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14. ABSTRACT Transformation optics is opening the door to new devices and applications by manipulating the flow of light on the nano-scale combining smart design, material engineering and fabrication. This level of controlling light requires unique and complex structures that are not possible to realize with traditional planar patterning and deposition techniques. While traditional physical vapor deposition systems only allow for 2-Dimensional top-down fabrication, Glancing Angle Deposition (GLAD) allows for quasi 3-Dimensional fabrication of structures.					
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Report Title

Glancing Angle Deposition System for Advanced Fabrication of Metamaterial and Transformation-Optics Devices

ABSTRACT

Transformation optics is opening the door to new devices and applications by manipulating the flow of light on the nano-scale combining smart design, material engineering and fabrication. This level of controlling light requires unique and complex structures that are not possible to realize with traditional planar patterning and deposition techniques. While traditional physical vapor deposition systems only allow for 2-Dimensional top-down fabrication, Glancing Angle Deposition (GLAD) allows for quasi 3-Dimensional fabrication of structures. Exploring and developing these new fabrication techniques truly opens the door to a new realm of manufacturing possibilities and realization of advanced transformation optics designs.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

A. Boltasseva, "Oxides and nitrides as plasmonic materials", META'12, Paris, France, April 19-22, 2012
A. Boltasseva, "Improved material building blocks for metamaterials", International Workshop on Electromagnetic Metamaterials (IWEM-V), Albuquerque, New Mexico, USA, March 26-27, 2012
A. Boltasseva, "Metamaterials and plasmonics: improved material building blocks", APS meeting, Boston, MA, USA February 27- March 2, 2012
G. V. Naik, J. Kim, P. R. West, N. K. Emani, A. Boltasseva, "The road ahead for metamaterials and plasmonics: Improved material building blocks", Physics of Quantum Electronics, Snowbird, Utah, USA, January 2-7, 2012

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
2012/06/15 11:11	Jacob B. Khurgin, Alexandra Boltasseva. Reflecting upon the losses in plasmonics and metamaterials, Accepted for MRS Bulletin, June 2012 (05 2012)

TOTAL: 1

Number of Manuscripts:

Books

<u>Received</u>	<u>Paper</u>
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TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in
science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue
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Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

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scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

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Total Number:

Names of personnel receiving PhDs

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Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

**Glancing Angle Deposition System
for Advanced Fabrication of Metamaterial and
Transformation-Optics Devices**

Report Type: Final Report
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Agreement Number: W911NF1010380
Proposal Title: Glancing Angle Deposition System for
Transformation-Optics Devices

Report Period Begin Date: 08/10/2010
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Abstract

Transformation optics is opening the door to new devices and applications by manipulating the flow of light on the nano-scale combining smart design, material engineering and fabrication. This level of controlling light requires unique and complex structures that are not possible to realize with traditional planar patterning and deposition techniques. While traditional physical vapor deposition systems only allow for 2-Dimensional top-down fabrication, Glancing Angle Deposition (GLAD) allows for quasi 3-Dimensional fabrication of structures. Exploring and developing these new fabrication techniques truly opens the door to a new realm of manufacturing possibilities and realization of advanced transformation optics designs.

Statement of the problem

The nanofabrication system that is capable of angle-controlled multi-material deposition enables realization of novel optical devices that can provide functionalities not achievable with conventional optics. Such devices are designed for extreme control over flow of light using a new methodology called Transformation Optics (TO). Two innovative examples of TO devices include a planar hyperlens and a light concentrator. A flat hyperlens is capable of magnifying nanometer-scale features of an object that is smaller than half the wavelength of the illuminating light (i.e. beyond the diffraction limit) and, because of its planar shape, it is compatible with conventional microscopes and can be used as a standard add-on tool. Such below-the-diffraction-limit resolution is not achievable with conventional optical probing. Thus, a flat magnifying hyperlens has potential to revolutionize the entire field of optical imaging and achieve nanoscale spatial resolution by combining it with microscopes. Having similar geometry to the hyperlens, a light concentrator efficiently concentrates light from all directions into a small, nanoscale region. Light concentrators can be used to dramatically improve photovoltaic efficiency as well as applications in subwavelength photolithography and imaging. While the hyperlens theory (formulated first for cylindrical geometry) was described several years ago, its realization in the planar geometry required for compatibility with conventional microscopes, has been elusive. The actual fabrication of the hyperlens is extremely challenging due to requirements on geometry, parameter control as well as constituent materials (optical losses). The fabrication issues can be addressed by developing a highly controllable method of making alternating metal-dielectric films with non-uniform thicknesses as required by the design geometry. Such layered structures with film thicknesses gradually changing along the substrate cannot be obtained using standard deposition machines. Optical performance of TO devices can be optimized via fabrication optimization (such as achieving low surface roughness) and careful material choice so that the constituent materials have acceptable optical loss in the near-IR and visible frequencies.

