



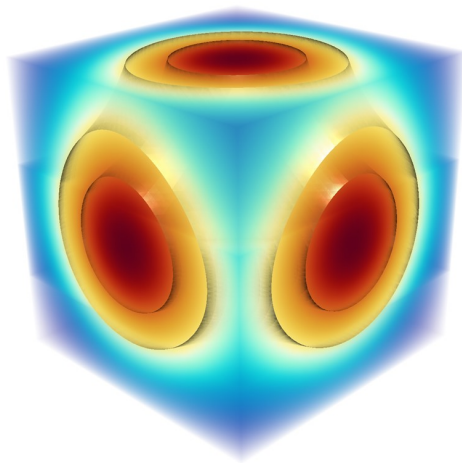
PennState
College of Engineering

**ENGINEERING SCIENCE
AND MECHANICS**

ESM Today 2018

February 10

1st Floor Lobby EES Building



15th Annual Engineering Science and Mechanics Research Symposium



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Schedule of Events

8:00 AM - 8:30 AM	Breakfast and Registration
8:30 AM - 8:45 AM	Introduction by Dr. Todd
8:45 AM - 9:15 AM	Keynote Speaker - Joseph Rose
9:15 AM - 9:30 AM	Coffee Break
9:30 AM – 11:45 AM	Oral Presentations
11:45 AM - 1:30 PM	Lunch, Poster Presentations & Art in Science Exhibition
1:30 PM - 1:45 PM	Deliberations
1:45 PM - 2:00 PM	Awards Ceremony

* The Art in Science Exhibition will be held in Room 116

Keynote Speaker – ESM Today 2018

Seeking the Edge to Achieve Extraordinary Engineering Success

Joseph Rose

The short talk will be focused on seeking the edge for engineers in describing a path to ultimate success in their profession. What is the secret? Is it great performance in all engineering and science subjects? Success could include such items as promotions, higher salaries, more responsibilities, more flexibility in carrying out your job, more free time for vacations and days off, writing patents, publications, books, or seeking entrepreneurial or intrapreneurial activities. Success could also be spending more personal time with family and friends, attaining happiness, acquiring material items of interest, being successful in sports, or of being religious in nature. Engineers can achieve astonishing success. Remember, in general for all of your efforts in life that “Failure is on the path to success.” Failure is better than mediocrity as it allows a person to begin again with lots of knowledge learned from the failure. The secret edge to engineering success is associated with understanding topics generally associated with business. Studying such topics as Leadership, Entrepreneurship, Negotiation Skills, Teamwork, Intellectual Property, Sales, Marketing & Advertising, and Engineering Ethics can change the direction of an engineering student to magnanimous success. Adding business concepts to engineering can change your life. A fine line separates excellence from mediocrity. It is this edge that makes success possible. The edge is that extra effort, ambition, consideration, topic, device or unique thinking. The short talk will discuss the authors background and experience in leading up to writing a book, “Seeking the Edge” and also in teaching a course “Business Opportunities in Engineering.”

Joseph L. Rose is a Professor in the Engineering Science and Mechanics Department at the Pennsylvania State University. He is also Founder and President of a small business, FBS, Inc.dba Guidedwave. Dr. Rose received a Ph.D. from Drexel University in 1970 and is an international and innovational leader in the fields of wave mechanics, ultrasound, and ultrasonic guided waves. Dr. Rose was also the recipient of a Penn State University Faculty Scholar Medal for achievement in Engineering in 1996. The ultrasonics accomplishments of Dr. Rose were also celebrated at the 16th US National Congress on Theoretical and Applied Mechanics in 2010. He also received two lifetime achievement awards, one from SPIE in 2011 and a second from the British Institute for Nondestructive testing in 2014. Dr. Rose is currently a fellow of four professional societies, author of thirty patents, five textbooks, and over 600 articles on ultrasonics. He has served as principal advisor to over 60 Ph.D. and 120 M.S. students. In pursuit of his work Dr. Rose has visited all 50 states and over 50 foreign countries. He has presented countless keynote and plenary lectures at conferences all over the world.

Oral Presentation Speaker List

	114 EES	116 EES
Faculty Judges	Dr. Guers	Dr. Rotkin
	Dr. McIntyre	Dr. Suliman
	Dr. Cusumano	Dr. Drapaca
	Dr. Harris	Dr. Das
	Dr. Palmer	Dr. Pitt
	Dr. Cheng	
	Presenters	
9:30 AM	Matt Waller	Rudy Haluza
9:42 AM	Ryan Waskiewicz	Karthik Venkataraman
9:54 AM	Ganesh Venkatesan	Zane Cohick
10:06 AM	Andrew Arnold	Faiz Ahmad
10:18 AM	Christopher Hakoda	Elias Frantz
10:30 AM	Amritanand Sebastian	Bugra Ayan
10:42 AM	Joseph Nasr	Suparno Bhattacharyya
10:54 AM	Monika Hospodiuk	Mostafa Hasanian
11:06 AM	Federico Scurti	Jeffrey Kim
11:18 AM	Caroline Van Pelt	Kerim Moncal
11:30 AM	Daniel Schulman	Duane McCrory
11:42 AM	Christopher Stutzman	Liqiang Ren

Oral Presentations - EES 114

Development of a High-Temperature Epoxy For Resin Transfer Molding

Matt Waller, advised by Dr. Kevin Koudela and Dr. Tom Juska

Resin transfer molding (RTM) is a versatile composites fabrication process which yields dimensionally precise parts and allows for a variety of resins, fibers and additives. This flexibility makes RTM ideally suited to R&D programs. However, to be compatible with RTM, a resin must possess sufficiently low viscosity and long gel time at the desired processing temperature. Currently, RTM is widely used with resins which meet these criteria, such as phenolic and bisphenol A and F epoxies [1]. While these resins excel at a variety of service applications from low to moderate temperature, high-temperature structural applications call for resins with high glass transition temperature (T_g) and thermal stability. The molecular characteristics – namely high crosslink density and aromatic carbon content – which afford high-temperature resins their thermal performance also tend to increase viscosity and affect post-cured mechanical properties. The high viscosities and relatively short gel times of current high-temperature resins such as novolac epoxies pose a challenge which hinders the use of RTM with high-temperature resins.

This study leverages knowledge of the molecular structures and reaction processes of several resins, reactive diluents, and catalysts towards development of an innovative resin which is both high-temperature and RTM compatible. Manufacturability of prototype resin mixtures is assessed by measuring viscosity and gel time. Post-cured thermomechanical performance is then evaluated by dynamic mechanical analysis (DMA) and thermogravimetric

analysis (TGA.) Development of this new high-temperature resin may provide future opportunities to implement RTM for emergent aerospace and defense industries.

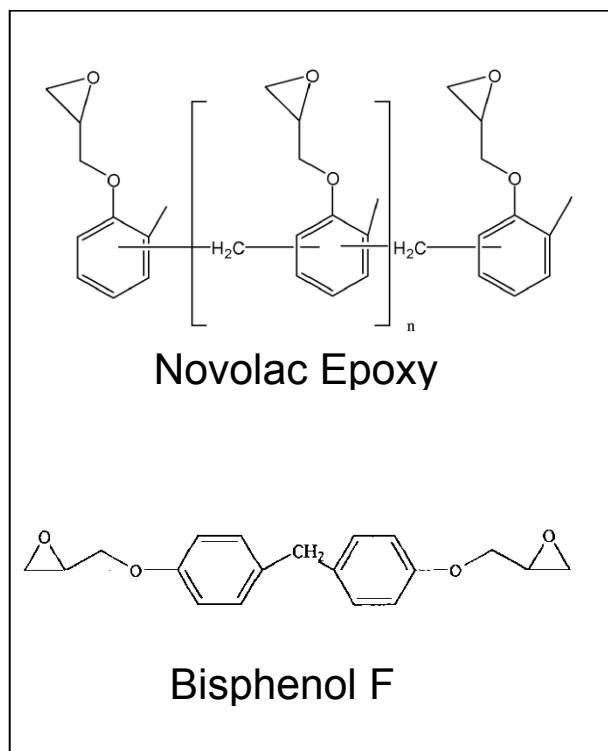
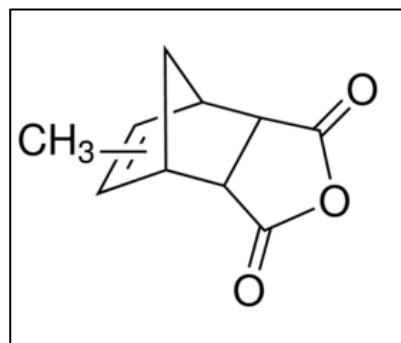
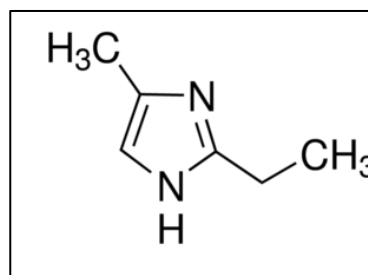


Figure 2: The greater cross link density of novolac provides a higher T_g than Bis F, but the viscosity is also increased.



Nadic methyl anhydride

Figure 1: Nadic methyl anhydride is used as a reactive diluent. Its long pot life and minor effect on T_g make it well-suited to a high-temperature, RTM resin.



EMI 24

Figure 3: Imidazole curing agents such as 2 ethyl, 4 methyl imidazole (EMI 24) cure epoxy resins catalytically and result in the highest T_g values possible for a given epoxy.

References:

[1] Sharma, S.D., Sowntharya, L., and Kar, K. K., 2017. *Composite Materials: Processing, Applications, Characterizations. Chapter 1: Polymer-Based Composite Structures*, Springer, New York, NY

Acknowledgements:

The Penn State Vertical Lift Research Center of Excellence (VLRCE), NASA Glenn, and the Army Research Lab are all thanked for providing financial support for this study through the ongoing Hybrid Gear Project. The author also thanks Dr. Tom Juska and Dr. Kevin Koudela of the Penn State Applied Research Lab for their guidance.

The Relationship Between Silicon Nitride Stoichiometries and Defect Structures Studied by Electrically Detected Magnetic Resonance

Ryan Waskiewicz, advised by Patrick Lenahan

Leakage currents in dielectric thin films utilized in present day integrated circuitry are important reliability concerns. Among the most important dielectric materials are amorphous hydrogenated silicon nitrides (a-SiN:H). These relatively high dielectric constant materials are utilized in many applications such as a passivating layer, an etch stop layer, a diffusion barrier to water, and a gate dielectric. Electron paramagnetic resonance (EPR) studies of a-SiN:H films have identified the K center (a silicon dangling bond back-bonded to three nitrogen atoms) as the single dominating paramagnetic defect in stoichiometric films. Previous studies of spin dependent trap assisted tunneling (SDTAT) detected via electrically detected magnetic resonance (EDMR) provide us with energy levels for these K center defects. [1] However, the effects of varying N/Si stoichiometry on defect levels and defect chemistry have not been studied with EDMR. We have initiated such an EDMR study of SDTAT in a-SiN:H dielectric samples of several stoichiometries.

In our SDTAT/EDMR measurements, a slowly varying magnetic field and an oscillating rf or microwave frequency magnetic field are applied to the thin film samples. As in conventional EPR, energy is absorbed by paramagnetic sites when the resonance

condition is met. In the simplest cases, this condition may be expressed by $h\nu = g\mu_B B$, where h is Planck's constant, g is an orientation dependent parameter often close to 2, μ_B is the Bohr magneton, and B is the magnetic field. In EDMR, the EPR is detected through a change in current, in our case due to SDTAT.

The devices in our study include 3 nm a-SiN:H stoichiometric samples, and 25 nm a-SiN:H samples with three N/Si ratios of 1, 1.35, and 1.5. The overall device structures under observation consist of Ti/a-SiN:H/p-Si capacitors. A comparison of EDMR measurements taken at high field and frequency (X-band frequency $\sim 9.75\text{GHz}$, 3500G) and low field and frequency (frequency $\sim 85\text{-}350\text{MHz}$, $30\text{-}125\text{G}$) provide us with information about defect structure. These comparisons allow us to extract information about the g matrix as well as hyperfine interactions. (The g and hyperfine details provide information about defect structure.) A comparison of EDMR measurements under various biasing conditions allow us to approximately determine the energy levels of the defects involved. This energy level and defect structure information should lead to a better understanding of transport in these technologically important materials.

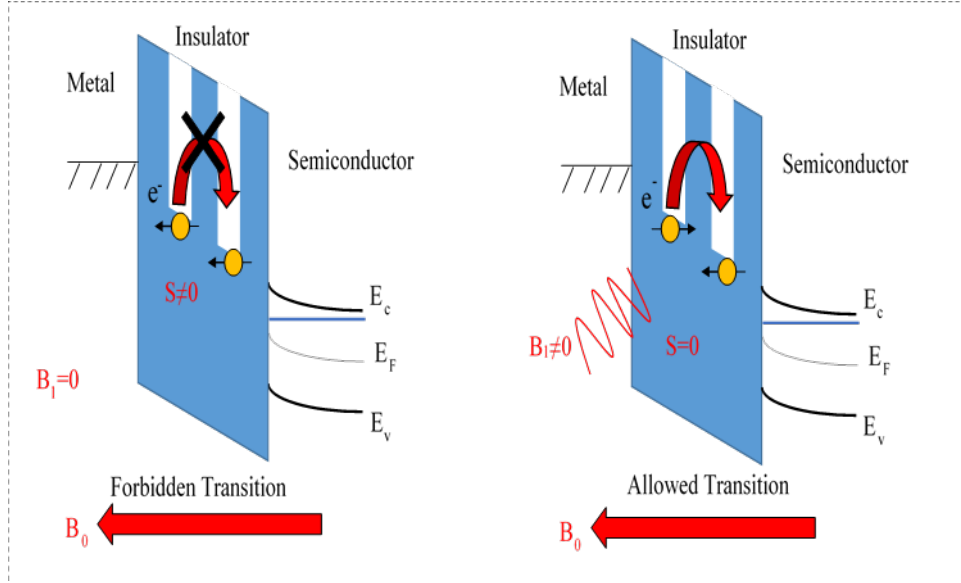


Figure 1: A cartoon illustration of SDTAT detected via EDMR. The forbidden transition (left) becomes allowed when the resonance condition is met (right) and a change in tunneling current is observed.

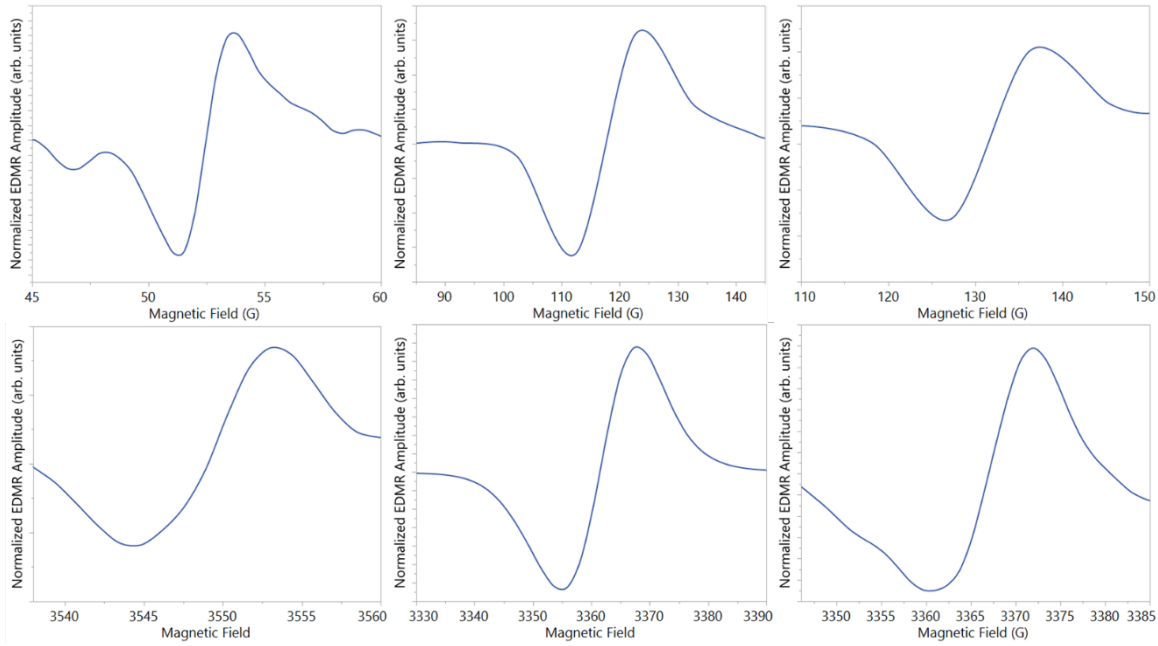


Figure 2: EDMR results at low frequency (top) and high frequency (bottom) for N/Si ratios of 1 (left), 1.35 (middle), and 1.5 (right). A large difference is observed in the Si rich samples compared to the other two stoichiometries.

References

- [1] M.J. Mutch, P.M. Lenahan, and S.W. King, Appl. Phys. Lett. 109(6), 062403 (2016). You can use any common citation format for your references: APA, MLA, etc.

Micromechanical Analysis of Transverse Young's Modulus of Glass/Carbon Hybrid Fiber Composites

Ganesh Venkatesan, advised by Dr. Charles E Bakis

Hybrid composites have much flexibility in **structural design** due to their wide scope of elastic and strength properties as a function of fiber directions. Little experimental and analytical data is available in literature on the longitudinal and transverse elastic properties of these composites. However, the accuracy of the **analytical data** is questionable since the voids in the matrix have not been considered or not modelled properly. Therefore, the objectives of the current investigation are to characterize the transverse properties of hybrid composite by modelling the voids implicitly as circular cylinder inclusions based on the “generalized self-consistent method” (GSCM) and explicitly as circular cylindrical holes in **Finite Element Analysis (FEA)**. Five hybrid composites with increasing glass-to-carbon fiber ratio chosen for the study and were modelled based on iso-stress model (ISM), modified iso-stress model (MISM) and modified Halpin-Tsai

model (MHTM). The compositions analyzed included 100% carbon, 75% carbon and 25% glass, 50% carbon and 50% glass, 25% carbon and 75% glass, and 100% glass. It was observed that MISM had excellent correlation with experimental modulus data and MHTM was the next best. As anticipated for a lower bound model, ISM always under-predicted the experimental moduli. FEA was performed on glass/epoxy with voids modelled as circular cylinder holes in an isotropic matrix. Based on the FEA studies on fiber packing arrangement and modelling approaches for voids, the geometry for successive hybrid models was justified. The transverse Young's modulus and transverse Poisson's ratio of hybrid composites obtained from FEA are validated using the **experimental data** from four-point bend test. The transverse properties of AS4D carbon fibers was backed out using the available experimental data for carbon/epoxy composite.

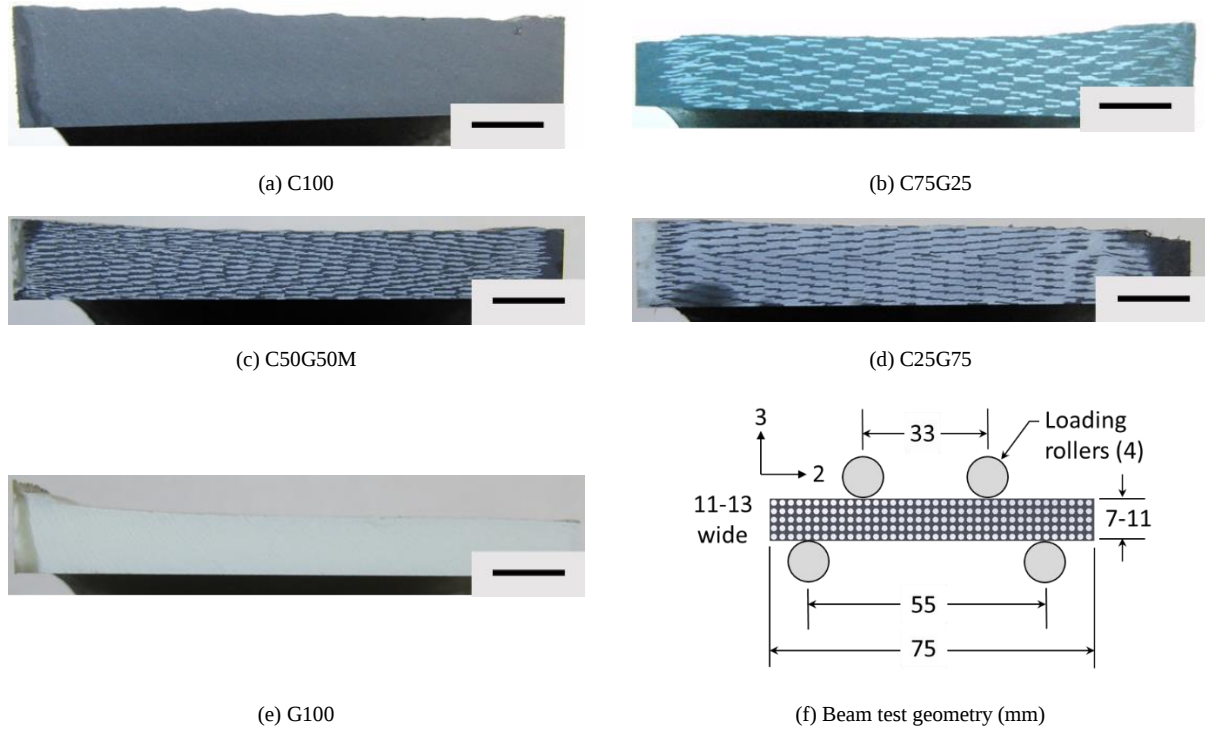


Figure 1. Photographs of axially-cut cross sections of as-wound composite rings before machining (a-e) and 4-point-loaded beam geometry (f). Scale marker in photographs is 10 mm.

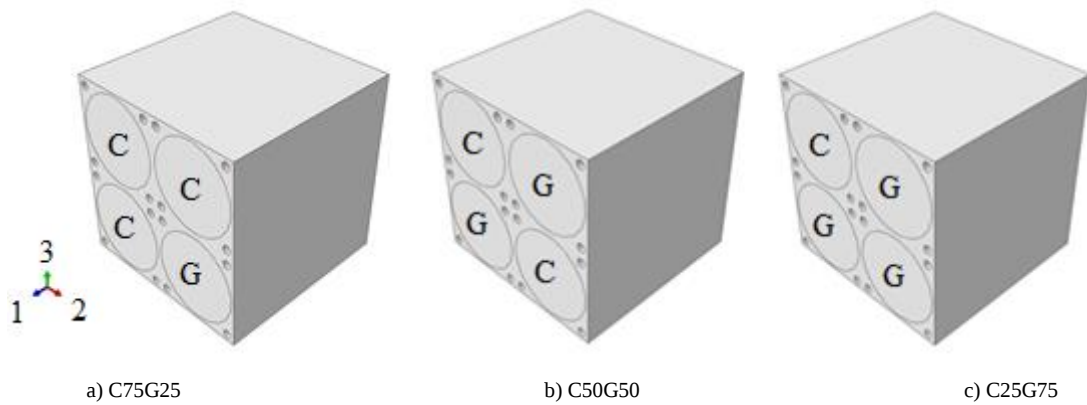


Figure 2: Representative volume element for various hybrid composites (C = carbon fiber; G = glass fiber)

References

Bakis, C.E., and Ripepi, M.J., 2015. "Transverse Mechanical Properties of Unidirectional Hybrid Fiber Composites," *Proc. 30th Technical Conference of the American Society for Composites*, X. Xiao, A. Loos, and D. Liu, eds., Lancaster, PA: DEStech.

Acknowledgement

This paper is based upon work partially supported by the Composites Manufacturing Technology Center at Penn State and the Department of Energy under Award Number DE-EE0005575, The assistance of Mr. Jeffrey Kim with the photomicrography and experiments is appreciated.

Mimicking Neurotransmitter Release in Chemical Synapses via Hysteresis Engineering in MoS₂ Transistors

Andrew Arnold, advised by Saptarshi Das and Thomas Jackson

Using a MoS₂ Field-Effect Transistor (FET) we have successfully demonstrated a transistor-based analogue for neurotransmitter release in chemical synapses. The device replicated three fundamental features of neurotransmitters: quantal release, stochastic release, and excitatory or inhibitory release. Researchers also used the MoS₂ FET to imitate synaptic plasticity – a crucial part of memory formation. Such technology could underpin future developments in intelligent machines, and provide insights into neurological diseases and disorders such as sclerosis, Parkinson’s disease and Alzheimer’s disease.

Chemical synapses are essential to the function of the central nervous system. A diagram of a typical neuron and synapse as well as the additive nature of the action potential pulse response is shown in figure 1. When an action potential reaches the end of a presynaptic axon vesicles containing neurotransmitters bind to the plasma membrane and are released into the synaptic cleft. These neurotransmitters diffuse to the postsynaptic neuron where they bind to receptors and lead to the generation of a postsynaptic current (PSC). An action potential is generated in the postsynaptic neuron if the PSC reaches a threshold value.

To achieve this transducing behavior in the MoS₂ FET, the gate voltage (V_G) pulse and the change in source to drain current (ΔI_{DS}) were equated with the induced PSC and the presynaptic action potential respectively. The MoS₂ FET was fabricated using a mechanically exfoliated 2nm-thick MoS₂ flake – about 3 monolayers – on a Si/SiO₂ substrate used as global back gate and gate dielectric respectively.

Mimicking neurotransmitter behavior was predicated upon a parallel between presynaptic vesicle exocytosis and electron traps in the MoS₂ FET. We developed a system whereby the quantal release, stochastic release, and excitatory or inhibitory release of neurotransmitters were associated with the frequency, amplitude and polarity of V_G pulses respectively.

The electron traps in the MoS₂ FET cause a shift in the threshold voltage of the device such that when the gate voltage is pulsed negatively ΔI_{DS} is positive – a response akin to an excitatory neurotransmitter release as shown in figure 2. The MoS₂ FET also replicates PSC saturation. In a real synapse this saturation occurs due to the finite number of neurotransmitters that can be released into the synaptic cleft. In the FET – for a set gate voltage there are a fixed number of traps induced and as the number of V_G pulses increases more traps become charged – at a higher number of pulses the threshold to charge all traps is reached and ΔI_{DS} will saturate.

We also took advantage of the electron traps in the MoS₂ FET to display behavior analogous to synaptic plasticity. This is the ability of synapses to strengthen and weaken dependent on the signaling activity and forms one of the building blocks of memory formation in mammals. In excitatory synapses a long-lasting signal increase is called long-term potentiation (LTP) and can be replicated in the MoS₂ FET because of the comparatively large discharge time constant of the electron traps. We confirmed through measurement that our device was able to achieve relaxation times comparable to biological synapses.

