Session L Abstracts

Thermal Characterization of Silicon Nitride Lightsails
Nina Cielica
Mentors: Harry Atwater and Ramon Gao

The Breakthrough Starshot Initiative envisions accelerating ultrathin lightsails to relativistic speeds with laser radiation pressure. Silicon nitride is a promising candidate material for lightsails, which must exhibit low absorption at the propulsion wavelength and efficient infrared emission for thermal management. We report first steps towards comprehensive characterization of the thermal properties of suspended subwavelength thick silicon nitride. To measure the temperature distribution of a laser-heated sample, an uncooled infrared thermal camera was set up. Radiometric calibration was needed to convert recorded values to temperature units using a black soot sample with an emissivity of one, heated to temperatures between 25°C and 100°C. To determine the emissivity of silicon nitride, infrared ellipsometry measurements were taken at 25°C, 50°C and 100°C. In this range, silicon nitride’s emissivity appears to be independent of temperature. To model laser-induced heating and design photonic structures for enhanced thermal cooling, finite-element simulations were carried out in COMSOL. The proposed structures will be fabricated and experimentally characterized in the home-built setup to compare both unpatterned and patterned laser-heated silicon nitride membranes in terms of their thermal performance and thus suitability for laser-driven lightsails.

Mechanical Modes in Tethered and Freely Accelerated Lightsails
Luis Carretero López
Mentors: Harry A. Atwater, Lior Michaeli, and Ramon Gao

Laser-driven lightsails represent a cornerstone of interstellar exploration as envisioned by the Breakthrough Starshot initiative. Understanding the emergence and evolution of mechanical modes excited by the driving laser in such freely accelerated membranes is crucial to assess structural and beam-riding stability. Vibrational modes offer insights into complex mechanical systems, and can be analyzed in stationary membranes and compared those in accelerated lightsails. Two types of numerical mass-spring models were implemented in MATLAB to simulate and visualize the dynamics and mechanics of ring-supported lightsail membranes. In the linear model, simulated modes match analytical predictions, but challenges arise due to the lightsail’s extreme aspect ratio (subwavelength thick, yet meter-sized) and large optical forces, particularly in the limit of zero tension. In comparison, the geometrically nonlinear model takes into account pretension, arbitrary orientation and large shape deformations, resulting in more realistic mechanical and dynamical representation of lightsails. Bridging the linear and nonlinear regime with my modelling approach establishes the framework for comparative modal analysis to deduce what one could infer from experiments on tethered lightsails in the laboratory about the structural dynamics of freely accelerated lightsails in space.

Quantifying the Ultrafast Dynamics of Monolayer Graphene Coupled to Plasmonic and Dielectric Resonators via Ultrafast Differential Reflectivity
Gloria Davidova
Mentors: Harry Atwater and Arun Nagpal

It has recently been shown that plasmon emission in graphene occurs, in the mid-infrared, but the ultrafast decay mechanisms are still not understood completely. This has laid groundwork for the ultrafast photoluminescence properties of monolayer graphene to be studied as a function of Fermi energy in a GFET configuration. Now the graphene plasmon is also studied when coupled to an array of resonator devices. Here, the graphene plasmons couple to gap plasmons in planar devices as well as the modes of plasmonic and dielectric microdisk resonators. In the planar devices, the thickness of the gap between the monolayer graphene and gold back-reflector was modified such that the effect of detuning- between the gap plasmon and graphene plasmon- on emission may be understood. Transfer matrix modelling was done to select the necessary thicknesses for the gap plasmons to be resonant with or slightly detuned from the graphene plasmons. Optical excitation of the devices was done at 800 nm with a pulse width ~40 fs to capture the emission of “hot” electrons in graphene coupled to electromagnetic modes supported by newly fabricated resonators. Device characterization involved Raman spectroscopy, ellipsometry, profilometry, and electrical transport measurements. The finite-difference-time-domain electromagnetic field solving algorithm was used to obtain mode profiles and time dynamics of the structures. This paves the way for stimulated emission from surface plasmons to be performed and even utilized for high efficiency light-to-electricity energy conversion later on.