Summary

Timeline of Glancing Angle Deposition (GLAD) system:

As this is a major new piece of equipment, it is useful to include a timeline of major events that have occurred throughout the purchasing and installation of the equipment. This evaporation system was custom-designed and ordered to match or exactly specifications. Furthermore, because the machine was installed in our cleanroom, there were additional planning and installation steps that were required to meet the guidelines of our facility. The timeline of major events are as follows:

- **07/08/2010:** Final quote received from vendor (PVD Products)
- **01/16/2011:** Utility form received for pre-installation connections
- **05/13/2011:** Trades (plumber, electrician, etc.) installation meeting
- **06/30/2011:** Evaporator shipped from vendor to Purdue
- **01/27/2012:** Utility installation was completed
- **02/16/2012:** Final Installation and system training
- **03/08/2012:** Extra crucible holders ordered
- **04/27/2012:** Crucible holders arrived

Recent Status

The machine is now in full working condition. We have discussed with the vendor some minor software upgrades that will streamline the fabrication of some of the future structures. Three of the four crucibles are currently in use, with beam alignment and sweep configured. We are also currently working with Purdue's Central Machine shop on designing and constructing new low-profile sample holding clips that are better suited for high-angle deposition, and a "quick-release" clip for more safe and reliable loading and unloading of substrate holders.

Scientific Plan and Capabilities

When first purchasing this system, the primary project we had in mind was a planar hyperlens. The planar hyperlens consists of a central semi-cylindrical center, surrounded on either side with alternating layers of metal and dielectric materials with non-conformal geometries (figure 1d). Such a device would be nearly impossible to fabricate with traditional techniques, as it requires curved, non-planar geometries.

However, by using Glancing Angle Deposition techniques, the structure may be fabricated in the following manner. Starting with a semi-cylindrical structure on the substrate (figure 1a), a dielectric material (such as SiO₂) can be deposited on a very sharp, glancing angle (figure 1b). By depositing at a sharp angle on a curved

geometry, a gradient thickness of dielectric will be deposited on the cylindrical structure. The dielectric can then be deposited on the opposite side at a glancing angle to create an identical structure on the opposite side. After the dielectric layer is complete, the same process can be repeated with a metal layer. By repeatedly depositing consecutive layers of metal and dielectric at glancing angles, we will finally achieve the desired structure shown in figure 1d).

