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14. ABSTRACT

In the course of this project, we met all of our initially stated objectives. Our research involved ongoing collaborations with colleagues at UMBC, the Marine Biological Laboratory, the University of Queensland, the University of California, Arizona State University, and the University of Pennsylvania. We regularly exchanged visits with our major collaborator and subcontractor, Nader Engheta of the University of Pennsylvania, to discuss our results and the construction of synthetic polarizers inspired by biological designs. Since finding began we published (or have in press) 31 papers in major scientific journals, of which ten result directly from new research supported by AFOSR funding and six more are reviews that include work directly related to AFOSR-funded research in my laboratory. We co-organized (with Justin Marshall) an international meeting held in June, 2008 that was largely funded by AFOSR and its European and Asian offices, delivered numerous invited seminars, several posters, and numerous invited talks at national and international meetings relating to this award. The PI of this award was selected Presidential Research Professor at UMBC at the beginning of 2009, an honor that extends for a term of three years.

15. SUBJECT TERMS
Biophotonics, polarization, optical retarders, molecular genetics, bio-inspired nanotechnology

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FINAL REPORT
AFOSR Award Number F49550-06-1-0117

"Inspired Biological Engineering: Detection and Production of Polarized Light by Animals"

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Objectives (*as stated in the original proposal*)

(1) To measure and describe patterns of polarized light in the upper atmosphere between the periods of sunset or sunrise and astronomical twilight. This period of time, extending for about one hour before sunrise or after sunset, has unusual patterns of upper-atmosphere polarization because the sky is illuminated by the sun and scatters dim light to the earth's surface, but the sun itself is not visible. The polarized light that reaches the earth is different from that normally seen during the day because it arrives from unusual heights in the atmosphere and must transit the lower atmosphere before reaching an observer or detector. We will use full-sky imaging and high-sensitivity spectral polarimetry to measure celestial polarization throughout this unusual period.

(2) To examine the molecular specializations of visual pigments of animals that enhance the detection and analysis of polarized light. Photoreceptors of invertebrate animals are often highly specialized for the analysis of polarized light. Theory predicts that polarization sensitivity of these receptors is greatest when the absorption dipoles of the visual pigments, produced by oriented chromophores, are parallel to the axes of the microvilli containing the visual pigments and are anchored in this position. We will use comparative molecular biological techniques to search for adaptations of visual pigments that could anchor and orient these proteins favorably for polarization sensitivity.

(3) To characterize the structural features of biologically specialized polarized-light reflectors in animals, both to understand their unusual optical properties and to use these to inspire artificial devices and structures with special polarizational properties. During the first period of AFOSR funding, we have discovered a variety of different biological polarizers with surprisingly diverse spectral and polarizational properties. It is now obvious that biological polarizers incorporate a diversity of unusual adaptations to control light's polarization, both linear and circular. We wish to follow up these initial findings with a detailed anatomical and theoretical study of how several different polarizing systems of animals operate. We plan to focus on both scattering and reflective linear polarizers, on static and dynamic polarizing systems, and on circular polarizers of scarab beetles.

(4) To construct prototypes of artificial polarizing systems with desirable special properties. In collaboration with laboratories specializing in electrical engineering and nanotechnological fabrication, we will use the biological polarizers described in Objective 3 to inspire artificial structures and devices with properties similar to those of the biological systems. These structures will not necessarily duplicate the natural structures in all details, but instead could be designed to operate in different spectral realms (including microwave or radio wavelengths).

Status of Effort

Throughout the term of this award we worked hard to meet all of our objectives, and of course, in doing the research we found new problems to run down. Our research involved ongoing collaborations with colleagues here at UMBC, as well as at the Marine Biological Laboratory (Woods Hole, MA), the University of Queensland (Brisbane, Australia), the University of California (Berkeley, CA), Arizona State University (Tempe, AZ), and the University of Pennsylvania (Philadelphia, PA). Research was carried out at UMBC, at Woods Hole, at the University of Pennsylvania Furthermore, we conducted extensive field research at the Lizard Island Research Station, Australia, where we measured night-time polarization spectra and collected animals for molecular and optical work on polarized-light receptors and polarization reflectors. We regularly exchanged visits with our major collaborator, Nader Engheta of the University of Pennsylvania, to discuss data interpretation and to plan our work involving the construction of synthetic polarizers inspired by biological designs.

Since finding began in December 2005, we published (or have in press) 31 papers in major scientific journals, of which ten result directly from new research supported by AFOSR funding and six more are reviews that include work directly related to AFOSR-funded research in my laboratory. We co-organized (with Justin Marshall) an international meeting held in June, 2008 that was largely funded by AFOSR and its European and Asian offices, delivered numerous invited seminars, several posters, and numerous invited talks at national and international meetings relating to this award. These are detailed at in later sections of this Final Report. During the term of this award the PI, Dr. Cronin, was selected "Presidential Research Professor" at UMBC, serving from July 1, 2009 to June 30, 2012.