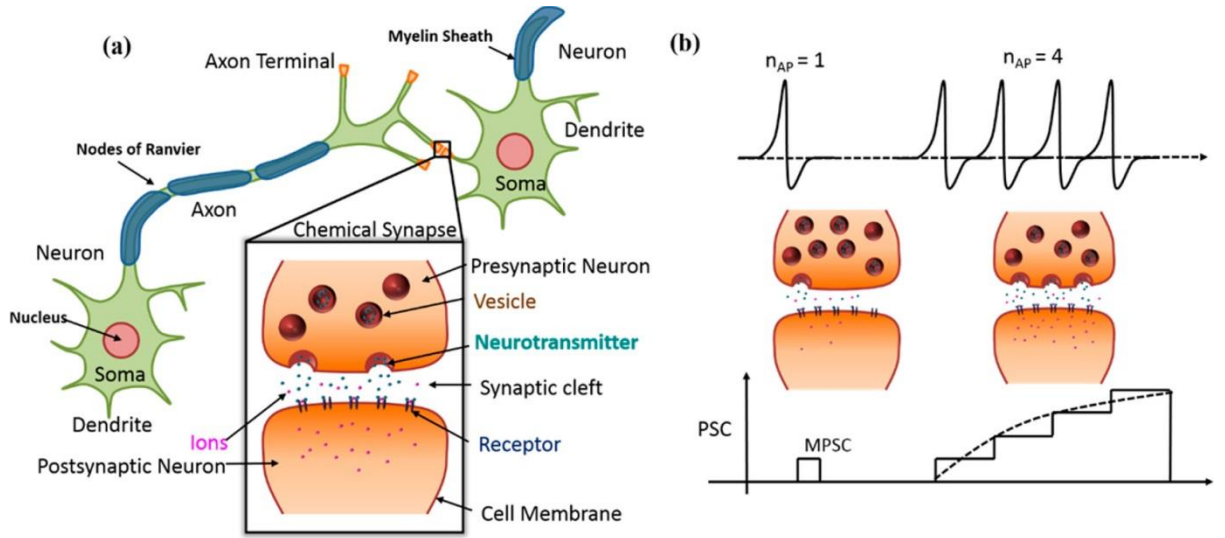


Figure 1: (a) Diagram of neurotransmitter release into a synapse. (b) An illustration of how PSC depends on the number of action potentials (n_{AP}) with the miniature PSC (MPSC) being the PSC induced by one vesicle of neurotransmitters.

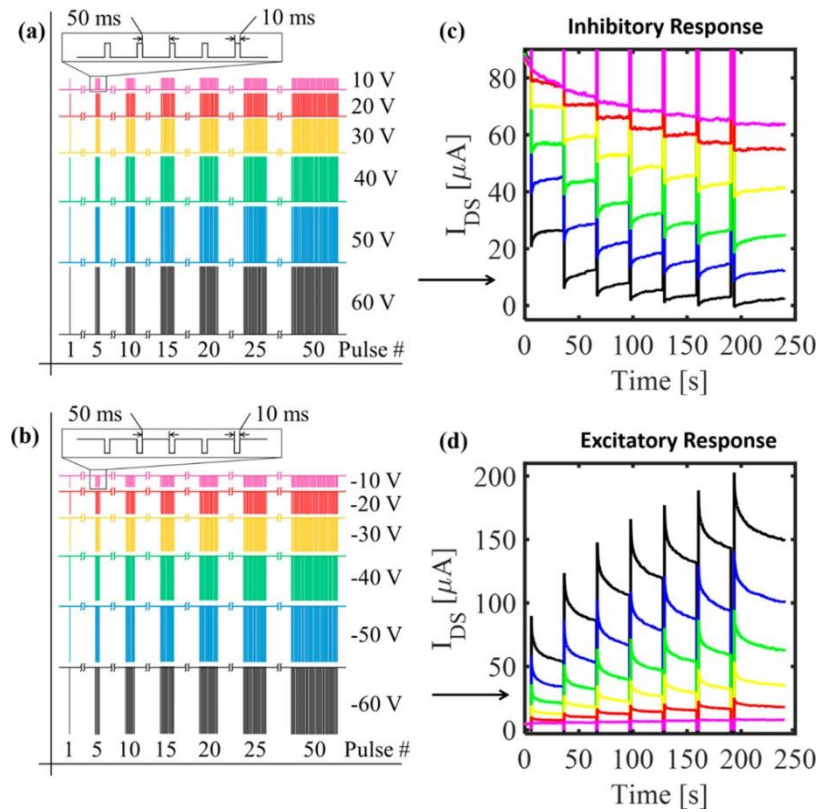


Figure 2: Short positive (a) and negative (b) VG pulses stimulate inhibitory (c) and excitatory (d) responses, respectively. The strength of the response increases with the number of pulses applied

A Low-Frequency, Sub-Wavelength Lamb Wave Reflector using a Boundary-Condition-Based Design Approach

Christopher Hakoda, advised by Dr. Cliff J. Lissenden and Dr. Parisa Shokouhi

In this oral presentation, an improved description of the underlying phenomena that causes Lamb Wave reflection by means of sub-wavelength reflectors is suggested. The path of logic that led to it, and the method used to design for it are described.

The State-of-the-Art:

In 2014, Rupin et al. [1] published a paper which demonstrated a method for effectively reflecting low-frequency A0 modes (a.k.a flexural waves). This led to two follow-up papers [2,3] in which explanations for the observed behavior in Rupin et al. [1] are mathematically theorized. In particular, Williams et al. [2] attributes the behavior to the resonators ability to “clamp the motion” of the plate in which the Lamb wave travels.

The Path of Logic:

The notion of using the resonator to clamp the low-frequency A0 Lamb wave motion seemed general enough to suggest that it may also apply for S0 Lamb waves. However, the extension of the similar vibrating beam models featured in Williams et al. [2], proved inaccurate for calculating the frequencies at which the S0-mode reflectors would be effective. As a result, a different way of describing this clamping was necessary for S0 modes. A pair of boundary conditions known collectively as Mindlin Boundary Conditions were found to be an accurate approach for calculating the frequencies at which a resonator could successfully clamp the motion of S0 Lamb waves. Named after the author of the 1955 monograph (which was reprinted with minor edits by J. Yang [4]) in which it was introduced, R.D. Mindlin originally used these boundary conditions to mathematically decouple the components of the Lamb wave in order to check numerical solutions of the dispersion relationships. That being said, at the time, the boundary conditions were not considered physically implementable and were applied over all surfaces of the plate waveguide that were once considered traction-free.

The Implementation of a Cut-On Frequency:

We propose the periodic enforcement of these boundary conditions by using the vibrational modes of a resonator. That is, to design resonators to vibrate in such a manner as to enforce the desired clamping behavior on the surface of the plate. Initial calculations of the periodic system’s dispersion characteristics revealed that if the Mindlin boundary conditions are enforced without frequency dependence (this is not the case, if they are enforced by resonators),

then the low-frequency Lamb wave modes (i.e. A0, S0, and SH0) will develop mode-specific cut-on frequencies. It is still unclear as to what occurs for the frequency-dependent case, though example calculations/measurements of what these dispersion curves may look like can be found in Rupin and Roux 2017 [5].

The Method of Resonator Design Based on Boundary Conditions:

Typically, resonators are designed in conjunction with the waveguide with which it interacts. [6,7,8,9] We propose studying the two separately by using the boundary condition as a commonality. That is, the frequency and vibrational modes of the resonator are designed to meet the Mindlin boundary conditions, and the effect of the boundary conditions on the travelling Lamb wave can be evaluated separately. There is a little more to it than that though, since they must interact with each other, but that is the essence of it. By using this approach to reduce the complexity of the problem, efficient and comparatively simpler resonators can be designed for specific frequencies.

Proof-of-Concept:

The goal is to design a resonator that meets the following conditions:

- efficiently reflects an S0 Lamb wave at 50 kHz,
- exists on only one of the two surfaces of the plate waveguide.

Simply described as a cube with four cylindrical rods protruding from its sides (see Fig 1), the resonator that we designed for this experiment demonstrated high efficiency in both FEM simulations (92% reflection) and experimental measurements (75% reflection as shown in Fig 2). A comparison was also made between a baseline measurement and a resonator designed by extending the vibrating beam models which we initially suspected would work based on previous work.

Conclusions:

Based on the results from our proof-of-concept simulations and experiments, we were able to demonstrate that the use of Mindlin boundary conditions and the resonator design method are effective for designing resonators for specific low-frequency Lamb Waves. That is, there was good agreement between simulation and experimental results, both of which demonstrated efficient increases in reflection by using the new approach.

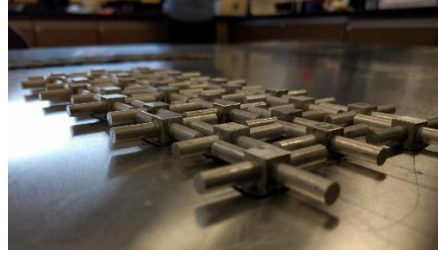


Figure 1: Picture of the resonator array used for proof-of-concept experiments.

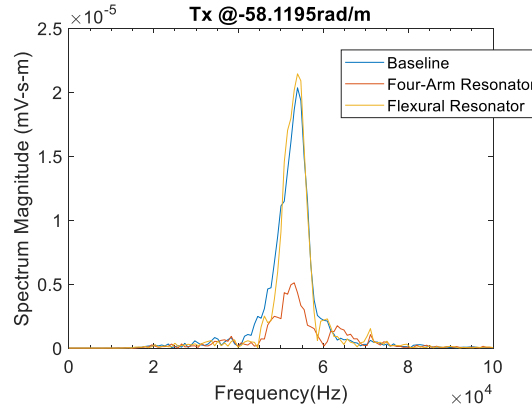


Figure 2. The frequency spectra of the transmitted signal, which was extracted from a calculated 2DFFT at a wavenumber of -58.1 rad/m .

References:

- [1] M. Rupin, F. Lemoult, G. Lerosey, and P. Roux, "Experimental Demonstration of Ordered and Disordered Multiresonant Metamaterials for Lamb Waves," *Physical Review Letters*, 112, 234301, 2014. DOI: 10.1103/PhysRevLett.112.234301
- [2] E.G. Williams, P. Roux, M. Rupin, and W.A. Kuperman, "Theory of multiresonant metamaterials for A0 Lamb Waves," *Physical Review B*, 91, 104307, 2017. DOI: 10.1103/PhysRevB.91.104307
- [3] J.Y. Yoritomo, R.L. Weaver, P. Roux, M. Rupin, and E.G. Williams, "On band gap predictions for multiresonant metamaterials on plates (L)," *The Journal of the Acoustical Society of America*, 139, 3, 2016. DOI: 10.1121/1.4944686
- [4] R. Mindlin, "An Introduction to the Mathematical Theory of Vibrations of Elastic Plates," J. Yang edition, Hackensack, NJ: World Scientific Publishing Co. Pte. Ltd., 2006.
- [5] M. Rupin, and P. Roux, "A multi-wave elastic metamaterial based on degenerate local resonances," *The Journal of the Acoustical Society of America*, 142, EL75, 2017. DOI: 10.1121/1.4992098
- [6] Y. Li, L. Zhu, and T. Chen, "Plate-type elastic metamaterials for low-frequency broadband elastic wave attenuation," *Ultrasonics*, 73, DOI: 10.1016/j.ultras.2016.08.019
- [7] O. Bilal, and M. Hussein, "Trampoline metamaterial: Local resonance enhancement by springboards," *Applied Physics Letters*, 103, 111901, 2013. DOI: 10.1063/1.4820796
- [8] T.-C. Wu, T.-T. Wu, and J.-C. Hsu. "Waveguiding and frequency selection of Lamb waves in a plate with a periodic stubbed surface," *Physics Review B*, 79, 104306, 2009. DOI: 10.1103/PhysRevB.79.104306
- [9] D.J. Colquitt, A. Colombi, R.V. Craster, P. Roux, and S.R.L. Guenneau, "Seismic metasurfaces: Sub-wavelength resonators and Rayleigh wave interaction," *arXiv:1608.01792 [physics.geo-ph]*, 2016.
- [10] J. Rose, "Ultrasonic Waves in Solid Media," New York: Cambridge University Press, 1999.
- [11] L. Brillouin, "Wave Propagation in Periodic Structures: Electric Filters and Crystal Lattices, New York, New York: McGraw-Hill Book Company, 1946.
- [12] P. Cawley, and D. Alleyne, "The Interaction of Lamb Waves with Defects," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, 39, 3, 1992. DOI: 10.1109/58.143172

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Electro-ablation Technique for synthesis of monolayer Transition Metal Dichalcogenides

Amritanand Sebastian, Saptarshi Das

Transition metal dichalcogenides (TMDs) have emerged as a strong contender in the field of two-dimensional (2D) nanoelectronics due to their semiconducting properties and 2D structure¹. Monolayers of these materials are of interest in optics owing to their direct bandgap. The van der Waals crystal structure of 2D materials facilitates easy cleavage to obtain monolayers but they have very low yield and are limited in size. Chemical vapor deposition (CVD) can provide large area monolayers but it requires high temperatures and long processing times. We discuss a low-cost, high yield electrochemical approach to thin bulk TMD materials such as MoS₂, WS₂, and MoSe₂ down to monolayer. This self-limiting anomalous corrosion process, referred as electroablation (EA) involves a TMD micromechanically exfoliated onto a conductive substrate such as titanium nitride (TiN) and subjecting it to a high anodic potential inside an electrochemical cell. The TMD material connected to the working electrode (WE) is subjected to a voltage of ~1.1-1.4V against a Ag/AgCl reference electrode (RE) for ~30s with Pt as the counter electrode (CE) in an electrochemical setup with 1M LiCl as the electrolyte. A schematic for this cell is shown in Fig. 1b and the mechanism is demonstrated in Fig. 1d. The EA process has already been demonstrated in MoS₂ and WS₂^{2,3}. Atomic force microscopy (AFM), photoluminescence (PL) and Raman spectroscopy is utilized to characterize the monolayers obtained.

The first focus is to understand the dynamics of the EA process for MoSe₂ and WSe₂ and to construct a

phenomenological physical framework to explain this process. This involves a study of the pH dependency of the electrolyte on etch rate (bulk and monolayer), as it is seen that the competing monolayer and bulk etch rate will determine the survival of the monolayer for MoSe₂ while for WSe₂ we see that the monolayer doesn't survive. This is studied using AFM. Fig 2a and 2b show the optical micrograph of MoSe₂ before and after EA treatment. The lighter region in Fig. 2b corresponds to monolayer which is confirmed by the PL map and Raman spectra. For WSe₂ it can be clearly seen from 2c and 2d that the monolayer is etched away. Additionally, Pourbiax diagrams are used to understand the probable products of the reaction.

The second focus is on application of the EA technique to planarize CVD grown TMDs. CVD growth can leave behind few-layer regions along with monolayers of the material. The EA process here can act as an excellent tool for post-processing of CVD grown TMDs. Figure 1a and 1c shows the before and after optical micrograph of CVD grown MoS₂.

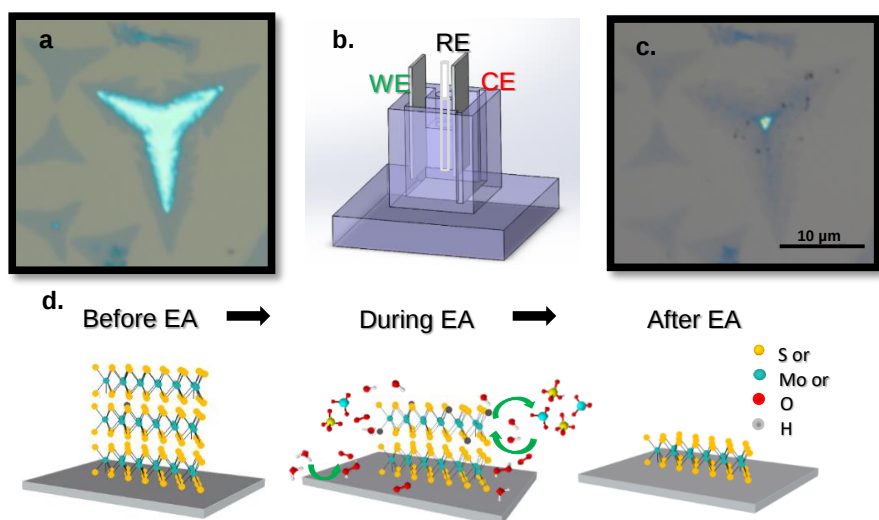


Figure 1: CVD grown MoS₂ optical images a) before and c) after EA. b) Electrochemical setup schematic. d) Schematic showing the mechanism of EA process resulting in monolayer.

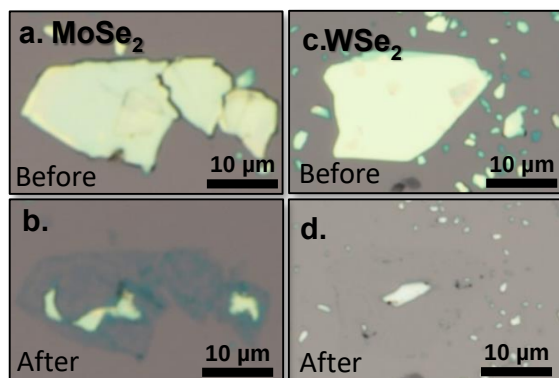


Figure 2. Optical images of a mechanically exfoliated MoSe₂ flake a) before and b) after 10s EA treatment. c) and d) are, respectively, the optical images of a WSe₂ flake before and after 10s EA treatment.

References

1. Schwierz, F., Pezoldt, J. & Granzner, R. Two-dimensional materials and their prospects in transistor electronics. *Nanoscale* **7**, 8261–8283 (2015).
2. Das, S. *et al.* A Self-Limiting Electro-Ablation Technique for the Top-Down Synthesis of Large-Area Monolayer Flakes of 2D Materials. *Sci. Rep.* **6**, 9 (2016).
3. Schulman, D. S., May-rawding, D. & Das, S. Superior Corrosion Resistance of Monolayer Transition Metal Disulfides. 1–24 (2017). doi:10.1021/acsami.7b17660

Acknowledgement

I thank Yu-Ting Huang and my lab members for teaching how to operate everything in our lab. I also thank Fu Zhang for providing the CVD grown sample.

Integration of 2D Materials on Glass

Joseph Nasr, Saptarshi Das

Developing cost effective, high performance and low power electronic devices and circuits on transparent glass substrates holds tremendous promise for the future of display technologies. Layered two-dimensional (2D) van der Waals materials like graphene, hexagonal boron nitride (h-BN), and the so-called transition metal dichalcogenides (TMDs) like MoS_2 could provide the ideal platform to realize such devices owing to their ultra-thin body nature. Their properties not only allow minimal light absorption in the visible spectra making these materials optically transparent but also facilitates aggressively device scaling in order to achieve high performance. Moreover, semiconducting TMDs offer high carrier mobilities ($10\text{-}100\text{cm}^2/\text{V-s}$)¹, large current ON-OFF ratios, mechanical flexibility, and wide-range temperature stability ($10\text{-}400\text{K}$) which are essential for thin film transistors (TFTs) used in display electronics.

Most TFT research based on TMDs has been done on heavily doped Si substrates with a thermally grown SiO_2 dielectric since these substrates offer back-gating capabilities. Regrettably, little device work has been done on other insulating substrates including glass which necessitates top-gated structures.

The 2D community has been working on different types of top-gated structures. These include: ionic liquid (IL) gating², ultra-thin h-BN³, and atomic layer deposition (ALD)⁴. Unfortunately, despite their unique advantages, the scalability issues with IL, the high-temperature growth of h-BN, and ALD nucleation problems due to the TMDs chemically inert basal planes limits the success of achieving a 2D-based top-gated structure.

The focus of this investigation is to develop a top-gate structure with the use of a spin-on silicon based Hydrogen Silsesquioxane (HSQ) dielectric polymer, commonly used as a negative resist or etch mask for microelectronics, as the top-gate dielectric since after high-dose electron beam exposure and curing it obtains SiO_2 dielectric properties. It can be scale down to 20 nm, and requires low-temperature processing.

In order to consider HSQ as the dielectric, a metal-insulator-metal (MIM) capacitor structure was fabricated to characterize its dielectric properties such as leakage current, dielectric breakdown, and dielectric constant. Fig. 1a) and 1b) depict the device schematic and optical image respectively. The effect of HSQ curing temperature was benchmarked using MoS_2 back-gated FETs concluding that curing temperatures above 350°C realigns the Ni contact Fermi level (Fig. 2a)) degrading the ON-OFF ratio and subthreshold swing (SS) (Fig b)).

To extract the dielectric constant of the HSQ we fabricated a dual-gated device as shown in Fig. 3a). By stepping the top-gate voltage, the threshold voltage of the back-gate shifts to compensate the charge coming from top-gate. Using a balance charge equation and plotting the back-gate threshold voltage as a function of the top-gate voltage we extracted the dielectric constant and found it comparable to SiO_2 for both monolayer and multilayer MoS_2 devices (Fig. 3b)).

Lastly, we demonstrated for the first time the monolithic integration of 2D materials on glass for FET devices provided by Dr. Josh Robison's group.

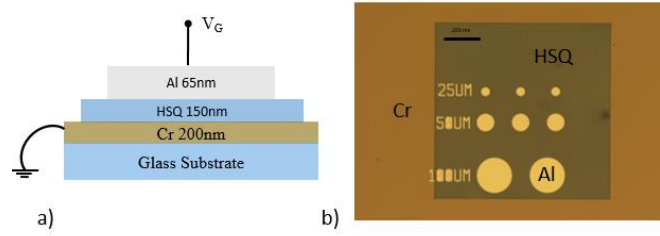


Figure 1: a) HSQ-based MIM capacitor schematic, and b) optical image of the device.

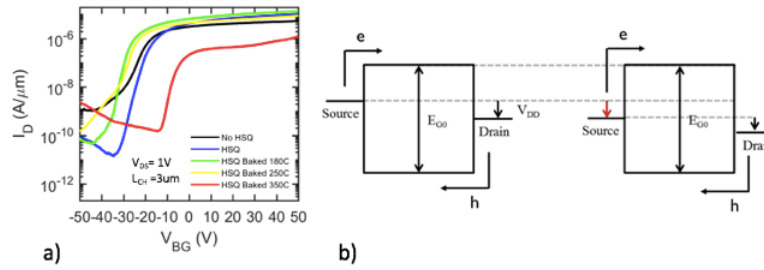


Figure 2: Effect on curing: a) transfer characteristics of MoS₂ FET encapsulated with HSQ. b) Energy band profile before and after contact Fermi level realignment.

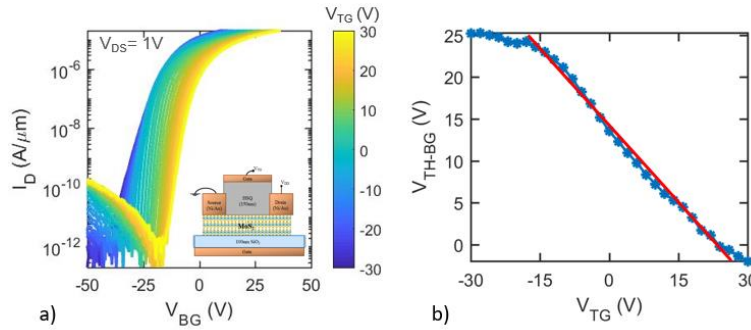


Figure 3: a) MoS₂ dual-gate measurements. b) Dielectric constant extraction by plotting threshold voltage of the back-gate vs. top-gate voltage.

References

- [1] Das, S., Chen, H. Y., Penumatcha, A. V., & Appenzeller, J. (2012). High performance multilayer MoS₂ transistors with scandium contacts. *Nano Letters*, 13(1), 100-105.
- [2] Perera, M. M., Lin, M. W., Chuang, H. J., Chamlagain, B. P., Wang, C., Tan, X., ... & Zhou, Z. (2013). Improved carrier mobility in few-layer MoS₂ field-effect transistors with ionic-liquid gating. *ACS Nano*, 7(5), 4449-4458.
- [3] Das, S., Gulotty, R., Sumant, A. V., & Roelofs, A. (2014). All two-dimensional, flexible, transparent, and thinnest thin film transistor. *Nano Letters*, 14(5), 2861-2866.
- [4] Price, K. M., Schauble, K. E., McGuire, F. A., Farmer, D. B., & Franklin, A. D. (2017). Uniform Growth of Sub-5-Nanometer High- κ Dielectrics on MoS₂ Using Plasma-Enhanced Atomic Layer Deposition. *ACS Applied Materials & Interfaces*, 9(27), 23072-23080.

Bioprinted Pancreas-On-A-Chip Model for Drug Screening in Diabetes Therapy

Monika Hospodiuk, advised by Prof. Ibrahim T. Ozbolat

Due the limited supply of organs for transplantation, successfully engineering a fully functional human organoid will be a milestone in the tissue engineering and regenerative medicine. Novel approaches have been investigated for vascularization of three-dimensional (3D) soft tissues, highly essential for successful fabrication of physiologically-relevant tissue models. A critical step in successful clinical transplantation of the pancreas is the re-vascularization of the organ [1]. The interaction between endothelial cells and pancreatic islet cells is crucial to initiate growth, maturation and function to the endocrine system. It has been reported that vascularization is critical issue after transplantation as it usually diminishes over time [2–4]. As demonstrated in this investigation, it is possible to recapitulate the synergistic relationship between endothelial cells and pancreatic β -cells to create a functional 3D *in vitro* model of pancreatic endocrine tissue.

In this research, the focused is on creation vascularized pancreatic islets, which will bring new perspectives in treatment for patients with type I diabetes or drug testing. This research is significant since diabetes type I will double over the next decade if current rates of increase continue. In this research, pancreatic spheroids were formed by pancreatic β -cells and endothelial cells. The high viability was maintained over 10-days culture period contrary to the control group shown in Fig. 1A. The morphology was a solid, compact and spherical-shaped structure with slightly irregular crown on the surface (Fig. 1B). The spheroids' deposition occurred in a designed pattern

by 3D bioprinting system on a fibrin-bacterial cellulose hydrogel scaffold. Co-cultured spheroids provide a vascularized network within the scaffold that supplies nutrients to cells and drains metabolites, including insulin. Moreover, placed close together, sprouts between them tended to merge as what appears to be a nascent vascular network made by endothelial cells associated into micro-vessels were interconnected with one another (Fig. 2). The tissue model is arranged for a long-term culture that provided data of cellular and molecular changes accompanying the tissue formation. For this reason, tissue spheroids will be precisely deposited in a perfusable, hydrogel-based device. The cell-laden matrix contains both fibrin and functionalized carboxymethyl bacterial cellulose, which complement each other's properties. The active perfusion of the engineered vascularized pancreas tissue within the device will provide dynamic culture conditions for over a month. The expected outcome is cell response to glucose and detection of insulin in real-time at the outlet of the device. It is possible by creating a hollow vasculature from the tissue spheroids to the channel that will allow quick exchange of fluids rather than diffusion through the hydrogel.

This approach combines fabrication of vascularized engineered islets and 3D bioprinting with preserved functionality useful for type I diabetes research. The constructed device will be useful for drug screening in a later stage of experimentation.