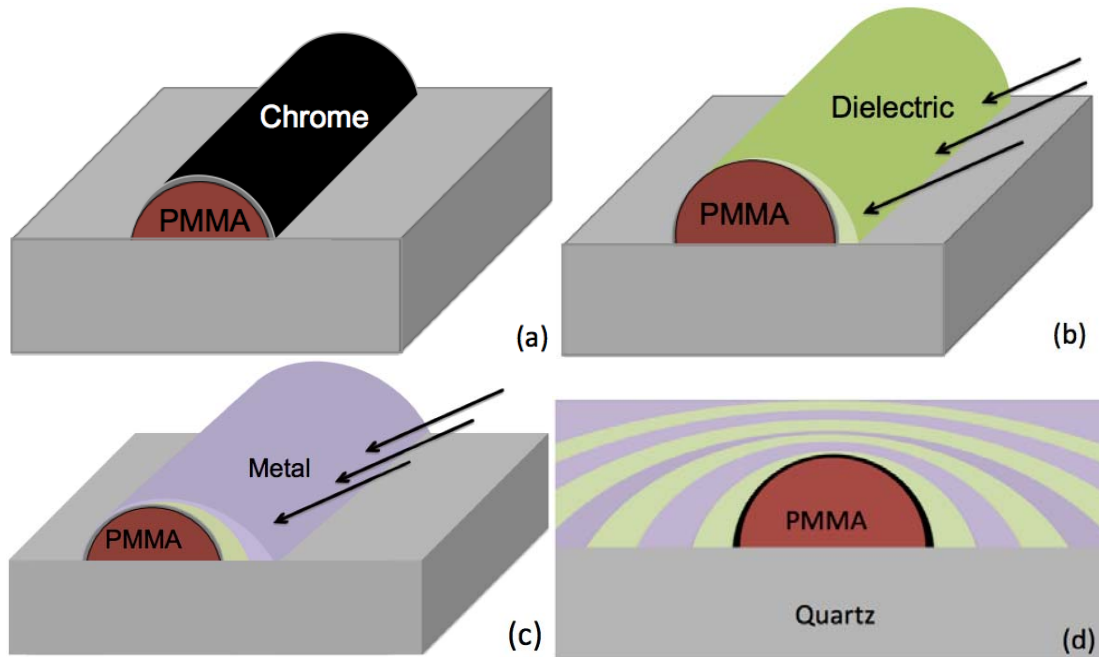


Figure 1: Major steps that are involved in the fabrication of a planar hyperlens

The hyperlens is just one example of a transformation optics device that requires non-conformal geometries. The field of transformation optics consists of a large family of devices that require non-conformal, non-traditional, quasi-3-dimensional fabrication techniques. Glancing angle deposition is one promising tool that may make the fabrication of such devices possible and practical.

Aside from non-conformal deposition, there are other unique applications for GLAD. Perhaps the most prevalent application for GLAD is in the growth of unique nano-wire structures. On a flat substrate, a material deposited on a very sharp, glancing angle will begin to be deposited randomly as small “islands” on the substrate. However, once these “islands” are formed, they cast a long shadow (from the deposited material) onto the substrate where the material may no longer be deposited (shown in figure 2).

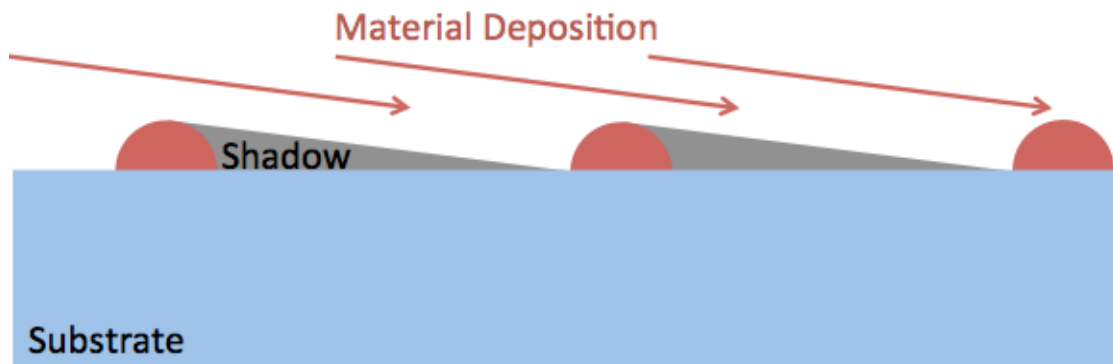


Figure 2: Deposited material will form small islands. Behind these islands, a shadow is cast, where no material will be deposited

Because material may not be deposited in the shadowed region, further deposition can only grow on these small “islands”. For this reason, continued deposition onto these structures will grow small nanowires as shown in figure 3. This work has been demonstrated by K. Robbie et al., J. Vac. Sci. Tech. B 16(3), 1115 (1998).