Overall Accomplishments/New Findings (Term of the Project)

1. Megan Porter, the postdoctoral fellow who has been funded by this award, developed an enormous project devoted largely to the extremely complicated problem the molecular genetics of stomatopod opsins. Her research continues to concentrate on a number of molecular properties that explain the diversity of visual pigments in stomatopod crustaceans that are specialized for color vision and analysis of polarized light. She has analyzed some 79 different transcripts of opsins (the proteins making visual pigments) from seven stomatopod species in an effort to understand the molecular properties that (1) tune the spectral absorption of visual pigments, (2) produce highly reliable polarization receptors, and (3) affect the physical and chemical associations between light-absorbing molecules and other components of the photoreceptor system. She continues to work on understanding evolutionary and molecular relationships among various color- and polarization-sensitive opsins to help us understand how these molecular machines achieve their unique properties.

Using evolutionary trace analysis, Megan identified 11 amino acid sites that are functionally divergent among stomatopod opsins - six in the chromophore binding pocket and five at the cytoplasmic interface of cytoplasmic loop III and transmembrane helix VI. These may contribute to some of the divergent properties in spectral or polarizational sensitivity of these

pigments. The scope of work demanded by this project will continue into future research with new AFOSR support secured this year (commencing March 1, 2009).

Megan is now preparing a major review of the opsins and their evolution across animals, and is continuing to develop our understanding of polarization opsins in stomatopods and other invertebrates. Her first report on stomatopod opsins is currently in press.

2. Our survey of natural polarizers used by mantis shrimps and cephalopod mollusks discovered a variety of completely unexpected polarizing mechanisms, including differential scattering and dichroic transmission using oriented carotenoid molecules. Virtually all the work in this area was the responsiblilty of "Short" (Tsyr-Huei) Chiou, and the work formed a major component of his PhD thesis, funded by AFOSR. Short has discovered some very unusual optical properties in a set of biological polarizers in some mantis shrimps, where the animals' cuticles combine dichroic polarizers based on the cuticular carotenoid, astaxanthin, with a phase-delay material probably built from aligned crystals of calcite. The result is a natural circular polarizer, which is detectable to a very specialized set of photoreceptors found in these same species. As mentioned above, Short demonstrated the presence of dichroic polarizers based on astaxanthin in animals – the first demonstration of a pigment-based polarizer intended for signaling in any biological system. We are preparing a paper for submission on the properties of these polarizers, and Short published a paper on the biological optics of this unusual circular polarization-based signaling system. He also published a paper in a symposium volume of SPIE reviewing biological polarizers. Short is continuing these projects with AFOSR support as a postdoc with Justin Marshall.

3. Yunfei Zhang, a masters student in my lab who was awarded his degree in early 2009, worked with Megan Porter and an undergraduate (Shivani Desai) to construct a molecular phylogeny of modern mantis shrimps. We will incorporateYunfei's work into a major report on stomatopod phylogeny and the evolution of visual characters. Our hope is that understanding how these animals have evolved will be useful in figuring out how these biological polarizers and polarization visual sensitivity arose, and perhaps in finding the evolutionary steps that produce the signaling and receptor systems. Such an understanding could be useful in working out how to build and use artificial analogues of these devices.

4. A new graduate student in my laboratory, Michael Bok, is well into his doctoral thesis on the properties of ultraviolet-sensitive photoreceptors in mantis shrimps. He has completed all requirements for entry to candidacy as a doctoral student. His research began with the support of the project just completed and will continue into the term of our subsequent award. Mike has identified the opsins that are present in polarization-sensitive photoreceptors in several species, and is now working to obtain their molecular sequences (for functional analysis) and their pattern of expression in UV and polarization receptors.

4. Our collaboration with Nader Engheta has been a great help in working out the optical function of polarizers in mantis shrimps and in cephalopod mollusks (specifically, squids and cuttlefishes). A paper by Short Chiou on cephalopod polarizers was featured on the cover of the *Journal of Experimental Biology* this year. That issue of the journal also included an editorial report on the paper. The work is described fully in the publication, which is available

as a pdf file on request, and does not need further elaboration here. This cover by Short was our second in *J Exp Biol* on polarization signals, as an earlier paper by Jon Douglas and others also was awarded a cover. Short is preparing a new paper on the optics of crustacean biological polarizers.

5. Our work with the Marshall laboratory at the University of Queensland continues to be unusually successful. Besides the paper on circular polarization sensitivity, we published together with Marshall's former postdoc, Sonja Kleinlogel, a review of stomatopod vision including the polarization senses. Several papers on biological polarizers and polarization receptors are either under review or in preparation.

6. We initiated a new project in collaboration with Roger Hanlon's laboratory at MBL Woods Hole, who has been a long-time colleague in projects with polarization signaling in cephalopods. It is likely that some visual, polarization-sensitive opsins normally expressed in retinas of these animals (squids and cuttlefishes) might appear in specialized receptors in skin tissue. We have begun to collaborate with Hanlon and Lydia Mathger (a postdoc in his laboratory) to learn whether we can detect the presence of visual pigments in skin cells. This work at UMBC was initiated in Phyllis Robinson's laboratory, and involved a rotation research project by my doctoral student, Michael Bok. A new graduate student, Alexandra Nahm, will take on this project for her thesis.