Recyclable Porous Carbon Solids for Oxygen Recovery in Long-Term Space Exploration
Alice Kutsyy
Mentors: Katherine Faber and Laura Quinn

The Sabatier reactor has traditionally been utilized for CO₂ to O₂ recycling within spacecraft cabins. However, only around 50% of oxygen is recovered, so recent work has been done to add a methane pyrolysis reactor, which
Improving Methods to Enhance Porous Ceramic Conductivity With Carbon Nanotubes
Matthieu (Finn) Sutcliffe
Mentors: Katherine Faber and Kevin Yu
The Faber group has developed a method to grow directionally porous ceramics by freeze-casting preceramic solutions. Silicon oxycarbide can be formed in this manner with a high degree of control over pore size, morphology and fraction, making it suitable for mass transport applications such as sensing and battery electrodes. However, the samples produced are electrically insulating, so the group has explored ways combine these ceramics with conductive carbon nanotubes. From these processes, specimen conductivity has been successfully increased by 10 orders of magnitudes up to around 0.01Scm-1. Further increases in conductivity require the investigation of methods that can achieve higher CNT loading. This work seeks to refine three such methods, namely dispersing nanotubes in the pre-ceramic solution, growing nanotubes from nickel dispersed in the pre-ceramic solution, and growth from nickel deposited after casting. For the first method, it was found that nanotube dispersion by ultrasonication is mechanically limited to no more than 12wt.% due to solvent saturation leading to a gel-like consistency. The second method remains limited by the formation of Ni2Si during pyrolysis, which does not oxidise in air below 1100°C. In the post-pyrolysis deposition method, it is theorised based on observation that nickel migration is dominated by segregation of a suspected silica phase homogeneously nucleating in the subsurface of the deposited layer.

Creating Superconducting Resonators to Probe Thin-Film Quality
Matthew Chalk
Mentors: Joseph Falson and Matthew Libersky
Falson Lab focuses on using molecular beam epitaxy (MBE) to grow high quality thin-films. Some of these films, such as those made of Niobium, can be fabricated into superconducting circuits for quantum information and sensing applications. Thin-film attributes undesirable for these fields, such as dielectric loss and two-level systems, can be measured by etching the films into microwave resonators. Varying geometric features of these resonators provides a method of probing the location and causes of these unwanted effects.
In this work, we use thin-films of Niobium on sapphire grown using MBE to create coplanar waveguide resonators. A recipe for photolithography was developed to realize the desired resonator geometry. Subsequently, we probed these resonators at DC and microwave frequencies. Automated measurements were performed in a Physical Property Measurement System (PPMS) down to single-digit Kelvin temperatures using lock-in amplifiers for low-frequency measurement and a vector network analyzer for microwave frequencies. The quality factor of the resonator as well as the residual-resistance ratio of the film will be used as guidance for subsequent resonator creation and future thin-film growths.

Epitaxial Growth of Rare-earth Antimonide Thin Films on Atomically Flat Oxide Substrates
Amari Butler
Mentors: Joseph Falson and Adrian Llanos
Lanthanum diantimonide (LaSb2) is a square net metallic compound that possesses fascinating electronic transport properties in bulk. It has been observed to exhibit superconductivity at temperatures below 2K and linear magnetoresistance in magnetic fields as high as 45 T. Using Molecular Beam Epitaxy (MBE), a technique for growing single crystal thin films by evaporating elemental source materials onto a crystalline substrate, we can synthesize and probe for these phenomena in thin film LaSb2. We prepared and grew on different substrates with different crystal structures and surface reconstructions to study how the epitaxial relationship between the film and the substrate affects the crystallinity and electronic properties of thin film LaSb2. This investigation sought to tune the electronic properties by modifying the crystal structure using the substrate. We have successfully prepared atomically flat Sapphire (0001) in the $\sqrt{31} \times \sqrt{31}$ surface reconstruction, Sapphire (11-20), and Magnesium Oxide
Design and Testing of Nanophotonic Cavities for T-center Integration
Antonia Ghiță
Mentors: Andrei Faraon and Adrian Beckert

Quantum networks require optically-addressable qubits with long coherence times. Spin qubits in solid state luminescent centers are promising candidates for such light-matter interfaces. The T-center, a recently rediscovered silicon color center, is a suitable photon-spin interface for quantum networks thanks to its high radiative efficiency in the telecommunications O-band and long-lived nuclear spins. Measurements of the linewidths of waveguides containing ensembles of T-centers have shown near-limitless optical transitions which makes the T-center very promising for high fidelity entanglement. Purcell enhancement via integration into a nanophotonic resonator will further increase its emission rate and pave the way to transform limited and indistinguishable photons. To couple the on-chip cavity electromagnetic field to the control and readout optics, high efficiency grating couplers and low loss waveguides are needed. I optimized the efficiency of grating couplers using subwavelength structures, simulated waveguide losses and designed a high Q-factor cavity with high transmission at the T-center optical transition wavelength. I tested the simulated devices experimentally and worked towards achieving fabrication tolerant designs. In the future, these designs will be fabricated on SOI wafers containing T-centers for characterization and control of silicon-based spin-photon interfaces.