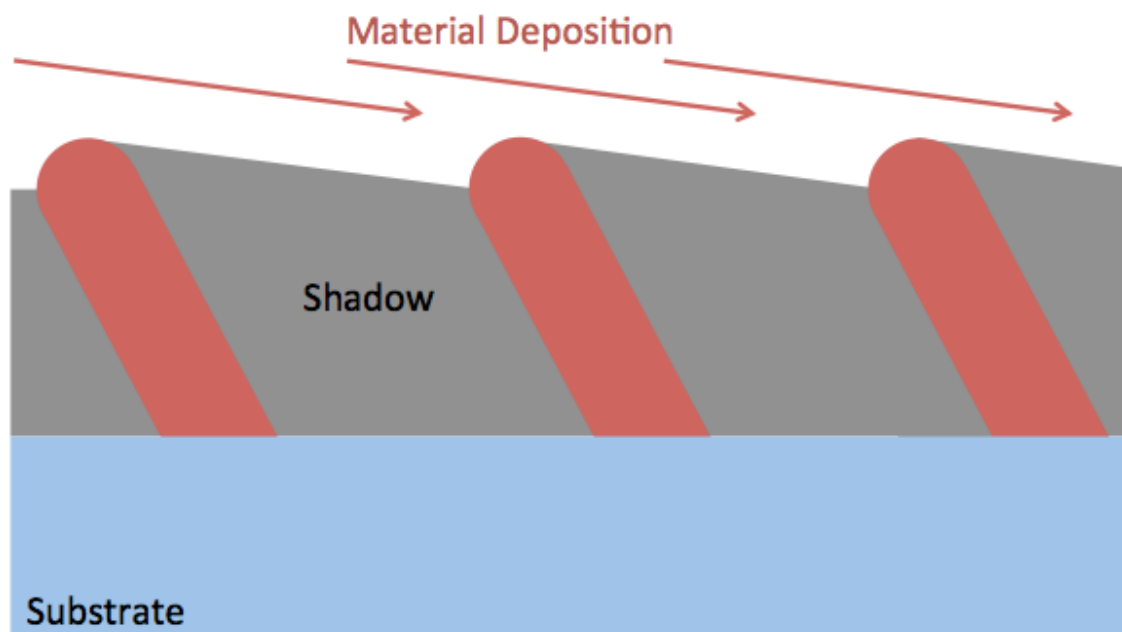


Figure 3: Nanowires can be grown by depositing material on a glancing angle

In this same paper, the group demonstrates how “curved” wires can be grown via the same technique, while adjusting the angle and rate of deposition as shown in figure 4.

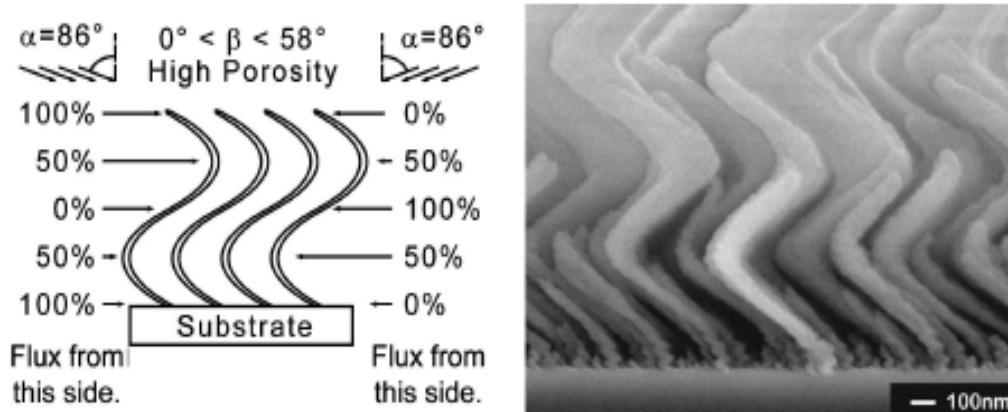


Figure 4: Curved nanowires can be grown by GLAD by adjusting the angle and rate of deposition

Even chiral structures can be created using this technique and rotating the substrate during deposition, as was demonstrated by M. O. Jensen and M. J. Brett, IEEE Trans. Nanotech. 4 (2), 269 (2005), and shown in figure 5.

