Bio-Inspired Surface Treatments and Quasi-Ordered Nanostructures to Control Broadband IR Response

Lesley Chan
Chemical Engineering, University of Southern California

NNIN REU Site: UCSB Nanofabrication Facility, University of California, Santa Barbara, CA
NNIN REU Principal Investigator: Prof. Michael J. Gordon, Chemical Engineering, University of California, Santa Barbara
NNIN REU Mentor: Federico Lora Gonzalez, Chemical Engineering, University of California, Santa Barbara
Contact: lesleywc@usc.edu, mjgordon@engr.ucsb.edu, floragonzalez@umail.ucsb.edu

Abstract:

Moth-eye nanostructures have been fabricated in silicon and germanium using colloidal lithography and reactive ion etching to enhance optical transmission in the near to far infrared wavelength range ($\lambda = 2\text{-}50\ \mu m$). In previous reports [1, 2], high transmission was achieved using a multi-step etching process to form silicon nanostructures. Here, we demonstrate the fabrication of similar nanostructures using a simplified, single-step vertical etch by systematic modification of etch parameters that include gas flow rates ($SF_6/C_4F_8/Ar$), RF power, and etch time. Using this method, fabrication of moth eye nanostructures on germanium (Ge) was also achieved. Nanostructures were optically characterized via Fourier transform infrared spectroscopy (FTIR). High transmission was observed for Si and Ge, for both single-sided (Si: ~ 94% of theoretical limit, Ge: ~ 97% of theoretical limit) and double-sided (Si: ~ 88% absolute transmission, Ge: ~ 92% absolute transmission) moth-eye samples.

Introduction:

Recent developments in nanotechnology have shown a need for enhanced anti-reflective coatings (ARCs) for infrared (IR) devices such as thermophotovoltaics, optoelectronics, and IR detectors. These mentioned devices are typically made from high refractive index materials, such as silicon (Si), resulting in large reflective losses. Conventional ARCs are composed of vacuum-deposited thin film dielectric materials that are known to have low acceptance angles and can only enhance transmission at specific designed wavelengths. Multi-layer ARCs can overcome some of these issues, but the deposition is time consuming, expensive, and substrate dependent. Therefore, we present "bio-inspired" moth-eye (ME) nanostructures for anti-reflection, depicted in Figure 1, that operate by the introduction of a refractive index gradient, which not only provides superior broadband anti-reflection, but fabrication is both quick and simple.

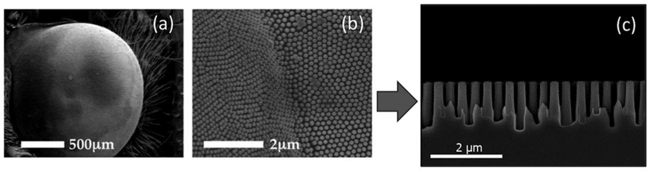
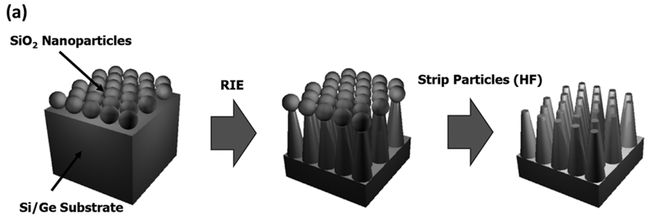


Figure 1: (a) SEM images of moth's eye showing hexagonally packed nanostructures [2]. (b) SEM image of moth-eye nanostructures fabricated on Si.

Typically, ME nanostructures have been used for anti-reflection in the visible range, but our work focuses on IR wavelength ranges. ME nanostructures are also scalable and substrate-independent, which means they can be theoretically implemented for any wavelength range and any material. Furthermore, using a simplified single-step vertical etch method, as opposed to a multi-step Bosch etch plus isotropic ICP-RIE as reported previously [1, 2], we were able to make high-performance and robust ME nanostructures.

Experimental Procedure:

Fabrication of ME nanostructures was done using a simple, two-step colloidal lithography method as shown in Figure 2.



(b)

Etch Parameter	Si	Ge
Nanoparticle Size	380 nm	540 nm
ICP Power	825 W	825 W
Bias Power	15 W	20 W
$SF_6/C_4F_8/Ar$	26/54/20 sccm	24/56/20 sccm
Pressure	19 mTorr	19 mTorr

Figure 2: (a) Process scheme to create moth eye anti-reflectors: fabrication of nanostructures started with SiO_2 mask deposition using Langmuir-Blodgettry, followed by reactive ion etching, and stripping of SiO_2 using HF. The process is repeated on the backside of the wafer to form double-sided nanostructures. (b) Etch parameters for reactive ion etching for both Si and Ge.

