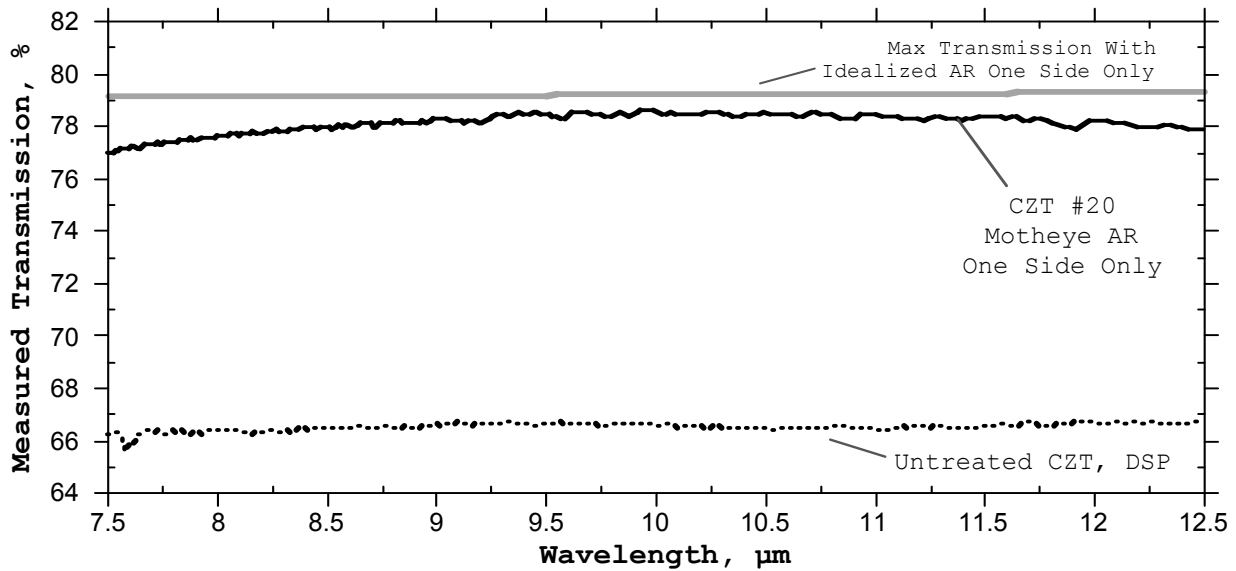


Figure 17: Measured transmission through a CZT window with a Motheye AR texture fabricated in one surface only.

### 6.6 Silicon, Si, ( $n = 3.42$ )

Silicon is a low cost optical material primarily used for MWIR windows and lenses. Silicon has a high refractive index, which makes it attractive for lenses, but also makes AR treatments more critical. Motheye AR structures have been fabricated in silicon for MWIR applications. The high index of silicon requires a Motheye design with a period much smaller than the wavelength range of interest to avoid diffractive effects, which results in a high aspect ratio structure. Figure 18 shows a silicon Motheye surface with an 800nm square grid period and 1800nm structure depth. Transmission data for the sample from 2 to 6 microns is shown in Figure 19, with an average loss of 1% within the target 3 to 5 micron spectral region. A slightly deeper structure would be required to get a flatter and lower loss response at the longer wavelengths, where the performance is beginning to trail off.

