Three-Dimensional Microstructures as Effectively Transparent Front Contacts for Solar Cells
Aleca Borsuk
Mentors: Harry Atwater and Rebecca Saive

For solar cells to achieve optimal photovoltaic performance, front contacts—electrodes at the surface of the solar cell—must offer excellent electrical conductance and optical transmission. At present, however, front contacts do not deliver on all criteria—e.g. metal grids shadow otherwise active surfaces, while transparent conducting oxides absorb photons. In the present work, a novel front contact architecture is realized—namely, three-dimensional (3-D) microstructured fingers that are highly conductive and effectively transparent. Here, fine metal grids with 3.0 μm finger width and 40 μm periodicity were first defined lithographically. These were superimposed with pyramidal structures with >45 degree angles, which re-direct incident light to the active surface of the solar cell. Pyramids were written with the Nanoscribe direct laser writing system, in which high intensity laser pulses induce polymerization of photoresist at nanoscale volumes. To achieve efficient re-direction of light, 3-D surfaces were selectively coated with a metal film using directional deposition. Spatially resolved laser beam induced current measurements (LBIC) show that 3-D contact patterning leads to significantly improved photocurrent as compared with planar contacts. Current-voltage (IV) curve characterization of 3-D contacts additionally indicates enhanced absolute current and increased efficiencies in state-of-the-art solar cells.

Band Structure Measurement of Gyroid Photonic Crystals in the Mid-Infrared
Emil T. Khabiboulline
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Like electronic topological insulators, photonic topological insulators form a new class of materials with exciting properties that have implications for many areas, including photovoltaics. The topology of their band structure gives rise to propagation of light that is unidirectional, fault-tolerant, polarized, and localized to the boundary. Theory predicts that gyroid photonic crystals are photonic topological insulators. We aim to provide experimental confirmation in the mid-infrared region.

Starting with two-photon lithography to fabricate the samples in polymer, a sequence of atomic layer deposition, focused ion beam milling, plasma cleaning, and chemical vapor deposition lead to alumina structures coated with amorphous silicon. Single and double gyroid crystals, with unit cells of 5 μm organized in a 10x10x10 cube, were fabricated this way on an intrinsic silicon substrate. We build a setup to perform angle-resolved spectroscopy using a quantum cascade laser as the source of the ~8 μm beam. From measurements of reflection and transmission over a range of wavelengths and incidence angles, we construct the band structure of the photonic crystals. Theory predicts band gaps for the single gyroid and Weyl points for the double gyroid. Comparison to experiment indicates whether or not our nanofabricated gyroid structures possess a topological nature.

Nanoindentation Characterization of Acrylic-Zinc Oxide Systems as Model Artists’ Paints
Ya Lun Chuan
Mentors: Katherine T. Faber and Matthew T. Johnson

In order to better preserve paintings that are important to our cultural heritage, conservation scientists are looking to characterize paint systems. Because it takes up to decades for paint to cure, it is important for conservation scientists and conservators to understand how these paint systems change mechanically as they cure. In this project, model paints of acrylic binders and zinc oxide pigments are produced and characterized as a function of pigment concentration with acrylic systems were compared to a fast drying alkyd binder. As the paints were set to cure in a dark, dry environment at room temperature, increases in the hardness and elastic modulus were observed for all pigment fractions. Scanning electron microscope images show that the pigment particle sizes are small relative to the indentation impression, proving that the indentation data are sampling both binder and pigments. Similar future experiments can be conducted on different binders, pigments, and pigment percentages.

Heat Treatment Stabilization of Yttria-Stabilized Zirconia Thermal Barrier Coatings
Giacomo Koszegi
Mentors: Katherine T. Faber and Matthew Johnson

Thermal barrier coatings (TBGs) are commonly used to protect the blades of gas turbine engines from high operating temperatures that would otherwise result in deformation or melting. Yttria-stabilized zirconia (YSZ) is particularly well-suited as a TBC due to its thermal conductivity and coefficient of thermal expansion. When YSZ TBCs are prepared via plasma-spray physical vapor deposition, the resulting coating contains non-stoichiometric and amorphous material, both of which compromise stability during thermal cycling. The goal of this research was to use heat treatments at 350°C and 700°C for times ranging from 1-16 hours to correct stoichiometry and promote crystallization. X-ray diffraction was used to evaluate the non-stoichiometric phases before and after
heating, as well as to provide a qualitative measure of amorphous content. Scanning electron microscopy was used to visualize microstructure. Similar experiments could be conducted in the future using other TBC ceramics, such as gadolinium zirconate.