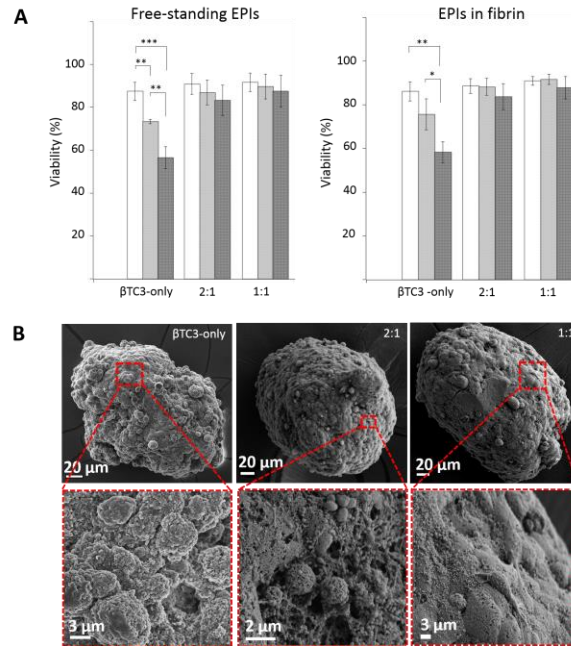


Figure 1: (A) Quantification of cell viability on free-standing EPIs (left) and EPIs embedded in fibrin (right) over 1, 5, and 10 days (n=10). (B) SEM images of three-day cultured EPIs with a high-magnification view of their surface morphology.

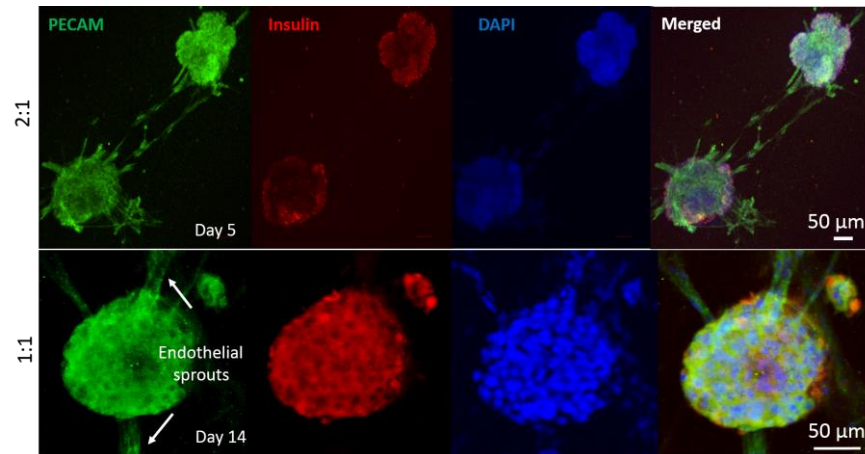


Figure 2: Immunocytochemistry images illustrating endothelial cells sprouting. Vascularization between two EPIs in 2:1 group (top) and in the core and outside of the EPI in 1:1 group (middle and bottom). Immunostaining with PECAM (CD31) stains RHMVECs in green, insulin stains β TC3 in red, and nuclei are shown in blue.

References

- [1] Jansson L and Carlsson P-O 2002 Graft vascular function after transplantation of pancreatic islets. *Diabetologia* **45** 749–63
- [2] Carlsson P O, Palm F and Mattsson G 2002 Low revascularization of experimentally transplanted human pancreatic islets *J. Clin. Endocrinol. Metab.* **87** 5418–23
- [3] Mattsson G, Jansson L and Carlsson P O 2002 Decreased vascular density in mouse pancreatic islets after transplantation *Diabetes* **51** 1362–6
- [4] Carlsson P, Palm F, Andersson A and Liss P 2001 Markedly Decreased Oxygen Tension in Transplanted Rat Pancreatic Islets Irrespective of the Implantation Site *Cell* **50**

Self-monitoring “SMART” (RE)Ba₂Cu₃O_{7-x} superconducting tape

Federico Scurti, advised by Dean Schwartz

A novel way to detect failure events in superconducting materials has been developed, based on Rayleigh-backscattering interrogated optical fibers (RIOF). RIOF are distributed sensors of temperature and strain that can be interrogated in real time and with high spatial resolution.

After showing the effectiveness of the technology by co-winding optical fibers with superconducting wire, a self-monitoring, “SMART” conductor has been conceived, developed and manufactured, via integration of optical fibers into a conventional (RE)B₂C₃O_{7-x} (REBCO) conductor architecture. REBCO is, by far, the most promising high temperature superconductor for applications. Samples of SMART REBCO have been characterized and their quench detection capability demonstrated and compared to that of voltage signals.

Rayleigh backscattering interrogated optical fibers (RIOF):

Optical fibers have been used as sensors of temperature and strains for several decades. The main type of sensor is Fiber Bragg Grating (FBG). The sensing mechanism behind FBG sensors is based on a reflection at a pre-defined location, where a grating was previously inscribed, with a specific period. The reflected photons will have a specific wavelength, determined by the Bragg's equation. Therefore, if the grating period is changed, because of an applied strain or a change in temperature, the reflected wavelength will also change. Although FBG is a robust sensing mechanism for temperature and strain measurements, it is a point sensors, which means that only changes of

temperature and strain that are localized on the grating position along the fiber will be detected and measured.

Another, more recent and more complex sensing mechanism is based on the Rayleigh backscattering interactions between photons and fiber material. The sensing mechanism can be thought of as an FBG sensor with a continuous grating with random period. Therefore, the amplitude of backscattered photons will be a random function in space, but static, because it depends on the defects structure in the fiber material. Therefore, a change in temperature or strain, will alter the backscattered spectrum in a specific location and the change will be detected via a cross correlation with a reference measurement.

High temperature superconductors (HTS) quench detection:

A quench is an irreversible transition from the superconducting to the normal state. A large amount of heat is associated with the transition, which is sufficient to irreversibly damage a magnet system (melting or even locally vaporizing the material). Therefore, superconducting materials need to be protected from these failure events. Low temperature superconductors have been successfully protected by detecting transitions via voltage signals. The same technique has shown to be inadequate when applied to HTS, because of the slow normal zone propagation velocity. Thus, developing an innovative quench detection method is an active research topic in the applied superconductivity community.

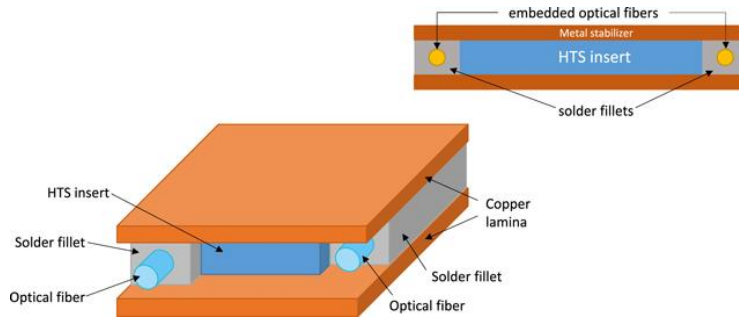


Figure 1: sketch of a SMART conductor with integrated optical fibers.

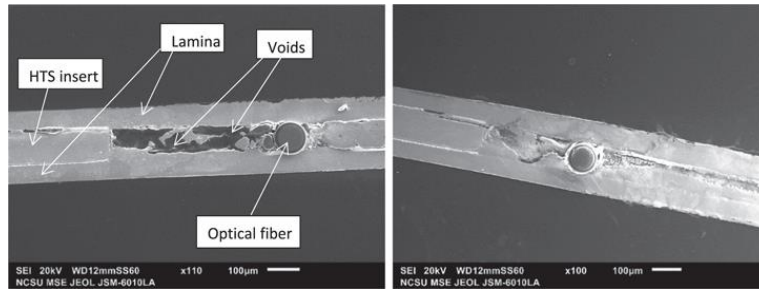


Figure 2: SEM micrographs of cross sections of SMART conductor [3]

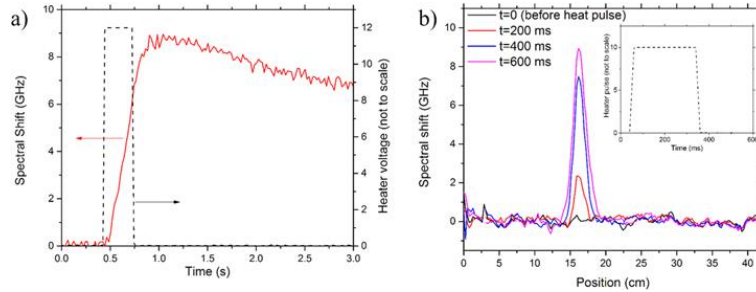


Figure 3: detection of a thermal perturbation by the smart conductor

References

- F. Scurti, J. McGarrah, J. Schwartz, "Effects of coatings on the thermal sensitivity of optical fiber sensors at cryogenic temperatures," *Optical Materials Express*, (submitted 2017)
- F. Scurti, S. Sathyamurthy, M. Rupich and J. Schwartz, "Self-monitoring SMART REBCO coated conductor via integrated optical fibers," *Superconductor Science and Technology*, (submitted 2017)
- F. Scurti, J. Schwartz, "Optical fiber distributed sensing for high temperature superconductor magnets", SPIE Proceedings, The 25th International Conference on Optical Fiber Sensors, (submitted 2016)
- F. Scurti, S. Ishmael, G. Flanagan and J. Schwartz, "Quench detection for high temperature superconductor magnets: a novel technique based on Rayleigh-backscattering interrogated optical fibers," *Superconductor Science & Technology Letters*, 29, no. 3 (2016): 03LT01.

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An Electrochemical Impedance Spectroscopy Corrosion Sensor for Difficult-to-Access Areas of U.S. Navy Vessels

Caroline Van Pelt, advised by Dr. Barbara Shaw and Dr. Elzbieta Sikora

Corrosion drains the U.S. Department of Defense of an estimated \$21.9 billion annually [1]. The U.S. Navy alone experiences about \$7.5 billion in corrosion-related costs each year [1], much of which is due to the extensive manpower and materials required for scheduled corrosion inspection in difficult-to-access areas of Navy vessels. Furthermore, this laborious process increases the amount of time vessels are docked and limits fleet readiness. These drawbacks generally mean that maintenance costs rise and difficult-to-access areas receive decreased quality of upkeep that leads to early failure by corrosion. Previous work has shown promise for an Electrochemical Impedance Spectroscopy (EIS) corrosion sensor that can perform remote inspection in these difficult-to-access areas [2].

This presentation focuses on design improvement and outdoor testing of a flexible, thin film EIS sensor comprised of silver-silver chloride reference and counter electrodes screenprinted on a polyimides substrate. Beginning in August 2017, seventeen sensors were exposed at a Bethesda, Maryland atmospheric corrosion testing site and seventeen sensors were exposed at a Ft. Lauderdale, Florida marine atmospheric corrosion testing site that experiences significant ultraviolet (UV) radiation. All sensors were attached to steel panels coated in various stages of the Navy's Chemical Agent Resistant Coating (CARC) system: zinc primer, zinc

primer plus intermediate coating, and the full three-part CARC system of zinc primer plus intermediate coating plus polyurethane topcoat (as seen in *Figure 1*). Additional sensors were tested in State College, Pennsylvania. For each panel, EIS was run with a control setup of saturated calomel (SCE) reference electrode and graphite counter electrode as well as the experimental setup of the sensor silver-silver-chloride electrodes.

Preliminary results indicate that the sensor is producing EIS data equivalent to that obtained with the control setup and providing accurate coating quality results under most atmospheric conditions (as indicated by the results in *Figure 2*). However, the three sensors on panels with only the zinc primer coating at the high UV exposure Ft. Lauderdale site show decreased quality and reliability of EIS results. Further investigation into the interaction of the zinc primer and the silver-silver-silver-chloride ink is required to determine the cause of this diminished performance. Future work includes continued atmospheric testing over longer time periods and with different coating systems in addition to testing under various immersion conditions. Design work is also underway, ranging from waterproofing of electrical connections to development of an appropriate long-term, shipboard power source. These design improvements and testing regimes will be followed by shipboard testing.



Figure 1: This sensor is attached to a carbon steel panel coated with full CARC system. The two sensor electrodes are silver-silver-chloride ink screenprinted on a polyimides substrate.

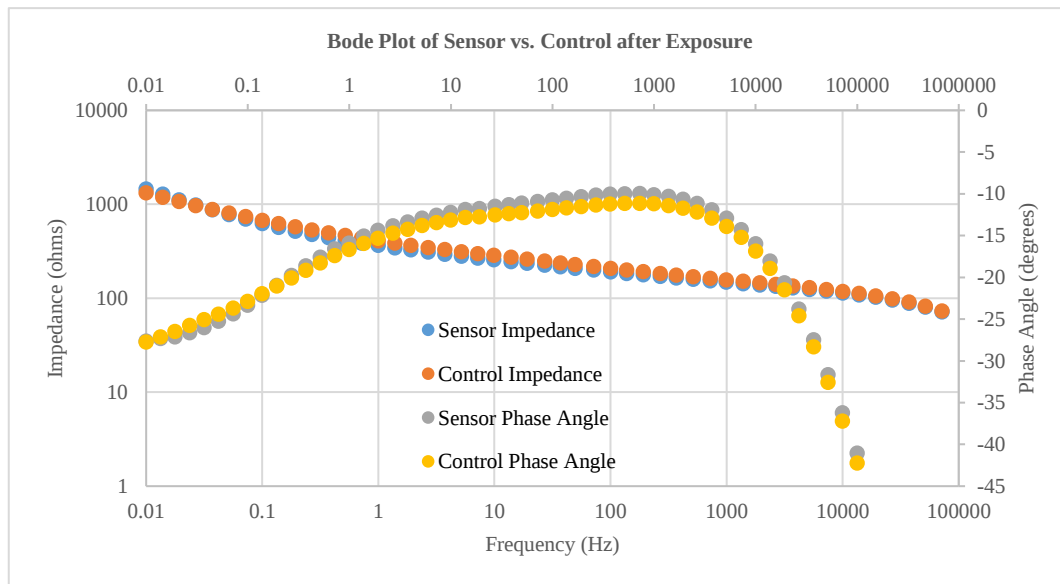


Figure 2: After approximately four months of atmospheric exposure at a Ft. Lauderdale, FL marine site that experiences a high amount of UV radiation, the sensor produced EIS results consistent with the control setup of saturated calomel and graphite. This sensor was attached to the panel in Figure 1, which was carbon steel coated with full CARC system.

References

- [1] Koch, Matthew and Thomas, E.D. "Corrosion Control in the US Navy: Ships & USMC Vehicles." Naval Air Systems Command Patuxent River MD, 2014. Accession number: ADA617077.
- [2] Kim, Faye. "Electrochemical Impedance Spectroscopy Based Sensor for Hard-to-Access Areas of Navy Ships." Undergraduate Thesis, Department of Engineering Science and Mechanics at Penn State University, 2014.

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A Steep Slope 2D Strain Field Effect Transistor: 2D-SFET

Daniel Schulman, Saptarshi Das

Numerous advancements have allowed aggressive dimensional scaling of CMOS to the current state of the art 10nm node but none are solutions to the fundamental Boltzmann statistics limits which have stalled Dennard voltage scaling. The 2D strain FET (2D-SFET) presented here uses a semiconducting 2D transition metal dichalcogenide (TMD) material in conjunction with a piezoelectric material. The proposed structure is shown in figure 1a. It consists of a piezoelectric deposited on a back contact which is biased with a voltage, V_B . The TMD is placed on top in a backgated type configuration comprising of a gate electrode, dielectric, and the semiconducting channel with source and drain contacts. Upon application of a gate voltage, V_{GS} , the transistor operates like a normal ultra-thin body metal oxide semiconductor field effect transistor (MOSFET) with the barrier height modulated by the surface potential, ψ_s . Assuming $V_B=0$, the applied gate voltage produces a field across the piezoelectric resulting in an upward elongation of the piezoelectric. Since the device is surrounded by a stiff encapsulating material, the piezoelectric strain is transferred into the 2D channel. The fraction of the maximum strain transferred to the 2D channel is given by the strain transfer coefficient, η .

The out-of-plane channel compression results in the reduction of the 2D semiconductor bandgap which manifests in a band movement, ψ_E , in addition to the surface potential, ψ_s , as shown in figure 1b. ψ_E is given by equation 1 and depends on the pressure in the 2D semiconductor, P_{2D} and the bandgap reduction coefficient, α . α is on the order of 80meV per GPa of applied pressure [1] with a factor of $\frac{1}{2}$ assuming equal conduction and valence band movement.

$$\psi_E = -\frac{\alpha}{2} P_{2D} \quad (1)$$

The pressure in the 2D channel, P_{2D} is given by equation 2 where $C_{33,2D}$ is the 2D channel stiffness in GPa, t_{2D} is the channel thickness, d_{33} is the piezoelectric coefficient in pm/V. Given the ultrathin body, 1:1 band movement where $V_G=\psi_s$ can be assumed. The expression for the total band movement in the subthreshold switching regime, ψ_T is given by equations 3. Clearly, internal voltage amplification is achieved since the total band movement is greater than the applied gate voltage and thus resulting in a sub 60mV/decade subthreshold slope.

$$P_{2D} = \eta \left(\frac{\alpha}{2} C_{33,2D} \frac{1}{t_{2D}} \right) (d_{33}) V_{GS} \quad (2)$$

$$\psi_T = V_G + \psi_E \quad (3)$$

The device characteristics were simulated using a Landauer based ballistic transport model with the electrostatics solved self consistently. Figure 1c and 1d, respectively, show the transfer and output characteristics of the device. A sub 60mV/decade subthreshold slope is observed improving with increasingly improved strain transfer. The increased band movement in the ON state results in ON currents $\sim 2X$ higher than the standard 2D FET. Ballistic transport simulations show that the 2D SFET can be a strong candidate for ultra-low power applications due to its sub-thermionic subthreshold slope, increased ON current and low leakage currents. Many challenges still exist before such a device can achieve this performance. Foremost is being able to fabricate a device which has a large strain transfer efficiency in a smaller transistor footprint.

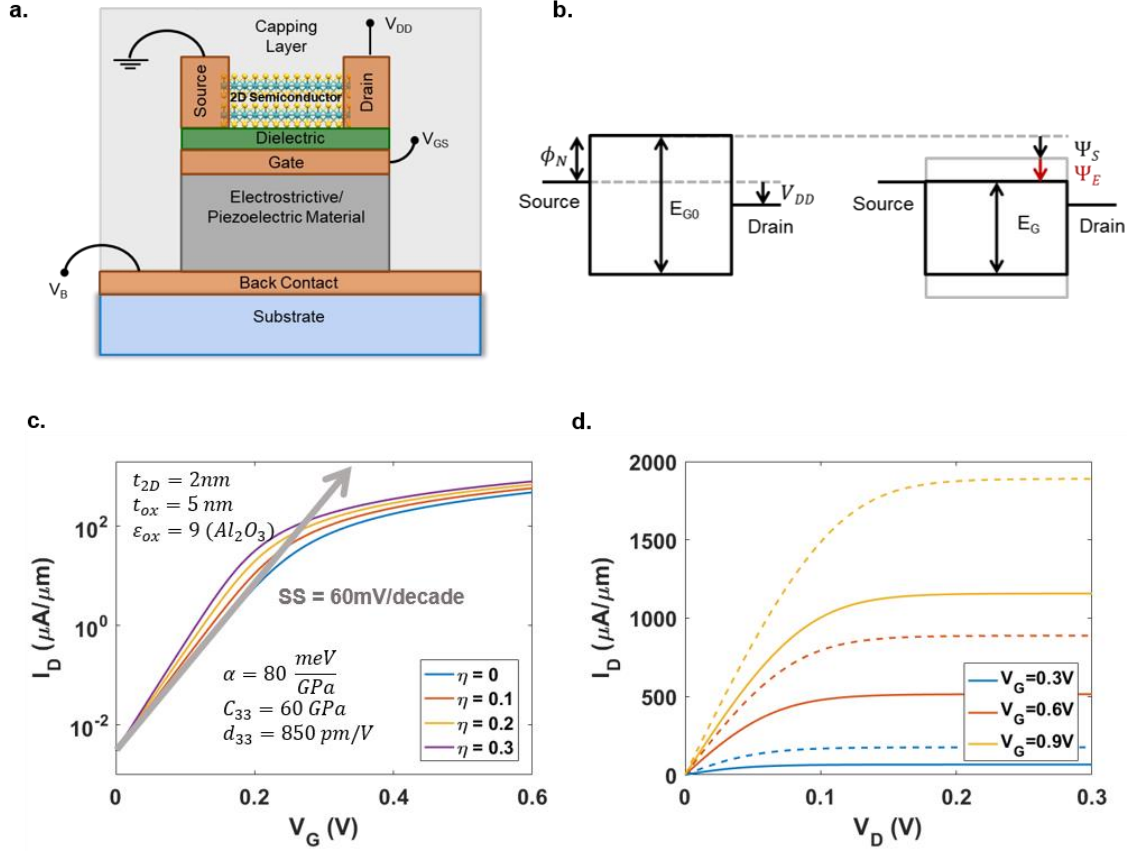


Figure 1: a) Cross-sectional schematic of 2D Strain FET. b) Band diagram showing the pressure induced bandgap reduction provides additional lowering of the barrier (ψ_E) compared to a 2D FET where the barrier lowering is limited (ψ_S). c) Drain current vs gate voltage showing improving sub 60mV/dec subthreshold slopes with larger strain transfer coefficients, η . d) Drain current vs drain voltage (solid: $\eta = 0$, dashed: $\eta = 0.3$). Simulation parameters are inset. [1] [2] [3]

References

- [1] A. P. Nayak *et al.*, "Pressure-induced semiconducting to metallic transition in multilayered molybdenum disulphide," *Nat Commun*, vol. 5, p. 3731, May 07 2014.
- [2] H. Peelaers and C. G. Van de Walle, "Elastic Constants and Pressure-Induced Effects in MoS2," *The Journal of Physical Chemistry C*, vol. 118, no. 22, pp. 12073-12076, 2014.
- [3] R. Keech *et al.*, "Lateral scaling of Pb(Mg1/3Nb2/3)O3-PbTiO3 thin films for piezoelectric logic applications," *Journal of Applied Physics*, vol. 115, no. 23, p. 234106, 2014.

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Multi-Sensor Investigations of Optical Emissions and their relation to DED processes and Quality

Christopher Stutzman, advised by Abdalla Nassar & Edward (Ted) Reutzel

Additive Manufacturing processes are prone to flaw generation during part formation. As such, some of these parts may be deemed mechanically-inadequate for use in failure critical industries such as aerospace or medical. Sensing techniques must be developed to allow these parts to enter into these failure critical industries.

Optical Emission Spectroscopy and Plume Imaging were used to investigate flaws generated during a directed energy deposition additive manufacturing process. Ti-6Al-4V cubes were deposited using varying combinations of laser power, powder flow rate, and hatch pattern to replicate anomalous processing condition shifts. After deposition, the parts were scanned using X-Ray Computed Tomography to determine flaw density and flaw location. Three quantifiable metrics that represent the state of the plasma-plume were developed 1) Line-to-Continuum Ratio around 430 nm, 2) Line-to-Continuum Ratio around 520 nm, and 3) Total Plume Area. A high correlation coefficient was shown between each of these metrics indicating that all three metrics were measuring the same phenomena or were internally consistent. It is shown that an isolated flaw (Figure 1a) in an otherwise flaw free part causes an increase in not only the plume size (Figure 2b), but also in the intensity of the plume emissions (Figure 2a). This is in comparison to a defect free region of the same part (Figure 1b) which shows a smooth spectrum (Figure 3a) and a smaller plume area (Figure 3b). Finally, it is shown that, for a constant

laser power, an increase in flaw density results in an increase in the median plume metric. These results provide a path forward for in-situ flaw detection and build-quality analysis for directed energy deposition and powder bed fusion additive manufacturing processes.

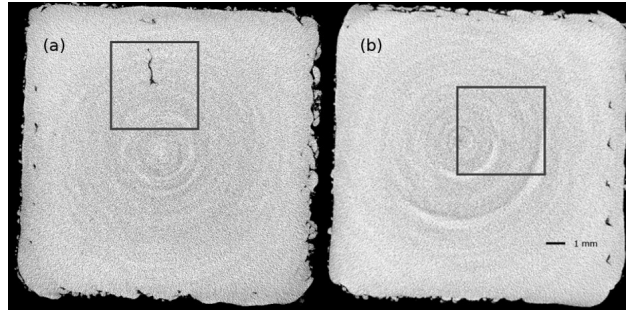


Figure 1: a Isolated flaw b Flaw-free region

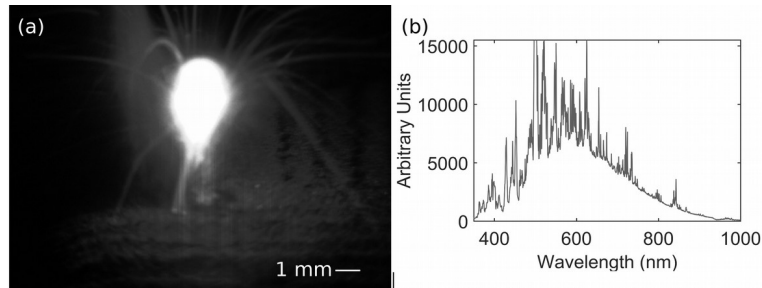


Figure 2: a Plume over the isolated flaw b Spectra over the isolated flaw

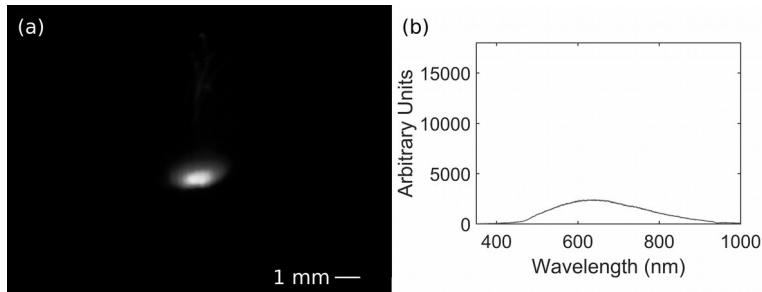


Figure 3: a Plume over a flaw-free region b spectrum over a flaw-free region

References

Note: These are references that are inspirations for the research and not references used above

- [1] A.R. Nassar, B. Starr, E.W. Reutzel, Process monitoring of directed energy deposition of Inconel 718 via plume imaging, in: Proc. Solid Free. Fabr. SFF Symp. Austin TX USA, 2015.
- [2] A.R. Nassar, T.J. Spurgeon, E.W. Reutzel, Sensing defects during directed energy additive manufacturing of metal parts using optical emissions spectroscopy, in: Solid Free. Fabr. Symp. Proc., University of Texas Austin, TX, 2014.
- [3] L. Song, J. Mazumder, Real Time Cr Measurement Using Optical Emission Spectroscopy During Direct Metal Deposition Process, IEEE Sens. J. 12 (2012) 958–964. doi:10.1109/JSEN.2011.2162316.