The silica nanoparticle mask was deposited on Si (University wafer, 225 μm thick, > 4000 Ohm-cm) and Ge (MTI Corp., 500 μm thick, > 50 Ohm-cm) wafers using a Langmuir-Blodgett dip coating process [1-3]. The nanoparticle sizes used were 380 and 540 nm for Si and Ge, respectively. Afterward, masked Si and Ge samples were plasma-etched (Plasma-Therm 770 SLR-RIE) using a single-step vertical etch with varying conditions for gas flow rates ($SF_6/C_4F_8/Ar$), bias power, and etch time as summarized in Figure 2.

After plasma etching, the silicon dioxide (SiO_2) nanoparticles were subsequently stripped using hydrofluoric acid (10%). The colloidal lithography process was repeated on the backside of the substrate to fabricate double-sided ME substrates. The ME nanostructures were characterized using scanning electron microscopy (SEM) for morphology and FTIR for transmission.

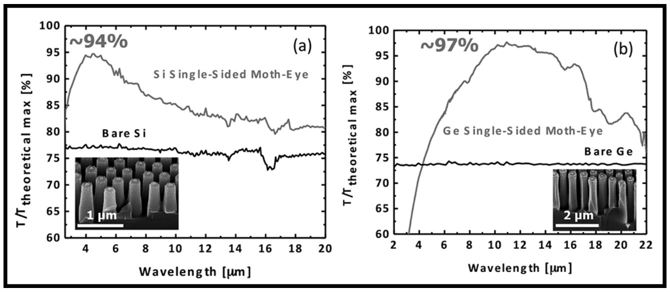


Figure 3: Normalized transmission with respect to theoretical maximum (Si: T_{max} ~ 70%, Ge: T_{max} ~ 64%) for single-sided ME nanostructures on Si and Ge and corresponding cross-sectional SEMs.

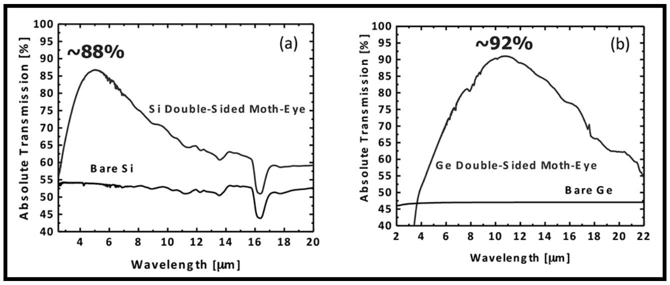


Figure 4: Absolute transmission for double-sided ME nanostructures on Si and Ge.

Results and Conclusions:

The theoretical maximum transmission was calculated to be ~ 70% for single-sided ME in Si and ~ 64% for single-sided ME in Ge. Direct transmission for single-sided Si and Ge nanostructured substrates had a peak transmission of 94% and 97% of the theoretical maximum, respectively, as shown in Figure 3. By implementing nanostructures on both sides of the substrate, the theoretical maximum increases to 100% in both materials.

Direct transmission for double-sided Si and Ge nanostructured substrates had a peak of 88% and 92% absolute transmission, respectively, as shown in Figure 4. Furthermore, by changing nanoparticle size, we were able to adjust the pitch, resulting in peak transmission wavelength shifting. For the 380 nm nanoparticle masks on Si, the resulting peak position for double-sided occurred at $\lambda = 5.5\ \mu$m, while for 540 nm nanoparticle masks on Ge, the peak position for double-sided occurred at $\lambda = 10.8\ \mu$m. This demonstrates the tunability of the IR response by simply modifying mask size.

Future Work:

In conclusion, using Langmuir-Blodgettry and a single-step vertical etch in different materials platforms to produce ME nanostructures, we were able to achieve high optical transmission in the IR. High increases in transmission were observed for both single-sided (Si: ~ 94% of theoretical limit, Ge: ~ 97% of theoretical limit) and double-sided (Si: ~ 88% absolute transmission, Ge: ~ 92% absolute transmission) nanostructures.

With further optimization of mask deposition and etch parameters, we can achieve even better anti-reflective properties, yielding higher IR transmission and also demonstrate the ability to produce ME nanostructures in additional materials.

Acknowledgements:

I would like to thank Professor Michael Gordon, my mentor Federico Lora Gonzalez, and Professor Daniel Morse for their help and guidance this summer, as well as Alex Berry for his help in nanoparticle synthesis and mask deposition. I would also like to thank the UCSB cleanroom staff for help with the plasma etching. This work was supported by the National Nanotechnology Infrastructure Network Research Experience for Undergraduates Program, the National Science Foundation, and the Institute for Collaborative Biotechnologies.

References:

[1] Federico Lora Gonzalez, Daniel E. Morse, Michael J. Gordon, Opt. Lett. 39, 13-16 (2014).

[2] Federico Lora Gonzalez, Michael J. Gordon, Opt. Express 22, 12808-12816 (2014).

[3] Federico Lora Gonzalez, Lesley Chan, Alex Berry, and Michael J. Gordon. JVST B (Submitted 2014).