7. A new collaborator, Nicholas Roberts (University of Manchester) joined the team in the final year of funding to apply his expertise in physics and optical modeling to understanding how biophotonic devices, used to control the polarization of light, function. This led immediately to the writing of a manuscript now under review for publication, and the collaboration will continue into future AFOSR-funded work.

8. We concluded our measurements of nocturnal polarization, using a new and extremely sensitive spectrometer from Ocean Optics, the QE65000. This instrument has a much greater dynamic range than spectrometers we had used in the past, and also has a thermoelectric cooling system which enables it to retain low levels of dark noise, permitting much extended measuring cycles (for greater photon capture). This allowed us to measure skylight polarization throughout twilight. The work was done at Lizard Island, Australia, to escape from potential influences on the celestial pattern that might arise from nearby artificial sources of light.

Personnel Supported During the Term of This Project

Principal Investigator:

Thomas W. Cronin, Dept. Biol. Sci, UMBC (Summer salary)

Postdoc:

Megan L. Porter (Research costs and full-time salary)

Graduate Students:

Tsyr-Huei Chiou (UMBC PhD student, research and salary)
Michael Bok (UMBC PhD student, research)
Yunfei Zhang (UMBC MS student, research)
Chia-Hua Lue (UMBC MS student, research)

Publications (* indicates AFOSR primary support; reprints available on request)

*M.L. Porter, M. Bok, P.R. Robinson, and T.W. Cronin. 2009. Molecular diversity of visual pigments in Stomatopoda (Crustacea). Visual Neuroscience (in press)

*T. Cronin. 2009. Polarized-light vision in land and aquatic animals. Encyclopedia of the Eye (in press)

L. Kiere, C.M. Hofmann, K. Omland, T.W. Cronin, and J. Price. 2009. Discrete evolutionary color changes in caciques suggest different modes of carotenoid evolution between closely related taxa. The Condor (in press).

*M.L. Porter and T.W. Cronin. 2009. A shrimp's eye view of evolution: how useful are visual characters in decapod phylogenies? Crustacean Issues (in press).

T.W. Cronin and M.L. Porter. 2009. Visual system: invertebrates. In: Encyclopedia of Neuroscience (Larry Squire et al., eds.), vol. 10. Academic Press, Oxford. pp 351-358.

*T.M. Frank, M. Porter, and T.W. Cronin. 2009. Spectral sensitivity, visual pigments and screening pigments in two life history stages of the ontogenetic migrator *Gnathophausia ingens*. Journal of Marine Biology of the U.K. 89:119-129.

*T.W. Cronin and M.L. Porter. 2008. Exceptional variation on a common theme: The evolution of crustacean compound eyes. Evolution: Education and Outreach 1:463-475.

*M.T. Walker, R.L. Brown, T.W. Cronin, and P.R. Robinson. 2008. Photochemistry of retinal chromophore in mouse melanopsin. Proceedings of the National Academy of Science 105:8861-8865.

C.M. Hofmann, T.W. Cronin, and K.E. Omland. 2008. Evolution of sexual dichromatism: 1. Convergent losses of elaborate female coloration in New World orioles (*Icterus spp.*). The Auk 125:778-789.

C.M. Hofmann, T.W. Cronin, and K.E. Omland. 2008. Evolution of sexual dichromatism: 2. Carotenoids and melanins contribute to sexual dichromatism in New World orioles (*Icterus spp.*). The Auk 125:790-795.

M.E. Cummings, J.M. Jordão, T.W. Cronin, and R.F. Oliveira. 2008. Visual ecology of the fiddler crab *Uca tangeri*: effects of sex, viewer and background on conspicuousness. Animal Behaviour 75:175-188.

*T.-H. Chiou, S. Kleinlogel, T.W. Cronin, R.L. Calwell, B. Lofle, A. Siddiqi, A. Goldizen and J. Marshall. 2008. Circular polarisation vision in a stomatopod crustacean. Current Biology 18:429-434.

T.W. Cronin. 2008. Visual ecology. In: The Senses: A Comprehensive Reference. Vision I, Volume 1 (eds. R. Masland and T.D. Albright). Academic Press, San Diego. pp. 211-246.

T.W. Cronin, M.R. Kinloch, and G.H. Olsen. 2007. Head-bobbing behaviour in walking whooping cranes (*Grus americana*) and sandhill cranes (*Grus canadensis*). Journal of Ornithology 148 (Suppl. 2):S563-569.

*J. Marshall, T.W. Cronin, and S. Kleinlogel. 2007. A review of stomatopod eye structure and function. Arthropod Structure & Development 36:420-448.

*T.-H. Chiou, L.M. Mäthger, R.T. Hanlon, and T.W. Cronin. 2007. Spectral and spatial properties of polarized light reflections from the arms of squid (*Loligo pealeii*) and cuttlefish (*Sepia officinalis* L.) Journal of Experimental Biology 210:3624-3635.