Oral Presentations - EES 116

Tensile Behavior of Out-of-Autoclave Textile Composites for Fatigue-Resistant Hydrokinetic Turbine Blades

Rudy Haluza, advised by Dr. Charles Bakis and Dr. Kevin Koudela

Marine hydrokinetic (MHK) turbines harvest power from natural waterways, but maintenance costs stemming from poor fatigue performance of glass/epoxy turbine blades impede this renewable energy technology. Thus, fatigue-resistant blades designed for multi-decade service life would improve the economic feasibility of MHK energy. Material systems chosen for multi-decade service life must undergo thorough characterization to understand their behavior in long-term underwater conditions.

This study researched the tensile-mechanical response of a quasi-isotropic woven and polyester-stitched laminate under quasi-static and fatigue loading. Tension-tension fatigue samples were either failed or underwent residual modulus and residual strength measurements. Both woven and stitched specimens were found to survive 10^7 cycles between

a maximum stress of +13.75 ksi, and +18 ksi.

Notably, the stitched composite only demonstrated superior fatigue life in long-life ($>10^5$ cycles) tests. Similarly, damaged (non-failed) samples showed that stitched samples had more damage at lower cycle counts, and vice-versa compared to woven samples.

Through optical macroscopic and microscopic investigation, intralaminar cracks were found to occur in damaged woven and stitched samples. Delaminations were also found, but mainly in samples tested at lower stress levels or nearly-failed samples. More intralaminar cracks were found within stitched specimens compared to woven specimens that had similar reductions in elastic modulus, yet stitched specimens showed greater strength retention compared to the woven specimens.

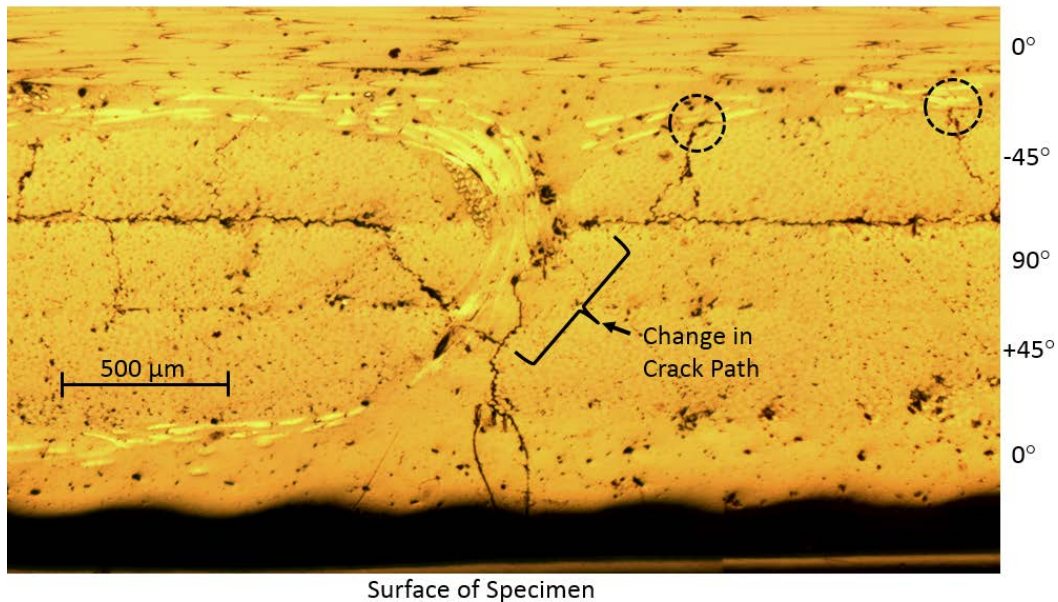


Figure 1: Tricot stitch within composite microstructure and relations to crack location and behavior. Dashed circles show cracks proximity to stitches. Change in crack path shown where tricot stitch goes through four plies. (Non-critical cross section of 18 ksi failed sample).

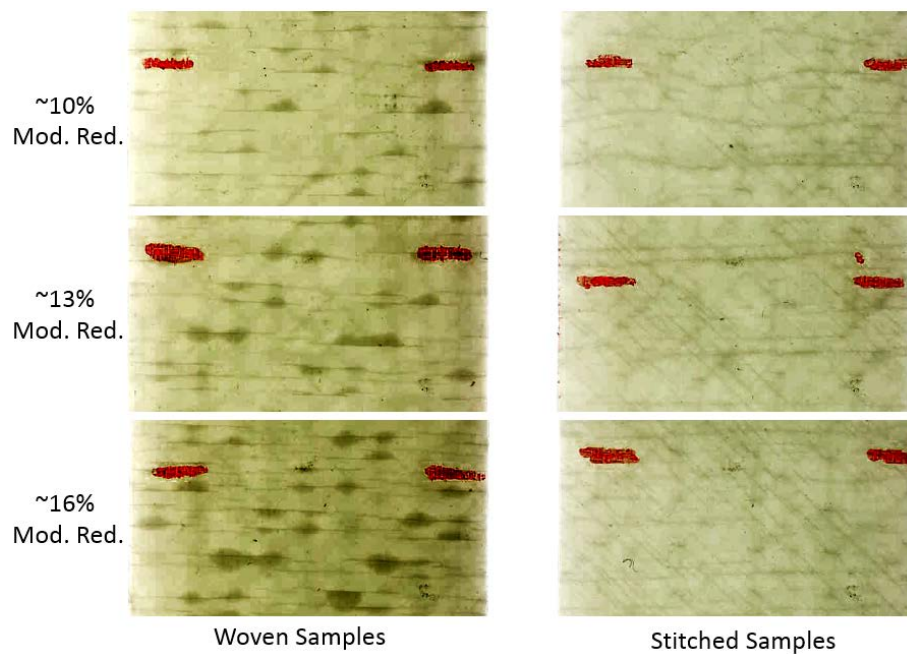


Figure 2: Images of damage within woven and stitched cross sections of dogbone faces revealed using film scanner. Red marker lines used to indicate the middle of dogbone gauge length during testing. Image contrast and saturation enhanced to highlight damage within the samples (13.75 ksi maximum).

Development of Sacrificial Magnesium Coating for the Protection of Magnesium Alloy Components

Karthik Srinivas Venkataraman, advised by Barbara Shaw and Elizabeth Sikora

With the development of newer magnesium alloys for aerospace applications, a greater emphasis needs to be placed on designing sacrificial coatings for protection of these alloys. Magnesium alloys exhibit low density and a high specific strength, making them especially useful for applications where weight reduction is of primary importance. To develop a sacrificial coating for Mg is challenging, as it is the most electrochemically active structural metal (1). Non-equilibrium physical vapor deposits of magnesium exhibit a more ‘active’ nature (lower open circuit potential, measured in a 0.1M NaCl solution) as compared to the bulk alloys. With only ‘one phase’ constituting the entire coating, physical vapor deposits of certain magnesium alloys exploit the preferentially corroding nature of magnesium to produce better candidates for sacrificial coatings. The difference in corrosion potential and corrosion rates between the bulk and the vapor deposited films is a result of both the composition of vapor deposit and its morphology; both of which can be controlled in the vapor deposited films. Vapor deposits of pure magnesium and rare earth containing magnesium alloys (WE43, EV31) showed promising results on silicon substrates.

As the transition is made from a Silicon (Si) substrate to Mg-alloy substrates (AZ61, for a start) to imitate the real-life applications, factors like interface morphology and residual stresses also play a crucial role in determining the electrochemical behavior of the sacrificial layer. After a deposition was made on the AZ61 substrate, the substrate with the sacrificial coating on top of it was heat treated to improve the adhesion between the substrate and the coating. Heat treatment significantly altered the morphology of the vapor deposits. Figure 1 compares the morphology between a non-heat-treated vapor deposit (left) and a heat-treated WE43 vapor deposit (right) at a magnification of 10K.

The vapor deposited films formed by evaporating wrought WE43 provide the best combination of corrosion potential and corrosion rate that we have seen to date. This is despite the fact that the alloying additions in the vapor deposit are present in much lower concentration than in the wrought WE43 starting material.

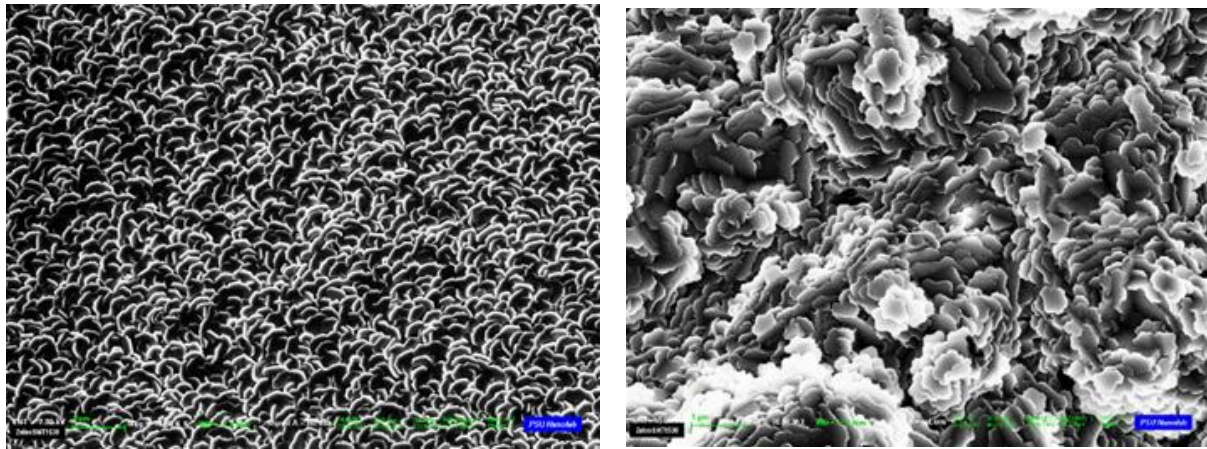


Figure 1: Comparison in morphology between a non-heat-treated vapor deposit (left) and a heat-treated WE43 vapor deposit (right) at 10K magnification

References:

1. *Fundamentals and Advances in Magnesium Alloy Corrosion*. Esmaily, M., J. E. Svensson, S. Fajardo, N. Birbilis, G. S. Frankel, S. Virtanen, R. Arrabal, S. Thomas, and L. G. Johansson. 2017, Progress in Materials Science.

Materials Studies of Split-Ring Resonator Plasma Generators

Zane Cohick, advised by Michael Lanagan and Douglas Wolfe

Non-equilibrium plasmas have been useful in a variety of contexts including materials processing and synthesis,¹ wound healing and cancer treatment,² greenhouse gas decomposition,³ and tunable metamaterials.⁴ Such plasmas can vary widely in their properties for reasons which include, but are not limited to, the many available techniques for plasma generation, the pressure of the plasma, the gases used to generate the plasma, and the power input to the plasma. This ability to dynamically change the plasma properties is what makes them interesting candidates for replacing metal components in metamaterials. By changing the plasma properties, the metamaterial properties can also change. Potential components of such plasma metamaterials and the focus of this work are microplasmas generated through the application of microwaves. The use of microwaves in plasma generation has many advantages including the potential for wireless excitation, lower voltage requirements than predicted by Paschen's law, high-electron densities, and relatively minimal sputtering damage to electrodes.⁵

Historically, plasma generation using microwaves was focused on plasmas which had little interaction with the materials or electrodes surrounding them. However, with the rise of interest in microplasmas, the dimensions in which the plasma is confined has led to the possibility of a significant interaction between the plasma and the electrodes. While sputtering damage is still not much of an issue since heavy ions are not mobilized very well by high-frequency electromagnetic oscillations, electron-electrode interactions can become significant. However, prior to this work no comparative study of different materials

has been made to explore the effect of such interactions on plasma generation. Although recent studies have shown that it is possible to generate microplasmas using all-dielectric devices,⁶ microwave-driven microplasma generators have typically utilized metal resonators. Screen-printed split-ring resonators of silver and gold serve as a platform for our comparative materials studies. These materials are selected due to their high-conductivity and differences in work function. As seen in Figure 1(left), silver resonators can ignite the plasma with less power than the gold resonators. It is expected that the Q-factor, a measure of a resonators ability to store energy, is believed to play an important role in breakdown. It is found that Q-factor is the main factor influencing the plasma ignition performance of silver and gold resonators as shown in Figure 1(right).

Figure 3 shows the performance of a silver resonator compared to the same resonator after 20 minutes of exposure to the plasma. The required power for plasma ignition increases by up to 20%. An associated dark film is visible on the resonator surface after plasma exposure and it is believed that this film, through interactions with plasma electrons, is reducing the performance of the resonator. The larger decrease in plasma ignition performance at low pressures is consistent with an increase in the electron mean free path and therefore more electron-surface interactions. In addition, it was found that by removing the film the plasma ignition performance of the resonator could be restored. This result suggests that with proper choice of materials, it may be possible to reduce the plasma ignition power required by microwave microplasma generators.

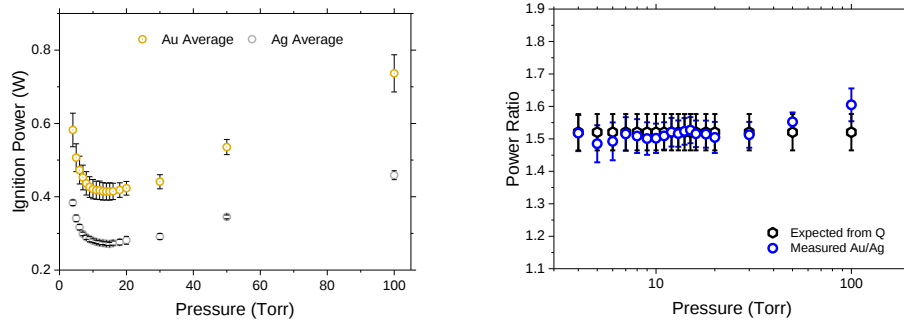


Figure 1: left) Plasma ignition power vs. pressure for silver and gold resonators. The curves show a Paschen-like behavior. At high pressures, the ignition power increases as electrons collide before having sufficient time to gain energy. At low pressures, the electrons gain enough energy to ionize gas atoms, but since gas atoms are relatively scarce ionizing collisions are less likely. right) The ratio of gold resonator ignition power to silver resonator ignition power is plotted against the expected power ratio after accounting for differences in Q-factor. Consistency between the measured and expected data suggest Q-factor is the primary determinant of plasma ignition performance.

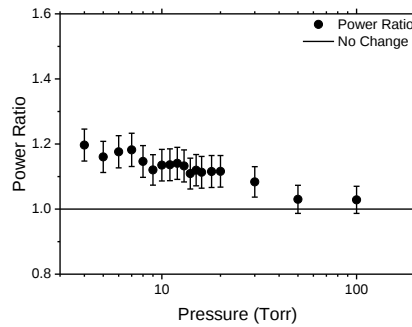


Figure 2: The ignition power ratio of a silver resonator with a film formed by the plasma to a clean silver resonator vs. pressure shows that the resonator with a film requires more power at low pressures. This behavior is qualitatively consistent with the notion that the increase in electron mean free path occurring at lower pressures allows more interactions with the electrodes.

References

1. M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, (John Wiley & Sons Inc, New Jersey, 2005).
2. G. Fridman, G. Friedman, A. Gutsol, A. B. Shekhter, V. N. Vasilets, and A. Fridman, "Applied plasma medicine" *Plasma Processes and Polymers* 5, 503-533 (2008).
3. H. S. Kwak, H. S. Uhm, Y. C. Hong, and E. H. Choi, "Disintegration of carbon dioxide molecules in a microwave Plasma Torch," *Scientific Reports* 5, 1-13 (2016).
4. O. Sakai and K. Tachibana, "Plasmas as metamaterials: a review," *Plasma Sources Science and Technology* 21, 013001 1-18 (2012).
5. J. Hopwood, A. R. Hoskinson, and J. Gregório, "Microwaves ignited and sustained by microwaves" *Plasma Sources Science and Technology* 23, 064002 1-13 (2014).
6. Z. Cohick, W. Luo, S. Perini, A. Baker, D. Wolfe, and M. Lanagan, "A novel, all-dielectric, microwave plasma generator towards development of plasma metamaterials," *Applied Physics Express* 9, 116201 1-4 (2016).

On optical-absorption peaks in a nonhomogeneous thin-film solar cell with a 2D periodically corrugated metallic backreflector

Faiz Ahmad, advised by Akhlesh Lakhtakia

Amorphous silicon (a-Si) thin-film solar cells are low cost and easy to manufacture compared to crystalline silicon solar cells. But their efficiency is low due to the high electron-hole recombination rate and low charge-carrier diffusion lengths in a-Si [1]. So, light-trapping techniques are necessary to enhance the efficiency of a-Si thin-film solar cells. Several light-trapping strategies have been studied both experimentally and theoretically so far [2, 3].

Of particular interest are plasmonic structures: nonhomogeneity in the solar cell absorber layer and periodically corrugated backreflectors [3, 4]. Plasmonic structures can enhance the optical electric field through the excitation of two types of guided-wave modes (GWMs): surface-plasmon-polariton (SPP) waves and waveguide modes (WGMs). The periodically corrugated interface of a metal and a semiconductor that is periodically nonhomogeneous in the thickness direction can guide multiple SPP waves at the same frequency [5].

Therefore, the incorporation of nonhomogeneity along the thickness direction in the semiconductor layers of a solar cell with a periodically corrugated backreflector (PCBR) can enhance photonic absorption and hence the generation rate of electron-hole pairs [4]. Much of the theoretical and experimental research done on thin-film solar cells with metallic PCBRs is confined to devices with a homogeneous semiconductor layer and a 1D metallic backreflector. Furthermore, in solar-cell research, often the excitation of GWMs is correlated with the total absorptance of the device which however is not a good measure of useful photonic absorption in a solar

cell, as photons absorbed in the metallic portions of a solar cell are not available for conversion into electric current. Therefore, the chief objective for the work reported here was to determine the spectrums of both the total absorptance and the useful absorptance in a tandem solar cell with a 2D PCBR, and correlation of useful absorptance peaks with predicted GWMs.

The rigorous coupled wave approach (RCWA) was implemented to investigate optical absorption in a triple-p-i-n-junction amorphous-silicon solar cell with a 2D PCBR (shown in Fig 1.) Both total and useful absorptances were computed with and without the PCBR-against the free-space wavelength for both s- and p-polarized polarization states with normal incidence (Fig. 2, 3). For correlation of absorptance peaks, the predicted wavenumbers of WGMs and SPP waves are obtained by solving two different canonical boundary value problems. The predicted wavenumbers are shown in Table-1 and the wavenumbers those found correlation with absorption peaks are highlighted in bold. Correlated absorptance peaks were indicated with arrows.

Use of the doubly periodic PCBR enhanced both useful and total absorptances in comparison to a planar backreflector. Several but not all GWMs could be correlated with the total and useful absorptance. Also, excitation of certain GWMs could be correlated with the total absorptance but not with the useful absorptance, the useful absorptance should be studied while devising light-trapping strategies.

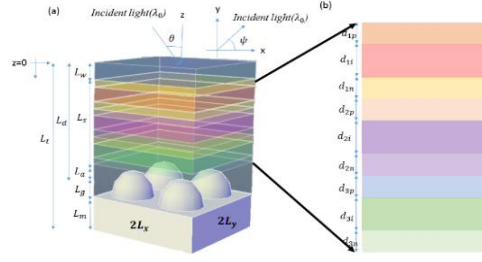


Fig. 1. (a) Schematic of the tandem solar cell comprising three p-i-n junctions of a-Si alloys on a 2D PCBR. (b) Nine semiconductor layers of the three p-i-n junctions.

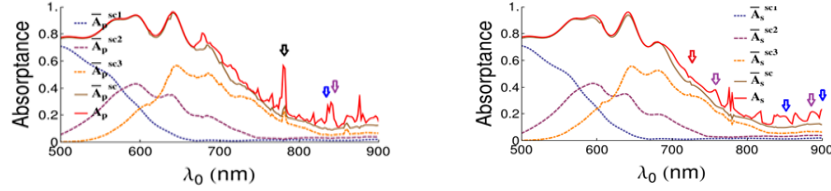


Fig. 2 Spectrums of total absorptance A_p for p- (left) and A_s for s-polarized (right) incident light. A_p^{sc} , A_s^{sc} is the useful absorptance of the triple p-i-n junction. Superscripts 1, 2, 3 represents absorptance in each p-i-n junction. Red arrows indicate the excitation of SPP waves that matched with both linear absorptances (A_p and A_s) and useful linear absorptances (A_p^{sc} and A_s^{sc}); black arrows indicate WGMs that matched with both linear absorptances and useful linear absorptances; blue arrows indicate the excitation of SPP waves that correlated with linear absorptances but not with useful linear absorptances; and purple arrows indicate the excitation of WGMs that correlated with linear absorptances but not with useful linear absorptances.

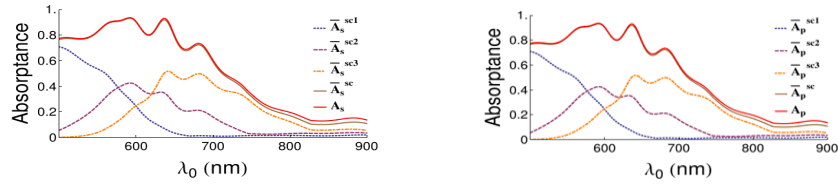


Fig. 3 Same as Fig. 2 except $L_g = 0$

Table-1 Values of free space wavelength (calculated at 1-nm intervals) for which the excitation of an SPP wave (left) and WGMs (right) as a Floquet harmonic of order (m, n) is predicted for normal incident, for the tandem solar cell with a 2D silver PCBR. SPP waves strongly excited in Fig. 2 are highlighted in bold.

Pol. State	λ_0 (nm)	$\text{Re}\{q/k_0\}$	θ°	(m, n)
s	730	1.816	0.856	(1, 0)
s	845	2.988	0.088	(1, 1)
p	570	2.027	0.991	(1, 1)
p	640	2.029	1.024	(±1, 0)
p	680	1.678	1.228	(1, 0)
p	897	2.988	0.847	(1, 0)

Pol. State	λ_0 (nm)	$\text{Re}\{q/k_0\}$	θ°	(m, n)
s	663	3.685	1.334	(-2, 1)
s	711	3.536	1.076	(-2, 0)
s	786	1.948	0.948	(-1, 0)
s	834	2.938	0.838	(-1, 1)
s	898	3.163	0.902	(-1, 1)
p	754	3.750	1.145	(-2, 0)
p	797	3.963	1.206	(-2, 0)
p	827	2.910	1.121	(-1, 1)
p	892	3.138	1.198	(-1, 1)

References:

- [1] M. A. Green, "Thin-film solar cells: review of materials, technologies and commercial status," J. Mater. Sci. Mater. Electron. 18(S1), 15–19 (2007).
- [2] S. A. Boden and D. M. Bagnall, "Sunrise to sunset optimization of thin film antireflective coatings for encapsulated, planar silicon solar cells," Prog. Photovoltaics Res. Appl. 17(4), 241–252 (2009).
- [3] L. M. Anderson, "Harnessing surface plasmons for solar energy conversion," Proc. SPIE 408(1), 172–178 (1983).
- [4] T. H. Anderson, T. G. Mackay, and A. Lakhtakia, "Enhanced efficiency of Schottky-barrier solar cell with periodically nonhomogeneous indium gallium nitride layer," J. Photon. Energy 7(1), 014502 (2017).
- [5] J. A. Polo Jr., T. G. Mackay, and A. Lakhtakia, Electromagnetic Surface Waves: A Modern Perspective, Elsevier, Waltham, MA, USA (2013).

Near Zero-Field Magnetoresistance and High and Ultra Low Frequency Electrically Detected Magnetic Resonance in 4H-SiC p-n Junctions

Elias Frantz, advised by Dr. Patrick Lenahan

We have investigated 4H-SiC p-n junction diodes with X-band ($\sim 10\text{GHz}$) and ultra-low frequency ($\sim 10\text{MHz}$) electrically detected magnetic resonance (EDMR) and compare the EDMR response to the near zero-field magnetoresistance (MR) of these devices as a function of junction bias. Representative results of our study are illustrated in figure 1 below. Development of a fundamental understanding of the near-zero field MR may be of real technological significance as the response can be exploited in a new class of magnetometers designed for deep space magnetic field sensing applications [1,2]. Both the EDMR and the MR involve spin-dependent recombination within the junction depletion region. Significantly as Cochrane et al. discussed the sensitivity of the near zero field magnetometer is a strong function of the width of the near zero field MR response. In this study we have explored the width the various features in

the MR response over a range of biasing conditions. We find that the width of various features of the MR response are in fact strongly dependent on biasing conditions and the detailed response also depends strongly upon the choice of dopant atoms within the devices. The EDMR measurements involve current change via resonance induced changes in triplets to singlets, whereas MR involves singlet – triplet mixing. The study involves several devices with significantly different doping. Therefore the EDMR and MR comparisons provide some physical insight into the MR. Comparing the MR to the relative well understood EDMR response at high and low frequencies may allow for better fundamental physical understanding to the MR response potentially allowing the extraction of spectroscopic and magnetic field information from these relative new MR measurements.

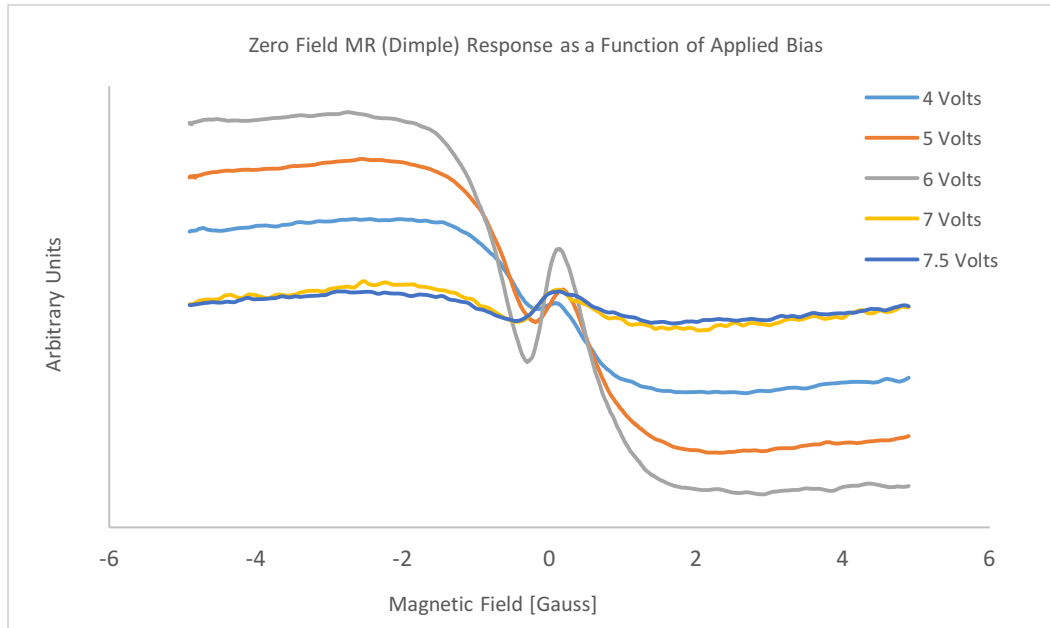


Figure 1: ZeroField (Dimple) Response as a Function of Applied Forward Bias

References

- [1] Cochrane, C. J., & Lenahan, P. M. (2012). Zero-field detection of spin dependent recombination with direct observation of electron nuclear hyperfine interactions in the absence of an oscillating electromagnetic field. *Journal of Applied Physics*, 112(12), 123714. doi:10.1063/1.4770472
- [2] Cochrane, C. J., Blacksberg, J., Anders, M. A., & Lenahan, P. M. (2016). Vectorized magnetometer for space applications using electrical readout of atomic scale defects in silicon carbide. *Scientific Reports*. Retrieved November 28, 2016, from <http://www.nature.com/scientificreports>

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An aspiration-assisted bioprinting for tissue biofabrication

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In contrast to traditional two-dimensional (2D) cell culture, three-dimensional (3D) tissue spheroids offer many advantages, such as the ability of cells to secrete their own extracellular matrix (ECM) and increasing effective communication between cells in a particular tissue microenvironment [1]. Recently, one of the primary focus of bioprinting research has been the development of various methods to automate the manufacturing process of functional 3D tissue constructs for large scale tissue biofabrication [2]. In order to bioprint tissue spheroids, we have investigated a new process, which enables precise positioning of tissue spheroids onto a fibrin scaffold. We have developed an aspiration-assisted bioprinter (ABB), where a pipette, mounted on the arm, picks the spheroids via the aspiration pressure and place them one by one onto fibrin (Figure 1). Each spheroid is visually inspected before printing onto desired location.