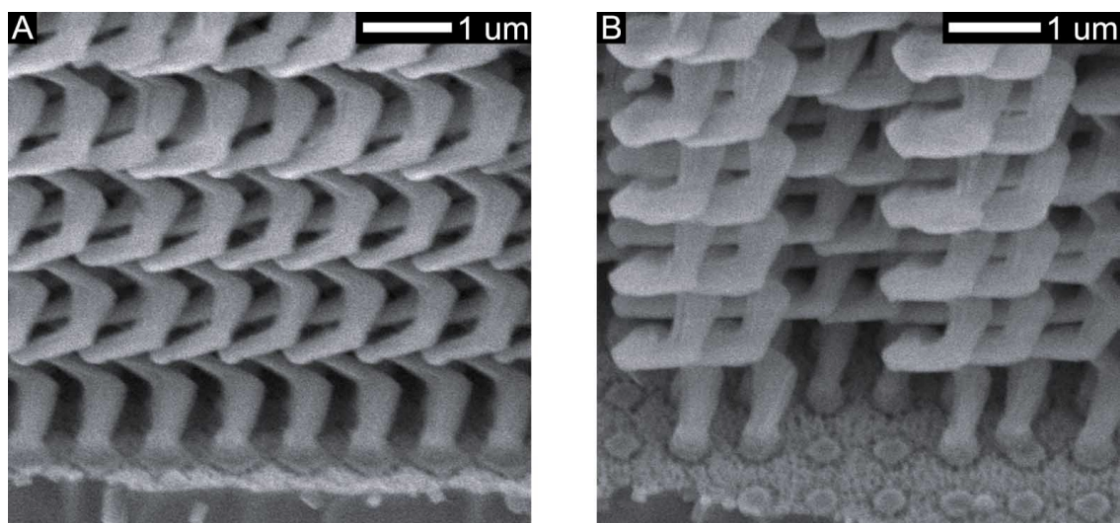


Figure 5: Chiral structures can be fabrication by GLAD by rotating the sample during deposition

Preparations for Experiments

In order to prepare for future experiments and fabrication projects, the following measures have been taken. Because the machine came with only one crucible holder, the first task was to order six new “Fabmate” graphite crucible liners, which have already arrived. We currently have one of the crucible holders filled with silver, and the other filled with silica (SiO_2) for preliminary testing of the multilayered metal/dielectric structures. All source material in our cleanroom is

serviced and regulated by building staff. Additional source materials (including Si, Al, TiO₂, Ge, and more) are in-stock if required. Substrates, including silicon, glass, ITO-coated glass, and quartz are on-hand and available when needed.

Electron-beam parameters (rise times, soak times, and powers) have also been tested and optimized for silver and SiO₂. Heating and cooling the source materials too quickly can result in problems including splashing, crucible cracking, and unstable deposition rates. On the other hand, heating the materials too slowly can result in lost time and source material, which is amplified when hundreds of layers are deposited.

Planned immediate experiments

Hyperlens fabrication is one structure that certainly requires the GLAD system. The required non-conformal geometries on cylindrical structures is certainly a challenge that has not been demonstrated to our knowledge. For this reason, we have planned immediate experiments that have and will be carried out to gain further insight into GLAD and to address any challenges that may arise before final hyperlens fabrication.

In order to test how silver will grow on a silica cylindrical structure, we conducted a GLAD run, depositing a thin layer of silver on a 5 micron silica sphere as shown in the schematic in figure 6.