Fabrication of Nanobeam Photonic Crystal Cavities in Nd:YVO for Efficient Light-Matter Interactions
Jake Rochman
Mentors: Andrei Faraon and Tian Zhong

Rare-earth ion doped crystals are of interest for quantum storage due to their long optical and spin coherence times. However, these systems are characterized by slow and have weak light-matter interactions. Here, photonic crystal cavities are fabricated in neodymium doped yttrium orthovanadate using focused ion beam milling to increase the emission rates of the emitters and enhance the light-matter interactions. High quality-factors and small mode volumes are realized within this fabrication scheme. A lifetime reduction from the Purcell effect is measured. Cavity-enhanced light-matter interactions are observed as the cavity is tuned on resonance. These results are promising for on-chip quantum memory or single ion qubits using rare-earth ions.

Electrochromic Inverse Opals for Smart Windows With Static and Dynamic Optical Transmittance
Christian Lau
Mentors: Julia Greer and Victoria Chernow

Most smart windows employ electrochromic coatings with tunable optical transmittance upon the insertion and extraction of charges. Incorporation of electrochromic coatings into windows have both reduced heat transfer into buildings and enhanced their aesthetic appearance. Nevertheless, electrochromic smart windows can be further improved by generating a photonic bandgap that continually reflects light in the near-Infrared range. Such a photonic bandgap can be generated by an array of periodically altering refractive index. Periodic inverse opal structures have been shown to produce complete photonic bandgaps in a wide range of frequencies. A number of groups have reported scalable methods for fabricating arrays of titania inverse opals. My project aims to employ these methods to produce the first smart window device with both dynamic electrochromism in the visible light spectrum and a static photonic bandgap in the near infrared range. I investigate several sol-gel methods that employ vertical evaporative deposition, drop-casting, and doctor-blade coating to optimize the fabrication of inverse opals. Characterization of the inverse-opal morphology, chemical composition, and optical transmittance is carried out to evaluate the performance of the device. Further study is needed to determine the most scalable fabrication strategy to manufacture inverse opals for industrial production.

Synthesizing a Bone Mimetic Scaffold Through the Electrochemical Deposition of Mineralized Collagen
Luizetta Navrazhnyh
Mentors: Julia Greer, Ottman Tertuliano, and Alessandor Maggi

Grafts can assist in treating bone disorders by functioning as frameworks for the growth on new bone, providing cell anchoring sites, mechanical stability and structural guidance. Ideally, the graft would integrate into the natural remodeling process and be gradually replaced with bone. However, collagen and hydroxyapatite, the dominant components of natural bone, are not frequently used in grafts since independently collagen is too weak while hydroxyapatite is too brittle for use in a load bearing structure. The goal of this project is to combine collagen and hydroxyapatite in a composite structure similar to natural bone and to examine emergent mechanical properties. Therefore films of varying morphology and composition were synthesized by concurrent electrochemical deposition of collagen and calcium phosphate. Their chemical composition was analyzed by Raman, FT-IR and Energy Dispersive X-ray spectroscopy and their morphology was examined by SEM. The films will be deposited into pillar structures to examine their compressive strength and hardness. An advantage of the electrochemical deposition method is the ability to deposit material into 3D molds. Thus the synthesized material can subsequently be deposited into 3D structures, allowing geometric effects to improve mechanical properties.

Towards Single Phonon Fock State Generation in an Optomechanical Crystal
Hengyun (Harry) Zhou
Mentors: Oskar Painter and Gregory MacCabe

Quantum information processing requires the generation and detection of non-classical quantum states and the ability to interface disparate quantum systems to utilize their respective advantages. Optomechanics provides a natural interfacing platform in which the generation of Fock states would be important progress. We analyze the experimental requirements for successful generation, heralding, and subsequent detection of a single phonon Fock state in an optomechanical crystal and describe ways to improve our system for optimal signal-to-noise ratio in a Hanbury-Brown Twiss measurement of phonon statistics. In particular, we highlight ways to engineer the mechanical thermalization rate by varying the period number of a phononic shield surrounding our device, so that
pulsed experiments can be performed at higher repetition rates, significantly reducing the acquisition time required for single phonon Fock state generation. These results are confirmed both numerically and experimentally, and could pave the way to future quantum information processing tasks in optomechanical systems.

**SERS Substrate for Detection of miR-10b**
Nico Mesyngier  
*Mentors: Axel Scherer and Sameer Walavalkar*

MicroRNA-10b (miR-10b) has been shown to strongly correlate with the presence and severity of glioblastoma. Even when treated, recurrence rates in patients surpasses 90%. Being able to closely monitor miR-10b therefore would serve as a powerful tool in diagnosing and treating patients in both the short term and the long term. This work attempts to achieve that goal using a nano-fabricated substrate with gold nano-bulbs for surface-enhanced Raman spectroscopy (SERS), which is functionalized with cDNA molecules designed to target this specific miRNA. Utilizing the electric field enhancement between nano-bulbs when excited by a laser, the Raman spectra of the miRNA can be amplified sufficiently to be detected at low concentrations. RNA strands are differentiated from DNA using direct identification, relying on peaks unique to RNA. Future work will involve developing a melting curve of the hybridization between the cDNA target and the miR-10b in order to limit variant strands of RNA from creating false positives as well as expanding the capabilities of the SERS substrate to other biological molecules.