During the spheroid fabrication, it was observed that the relative size of the spheroid depends on cell number, culture time and cell type (Figure 2). The average diameter of 3T3 (NIH 3T3 mouse embryonic fibroblast cells) spheroids made of 2.5k cells decreased by 18.9% ($248.31 \pm 4.26 \mu\text{m}$) on day 2 and 26.8% ($229.92 \pm 15.84 \mu\text{m}$) on day 3. The average diameter of 3T3 spheroids with made of 5k cells displayed a decrease in diameter by 16.19% on day 2 ($522.1 \pm 36.85 \mu\text{m}$) and 24.34% on day 3 ($533.2 \pm 26.66 \mu\text{m}$), while the average diameter of 3T3 spheroids made of 10k cells diameter was declined by 18.9% on day 2 ($795.75 \pm 33 \mu\text{m}$) and 26.8% on day 3 ($699 \pm 34.41 \mu\text{m}$). Significant increase in average

diameter of 3T3 spheroids was observed when the cell number was increased.

A tissue spheroid is lifted by pipette aspiration after overcoming the gravity, buoyance force, hydraulic drag, and a thermodynamic barrier at the interface. The main difficulty in lifting a spheroid is the binding energy caused by the surface tension at the interface between the tissue media and air. The spheroid contributes to the lifting barrier in the form of a contact angle at the three-phase (spheroid, air, and tissue media) contact line (Figure 3):

$$P_C = mF_{max}/A_h = 2mR_S\sigma_{1,2}\cos^2\frac{\theta_d}{2}/\pi R_h^2$$

The critical pressure (P_C) is proportional to the surface tension coefficient of tissue media – air interface, the radius of the spheroid, the dynamic contact angle at the three-phase contact line, and the tapered angle of the pipette.

The inspection process reduces the chances of contamination and ensures that only the spheroids of desired size and shape are used to construct the tissue (Figure 4). Automatic and semi-automatic control modes implement a rapid process cycle with a variable level of control and process automation. By monitoring spheroids and reducing the handling time we maximize the cell proliferation of the final biostructure

This printing technique has the ability to monitor and maintain required back pressure while capturing and placing the spheroids during their placement. This novel bioprinting technique can be used for many organ-on-a-chip platforms for drug screening.

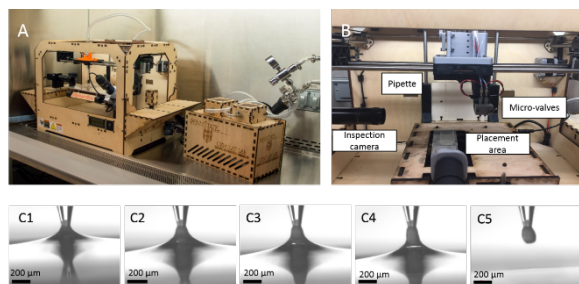


Figure 1. Aspiration-assisted bioprinting technique (A) bioprinter setup, (B) spheroid pick and place platform including an inspection camera, a pipette and microvalves (C1-C5) time-lapsed images of spheroid lifting process at interface between cell media and air

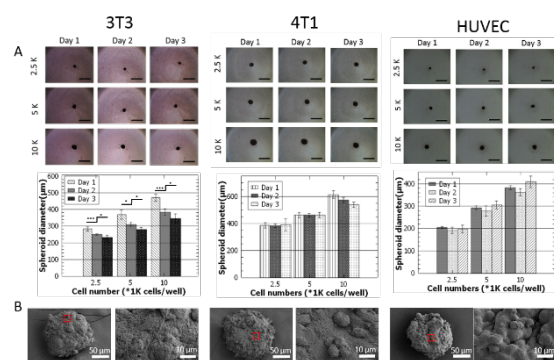


Figure 2. Fabrication of 3T3, 4T1 and HUVEC spheroids: (A) Different cell seeding concentrations influenced the diameter of spheroids at Day 1, Day 2 and Day 3 (scale bars represent 1,000 μm), (B) SEM images of 3T3 (left), 4T1 (middle), and HUVEC (right) spheroids

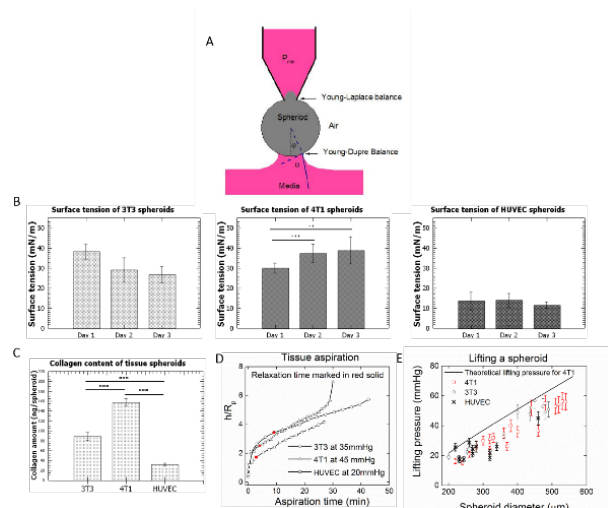


Figure 3. (A) A schematic illustration of picking, holding and

placing process,, (B) surface tension of 3T3 (left), 4T1 (middle) and HUVEC spheroids at Day 1, Day 2 and Day 3, (C) the collagen content of 3T3, 4T1 and HUVEC spheroids, (D) viscoelastic behavior of spheroids under pipette aspiration. Here, h is the advancement of the spheroid inside the pipette. (E) the lifting pressure of spheroids from tissue media for. The tissue radius ranges from 200 to 600 μm

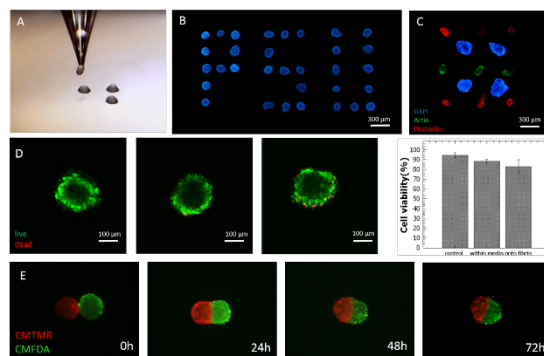


Figure 4. Spheroid placement: (A) an image from side camera represents spheroid placement onto fibrin, (B-C) complex spheroid patterns, (D) cell viability of spheroids before and after bioprinting: confocal images of spheroids before bioprinting (left), after bioprinting within cell media (middle), after bioprinting onto fibrin (right), **confocal images** a graph represent cell viability before bioprinting(left), after bioprinting within cell media (middle) and bioprinting onto fibrin (right), (E) time-lapse images of self-assembly of 3T3 spheroids at 0h, 24h, 48h and 72h.

References

- [1] V. Mironov, R.P. Visconti, V. Kasyanov, G. Forgacs, C.J. Drake, R.R. Markwald, Organ printing : Tissue spheroids as building blocks q, Biomaterials. 30 (2009) 2164–2174.
- [2] W. Peng, U. Derya, I.T. Ozbolat, Bioprinting Towards Physiologically-relevant Tissue Models for Pharmaceuticals, Trends Biotechnol. 34 (2016) 722–732

The importance of energy criteria for selecting modes in reduced order modeling

Suparno Bhattacharyya, advised by Joseph Cusumano

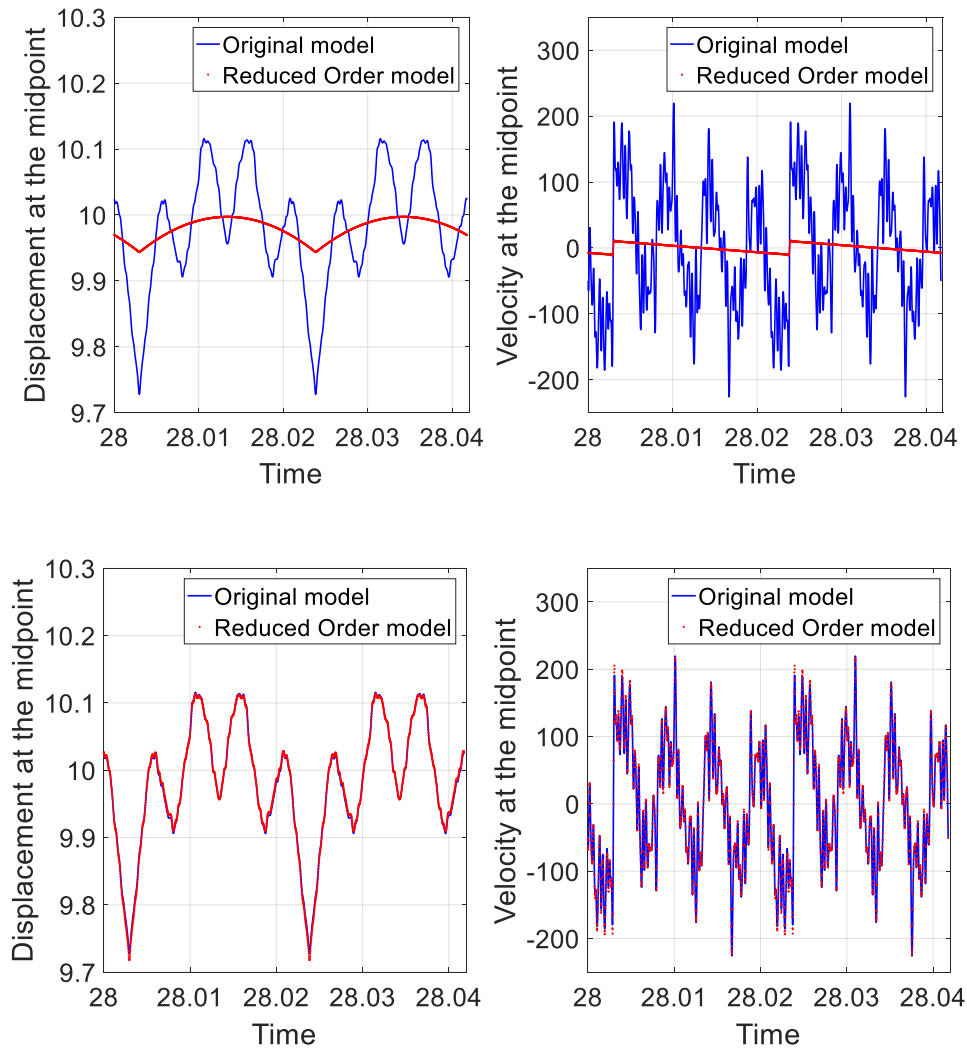
Simulating vibrating structures and other high dimensional systems is often challenging because of high computational costs and data management issues. Model reduction is a process that estimates the effective dimension of a high dimensional system. Subsequently, the system is projected onto an appropriate low dimensional subspace to obtain a model that can be simulated more efficiently. Here, we analyze the performance of the proper orthogonal decomposition (POD), a widely-used data-driven model reduction technique [1-3]. The POD ensures the most effective way of capturing the dominant components of any high dimensional system with surprisingly few Proper Orthogonal Modes (POMs). These POMs, chosen to form a lower dimensional subspace for model reduction, optimally capture 90% or more of the variance of any high dimensional spatial time series obtained from the system [1,4].

From a first principles perspective, the dynamics of a structural dynamical is characterized by its generalized displacement and velocity fields. However, in order to study such systems experimentally, displacement, strain, velocity, or even acceleration data can be acquired.

Since POD is data driven, it is reasonable to expect the accuracy of a reduced-order model obtained using it to depend on the choice of the data set. Typically, in the literature, one finds that POD is used without addressing this issue.

Here, we used a simply supported Euler-Bernoulli beam subjected to periodic impulsive loads in

numerical experiments to compare the accuracy of different reduced order models (ROMs) obtained using displacement, velocity, and curvature (i.e. strain) spatial time series. The spatial and temporal distribution of the impulses were tuned to control the number of excited modes in, and hence the dimensionality of, the system's response. We used the problem's normal modes and modal analysis to obtain closed form solutions and to generate displacement, curvature, and velocity time series. Each of these time series were then used to generate a reduced order model via the POD. The proper orthogonal modes (POMs) so obtained were expressed in terms of the beam's linear normal modes, to define a lower dimensional subspace for model reduction. We observed that application of the POD to curvature and velocity time series resulted in ROMs that can more accurately represent the dynamics of the original system than those based on displacement time series, irrespective of the dimensionality of the original data. Since the curvature and velocity time series are directly related to the system's potential and kinetic energies, respectively. In contrast, the displacement field does not by itself yield and estimate of the system's energy. Thus, we have shown that the selection of empirical modes (i.e., POMs) for reduced order models should by considering the total mechanical energy that they capture. This is of central importance in properly identifying the low dimensional subspace needed for model reduction. Hence it is necessary to use a data set that either in itself is representative of the system's energy, or that can be related to the system's energy.



Figures showing comparison between original data from the system and reconstructed data corresponding to ROMs. In these cases POD was used with displacement, velocity and curvature timeseries to obtain the reduced order models. The first figure corresponds to the ROM based on displacement time series where the reconstruction is quite erroneous (relative error 127.5% and 099.8% for displacement and velocity time series respectively). In the second figure the reconstruction corresponds to the ROM based on velocity spatial timeseries, which is quite accurate (relative error 0.07% and 4.35% for displacement and velocity time series respectively). The ROM based on curvature time series yields results very similar those based on velocity time series.

Reference

- [1] Holmes, P., Lumley, J., & Berkooz, G. (1996). Turbulence, Coherent Structures, Dynamical Systems and Symmetry (Cambridge Monographs on Mechanics). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511622700
- [2] J. P. Cusumano and B. Y. Bai. Period-infinity periodic motions, chaos, and spatial coherence in a 10 degree of freedom impact oscillator. *Chaos, Solitons & Fractals*, 3(5):515–535, September 1993.
- [3] M.F.A. Azeez and A.F. Vakakis. Proper orthogonal decomposition (pod) of a class of vibroimpact oscillations. *Journal of Sound and Vibration*, 240(5):859–889, March 2001.
- [4] L. Sirovich. Chaotic dynamics of coherent structures. *Physica D*, 37:126–43, 1989.

Nonlinear interaction of elastic waves in an isotropic plate, applications for nondestructive characterization

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The collision of objects is always a fascinating subject, especially when scattering of small fragments is expected to occur outside of the collision zone. Likewise, for the case of elastic waves, where waves can be considered as the motion of energy, while collisions are generally denoted as the impact of masses. In the case of linear elastic materials, the superposition principle is applied to wave interactions, and as a result any energy lost or new scattering out of the interaction zone is inconceivable. Considering nonlinear elastic materials, such as hyperelastic ones, each strain contains a small portion of nonlinear deformation. These nonlinear deformations nullify the general superposition principle and result in the perturbation of small harmonic displacements[1].

Figure 1 illustrates how localized interaction of waves in a nonlinear elastic isotropic plate can lead to generation of slight perturbations. These perturbations can move and scatter out of the mixing zone and upon specific conditions they appear in the form of a new guided waves in the plate[2]. In this work, the required conditions to fulfil generation of a new wave, based on the nonlinear interaction of two ultrasonic guided waves, are investigated. This is accomplished by a wave vector analysis in original studies on nonlinear interaction of guided waves in plate[2]. Results show the possibility of generating numerous different types of waves in the mixing zone, only some of which are of practical importance.

As a particular case study with some very unique features, counter propagating Shear Horizontal (SH) guided wave mixing is analyzed (see Figure 2)[2]. The interaction of SH waves having certain frequencies and directions generates a secondary Lamb wave at the sum frequency of the primary SH waves has been modeled. An experimental investigation has been conducted by using Magnetostrictive Transducers (MST) for generation, and Air-coupled transducers (AC) for reception of the Lamb wave (Figure 2a). Figure 2b shows the frequency content from Tests A and B, which correspond to excitation of the two transducers individually, and the Test A+B where both transducers were excited simultaneously. The difference signal, $(A+B)-A-B$, is the subtraction of signals of Tests A and B from the signal of Test A+B. Results indicate a strong new frequency content around 2 MHz, which is the sum frequency of the SH waves.

Generation of a new nonlinear wave field is mainly based on the nonlinear properties of the material that are sensitivity to incipient damage, such as cyclic fatigue or plastic deformation, as has been shown previously[2]. Therefore, this study provides fundamental principles for nondestructive characterization of materials in order to identify damage at an early time.

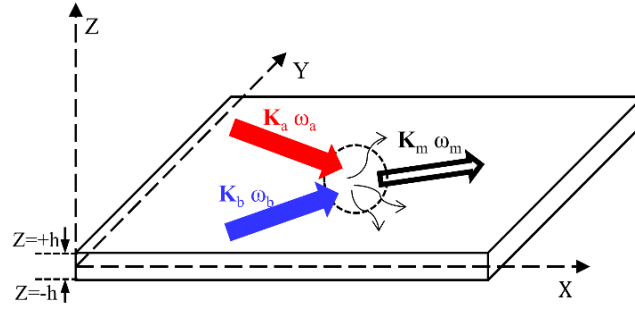


Figure 1: Schematic demonstration of nonlinear wave interaction in a plate. Waves “a” and “b” interact in a confined region then consequently, if conditions are satisfied, new waves (K_m) are perturbed and scattered out of the mixing zone.

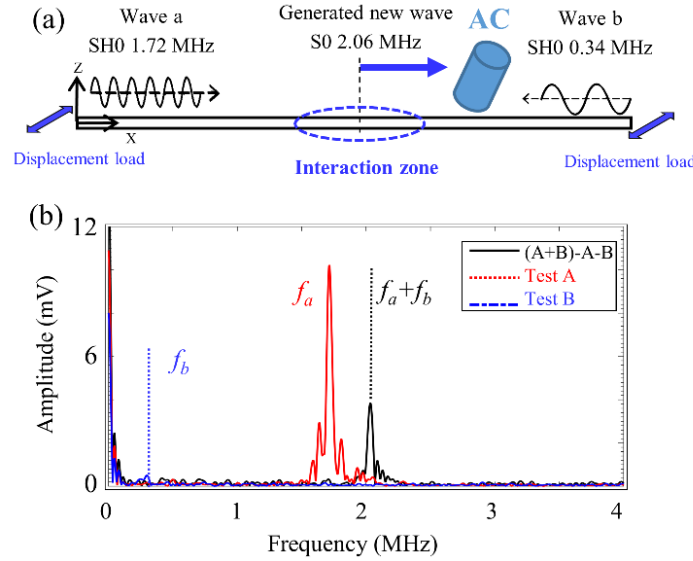


Figure 2: (a) Counter-propagating SH waves interaction, leading to generation of a symmetric Lamb wave “S0” which is captured by an Air-coupled (AC) transducer. (b) Frequency content of three tests conducted by excitation of Wave a, Wave b, and both waves (a+b). Note 1: Difference signal, (A+B)-A-B, is the remnant of tests A and B subtracted from Test A+B. Note 2: Frequency content at f_b is insignificant since AC was aligned to receive left-propagating waves.

References

- [1] Krishna Chillara, V., and Lissenden, C. J., 2012, “Interaction of guided wave modes in isotropic weakly nonlinear elastic plates: Higher harmonic generation,” *J. Appl. Phys.*, **111**(12).
- [2] Hasanian, M., and Lissenden, C. J., 2017, “Second order harmonic guided wave mutual interactions in plate: Vector analysis, numerical simulation, and experimental results,” *J. Appl. Phys.*, **122**(8), p. 84901.

Acknowledgements

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Experimental Evaluation on Damping Behavior of Carbon Fiber Reinforced Polymer with Nanoparticles

Jeffrey Kim, advised by Charles E. Bakis, Edward C. Smith

In the helicopter society, researchers tried to reduce the vibration in various aircraft structures such as rotorcraft blades. In recent years, carbon nanotubes (CNTs) were dispersed in resin matrix to enhance the damping effect of resins such as bisphenol F epoxide, through a mechanism called stick-slip [1,2]. Straining resin specimens, in which CNTs are weakly bonded to resin, will break the interfacial bond between CNTs and the matrix, allowing the CNTs to slip and stick back to the matrix (Figure 1). This reversible movement of CNTs will dissipate energy through coulombic and internal friction, enhancing the damping behavior of the system. However, the benefit of adding CNTs was not impressive once continuous fibers were introduced as well because adding CNTs increased the viscosity level to the degree that fabricating continuous fiber reinforced specimens was not feasible, so only small amount of CNTs were added which lead to minimal benefit from CNTs. However, instead of dispersing CNTs in the matrix, researchers fabricated highly dense CNT paper called buckypaper [3]. Buckypaper can also be made with other nanoparticles such as graphene nanoplatelet (GNP). Our recent goal of the investigation is to observe the damping behavior of CFRP with buckypaper made of CNT or GNP in the interlayers.

In addition to CNT or GNP buckypaper, various damping materials were incorporated in the interlayers of 6 layer-unidirectional carbon fiber reinforced polymer composite specimens in 0° and 90° direction.

Bisphenol F epoxide cured diethyltoluenediamine (DETDA) was used as the matrix material.

The addition of CNT buckypaper showed insignificant increase in the damping parameter, the loss factor, which is the tangent of the phase shift between stress and strain signals collected from the dynamic cyclic load tension-tension test on specimens (Figure 2). On the other hand, the addition of GNP buckypaper induced noticeable increase in the loss factor of the specimen (Figure 3).

Although CFRP specimen with GNP buckypaper showed improvement in the damping behavior, the fact that the specimen will continue to perform at the high level is an unknown factor. We expect to run fatigue testing on specimens in order to find out about the lifecycle of the specimens.

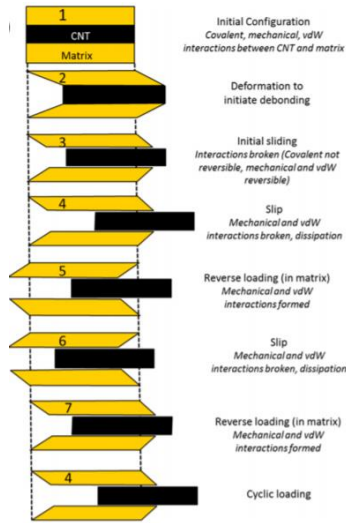


Figure 1: CNT embedded in matrix (stick-slip behavior) [1]

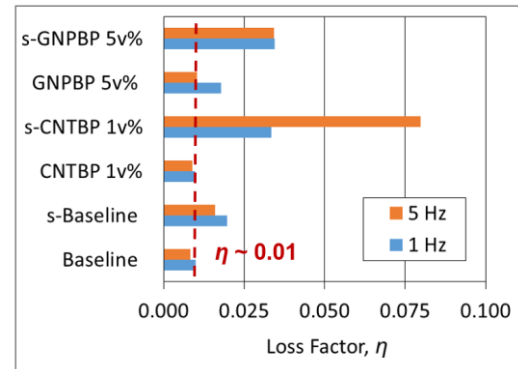


Figure 3: Result of damping test

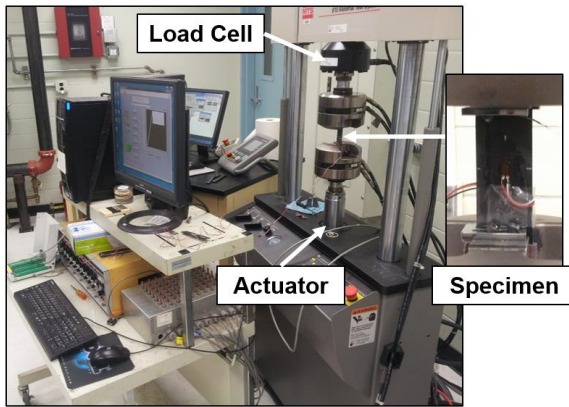


Figure 2: Damping test set up

References

- [1] Gardea, F., Glaz, B., Riddick, J., Lagoudas, D. C., & Naraghi, M. (2015). Energy dissipation due to interfacial slip in nanocomposites reinforced with aligned carbon nanotubes. *ACS applied materials & interfaces*, 7(18), 9725-9735.
- [2] Zhou, X., Shin, E., Wang, K. W., & Bakis, C. E. (2004). Interfacial damping characteristics of carbon nanotube-based composites. *Composites Science and Technology*, 64(15), 2425-2437.
- [3] Wang, Z., Liang, Z., Wang, B., Zhang, C., & Kramer, L. (2004). Processing and property investigation of single-walled carbon nanotube (SWNT) buckypaper/epoxy resin matrix nanocomposites. *Composites Part A: applied science and manufacturing*, 35(10), 1225-1232.

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In Situ Bioprinting of Bone Tissue Constructs

Kazim Kerim Moncal advised by Dr. Ibrahim Tarik Ozbolat

Statement of Purpose: Although relatively nascent, surgical robotic technology has been shown to improve dexterity and facilitate surgeries that were previously unfeasible [1]. In the same vein, 3D bioprinting for biomedical applications allows precise placement and patterning for shear-thinning biomaterials such as hydrogels. *In-situ* bioprinting lies at the crossroads of these two disciplines. In this study, new printable bio-ink including BMP2 was developed and bioprinted directly on the critical-size calvarial defect on rats in an operation room using the Multi-Arm Bioprinter (See Fig. 1.) [2]. Bone regeneration was then analyzed from micro-CT (μ CT) scanning results of the rat skulls at six weeks. From these results, novel printable bio-ink is suitable for *in-situ* bioprinting applications to facilitate increased bone regeneration.