L.M. Kiere, C.M. Hofmann, I.E. Tracy, T.W. Cronin, J. Leips, and K.E. Omland. 2007. Using color to define species boundaries: quantitative analysis in the orchard oriole complex supports the recognition of two species. The Condor 109:692-697.

*B. Greiner, T.W. Cronin, W.A. Ribi, W.T. Wscilo, and E.J. Warrant. 2007. Anatomical and physiological evidence for polarisation vision in the nocturnal bee, *Megalopta genalis*. Journal of Comparative Physiology A 193:591-600.

C.M. Hofmann, K.J. McGraw, T.W. Cronin, and K.E. Omland. 2007. Melanin coloration in New World orioles. I: Carotenoid masking and pigment dichromatism in the orchard oriole complex. Journal of Avian Biology 38:163-171.

C.M. Hofmann, K.J. McGraw, T.W. Cronin, and K.E. Omland. 2007. Melanin coloration in New World orioles. II: Ancestral state reconstruction reveals lability in the use of carotenoids and phaeomelanins. Journal of Avian Biology 38:172-181.

*J.M. Douglas, T.W. Cronin, T.-H. Chiou, and N.J. Dominy. 2007. Light habitats and the role of polarized iridescence in the sensory ecology of Neotropical nymphalid butterflies (Lepidoptera: Nymphalidae). Journal of Experimental Biology 210:788-799.

J.M. Jordão, T.W. Cronin,and R.F. Oliveira. 2007. Spectral sensitivity of four species of fiddler crabs (*Uca pugnax*, *Uca pugilator*, *Uca vomeris* and *Uca tangeri*) measured by *in situ* microspectrophotometry. Journal of Experimental Biology 210:447-453.

*M.L. Porter, T.W. Cronin, D.A. McClellan, and K.A. Crandall. 2007. Molecular characterization of crustacean visual pigments and the evolution of pancrustacean opsins. Molecular Biology & Evolution 24:253-268.

T.W. Cronin, R.L. Caldwell, and J. Marshall. 2006. Learning in stomatopod crustaceans. International Journal of Comparative Psychology 19:297-317.

T.W. Cronin. 2006. Evolution of color vision and visual pigments in invertebrates. In: Evolution of Nervous Systems, vol I (J.H. Kaas, ed). Academic Press, Oxford, pp. 361-366.

A.G. Cheroske, P.H. Barber, and T.W. Cronin. 2006. Evolutionary variation in the expression of phenotypically plastic color vision in Caribbean mantis shrimps, genus *Neogonodactylus*. Marine Biology 150:213-220.

C.M. Hofmann, T.W. Cronin, and K.E. Omland. 2006. Using spectral data to reconstruct evolutionary changes in coloration: carotenoid color evolution in New World orioles. Evolution 60:1680-1691.

T.W. Cronin. 2006. Invertebrate vision in water. In: Invertebrate Vision (E. Warrant and D.E. Nilsson, eds). Cambridge University Press, Cambridge UK, pp. 211-249.

*T.W. Cronin, E.J. Warrant, and B. Greiner. 2006. Celestial polarization patterns during twilight. Applied Optics 45:5582-5589.

T.W. Cronin. 2006. Fluorescent signaling in mantis shrimps. McGraw-Hill Yearbook of Science & Technology. McGraw-Hill, New York, pp. 130-131.

T.W. Cronin. 2006. Quick guide: Stomatopods. Current Biology 19:R235-R236.

Interactions/Transitions

a. Participation/presentations at meetings, conferences, seminars, etc.

Cronin - Invited academic seminars:
University of California, Santa Barbara, March 20, 2006
University of Illinois at Champaign-Urbana, March 28, 2006
University of Texas on November 2, 2006
Whitney Laboratory of the University of Florida, February 8 and 9, 2007
Queens University, Kingston, Ontario on March 30, 2007
Arizona State University on October 5, 2007.
Boston University on October 15 and 16, 2007
University of Cincinnati on October 27, 2008
University of Lund, Sweden, on February 27, 2009

Cronin - Invited presentations at international meetings:
Workshop on Color Vision, University of Virginia, October 23, 2006
International Ornithological Congress, Hamburg, Germany, August 19, 2006
European Conference on Visual Perception, St Petersburg, Russia, August 24, 2006
FASEB meeting: Biochemistry of Vision, Snowmass Colorado on June 21, 2007
Vision Down Under meeting, Palm Cove, Queensland, Australia on July 21, 2007
International Congress of Neuroethology, Vancouver Canada on July 25, 2007
(Cronin was also invited to give two presentations in 2008 but was unable to deliver them due to a medical emergency.)