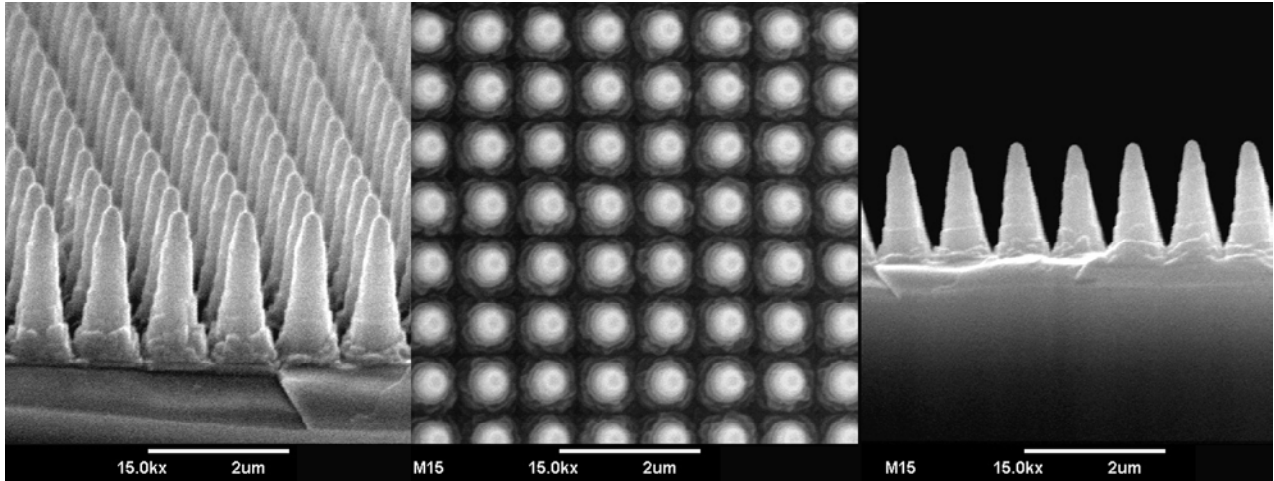


Figure 18: SEM photographs of AR textures fabricated in a silicon window.

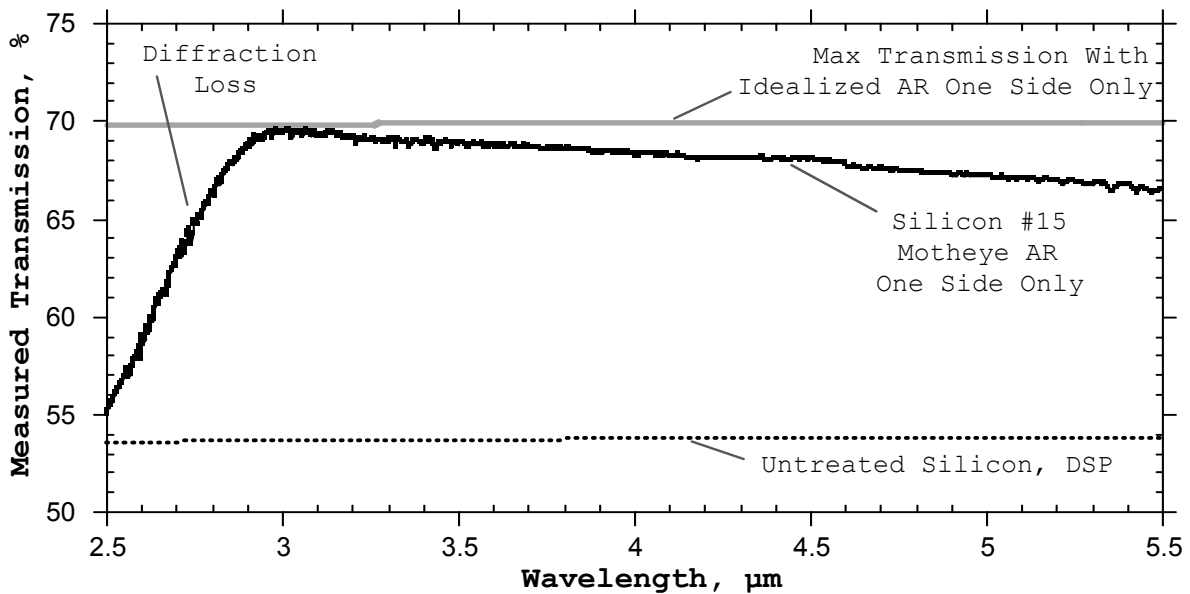


Figure 19: Measured transmission through a silicon window with a Motheye AR texture fabricated in one surface only.

### 6.7 Germanium, Ge, ( $n = 4.01$ )

Germanium is a preferred lens and window material for high performance infrared imaging systems in the LWIR. Its high refractive index is ideal for imaging systems because of reduced surface curvature requirements. However, the index also results in high surface reflections, resulting in the need for high performance AR treatments. Preliminary fabrication and etching work with Ge has focused on an SWS structure. Figure 20 shows an etched SWS structure in a Ge window. The etch depth has reached the target of 1250nm, however the hole diameter has been etched larger than the target which reduces the effective index of the surface and results in the observed performance shift to shorter wavelengths. The transmission of the SWS textured Ge window is shown in Figure 21. The reflection loss at 8.2 microns is only 1.5%, a significant improvement over an untreated Ge surface that loses 36% to reflection. Internal process development is ongoing to optimize the structure for LWIR applications.