Methods: PEI-pDNA polyplexes for *in-vivo* bio-ink was prepared based on 50 μ g plasmid per defect in bio-ink solution. First of all, PEI (2 mg/ml) and pDNA solutions (2 μ g/ μ l) were complexed and freeze-dried day before printing process and then combined with β -Glycerophosphate disodium salt hydrate (β GP) mixed with chitosan solution (CS- β GP). Collagen (Coll) (extracted from rat tail [3]) was dissolved in acetic acid to prepare a Coll solution, and then mixed with ratio of 4:1 (v/v) (CS- β GP:Coll). Additionally, collagen

sponges were added to the overall solution and mixed for 30 min. at room temperature until a homogenous solution was achieved. Finally, hydroxyapatite (HA) nanoparticles in powder form was added to the final solution and mixed for 15 min.

Results: The scaffold architecture had a circular pattern with 0.3 mm pore size and 0.3 mm filament diameter for *in vivo* study. *In-situ* bioprinting process was occurred after opening 5 mm-diameter 2 mm-thick two defects on rat skulls. Then, the bio-ink, bio-ink incorporated BMP2 was bioprinted into the defect sides. After six weeks of bioprinting, calvarium tissues were harvested to measure bone volume fractions via μ CT scanning (see Fig. 2). Scanned images were imported to Avizo software to calculate bone volume fraction.

Conclusions: New bio-ink, and BMP2 included bio-ink were able to bio-print using an extrusion-based bioprinting system. Also, both bioink solutions were able to support bone regeneration over time by providing newly-formed mineralize tissue. BMP2 incorporation was demonstrated increased bone formation compared to the only bio-ink scaffolds.

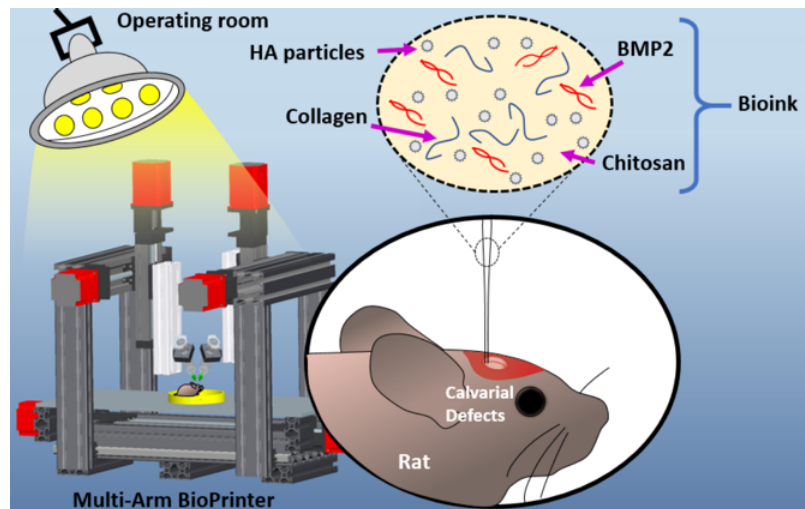


Figure1. *In-vivo* bioprinting process of bone tissue constructs

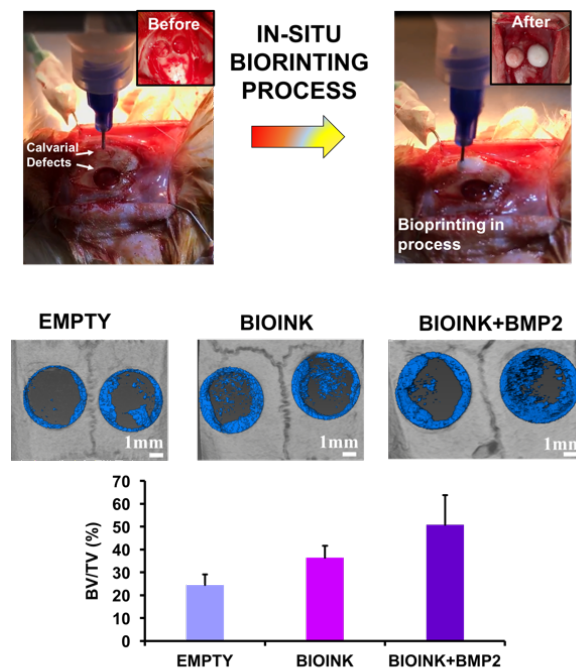


Figure 2. Results of bone volume fraction at 6 weeks (Values are expressed as $\pm$ SEM (n=3))

References:

- [1] Lanfranco, Anthony R., et al. *Annals of surgery* 239.1 (2004): 14.
- [2] Ozbolat, Ibrahim T., et al. *Robotics and Computer-Integrated Manufacturing* 30.3 (2014): 295-304.
- [3] Rajan, Navneeta, et al. *Nature protocols* 1.6 (2006): 2753.

INCORPORATING MAGNETIC RESONANCE INTO A WAFER PROBING STATION

Duane McCrory, advised by Dr. Patrick Lenahan

Abstract

As semiconductor technology continues to scale, and newer material systems are introduced, it is imperative to have reliability measurements that are capable of identifying performance-limiting defects at the atomic scale. Conventionally, most reliability measurements are performed using wafer probing stations. The electrical measurements made at these stations have proven widespread and high-volume applicability for electrical measurements. However, these measurements yield limited information about the atomic-scale nature of the defects that ultimately govern reliability. The most sensitive technique for identifying atomic-scale defects in semiconductor devices is electrically detected magnetic resonance (EDMR). This technique is a derivative of electron paramagnetic resonance (EPR) in which the measurement is performed on fully processed device structures. EDMR is at least ten million times more sensitive than conventional EPR [4], and thus adequately addresses the sensitivity needs associated with advanced device structures. EDMR is a powerful tool for investigating performance limiting defects in many different material systems [4]-[8]. Unfortunately, EDMR measurements require significant sample preparation and expensive spectrometers. Despite the rich information provided by EDMR, the experimental barriers relegate it as a technique only suitable for individual device measurements. Clearly there is a need for an EDMR spectrometer that eliminates sample preparation and can be incorporated into a conventional wafer probing station.

We report on a novel semiconductor reliability technique that merges electrically detected magnetic resonance (EDMR) with a conventional semiconductor wafer probing station (Fig. 1). This union with a semiconductor probing station allows EDMR measurements to be performed at the wafer level. Our measurements forgo a microwave cavity or resonator for a very small non-resonant near field microwave probe (Fig. 2) [1], [9]. Bipolar amplification effect (BAE) [2] (Fig 3), and spin dependent charge pumping (SDCP) (Fig. 4) [3], were demonstrated on various SiC MOSFET structures. These measurements were made via frequency-swept EDMR. The elimination of the resonance cavity, and incorporation with a wafer probing station, greatly simplifies the EDMR detection scheme and offers promise for widespread EDMR adoption in semiconductor reliability laboratories.

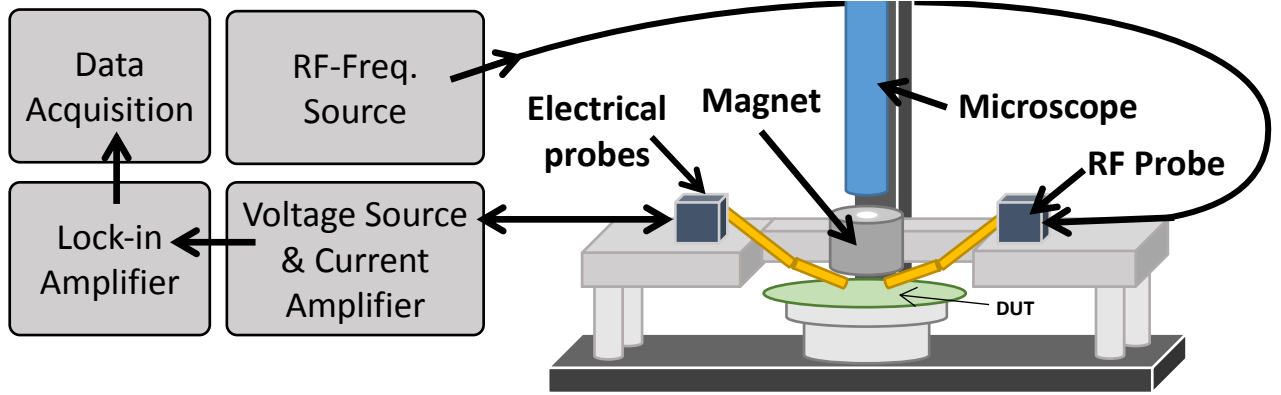


Fig. 1: Wafer-Level EDMR Spectrometer. Cartoon depiction with labels of the spectrometer. The entire setup fits conveniently into one wafer station and one computer rack. This compact setup may allow for more widespread use.

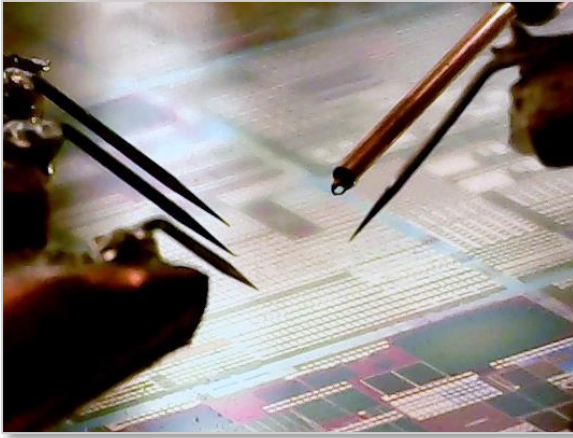


Fig. 2: Side view of the non-resonant near field microwave probe (top right) utilized in all EDMR measurements made in this paper. The four other probes are home-built high-frequency current probes used to measure device characteristics.

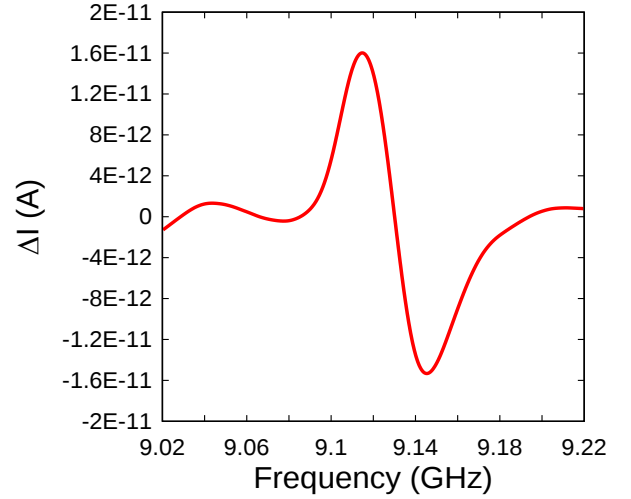


Fig. 3: EDMR of the same 4H-SiC MOSFET utilizing the BAE biasing scheme. $V_G - V_{th} = 1$ V and -2.9 V applied to the source of the MOSFET.

References

- [1] J. P. Campbell, J. T. Ryan, P. R. Shrestha, Z. Liu, C. Vaz, J. H. Kim, V. Georgiou, and K. P. Cheung, *Anal. Chem.*, vol. 87, no. 9, pp. 4910–4916, 2015.
- [2] T. Aichinger and P. M. Lenahan, *Appl. Phys. Lett.*, vol. 101, no. 8, 2012.
- [3] B. C. Bittel, P. M. Lenahan, J. T. Ryan, J. Fronheiser, and A. J. Leles, *Appl. Phys. Lett.*, vol. 99, 2011.
- [4] C. J. Cochrane, P. M. Lenahan, and A. J. Leles, *Appl. Phys. Lett.*, vol. 90, no. 12, pp. 2–5, 2007.
- [5] D. J. Meyer, N. A. Bohna, and P. M. Lenahan, *Applied Physics Letters*, vol. 84, no. 17, pp. 3406–3408; 2004
- [6] M. A. Anders, P. M. Lenahan, C. J. Cochrane, and A. J. Leles, *IEEE Trans. Electron Devices*, vol. 62, no. 2, pp. 301–308, 2015.
- [7] M. J. Mutch, P. M. Lenahan, and S. W. King, *J. Appl. Phys.*, vol. 119, 2016.
- [8] M. A. Anders, P. M. Lenahan, and A. J. Leles, "A new electrically detected magnetic resonance approach for the study of metal-oxide-semiconductor field-effect transistor interfaces: multi resonance frequency spin dependent charge pumping and spin dependent recombination - applied to the 4H-SiC/SiO₂ interface" *unpublished*

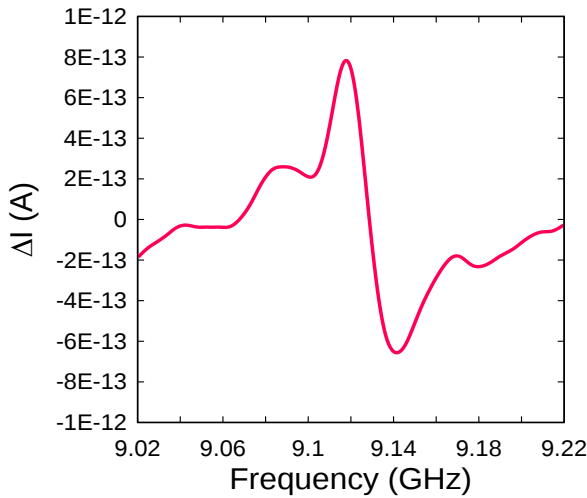


Fig. 4: SDCP of the same 4H-SiC MOSFET with ± 16 V square wave applied to the gate with a rise/fall time of $1\mu s$.

Standing surface acoustic wave (SSAW)-based fluorescence-activated cell sorter

Liqiang Ren, advised by Tony Jun Huang and Thomas E. Mallouk

Fluorescence-activated cell sorter (FACS) is high-throughput, single-cell characterization and sorting tool that has revolutionized how cells are studied and purified.^[1,2] In the past decades, FACS has become indispensable for a wide variety of applications in fundamental biological/biomedical research and clinical practice. Despite the significant impact, current benchtop FACS systems have the following drawbacks: high cost for use and maintenance, large size, complex configuration, low biocompatibility, biosafety concerns, and difficulty in handling small sample volumes. Microfluidic FACS (μ FACS), the combination of microfluidics and cell sorting techniques, has been regarded as an excellent candidate to overcome the limitations of the traditional FACS. A μ FACS sorts cells in an enclosed environment to avoid potential aerosol contamination, and is inherently good at handling tiny amounts of sample, generating smaller volume of waste, and utilizing less costly reagents. Additionally, the cost and size of a μ FACS is also expected to be much lower than traditional FACS.

Among the various microfluidic techniques for FACS, acoustofluidics (*i.e.*, the fusion of acoustics and microfluidics) is attractive because of its amenability to integration, miniaturization, and biocompatible cell manipulation. For example, Jakobsson *et al.* have demonstrated an acoustofluidic FACS using bulk acoustic waves (BAW) for both cell focusing and cell deflection, and achieved a throughput of ~ 150

events/sec. Aside from BAW, surface acoustic waves (SAW) have also been extensively utilized to develop acoustofluidic cell sorters. Unlike the BAW-based devices, SAW-based cell sorters use microfabricated interdigital transducers (IDT) as wave generators and show better resolution and controllability on cell manipulation, allowing a higher throughput to be achieved.

In this work, we employ standing surface acoustic waves (SSAW) to realize both cell focusing and cell deflection, and demonstrate an all-in-one FACS by integrating a SSAW-based 3D cell-focusing unit, a SSAW-based cell-deflection unit, and an in-plane-integrated optical fiber-based cell-detection unit into a single chip. The sheathless, SSAW-based 3D cell-focusing greatly simplifies the design of the microfluidic device and reduces the volume of biohazard waste and complexity of pump system. Without using sheath flow, the impact of shear stress on cells caused by sheath flow can also be avoided. A precisely 3D focusing enables the utilization of in-plane-integrated optical fibers for fluorescent excitation and detection. In the cell-deflection unit, a focused-IDTs is adopted to generate high-resolution SSAW for high-throughput cell deflection. With the integrated SSAW-based FACS, we demonstrate the sorting of fluorescently-labeled HeLa cells from unlabeled group with a sorting purity over 90% at a throughput of 2,500 events/sec.

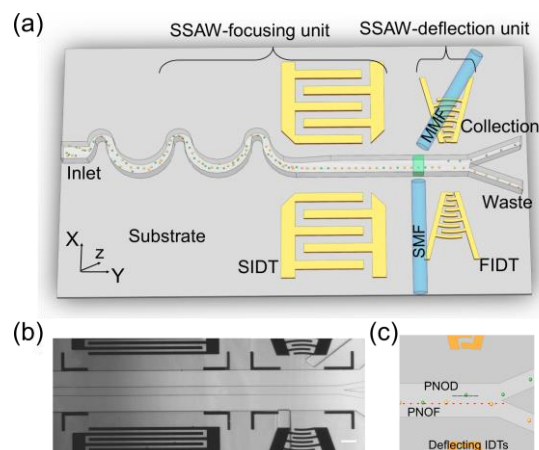


Figure 1. (a)Schematic of the SSAW-based FACS chip. (b)Microscopic image of the SSAW-based focusing and deflection units. (c)Schematic indicates the position of pressure nodes from the deflecting IDT (PNOD, black dashed line) and pressure nodes from a focusing IDT (PNOF, red dotted line). Scale bar: 200 μm .

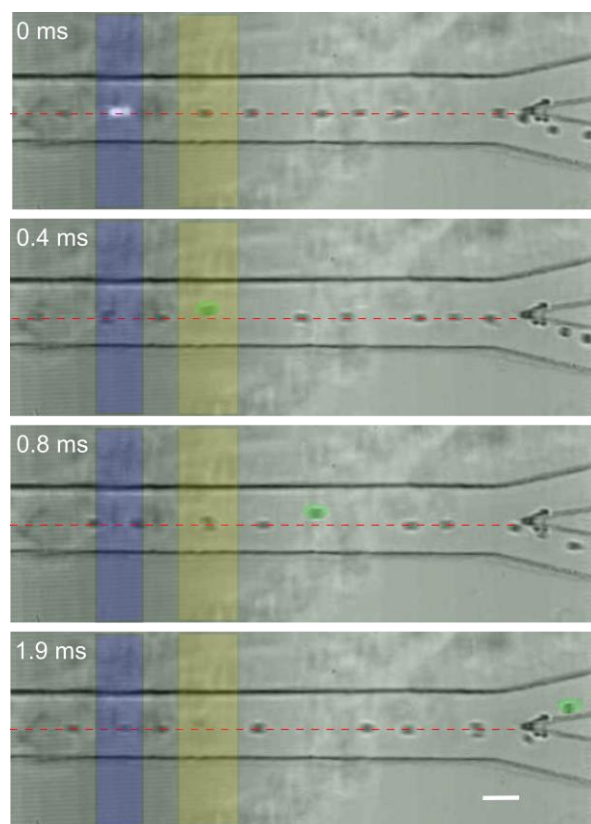


Figure 2. A time-lapsed image of high-throughput sorting. The FL-labeled Hela cell was sorted into the top outlet (collection), while the non-labeled cells entered the bottom outlet (waste). The FL-labeled cell was excited by the laser at 0 msec and thereafter was presented as a green dot. The blue area indicates the detection area while the yellow area indicates the deflection area. Scale bar: 50 μm

References

- [1] H. R. Hulett, W. A. Bonner, J. Barrett, L. A. Herzenberg, *Science* **1969**, 166, 747.
- [2] J. F. Leary, *Cytom. Part A* **2005**, 67A, 76.

Poster Presentations

Development of high energy density supercapacitors

A. R. Aref, C. A. Randall, M. T. Lanagan, R. Rajagopalan

Supercapacitors are receiving extensively attention as potential energy storage devices due to their high capacitance, high power density, and long cycle life. The energy density of the supercapacitor is limited by the specific capacitance of the activated carbon electrodes. Presently, we demonstrate a high energy density supercapacitors made of a high purity polymer derived carbon with controlled pore size and high surface area. In particular, we focused on developing two types of supercapacitors that includes:

1) Electrochemical double layer capacitors(EDLC)

Charge storage mechanism in EDLC is primarily based on the formation of electrical double layer at electrode/electrolyte interface. Symmetric EDLC capacitors were made using high purity carbon electrodes derived from polymer precursors with surface area $> 2000 \text{ m}^2/\text{g}$ that suppressed solvent decomposition and leakage current.

2) Lithium ion Capacitors (LIC)

Asymmetric design based on the use of a double layer electrode and a prelithiated anode that provides larger

cell voltage ($> 4\text{V}$) and high energy density were fabricated. Various carbon nanomaterials are currently being synthesized to push the energy density beyond 300 J/cc .

In this investigation, symmetric capacitors made using the synthesized carbon electrodes in neat 1-butyl 3-methylimidazolium tetrafluoroborate exhibited a specific capacitance of 136 F/g at 1 A/g when charged and discharged between 0 to 3.8V . The capacitor also showed 90% capacitance retention over 5000 cycles. In order to further evaluate the fabricated capacitor, accelerated floating voltage was conducted. The tests showed that the capacitor retained 80% of its initial value after 55 hours at 3.8V and 90% retention at 3.5V after 260 hours. The maximum gravimetric and volumetric energy density of the capacitor was 74.4 Wh/kg and 37.5 Wh/l , respectively.

In addition, rate capability of LIC was improved by using nanographite anode with particle size $\sim 30 \text{ nm}$.

In order to synthesize bimodal pore size distribution carbon, we used soft template approach where surfactant act as a templating agent (Figure 1). The PFA-Ph activated carbon was made using acid polymerization of Furfuryl alcohol and Phloroglucinol in the presence of Pluronic F-127 surfactant.

This was followed by pyrolysis and activation of synthesized polymer at 800 °C to yield PFA-Ph activated carbon. By using synthesized hierarchical activated carbon, we were able to double specific capacitance of the device compared with state of the art YP50 (pure microporous carbon).

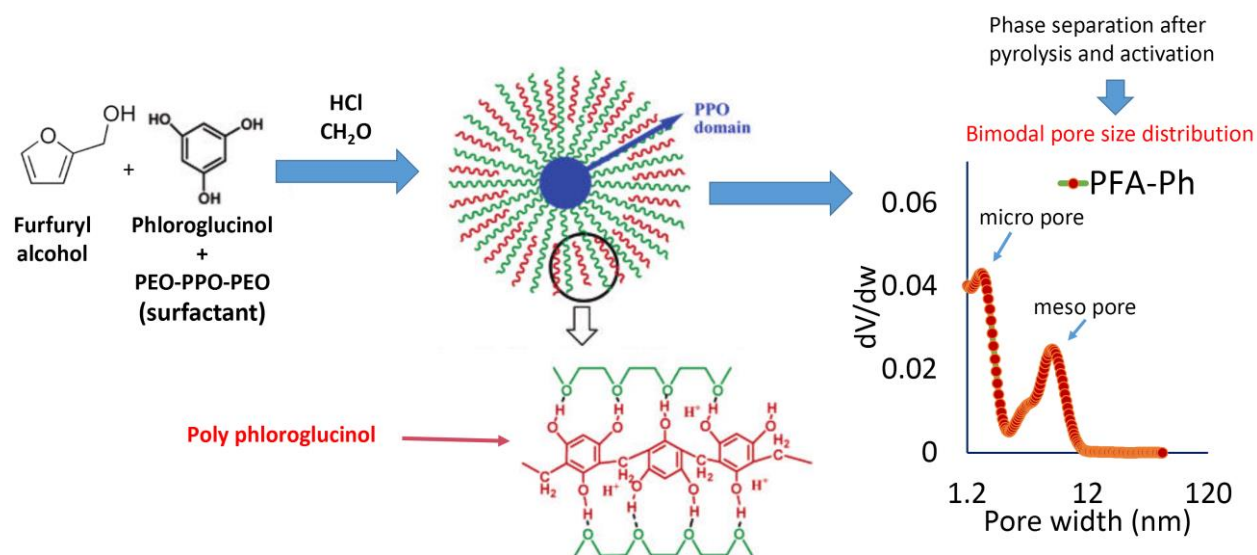


Figure 1: Schematic representation of synthesis approach using soft templating agent (surfactant)

References

- [1] 1. S. A. Hamidi, D. M. Ionel and A. Nasiri, Electr Pow Compo Sys, 2015, 43, 1434-1452.
- [2] 2. L. C. Haspert, E. Gillette, S. B. Lee and G. W. Rubloff, Energ Environ Sci, 2013, 6, 2578-2590.
- [3] 3. P. Sharma and T. S. Bhatti, Energ Convers Manage, 2010, 51, 2901-2912.
- [4] 4. W. H. H. Zhu and B. J. Tatarchuk, Appl Energ, 2016, 169, 460-468.
- [5] 5. W. T. Gu and G. Yushin, Wires Energy Environ, 2014, 3, 424-473.

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Circular Polarization Filters for Mid-IR Light using Chiral Sculptured Thin Films

Vikas Vepachedu, advised by Dr. Akhlesh Lakhtakia

A chiral sculptured thin film (Chiral STF) consists of an array of helicoidal columns with fixed pitch. Such films were fabricated out of zinc selenide using resistive-heating physical vapor deposition for the purpose of creating circular polarizer filters by exploiting the circular Bragg phenomenon (CBP). During the deposition, the substrate was tilted at an angle of 20° with respect to the incident vapor flux and rotated as per the asymmetric serial bideposition (ASBD) technique. The pitch of each successive chiral STF was made to be double that of the previous chiral STF resulting in a total of five samples which collectively act as polarization filters at wavelengths between around 732 nm and 11,712 nm. For this reason, zinc selenide was chosen for the material due to its practically constant refractive index over this range of wavelengths. In general, as the period is increased, the center wavelength of the CBP is increased as well. Additionally, the thickness of one of these samples was doubled to study the

impact of thickness on the performance of these filters. All of these filters were characterized morphologically (using a scanning electron microscope) and optically (using various spectrophotometers depending on the wavelength range of interest). Shown in Figure 1 is a micrograph of the cross sections of one of the thin films fabricated for this study. The corresponding optical properties of this film are shown in Figure 2; the sample reflects right circularly polarized light and transmits left circularly polarized light. Similar results can be obtained for the other samples. Furthermore, we have shown that the morphological characteristics remain stable as the period is increased. Thus, we were not only able to fabricate circular polarizer filters for the visible light regime but also for the infrared regime (up to mid-IR wavelengths).

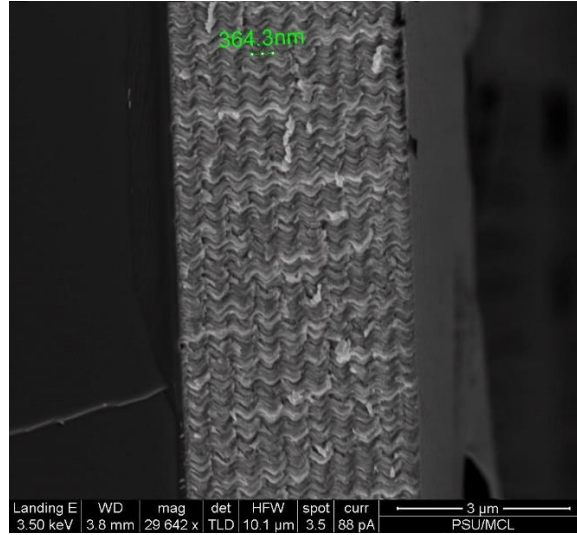


Figure 1: Cross-sectional, scanning electron microscope image of a chiral STF with a period of around 366 nm. This sample is composed of 10 periods total. The wavy appearance is given by the parallel helicoids it is composed of.