Accessing the Temperature-Dependent Vibrational Dynamics of Pb Using Inelastic Neutron Scanning
Zhiyi Zheng
Mentors: Brent Fultz and Camille Marie Bernal-Choban

Inelastic neutron scattering serves as a powerful experimental technique to investigate the temperature-dependent phonon anharmonicity of materials. Such analysis offers insights into anharmonicity’s effect on the sample’s thermal properties, such as vibrational entropy and thermal expansion. This study applies this method to face-centered cubic (fcc) solid lead (Pb), investigating its behavior within the temperature range of 298 K to 573 K. By employing MCViNE simulations, the vibrational densities of states (DOS) were determined, allowing for a comprehensive examination of the vibrational dynamics response. Preliminary results indicate that the crystal’s vibrational entropy constitutes the primary component of its total entropy, with a contribution exceeding 85 percent. The material’s overall thermal behavior will also be discussed.

Development of a Chemically Recyclable, 3D Printable Silicone Material
Hongyi Zhang
Mentor: Julia R. Greer, Seneca Velling, Sammy Shaker, Seola Lee, and Akash Dhawan

Silicone is a versatile polymer material with many desirable characteristics, such as corrosion resistance, thermal stability, low toxicity, and electrical insulation properties, and has widespread application in commercial, medical, and research scenarios. However, its 3D crosslinked structure has impeded its recycling and manufacturing through extrusion-based 3D printing techniques, and its high gas permeability and crosslink chemistry prevented its application in UV-curing-based 3D printing techniques. Previously, it was reported that the photoinitiated thiol-ene click chemistry, where a thiol and an alkene connect to form a thioester, allowed the UV-crosslinking of mercaptafunctionalized polysiloxane and vinyl-terminated polysiloxane and enabled the digital light processing 3D printing of silicone elastomers. Separately, introduction of disulfide moieties in polymer chains was shown to facilitate the chemical degradation of the cured material through base-catalyzed thiol-disulfide exchange reaction. This work aims to develop a chemically recyclable, 3D-printable silicone materials by integrating the thiol-disulfide exchange reaction with the photoinitiated thiol-ene silicone system. We show that disulfide moieties can be introduced into mercaptan-functionalized polysiloxanes through a clean and facile iodide-catalyzed oxidative coupling reaction, and the resulting partially oxidized mercaptan-functionalized polysiloxanes, when mixed with vinyl-functionalized polysiloxane and photoinitiators, can be UV-cured to form disulfide-containing silicone networks. Ongoing work focuses on performing chemical degradation on the cured disulfide-containing silicone and characterizing the thermomechanical properties of silicones prepared from the recrosslinking of recycled polysiloxane oligomer.

Characterizing the Fabrication Parameters of Holographic Lithography for Scalable Production of Architected Materials
Zhangqi (Jackie) Zheng
Mentors: Julia Greer and Kevin Nakahara

Nanoarchitected materials have recently emerged as a highly desirable class of materials capable of exhibiting combinations of properties, for example, ultra-low density, high energy absorption, stimulus responsivity, and enhanced damage tolerance, exceeding the limits of their constituent materials. Using a 3D laser interference lithography (LIL) process with a metasurface mask, we produce nano-architected sheets (35 μm thick and 2.5 x 2.5 cm² wide, 500 nm internal feature size) made of negative tone epoxy-based photosensitive resist (SU-8). During the LIL fabrication, a wide variety of defects and morphological variations arise due to chemical, thermal,
and optical gradients inherent to photopolymer development. This work shows that by characterizing and decoupling the contributions of all the dosage steps and optimizing their energies relative to the resin formulation, we can reduce the processing time and increase the yield of the LIL process significantly. Using the optimized energy contributions, we also present how active adjustments may be made to the fabrication recipe to mitigate the likelihood that an imperfect dosage at one step will lead to an unwanted defect in the resulting structure. Furthermore, by tuning the resin composition and compensating with corresponding dosage steps, we can expand the range of sample thicknesses to better suit different experimental needs.