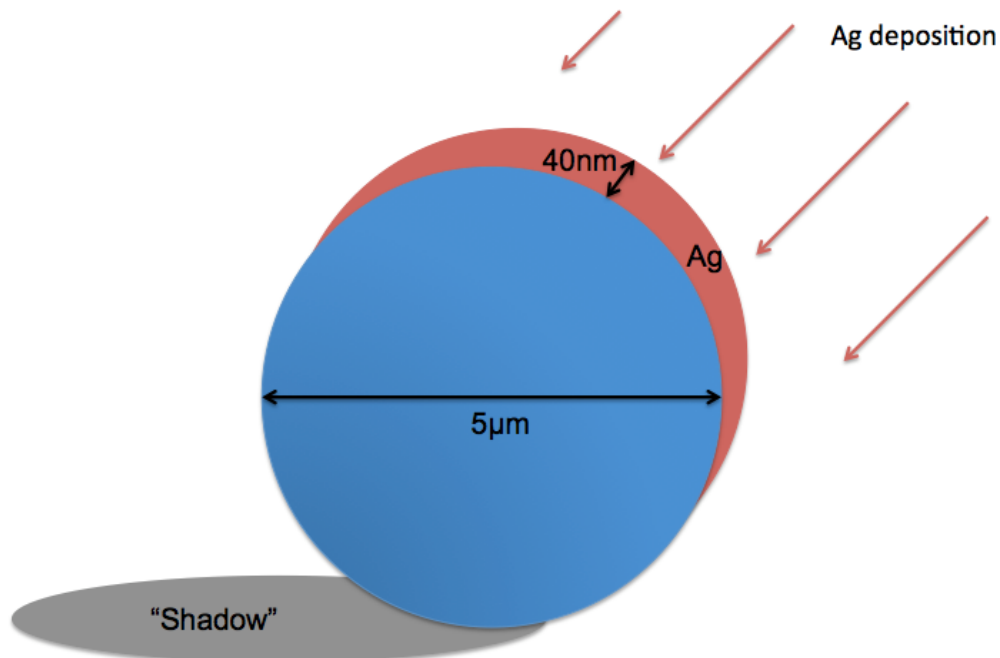


Figure 6: Deposition silver on a sphere at a glancing angle will create a gradient film thickness around the sphere.

From our previous expertise in silver growth on silica substrates, we know that silver will first be deposited in small “islands” when the deposition thickness is between 0 and about 10nm due to surface energy differences between silver and silica. When the deposition, thickness is between about 10 and 20nm, a semicontinuous film of silver will form, and only above about 20nm will the silver form a continuous film on silica. By depositing 40nm of silver on the silica sphere, as shown in the schematic above, we expect to observe this entire range of coverage on the silica sphere. SEM images of this experiment have confirmed this hypothesis as shown in figure 7.

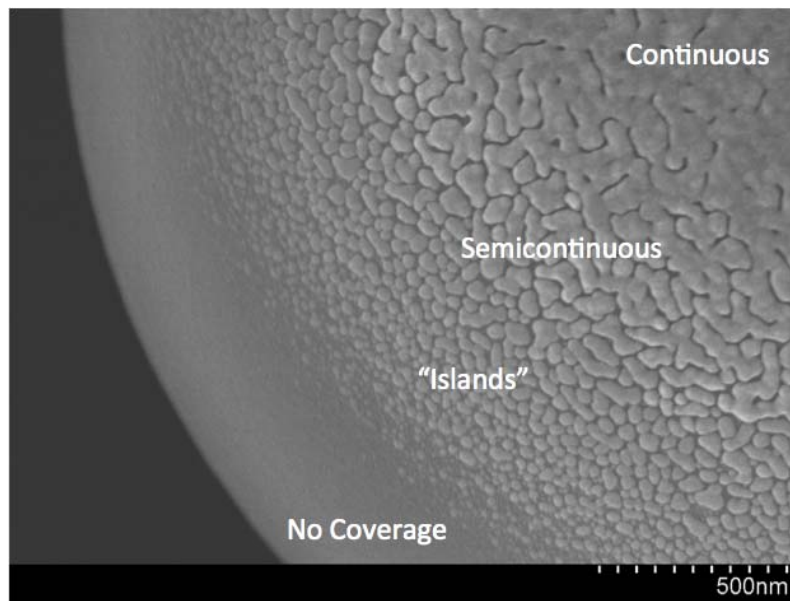


Figure 7: A gradient thickness of silver is deposited along the edge of a sphere via glancing angle deposition

While deposition on non-conformal geometries is interesting, the “shadow effect” caused by a structure may also provide interesting results. One experiment we will conduct in the near future will use a profiled mask (such as a glass substrate) to cast a shadow over part of the substrate. We expect this shadow region to produce a gradient thickness deposition on the substrate, creating a wedge- or ramp-like structure as shown in figure 8.