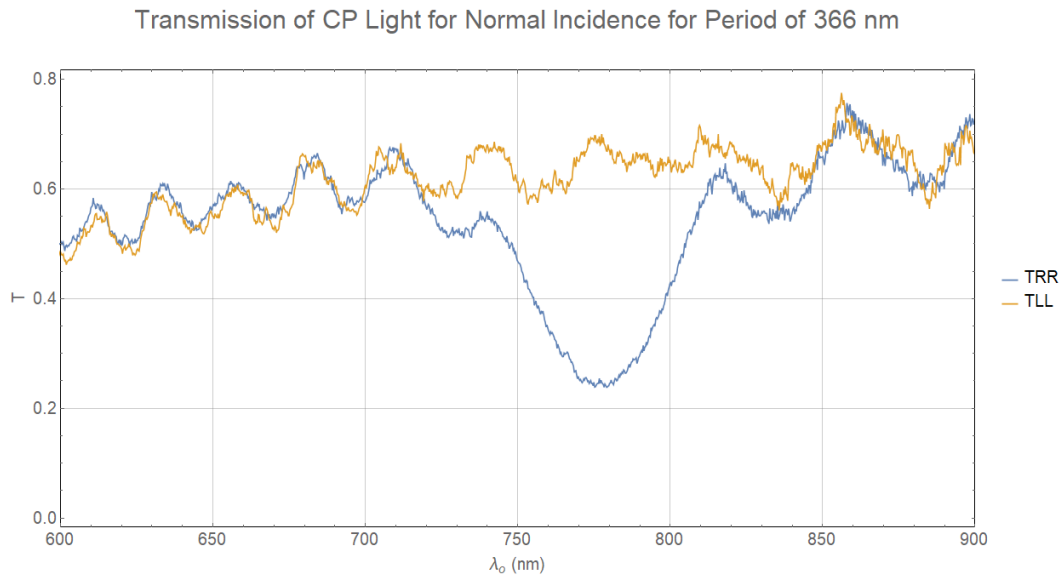


Figure 2: Experimentally measured transmission of circularly polarized light through the sample shown in Figure 1. TRR is the amount of RCP light transmitted when RCP light is incident. Likewise for TLL but with LCP light. The dip in TRR is indicative of the Bragg phenomenon.

References

- [1] M. Querry, Optical constants of minerals and other materials from the millimeter to the ultraviolet.
- [2] CERDEC U.S. Army RDECOM, Aberdeen, MD, USA (1987).
- [3] P. D. McAtee, "Reflection and transmission of obliquely incident light by asymmetric serialbideposited chiral sculptured thin films," Master's thesis, The Pennsylvania State University (2016).

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Electrically Detected Magnetic Resonance on Multi-Gate Metal Oxide Silicon Transistors

Kenneth Myers, advised by Dr. Patrick Lenahan

Multi-gated metal oxide semiconductor field effect transistors (MOSFETs) have recently become important in high-performances CMOS integrated circuits. Multi-gated devices, commonly called FinFETs, have reduced short channel effects, allowing for greater scalability.[1] However, there is little in the literature about the atomic defects at the semiconductor-dielectric interface in FinFETs. In this study, we explore traps at the FinFET Si/dielectric interface with electrically detected magnetic resonance (EDMR). The devices involved in this experiment are on (100) silicon-on-insulator wafers with 90nm Si layers and 125nm buried oxides. The FETs have 1nm SiO₂ and 2nm HfSiON/TiN/polySi-capped gate stacks with an effective oxide thickness of about 1.1nm. The body of the devices are lightly doped p-type at $2 \times 10^{15}/\text{cm}^3$. Each FinFET is configured as a gated diode with n+/p-/p+ with a fin length of 500nm, fin height of 80nm, and fin width of 50nm. For a single set of contacts, 500 fins are connected in parallel. Extensive electrical measurements on these devices have been reported by Young *et al.*[2][3]

In order to increase the defect density and maximize the size of the resonance response, we have irradiated the FinFETs to 1 MRad through exposure to a ⁶⁰Co

gamma source. During irradiation, a bias of +0.25V was applied to the gate contact. Pre irradiated EDMR spectra are weak and poorly resolved whereas quite strong signal to noise spectra appear after the irradiation.

Our EDMR measurements utilized a home-built spectrometer. The X-band (≈ 9.5 GHz) spectrometer includes a 4-inch Lakeshore electromagnet with a Micro-Now microwave bridge and a TE₁₀₂ cavity. Spin dependent device current was measured with a Stanford Research Systems Low-Noise Current Preamplifier. The detection utilized a home-built virtual lock-in amplifier. Measurements were conducted at room temperature.

The observed EDMR spectra involve multiple overlapping lines with g values ranging from 2.0011 to 2.0084. Such g values are generally consistent with P_b centers (silicon dangling bonds), however the linewidths of these spectra are significantly broader than those typically observed for P_b center defects. The spectra can be observed in Figures 1 and 2. In both figures, a large peak is seen in the center of the sweep, which is presumed to be the same resonance response. Figure 2 contains at least one more line which partially overlaps the central peak.

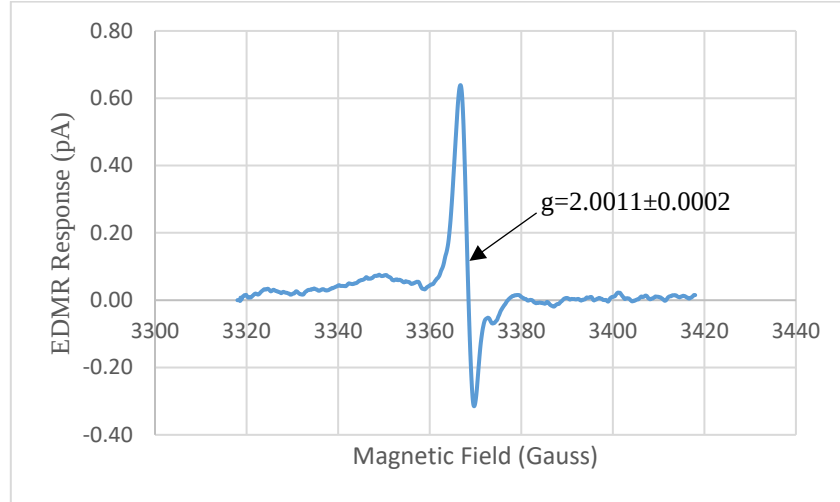


Figure 1: In-Phase portion of the EDMR trace containing a line with the g value of 2.0011 ± 0.0002

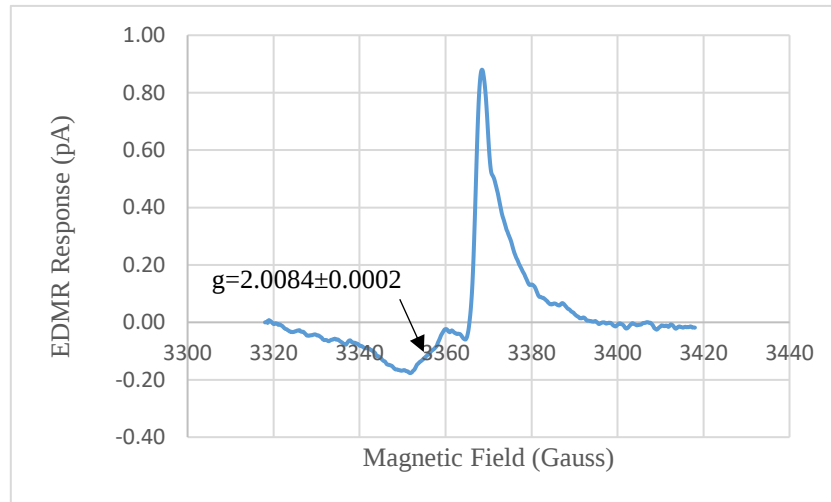


Figure 2: Quadrature portion of the EDMR trace containing a line with the g value of 2.0084 ± 0.0002

References

- [1] Wann, C. H., Noda, K., Tanaka, T., Yoshida, M., & Hu, C. (1996). *IEEE Transactions on Electron Devices*, 43(10), 1742-1753.
- [2] Young, C. D., Neugroschel, A., Matthews, K., Smith, C., Heh, D., Park, H., ... Bersuker, G. (2010). *IEEE Electron Device Letters*, 31(7), 653–655.
- [3] Young, C. D., Neugroschel, A., Matthews, K., Smith, C., Park, H., Hussain, M. M., ... Bersuker, G. (2010). *Proceedings of 2010 International Symposium on VLSI Technology, System and Application, VLSI-TSA 2010*, 68–69.

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Plasma Metamaterials

Sarah Antonsson, advised by Michael Lanagan and Clive Randall

Metamaterials are a class of man-made materials which showcase unnatural optical behaviors, such as negative refraction. By integrating a controllable plasma array into the metamaterial, electromagnetic properties can be dynamically altered. To obtain a negative index of refraction, the material must have negative electric permittivity and magnetic permeability in the same frequency range [1]. Plasma contributes negative permittivity to the metamaterial for electromagnetic waves with a frequency below the plasma frequency [2]. This integration is possible due to the resonant nature of metamaterials, which creates strong electric fields that can break down the surrounding gas to ignite plasma. To evaluate constituent material performance for plasma production, we have developed a double-ridge waveguide (DRWG) to measure the performance of resonating dielectric blocks. DRWGs focus electric field between conductive ridges which run along the top and bottom of the waveguide, and a dielectric block is placed between the ridges. The DRWG is then vacuum-pumped and backfilled with low-pressure argon gas and, when powered, forms argon plasma within a gap between the dielectric and upper ridge. Simulations show that the dielectric block sharply increases the electric field strength within the gap, enabling this plasma ignition. Argon pressure is varied and power data is collected to determine the minimum power needed for plasma ignition. In this setting, dielectric work functions and the electronic properties of plasma can be closely measured.

Experimental Setup

A small dielectric block (approximately 10 mm long, 8 mm wide and 3.5 mm tall) is placed between the ridges of a DRWG. On one sidewall of the DRWG, two holes were cut for a vacuum port and an argon inlet. On the opposite sidewall, a hole was cut for a sapphire lens with which to look into the DRWG and view the plasma. Because very little current traverses the sidewalls of the DRWG, cutting holes into the sidewalls does not adversely affect its wave-guiding ability. A cross section of the DRWG is shown in fig. 1. The waveguide is powered by an amplified signal between 2 - 3 GHz, and the forward and reflected power are measured (fig. 2).

Results

When plasma is ignited at the first frequency peak (fig. 2) above the DRWG cutoff frequency ($f_{\text{cut-off}} \sim 2.2$ GHz), plasma is seen between the corners of the dielectric block and the upper ridge (fig. 3, left). S21 data consistently shows a resonance peak below the cutoff frequency (fig. 2). When the DRWG is powered at this sub-cutoff frequency, plasma is formed above the entire length of the dielectric block (fig. 3, right). Normally, energy cannot propagate below the cutoff frequency of a waveguide, but we suspect that the dielectric block lowers the cutoff frequency for that portion of the DRWG, giving a boost in local power for the attenuating waves that can reach it and resonate within. This will be explored by changing the distance between the dielectric block and the input power.

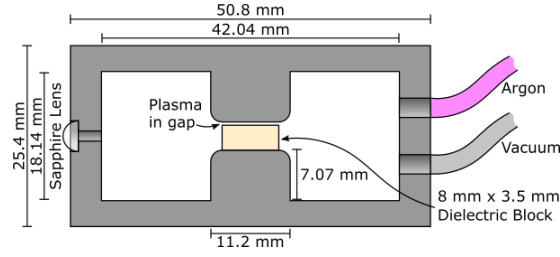


Figure 1: This schematic cross section of the double-ridge waveguide highlights dimensions, dielectric block placement, plasma area, and locations of the viewing lens, gas inlet, and vacuum outlet.

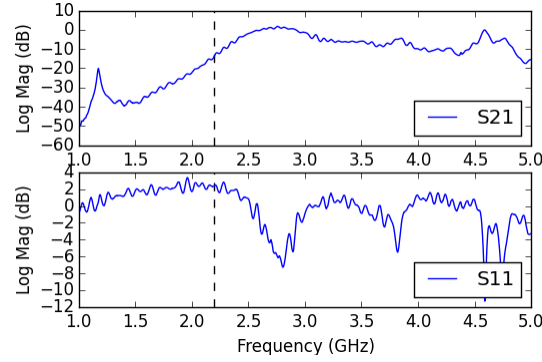


Figure 2: Plots of forward (S_{21}) and reflected (S_{11}) power show resonant frequencies for a calcium titanate block placed within the DRWG. Speaks in S_{21} correspond to sharp drops in S_{11} at points of resonance. The dashed line indicates the cutoff frequency of 2.2 GHz.

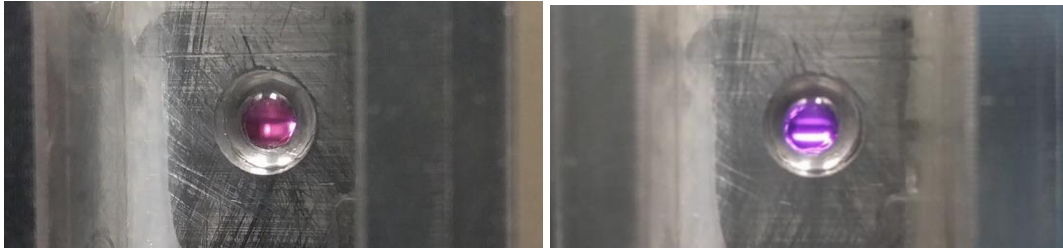


Figure 3: Argon plasma is visible through the sapphire window in the DRWG. Due to refraction of the lens, the view is flipped horizontally and vertically. (Left) Above the cutoff frequency, plasma forms on the corners of the dielectric block. (Right) Below the cutoff frequency, plasma forms along the full length of the dielectric block.

References

- [1] V. G. Veselago, Sov. phys. Usp., 10, 509-514 (1968).
- [2] R. Fitzpatrick, "Dielectric constant of a plasma," *Classical Electromagnetism: An intermediate level course*, The University of Texas at Austin (2006).

Facile Electrochemical Synthesis of 2D Monolayers for Thin Film Transistors

Daniel Schulman, Saptarshi Das

The class of two-dimensional (2D) layered transition metal dichalcogenide (TMD) materials has garnered significant interest because of their robust semiconducting and optoelectronic properties down to the single monolayer limit. Despite the high demand for monolayer TMDs, they have been either costly or challenging to acquire, hence the need for facile synthesis techniques such as the electro-ablation (EA). The EA process[1] has key advantages over mechanical exfoliation and chemical vapor deposition (CVD) methods. Mechanical exfoliation results in extremely small, low yields of monolayers, whereas wafer-scale CVD growth of high-quality monolayers demands expensive infrastructure and resources. The EA process to convert MoS₂, WS₂, and MoSe₂ multilayer films to monolayers is schematically shown in Figure 1a–c.[2] First, the TMD material is mechanically exfoliated onto a conductive TiN film on Si. The sample is then placed in a three-terminal electrochemical cell where the conductive TiN functions as the working electrode. Next, a relatively small anodic potential of less than ~1.4 V applied against an Ag/AgCl reference electrode for a period of time up to 120 s converts the exfoliated multilayers into their corresponding monolayers via an anomalous but self-limiting corrosion process consistently over the entire substrate irrespective of the initial thickness of the multilayer flakes as shown in the before and after optical images for MoS₂ in Figure 1 d,e. Intense PL shown in Figure 1f is observed across the entire monolayer MoS₂ flake at an energy of ~1.85 eV corresponding to the monolayer direct band gap.[3] Similar results were found for WS₂ and MoSe₂.

Monolayer MoS₂ transistor characteristics are shown in Figure 1g.[2] MoS₂ and WS₂ devices have an average mobility of 19.4 ± 2.6 cm²/V s and 6.7 ± 3.3 cm²/V s respectively which are comparable with the highest performing CVD monolayer materials. [4][5] MoSe₂ devices average electron mobility of 2.6 ± 0.6 cm²/V s, which is about an order of magnitude lower than what has been achieved with CVD materials.[6] Note that for WS₂ and MoSe₂, although there are reports of higher mobility monolayer materials, [5, 6] the ON currents reported here, namely, 40 μ A/ μ m for WS₂ and 40 μ A/ μ m for MoSe₂ are much larger.

It was found from temperature dependent measurements that an abrupt Anderson-type semiconductor/insulator-to-metal transition exists for these monolayers.[7] At low applied gate voltages where the carrier concentration is relatively low, the strongly bound electron system exhibits an “insulator” type behavior where the resistivity decreases, and hence current increases with increasing temperature. In the disordered 2D electron gas, an abrupt quantum phase transition to a “metallic” phase occurs when the energy exceeds the mobility edge or critical energy. The delocalized electrons, now stabilized by electron interactions, decrease in mobility with increasing temperature. This insulator-to-metal transition is desirable for high-power devices as it prevents thermal runaway from occurring.

This work has demonstrated that EA synthesis can facilitate the study of the rich monolayer physics for a diverse set of materials, especially for those requiring inexpensive, high-yield, large domain materials.

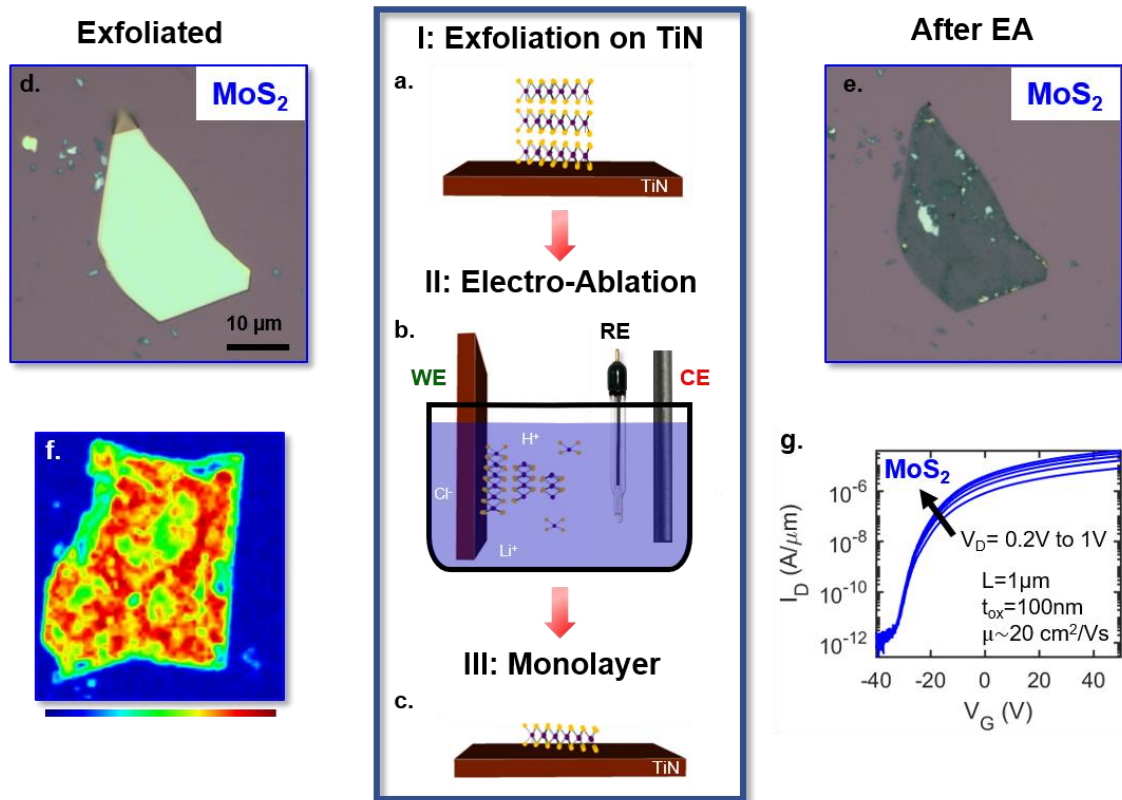


Figure 1: Schematic of the EA process (a) flakes of TMD are mechanically exfoliated onto a 100 nm thick conductive TiN film on Si. (b) Sample is placed into an electrochemical cell with a 1 M conductive LiCl electrolyte where an anodic potential is applied to TiN. (c) Within seconds, the bulk material begins to ablate into the solution converting the multilayer flakes to single monolayers strongly adhered to the TiN substrate. Optical images of (d,e) MoS₂ after exfoliation and after EA. (f) PL intensity map showing intense PL across the monolayers an energy of ~ 1.85 corresponding to the direct band gaps of MoS₂. (g) Transfer characteristics in the log scale at different drain biases (V_D) for a backgated monolayer MoS₂ transistor.

References

- [1] S. Das *et al.*, "A Self-Limiting Electro-Ablation Technique for the Top-Down Synthesis of Large-Area Monolayer Flakes of 2D Materials," *Sci Rep*, vol. 6, no. May, p. 28195, Jun 21 2016.
- [2] D. S. Schulman, A. Sebastian, D. Buzzell, Y. T. Huang, A. J. Arnold, and S. Das, "Facile Electrochemical Synthesis of 2D Monolayers for High-Performance Thin-Film Transistors," *ACS Appl Mater Interfaces*, vol. 9, no. 51, pp. 44617-44624, Dec 27 2017.
- [3] G. R. Bhimanapati *et al.*, "Recent Advances in Two-Dimensional Materials beyond Graphene," *ACS Nano*, vol. 9, no. 12, pp. 11509-39, Dec 22 2015.
- [4] K. K. H. Smithe, C. D. English, S. V. Suryavanshi, and E. Pop, "Intrinsic electrical transport and performance projections of synthetic monolayer MoS₂ devices," *2D Materials*, vol. 4, no. 1, p. 011009, 2016.
- [5] D. Ovchinnikov, A. Allain, Y.-S. Huang, D. Dumcenco, and A. Kis, "Electrical Transport Properties of Single-Layer WS₂," *ACS Nano*, vol. 8, no. 8, pp. 8174-8181, 2014/08/26 2014.
- [6] X. Wang *et al.*, "Chemical vapor deposition growth of crystalline monolayer MoSe₂," *ACS Nano*, vol. 8, no. 5, pp. 5125-31, May 27 2014.
- [7] A. Punnoose and A. M. Finkel'stein, "Metal-insulator transition in disordered two-dimensional electron systems," *Science*, vol. 310, no. 5746, pp. 289-91, Oct 14 2005.

Fabrication of a Vascularized Tumor Microenvironment for Immunotherapy

Madhuri Dey, Ibrahim Ozbolat

Despite the plethora of research and advances in treatment, cancer remains one of the leading causes of mortality worldwide¹. Cure and prevention of such a complex disease can be possible by creating physiologically relevant three dimensional (3D) tumor models for understanding cancer genesis and progression. Immunotherapy for cancer treatment is an emerging field of research but lacks a proper understanding of cancer-immune cell interaction which is vital to tumor progression². In vitro tissue models that can recapitulate the dynamic immune-cancer microenvironment are greatly needed to understand these complex interactions. In this study, a relatively simple tumor spheroid model has been employed to study the effects of engineered immune cells on the fabricated tumors. Primary human T cells with T cell receptors (TCRs) that can recognize bacterial metabolites in the context of MR1 molecule³ are engineered by Dr. Derya's team at Jackson Labs. These engineered TCR+ T cells are employed to study the immune-cancer interaction in 3D and successful eradication of the fabricated tumor mass is observed over time. Introduction of TCR engineered T cells to 3D tumor spheroids in the presence of bacterial supernatant⁴ exhibits about 80% cytotoxicity over three days of culture as shown in Figure 1.

Morphologically the tumor spheroids disengages to smaller clusters on T cell exposure and this is further quantified by staining the dead nuclei with ethidium bromide and quantifying the decrease in GFP fluorescence intensity of tumor spheroids, as compared to control group which maintain structural integrity over this time. Additionally, a 3D organoid based vascularized breast tumor microenvironment is fabricated using a highly metastatic breast cancer cell line, MDA-MB-231. Pre-vascularized mini tumors encapsulated in fibrin exhibits extensive capillary sprouting which anastomose to form a well-connected capillary network. The presence of a hollow lumen as well as intravasation of cancer cells¹ in these capillaries was confirmed by 3D surface rendered images from two-photon microscopy, as shown in Figure 2. The encapsulated tumors exhibited not only robust vascular network formation around the growing tumor but also enabled contiguous internal vascularization of the tumor itself, mimicking native physiology¹. Thus, this system creates a platform for studying immune-cancer cell interactions, as well as for anti-cancer drug screening therapies for breast cancer in future^{3,4}.

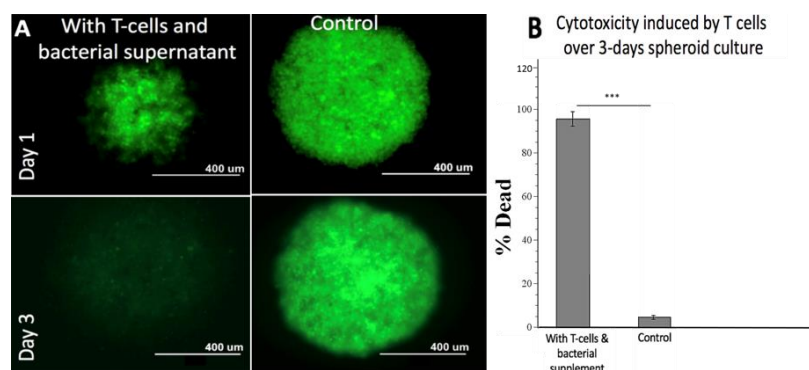


Figure 1: (A) Morphology of 3D tumor spheroids after T cell treatment for 3days. (B) Quantification of cancer cell death over 3-days of 3D tumor spheroid culture

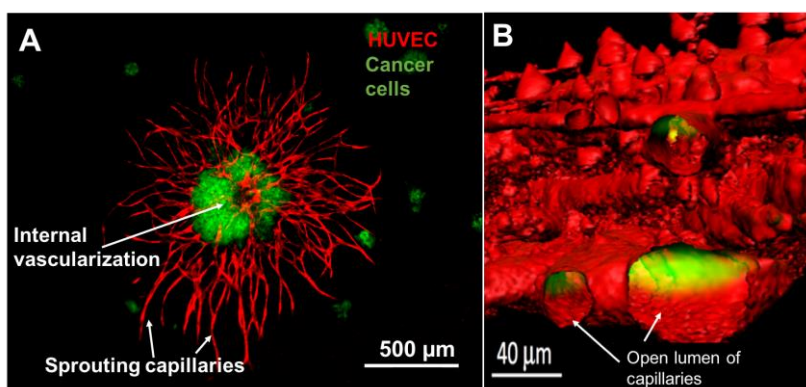


Figure 2: (A) Epifluorescent images of tumor spheroid in fibrin sprouting capillaries and exhibiting internal capillarization of the tumor (B) a high-resolution two-photon microscopy image showing the metastasis of BC cells in engineered capillaries

References

- [1] Hanahan, D. & Weinberg, R. A. Hallmarks of cancer: The next generation. *Cell* .**2011**, 144, 646–674.
- [2] Fridman, W. H. et al. The immune microenvironment of human tumors: General significance and clinical impact. *Cancer Microenviron.* **2013**, 6, 117–122.
- [3] Gold, M. C. & Lewinsohn, D. M. Co-dependents: MR1-restricted MAIT cells and their antimicrobial function. *Nat. Rev. Microbiol.* **2013**, 11, 14–19.
- [4] Edmondson, R., Broglie, J. J., Adcock, A. F. & Yang, L. Three-dimensional cell culture systems and their applications in drug discovery and cell-based biosensors. *Assay Drug Dev. Technol.* **2014**, 12, 207–18.