Porter - Invited or contributed presentations at international meetings:
FASEB meeting: Biochemistry of Vision, Snowmass Colorado on June 20, 2007
Vision Down Under meeting, Palm Cove, Queensland, Australia on July 21, 2007
Department of Electrical Engineering at UMBC in October, 2007
Polarization Conference, Heron Island Australia, June 4, 2008.
International Conference on Invertebrate Vision, Backaskog Sweden, August 2, 2008

"Short" Chiou - Presentations and posters at international meetings:
MBL's annual meeting on behavior and physiology, Woods Hole, May 27 2006
Vision Down Under meeting, Palm Cove, Queensland, Australia on July 21, 2007
International Congress of Neuroethology, Vancouver Canada on July 25, 2007
SPIE, Orlando, Florida, March 20, 2008.
Polarization Conference, Heron Island Australia, June 4, 2008.
International Conference on Invertebrate Vision, Backaskog Sweden, August 3, 2008

Michael Bok - Presentations and posters at international meetings:
Polarization Conference, Heron Island Australia, June 4, 2008.

b. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories.

We worked closely with Justin Marshall, University of Queensland, Australia, who is supported for joint projects by the AFOSR international office, Tokyo. We have a number of collaborative projects on the biology of linear and circular polarization.

We worked closely with Roy L. Caldwell, University of California Berkeley, sharing experimental animals. Dr. Caldwell also assisted us with critical field work in Australia throughout the project.

We joined forces with Roger Hanlon, Marine Biological Laboratory, Woods Hole, Massachusetts, to work on polarization sensing and reflections in cephalopod mollusks (squid, cuttlefish).

We met frequently with our AFOSR-supported co-grantee, Nader Engheta (Department of Electrical Engineering, University of Pennsylvania), for day-long sessions either at UMBC or in Pennsylvania.

We met with our Dutch colleague Doekele Stavenga, who is also supported by AF funds, at UMBC in May, 2007 to discuss animal optical structure.

Together with Justin Marshall, Short Chiou and I met with a number of Air Force researchers at Eglin AFB in early September, 2007. Our host was Martin Wehling. We each presented recent results from AF-funded research and discussed research plans with several individuals in Wehling's group. We also toured Dennis Goldstein's laboratory at Eglin and made plans to have biological materials measured in his facility. Powerpoint presentations of talks given at that meeting are available on request.

We began new a new collaboration with Nicholas Roberts, University of Manchester, on modeling the optics of biological polarizers and analyzers.

c. Transitions.

None as of yet, other than our ongoing collaboration with the AFOSR-supported engineer, Nader Engheta, University of Pennsylvania (nanotechnology and fabrication).

New Discoveries, Inventions, or Patent Disclosures

None, other than those already mentioned and described in detail above.

Honors/Awards

Dr. Cronin, was selected "Presidential Research Professor" at UMBC, serving from July 1, 2009 to June 30, 2012. Only one faculty member of the university is selected each year.

APPENDIX: Final report from subcontractor Nader Engheta (U of Pennsylvania)

Constructing Polarization Filter Arrays on Surfaces

As part of the collaborative projects with Professor Cronin's team at the University of Maryland at Baltimore County, here at University of Pennsylvania (Viktor Gruev, Yong Sun, and Nader Engheta) we have investigated the possibility of constructing polarization analyzing filters (i.e., micropolarizer arrays) with specific orientation of polarization on flat surfaces. The purpose of the micropolarization array is to filter and manipulate the polarization of the incoming light waves. The extinction ratios of the polarization filter, i.e., the ratio of the parallel polarized light to cross polarized light has to be as large as possible (e.g., 100 or higher) in order to be able to extract useful information. In our group, we have explored two directions in the design of polarization filter array. The first approach focused on designing a micropolarizer array composed of layers (e.g., two layers) of nano-wire grid polarization filters. The dual layer micropolarizer array is constructed using combination of optimized micro fabrication steps. The second approach explored the design of single layer micropolarizer filter array using electron-beam lithography. The micropolarizer array may be composed of pixels with 4 different polarization orientations. Such polarization arrays have also been useful for our various polarization projects.

Dual Layer Micropolarization Array: Constructing nano-wire polarization filters is not possible using standard UV lithography processes due to diffraction limitations. Since polarization filters are composed of periodic structures, interference lithography or holographic lithography is suitable for patterning. This technique requires use of two lasers, for example UV lasers operating at 280 nm, interfering at 90 degrees. The interference pattern period generated by the two laser can be estimated to be $X = \lambda / 2\sin(\Theta)$, where λ is the wavelength and Θ is the interference angle of the two lasers. The blue wavelength of the UV laser is also compatible with typical photoresist exposure wavelengths and it can be used to pattern directly the photoresist. Standard reactive ion etching aluminum etch recipe is used to transfer the photoresist pattern to the aluminum substrate. A scanning electron microscope (SEM) image of the nano-wire polarization filter is shown in Figure 1. The aluminum wires are 160 nm thick, 80 nm wide and have 160 nm pitch (i.e. period). This provided us with a single layer of nano-wire grid polarizers.