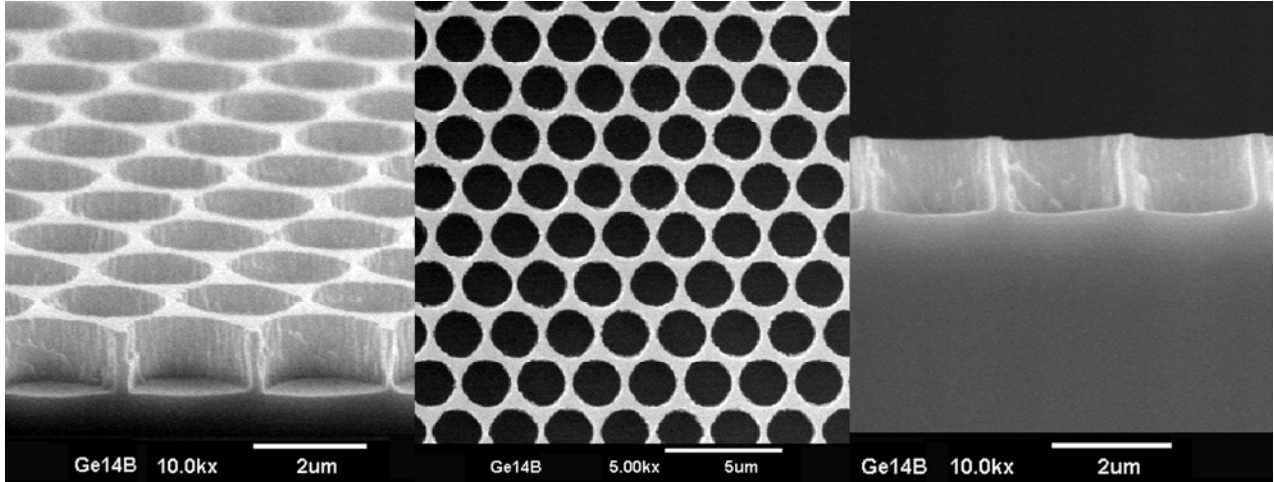


Figure 20: SEM photographs of LWIR AR textures fabricated in a Ge window.

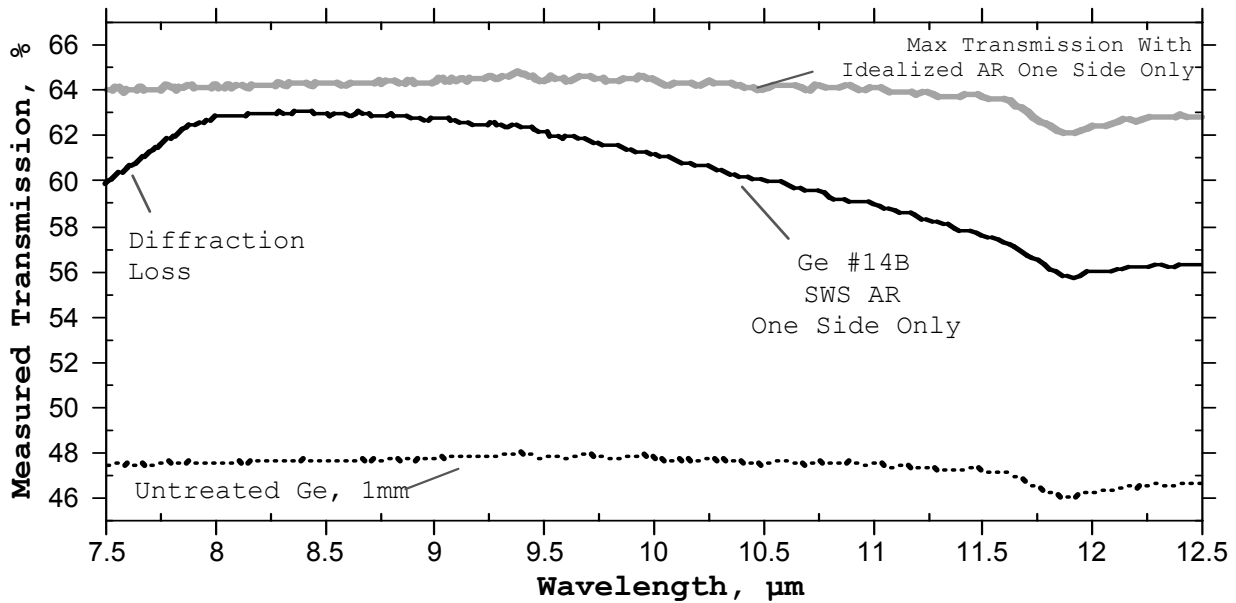


Figure 21: Measured transmission through a Ge window with an SWS AR texture fabricated in one surface only.