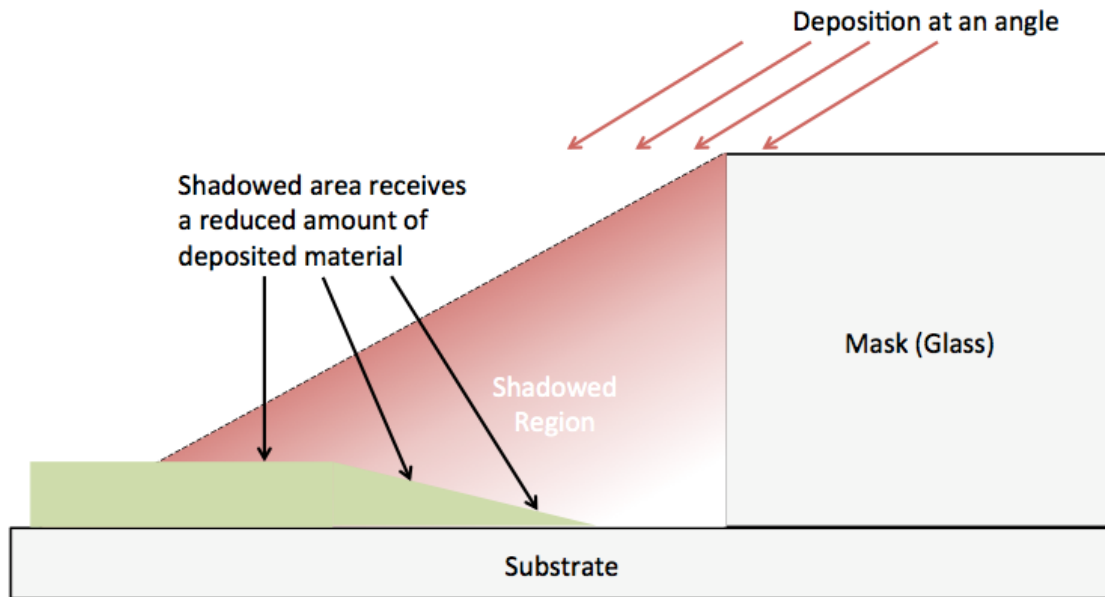


Figure 8: A mask can be used to create a “shadowed region” that will deposit a gradient film thickness

Repeatedly alternating metal and dielectric wedge-like structures will provide a wedge hyperbolic metamaterial with very unique interesting properties that have not been previously studied (shown in figure 9).

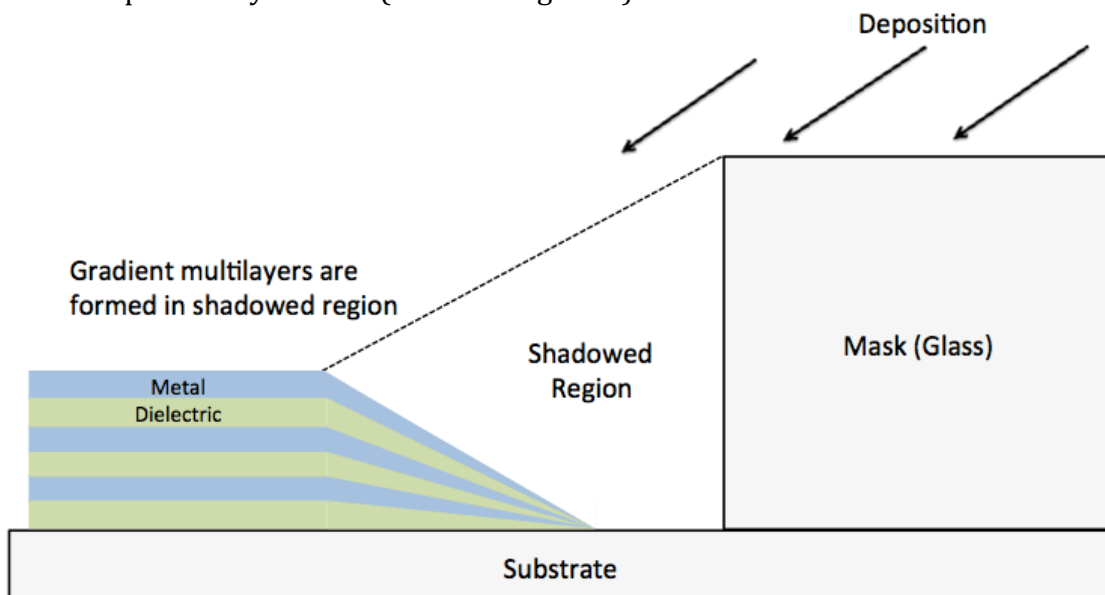


Figure 9: A wedge-like hyperbolic metamaterial can be created by alternating layers of metal and dielectric in the shadowed region of glancing angle deposition.