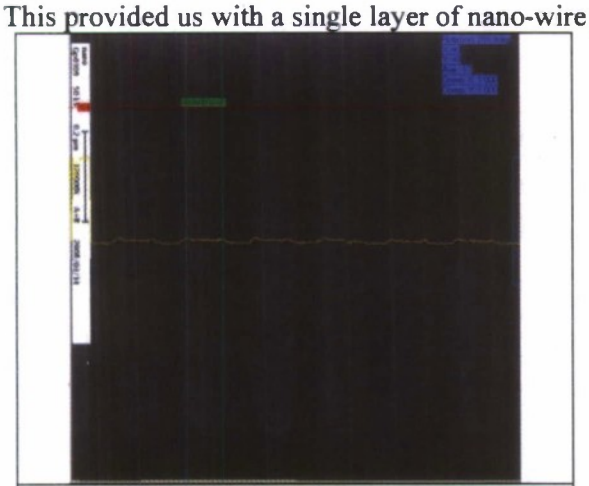


Figure 1: SEM image of the polarization filter composed of 80 nm aluminum wires and wire pitch of 160 nm.

To have two layers of wire grid polarizers (with different polarization characteristics), two separate nano-wire polarization filters were used to create a dual layer polarization filters. Both filters were

individually patterned with 6 micron pitch pixels using two separate masks and etched using RIE equipment. The micro fabrication steps are described below and illustrated in Figure 2:

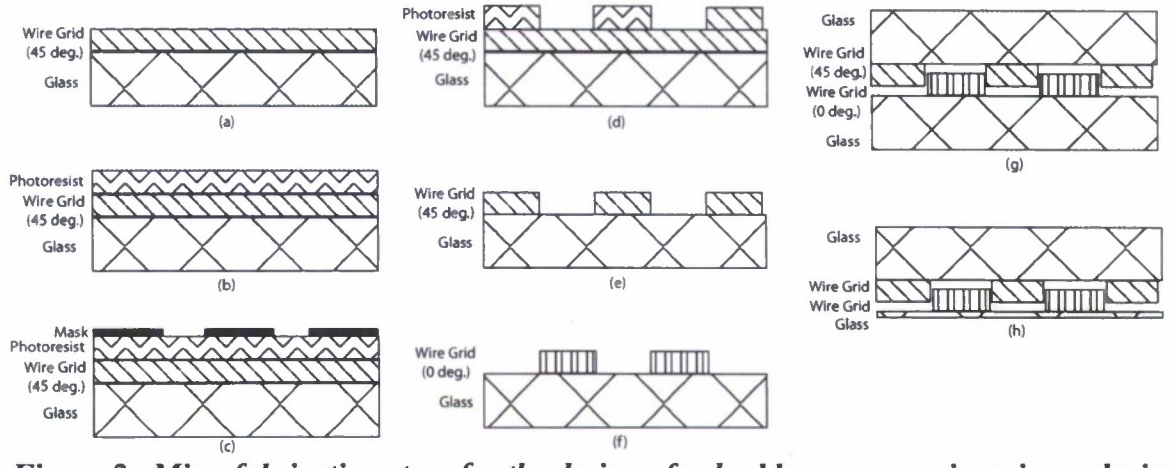


Figure 2. Microfabrication steps for the design of a dual layer nano-wire micropolarizer filter array.

(1) Clean the surface of the polarization filter with DI water and isopropyl alcohol. Dry the sample with air. Heat to a temperature of 95° C for 10 minutes. This ensures that the surface of the filter is completely dry. It is recommended that the samples is gradually heated and cooled off in order to avoid stress on the aluminum nano wires (Fig. 2-a).

(2) A negative SU-8 2002 photoresist is applied next on the sample. The negative photoresist, SU-8 2002, is hydrophobic and requires the applied surface to be absolutely free of any water molecules. Hence, the heating of the sample in step one removes any water molecules that can be trapped in the air space between the aluminum nano wires (Fig. 2-b).

(3) Spin coat the photoresist at 500 rpm for 10 seconds and then at 3000 rpm for 50 seconds with 500 rpm per second acceleration. The resulting photoresist thickness is 2 μm. It is important to have a very good precise ramp up from 500 to 3000 rpm. The acceleration will define the final thickness of the photoresist (Fig. 2-b).

(4) Bake the sample at 65° C for 1 min and then at 95° C for 2min on a hot plate. It is recommended that the sample cools down at 65° C for 1 min in order to gradually decrease the temperature of the sample. Gradual changes of the temperature during the baking process avoids rapid temperature differences and prevents the photoresist from cracking.

(5) Expose the photoresist at 375nm for 22 seconds at 5mW/cm^2 intensity. The mask used to pattern the photoresist contains 6 μm by 6 μm square checkerboard patterns (Fig. 2-c).

(6) Post-bake the sample at 65° C for 1 min and then at 95° C for 3 min. The sample is cooled down at 65° C for 1 min in order to gradually decrease the temperature and minimize stress and cracking on the photoresist.