## 7. SUMMARY

Engineered AR surface structures can be an attractive alternative to thin-film coatings for many applications requiring mechanical durability, high laser damage thresholds, and wide-band performance. The practical design of Motheye and SWS AR textures have been discussed for a variety of important infrared transmitting materials. Interference lithography is utilized to pattern the repetitive structures because of the large field size, large depth of focus, and high process throughput characteristics of the technique. Motheye and SWS AR structures were fabricated in materials used throughout the infrared spectrum. SEM images of the structures are shown and discussed in relation to optical performance and durability. Transmission data is presented for each material, with experimental results closely matching the predicted performance. The wide-band AR performance presented demonstrate that rugged and durable surface structures can replace thin-film AR coatings in applications where coatings fail to address performance or durability requirements.

## 8. ACKNOWLEDGEMENTS

Janos Technologies of Vermont has generously supplied ZnSe, ClearTran, Ge, and sapphire substrates for our internal Motheye development work. The work with CZT is funded under a 2004 Phase I SBIR sponsored by The Department of Defense, Missile Defense Agency, Wright Patterson Air Base. All SEM analysis was performed by Mr. John Knowles at MicroVision Laboratories, Inc., (781-272-9909).

## 9. REFERENCES

- [1] Bernhard, C. G., "Structural and functional adaptation in a visual system", *Endeavour*, 26, pgs. 79-84, 1967
- [2] Clapham, P.B. and Hutley, M.C., "Reduction of lens reflexion by the 'Moth Eye' principle", *Nature*, 244, 281-2, Aug. 3, 1973)
- [3] Cowan, J. J., "Holographic Honeycomb Microlens", *Opt. Eng.* 24, pp. 796-802 (1985)
- [4] Thornton, B.S., "Limit of moth's eye principle and other impedance-matching corrugations for solar-absorber design." *JOSA*, Vol. 65, No. 3, pgs 267-270, March 1975
- [5] Wilson, S.J. & Hutley, M.C., "The optical properties of 'moth eye' antireflection surfaces", *Optica Acta*, Vol. 29, No. 7, pgs 993-1009, 1982
- [6] Southwell, W. H., "Pyramid-array surface-relief structures producing antireflection index matching on optical surfaces", *JOSA A*, Vol. 8, No. 3, pgs 549-553, March 1991
- [7] Raguin, D.H. & Morris, G.M., "Antireflection structured surfaces for the infrared spectral region", *Applied Optics*, Vol. 32, No.7, pg 1154, March 1993
- [8] DeNatale, J. F., et. al., "Fabrication and characterization of diamond moth eye antireflective surfaces on Ge", *J. Appl. Phys.*, 71, (3), pg1388, Feb. 1992
- [9] Harker, A.B. and DeNatale, J.F., "Diamond gradient index 'moth-eye' antireflection surfaces for LWIR windows.", *SPIE Vol. 1760, Window and Dome Technologies and Materials III*, pgs. 261-267, July 1992
- [10] Cowan, J. J., U.S. Patent 4,496,216, "Method and Apparatus for Exposing Photosensitive Material" (Jan. 29, 1985).
- [11] Hobbs, D.S., et. al., "Automated Interference Lithography Systems for Generation of Sub-Micron Feature Size Patterns", *SPIE Conference on Micromachine Technology for Diffractive and Holographic Optics*, Proc. SPIE, Vol. 3879, September 1999, pg 124-136
- [12] MacLeod, B.D., and Hobbs, D.S., "Low-Cost Anti-Reflection Technology For Automobile Displays", *Journal of the Society for Information Display, Automotive Display Conference*, November 2004.
- [13] Weimer, Wayne A. and Klocek, P. "Advances in low-cost long-wave infrared polymer windows.", *SPIE Vol. 3705, Window and Dome Technologies and Materials VI*, pgs. 276-281, July 1999
- [14] Harker, A.B., DeNatale, J.F. et. al. U.S. Patent 5334,342, August 2, 1994
- [15] Hobbs, D.S., and Dorschner, T.A., "Fourier Lithography: A New Manufacturing Tool for Optics", *Workshop For Electro-Optics Manufacturing Science and Technology, Army Night Vision Labs*, 95-498, May 1995