(7) Develop the photoresist for 3 min in an SU-8 developer using an ultrasound bath and gently rinse it with isopropyl alcohol. If white colored liquid appears on the surface, the photoresist is not completely developed and it is submerged in the developer again (Fig. 2-d). Steps 1-7 are repeated for the second polarization filter. The second polarization filter is physically rotated by the required angle θ for the design (e.g., we did it for 45 degrees) during the alignment procedure (step 5) and a second mask with a different pattern is used. This guarantees that the two polarization layers are offset by θ degrees.

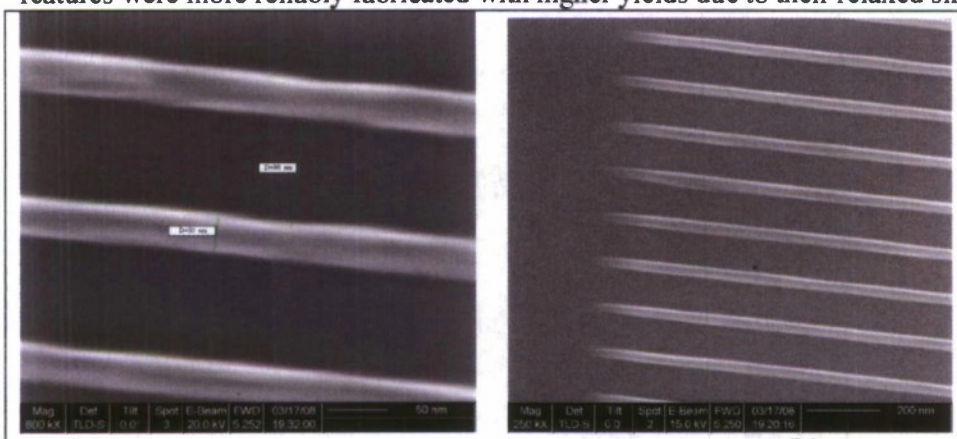
(8) Selective reactive ion etching is performed on both 0 degree and θ degree polarization layers simultaneously. The reactive ion etching tool first is cleaned prior to etching the aluminum samples. Any residual impurities in the etching chamber can interfere with the etching rates and isotropic

etching of the sample. The bottom plate of the RIE chamber is heated to 70 degrees. The etching of aluminum is performed in 8 consecutive step and they are described in Table 1, with the respective gas concentration, temperature and pressure information (Figs. 2-e & 2-f).

Single layer micropolarization array using electron-beam lithography Creating a single layer micropolarizer array can be achieved using electron-beam lithography. For these experiments we used Ellionix e-beam writing tool with 20nm resolution. The polarization patterns, i.e. line width, pitch and orientation were design using CAD software. The patterns of the polarization filter are first planned and designed in EllinoixCAD software. The objective is to create a polarization array with pixels of 10 micron pitch and each pixel has sub wavelength line width and pitch. The aspect ratio of the nano wires i.e. the ratio of the thickness to the width, preferably should be very high. Due to structural limitations, reliable ratios of ~2 are achieved and fabricated. Using cad software various patterns were designed and the limits of the e-beam writing tool were explored.

The test sample is prepared on a glass substrate. A thin layer of aluminum is deposited on the glass using e-beam deposition tool. The thickness of the aluminum is ~80nm after deposition is completed. Next, e-beam resist (ZEP590) is spin coated on the sample and the sample is placed in the e-beam writing tool. The pattern from the cad software is transferred on the photoresist and developed using ZEP developer. After the photoresist is developed and inspected under an SEM, the pattern is transferred on the aluminum substrate using a standard aluminum etching recipe in an RIE/ICP tool.

Figure 3 presents an SEM image of the e-beam resist after being exposed and developed. We have been able to successfully create 30 nm e-beam resist lines, with 120 nm pitch and 80 nm height/thickness. These were the smallest features that we were able to reliably construct using the Ellionix e-beam writing tool. Larger features were also created and shown in Figure 4-b. Larger features were more reliably fabricated with higher yields due to their relaxed size constraints.



(a) (b)

Figure 3: SEM images of e-beam resist after exposure and development with (a) line width of 30 nm and 120 nm pitch; (b) line width of 80 nm and 200 nm pitch

Figure 4 presents an SEM image of the smallest feature that we were able to transfer on aluminum last year. In this example, the pitch of the aluminum nanowires is about 150 nm and the wire width is 40 nm. The sizes of these test structure demonstrate the physical limits that we can design for a polarization filter using e-beam lithography and reactive ion etching combined. The smallest polarization filter can have aluminum nanowires with line width of 40 nm with 80 nm pitch. Due to the limitation of the e-beam deposition tool, high granularity of the deposited aluminum is observed

in the sample. Lowering the working pressure in the deposition tool can minimize the granularity of the deposited material.

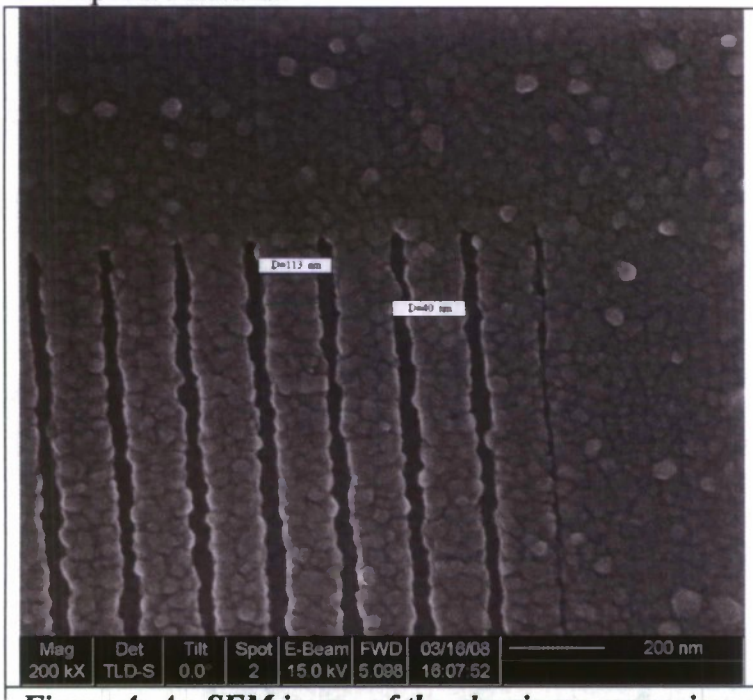


Figure 4: An SEM image of the aluminum nanowires on glass substrate. The nanowries are 40 nm wide, 150 nm pitch and 80 nm tall/thick.

Currently, we are continuing our efforts in making wire grid polarizer arrays using gold (over SiO2) in the user facilities at the Cornell Nanscale Science and Technology Facilities (CNF). Figure 5 shows a sample from our ongoing work on these structures.

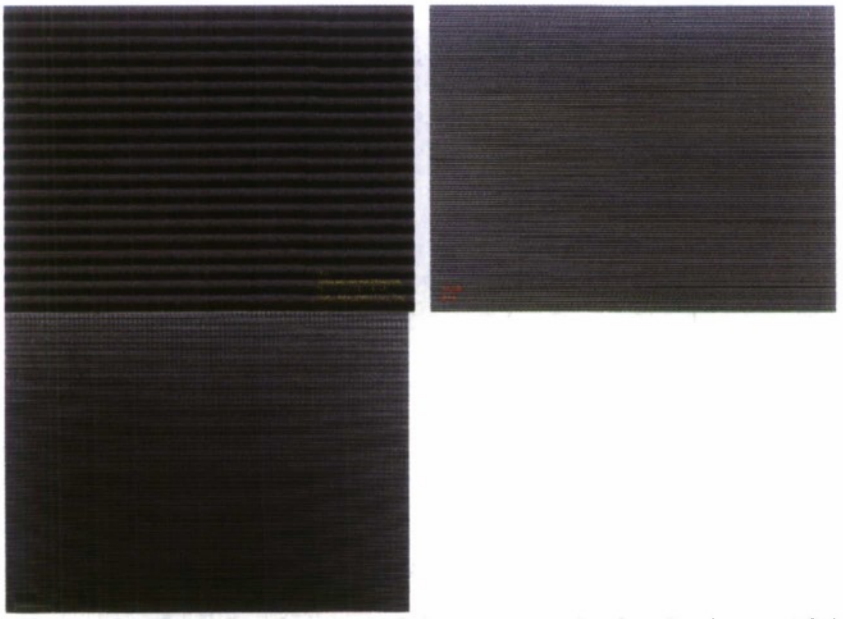


Figure 5. Sample of our work in progress in developing gold (over SiO2) nanowire grid polarizer arrays.

The 3 SEM images in Fig. 5 show a wire grid polarizer sample at different magnifications (scale bar on bottom left. They are (from left to right panels) 1 μm, 1 μm, and 5 μm). The nanowire width is 100 nm, depth/thickness is around ~300nm, and the Pitch (period) is around 200nm. The material is Quartz (SiO2) nanowires coated with a thin layer of gold (~5nm) (Here the Gold layer is sputtered as a discharge layer for SEM, because it's so thin, it forms clusters on Quartz surface, that's why we see the nanowires covered by big Au grains rather than being smooth). Here the fabrication process is as follows: 1. Spin coat Quartz wafer with e-beam resist (ZEP 520A, ~200nm thick); 2. e-beam exposure with Leica VB6 (Gun: 100KV; Current: 1nA; Dose: 230 uC/cm^2); 3. Develop for 60s (in ZED N50 developer), rinse with IPA, blow dry with N2; 4. Evaporate 30 nm Cr in an angle (45 degree); 5. 3 minutes Reactive ion etching with Oxford 80 (gases: CHF3 / O2 = 50sccm / 5sccm; RF Power 250W; Chamber pressure: 150mTorr); 6. Cr etch (wet etch); 7. Strip off ebeam resist; 8. Sputter 5nm of Au.

We continue our efforts on constructing these nanoscale structures for use in the follow-up to this project, as well as other relevant aspects of our other ongoing research programs.