Acknowledgements

Dr. Derya Unutmaz's group at Jackson labs for providing us with engineered T cells for the immunotherapy experiments.

Radiation Effects on MoS₂ Field Effect Transistors

Andrew Arnold, advised by Saptarshi Das and Thomas Jackson

Two dimensional semiconductors have attracted a lot of attention recently due to the unique advantages that come along with their atomically thin structure. Their ultra-thin nature provides superior electrostatic control and resistance to short channel effects when they are used as the channel material in field effect transistor (FET) structures. This improves their scalability, making them promising candidates as a replacement material for silicon as it reaches its fundamental material limits as transistors continued to be scaled down according to Moore's law.

If 2D materials are to replace silicon, they must be able to match or exceed its performance in many applications beyond just the most standard. The goal of this research is to study 2D FETs under extreme operating conditions, especially radiation exposure of various types and doses for defense and space applications. Objects in Earth orbit are subject to constant bombardment by high energy particles which induce radiation damage in any electronics aboard. The outcome of these studies will help us to understand the failure mechanisms and robustness of 2D FETs and ultimately determine their applicability in specific applications.

In order to evaluate the robustness of 2D transistors for space applications it is necessary to test them under similar radiation types, energies, and doses as would be experienced by space vehicles. There are two main sources of this radiation. The first is the Earth's van Allen belts, which are large bands of high energy particles, mostly protons and electrons, captured from solar winds by the Earth's magnetic field. The second

source is cosmic rays, which are extremely high energy particles, mostly protons and helium nuclei, that originate from outside the solar system.

In order to test this we fabricated MoS₂ transistors on Si/SiO₂ substrates and exposed them to high energy proton and helium ion radiation in collaboration with Prof. Jovanovic's group at the University of Michigan as shown in figure 1. We then measured the devices to see if any change was visible in their electrical characteristics. We found that for proton radiation with a dose of 10^{14} particles/cm² there was only a small shift in the threshold voltage. However, for Helium ions with doses of 2×10^{15} and 10^{16} ions/cm², there was a large degradation in the device performance. It should be noted that all of these doses are much higher than would be experienced by satellites. The higher doses were selected to model the radiation damage at an accelerated rate since it would be impractical to expose our devices to low level radiation for a period of years as experienced by real space vehicles.

It is also important to note that the radiation does not only affect the MoS₂. It will also damage the oxide layer which allows the gate to control the behavior of the transistor. This may be the source of the degradation observed in the electrical characteristics rather than damage to the MoS₂. In order to compensate for this, we fabricated a second set of devices according to the scheme shown in figure 2. Because we tested samples where the flakes and substrate were irradiated individually, we will be able to explicitly determine the radiation damage to the 2D material itself.

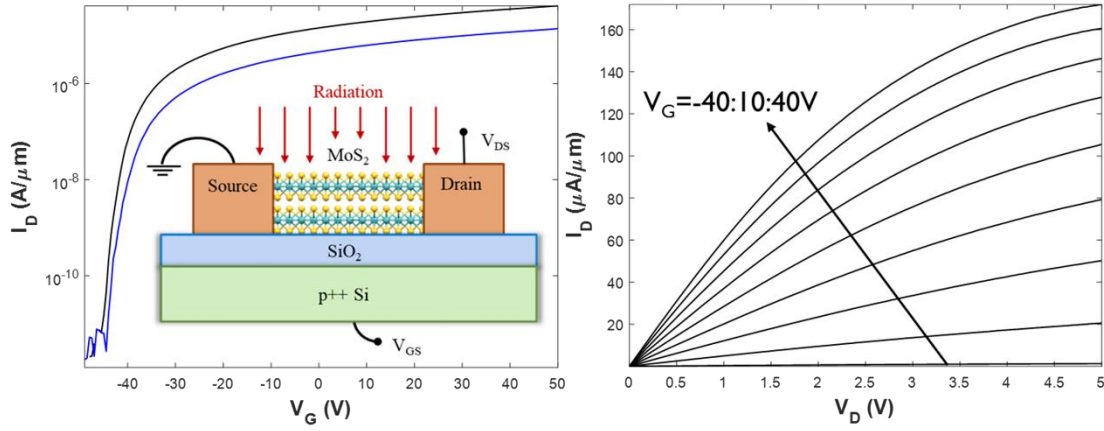


Figure 1: Diagram and typical unirradiated electrical characteristics of the MoS₂ FET tested

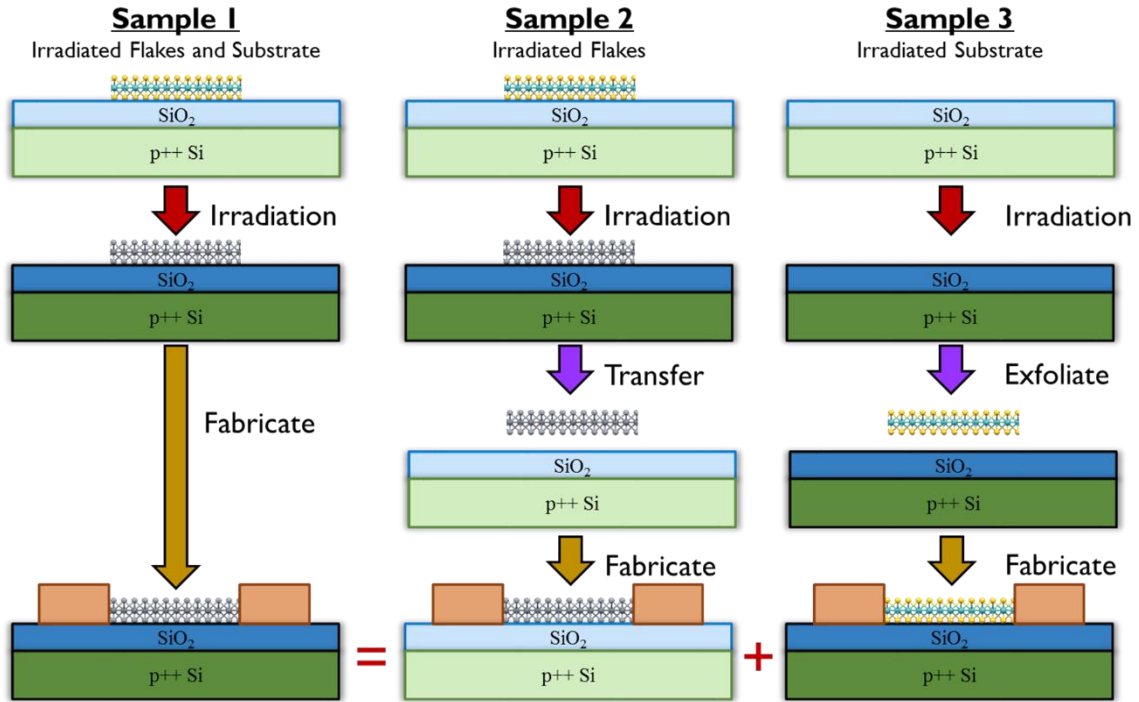


Figure 2: Method for isolating the radiation effects on the MoS₂ from the damage to the SiO₂ layer.

Acknowledgements

I would like to thank Prof. Jovanovic, and Tan Shi from the University of Michigan for assisting with the irradiation of the MoS₂ transistors. I would also like to thank Fu Zhang and Amritanand Sebastian for assisting with the transfer of the 2D flakes for the isolation of the radiation effects in the 2D material.

Spin Dependent Frequency Modulated Charge Pumping

C.G. McKay, advised by P.M. Lenahan

Until recently, a standard MOS electrical measurement called charge pumping (CP) has been very useful in determining the number of defects at the semiconductor/oxide interface as well as other characteristic information.[1] However, as device dimensions have extended into the nanometer realm, the capabilities of the CP technique have reached a fundamental physical limit: quantum mechanical tunneling.[2]–[4] Our group recently developed a spin dependent charge pumping (SDCP) magnetic resonance technique exploiting the spin dependence of the CP measurement to analyze the physical and chemical nature of defects at semiconductor/oxide interfaces.[5]–[7] However, as is the case for the purely electrical CP measurements, decreasing device dimensions and increasing tunneling currents render such measurements very difficult if not impossible. To overcome this problem in technologically relevant nanoscale devices, the electrical measurement, frequency modulated charge pumping (FMCP), was introduced.[2]–[4] We have utilized FMCP to develop a new magnetic resonance spectroscopy technique: spin dependent frequency modulated charge pumping (SDFMCP). To make any CP measurements, a trapezoidal waveform is applied to the gate of a MOSFET while measuring the current through the body. The gate bias alternates between inversion and accumulation periodically filling and emptying traps via recombination events. Assuming minimal tunneling through the gate, the CP current measured through the body is composed of the majority carriers that interact with the trapped charges and recombine. CP current is proportional to the number of defects, the frequency of the waveform, and

the energy window probed in the bandgap of the semiconductor.[1] Recombination is a spin dependent process so the CP current changes when the system undergoes magnetic resonance. It is this spin dependent change in the CP current that is measured during SDCP. This incredibly sensitive magnetic resonance technique requires about 10^3 electrically active defects in a device and is only sensitive to defects which affect the performance of the device. In nanoscale devices, since the current through the body is the sum of the CP current and the tunneling current, large tunneling currents can overpower the CP current making such measurements nearly impossible. In FMCP the gate bias waveform is composed of two alternating trapezoidal waveforms of different frequencies. Since the tunneling current through the gate is essentially frequency independent, the difference in the body currents at the two frequencies is just the difference in the CP currents, essentially removing the tunneling current from the measurement. Since the recombination events which make up the CP currents are still spin dependent, the individual CP currents will change when the system undergoes resonance changing the FMCP signal. Measuring the change in the FMCP during resonance provides information about the physical and chemical nature of the defects near the semiconductor/oxide interface in nanoscale devices with leaky gates. We have evaluated the analytical power of this new SDFMCP technique on 4H-SiC MOSFETs and show that it has great potential in the field of semiconductor/oxide interfaces. The spectrum is shown in figure 1.

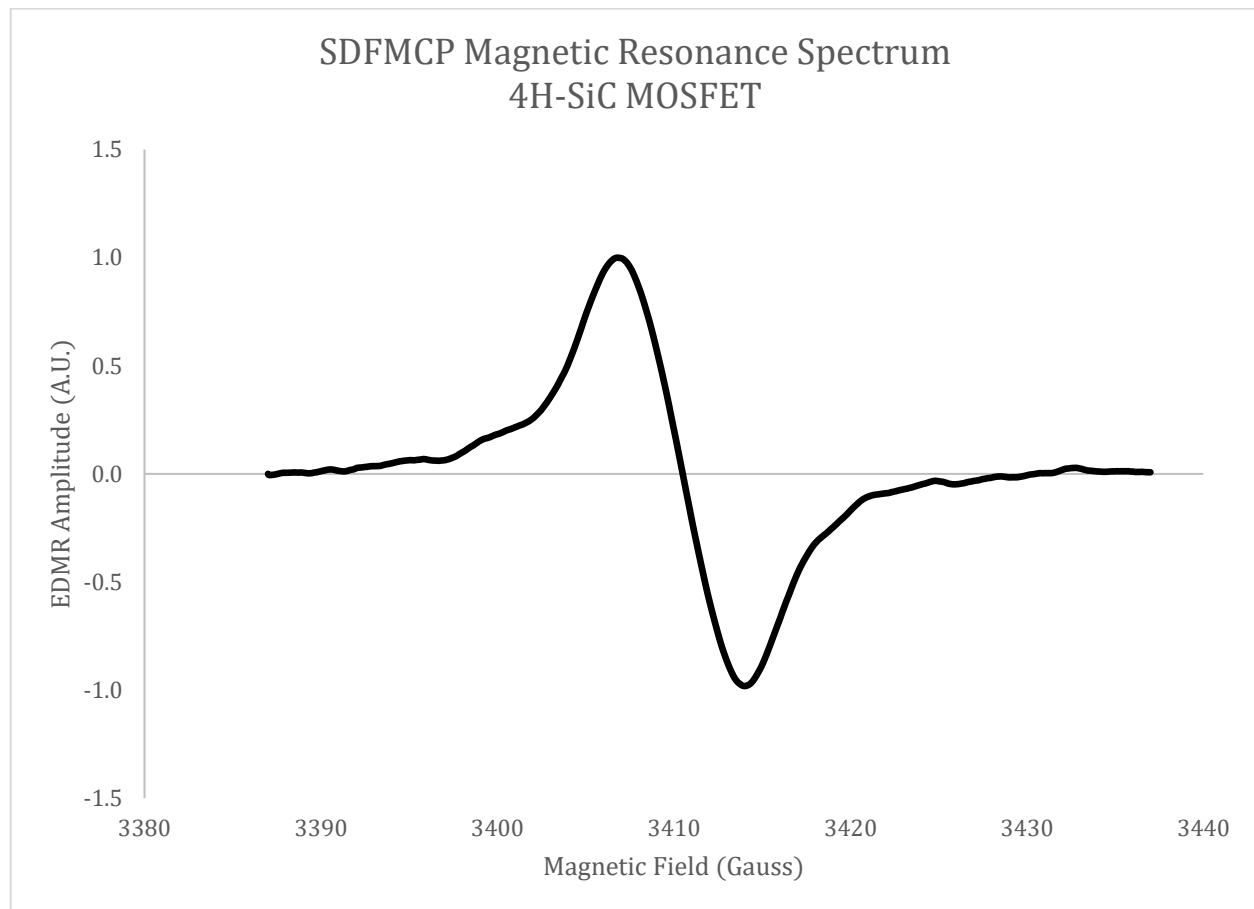


Figure 1: Magnetic resonance spectrum of 4H-SiC MOSFET during SDFMCP measurement

References:

- [1] G. Groeseneken, H. E. Maes, N. Beltran, and R. F. D. Keersmaecker, "A reliable approach to charge-pumping measurements in MOS transistors," *IEEE Trans. Electron Devices*, vol. 31, no. 1, pp. 42–53, Jan. 1984.
- [2] J. T. Ryan, J. P. Campbell, K. P. Cheung, J. S. Suehle, R. G. Southwick, and A. S. Oates, "Reliability monitoring for highly leaky devices," in *2013 IEEE International Reliability Physics Symposium (IRPS)*, 2013, p. 2D.5.1-2D.5.4.
- [3] J. T. Ryan, R. G. Southwick, J. P. Campbell, K. P. Cheung, A. S. Oates, and J. S. Suehle, "Frequency-Modulated Charge Pumping: Defect Measurements With High Gate Leakage," *IEEE Electron Device Lett.*, vol. PP, no. 99, pp. 1–1, 2014.
- [4] J. T. Ryan *et al.*, "Frequency-Modulated Charge Pumping With Extremely High Gate Leakage," *IEEE Trans. Electron Devices*, vol. 62, no. 3, pp. 769–775, Mar. 2015.
- [5] B. C. Bittel, P. M. Lenahan, J. T. Ryan, J. Fronheiser, and A. J. Lelis, "Spin dependent charge pumping in SiC metal-oxide-semiconductor field-effect-transistors," *Appl. Phys. Lett.*, vol. 99, no. 8, p. 083504, Aug. 2011.
- [6] B. C. Bittel, P. M. Lenahan, J. T. Ryan, J. Fronheiser, and A. J. Lelis, "Spin dependent charge pumping: A new tool for MOS interface characterization," in *2011 International Semiconductor Device Research Symposium (ISDRS)*, 2011, pp. 1–2.
- [7] C. P. Poole, *Electron Spin Resonance: A Comprehensive Treatise on Experimental Techniques*. Dover Publications, 1996.

Preparation and Characterization of Microcrystals Grown on Monolayer Graphene

Xinyi Li, advised by Slava V. Rotkin

Graphene is a 2D material formed from a hexagonal lattice of sp^2 carbon atoms. It has a wide variety of applications due to its impressive properties, such as high intrinsic mobility, high transparency, high thermal conductivity and large tensile strength ^[1]. When force is exerted on monolayer graphene, it will cause strain, resulting in a shift of its Raman G peak and 2D peak positions. By using Raman spectroscopy to measure the strain on graphene, we can quantify the force exerted on it. One possible application of this will be to understand the nuances of growth of layered or thin film materials on top of graphene. Here, we explore growing TiO_2 crystals on graphene as a model to create a calibration curve on which to base any strain measurements.

TiO_2 is a useful oxide material because of its peculiar physicochemical properties ^[3]. The synthesis of TiO_2 has been well studied and there are many different methods of growing TiO_2 crystals ^[4]. Also, TiO_2 is known to have Raman signature lines that do not overlap the graphene peaks, which makes it easy for fast inspection whether TiO_2 was successfully grown on graphene.

We have performed transfers of CVD grown graphene from copper substrates to glass substrates with continuity and high quality of graphene layers. We also modified the thermal polyol method of TiO_2 microcrystal growth, and successfully synthesized TiO_2 crystals on monolayer graphene in a setup shown in figure 1. We also verified that the graphene retained high quality after the growth process by using both Raman and optical microscopy.

AFM characterization was conducted to demonstrate that the TiO_2 crystals have sizes between 400 nm and 600 nm. High resolution micro-Raman hyperspectral maps were taken where the individual single point spectra, like the one shown in figure 2, indicate the TiO_2 is in anatase phase.

The changes in graphene spectrum upon growing TiO_2 crystals on top of it were analyzed and the peak shifts were to construct the maps showing the correlation between graphene strain (from Raman spectra) and its spatial proximity to TiO_2 crystals.

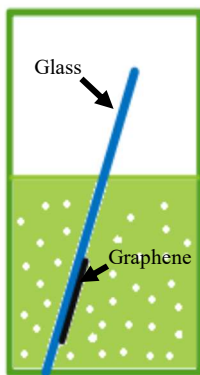


Figure 1. A sketch illustrating the side view cross-section of experimental setup: the substrate (with graphene) placed in the precursor solution in the autoclave.

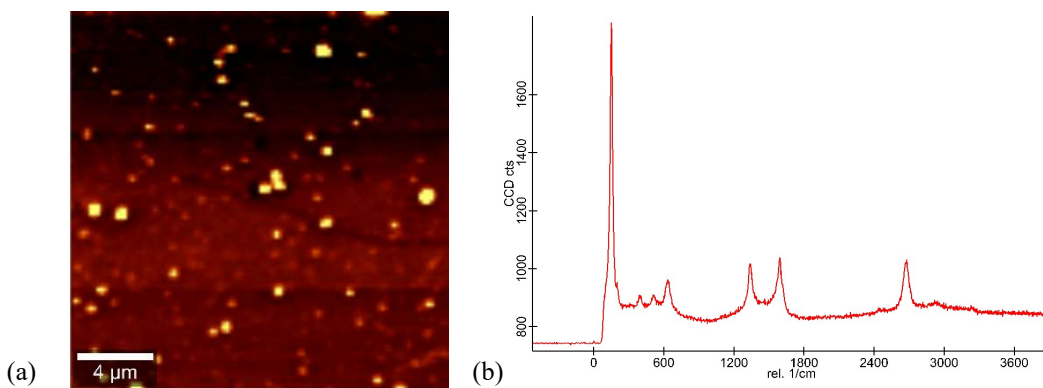


Figure 2. (a) Micro-Raman map of TiO_2 crystals (shown as bright spots) grown on monolayer graphene.

(b) Single point spectrum showing characteristic features of crystalline TiO_2 on graphene.

References

- [1] C. J. Lockhart de la Rosa, J. Sun, N. Lindvall, M. T. Cole, *Appl. Phys. Lett.* 102, 022101 (2013).
- [2] Hsiao M. C., Liao S. H., Yen M. Y., Liu P. I., Wang C. A., Ma C. C., *ACS Appl. Mater. Interfaces* 2, 3201 (2010).
- [3] Yu J., Liu W. and Yu H., *Cryst. Growth Des.* 8, 930 (2008).
- [4] Cargnello M., Gordon T. R. and Murray C. B., *Chem. Rev.* 114, 9319-45 (2014).

Acknowledgements

We thank Dr. Snyder for his advice on synthesizing TiO_2 crystals and providing lab setup for crystal growth.

Microstructural Characterization of Additive Manufactured Specimens using Laser based Nonlinear Rayleigh Waves

Chaitanya Bakre, Cliff Lissenden

Additive manufacturing (AM) has gained phenomenal attention in industry, research, and media due to its unprecedented design flexibility and manufacturing of complex geometries that are difficult or unattainable by conventional subtractive manufacturing processes. However, the idiosyncratic nature of AM - consolidation of part layer-upon-layer, results into an atypical, anisotropic structure consisting of defects on surface and bulk of the material, and significantly different microstructural properties as compared to the conventional manufacturing. This research presents preliminary investigations of microstructural characterization of

AM components using nonlinear ultrasonic technique. Here, a laser based slit-mask method is used for non-contact generation and laser interferometric reception of nonlinear Rayleigh waves. High sensitivity of nonlinear ultrasonic waves to the microstructural features and non-contact inspection methodology; thereby addressing the problem of unusual surface texture of AM component and providing ability for in-situ evaluation, makes this technique highly favorable.

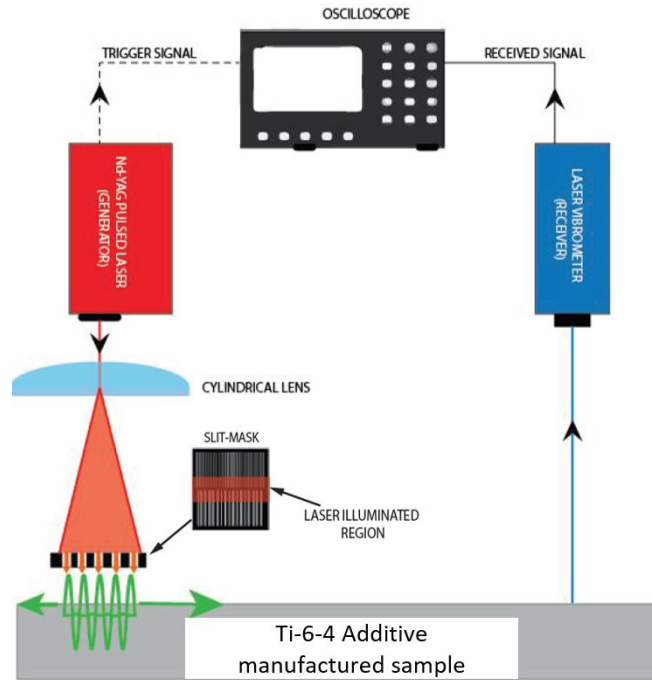


Figure 1: Schematic of the experimental setup

References

- [1] Choi, Sungho, et al. "Frequency response of narrowband surface waves generated by laser beams spatially modulated with a line-arrayed slit mask." *Journal of the Korean Physical Society* 60.1 (2012): 26-30.
- [2] Everton, Sarah, et al. "Evaluation of laser ultrasonic testing for inspection of metal additive manufacturing." *SPIE LASE*. International Society for Optics and Photonics, 2015.

Art in Science

Brownian Trees on Etched SiO_2

Andrew Arnold, advised by Saptarshi Das and Thomas Jackson



These Brownian Trees are formed on the surface of a silicon wafer after etching a SiO_2 thin film using NaOH . A diffusion-limited aggregation process forms these fractal like patterns as particles undergo a “random walk” due to Brownian motion and aggregate.

Bioprinting of Cancer Tissues

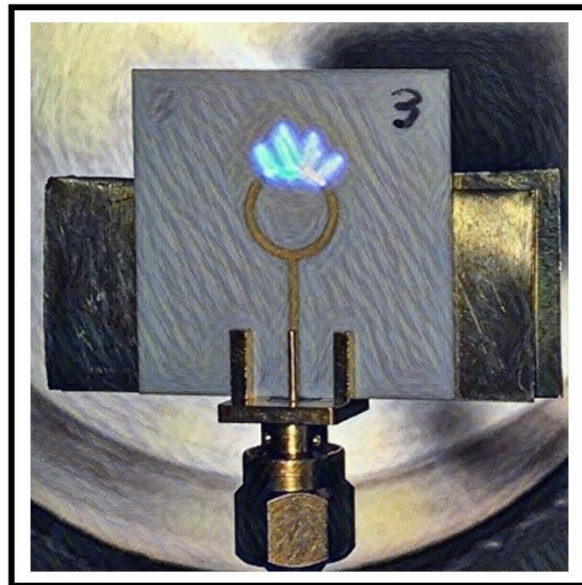
Bugra Ayan, advised by Ibrahim Tarik Ozbolat



A fluorescence microscopy image showing bioprinting of breast cancer tissue spheroids (each of around 200 μm) using aspiration-assisted bioprinting method in initials of Penn State University.

Plasma Crown

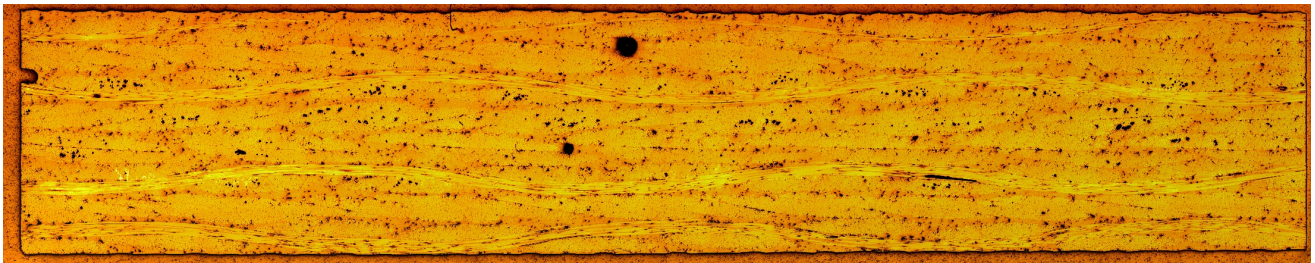
Zane Cohick, advised by Michael Lanagan and Douglas Wolfe



Microwave, split-ring resonators were important components in the famed first demonstration of electromagnetic cloaking. The sub-wavelength focusing of electromagnetic energy also makes such resonators useful for plasma generation as shown above in 200 Torr of Ar. A polymer coating reduces the plasma ignition power and modifies plasma color.

Woven Composite

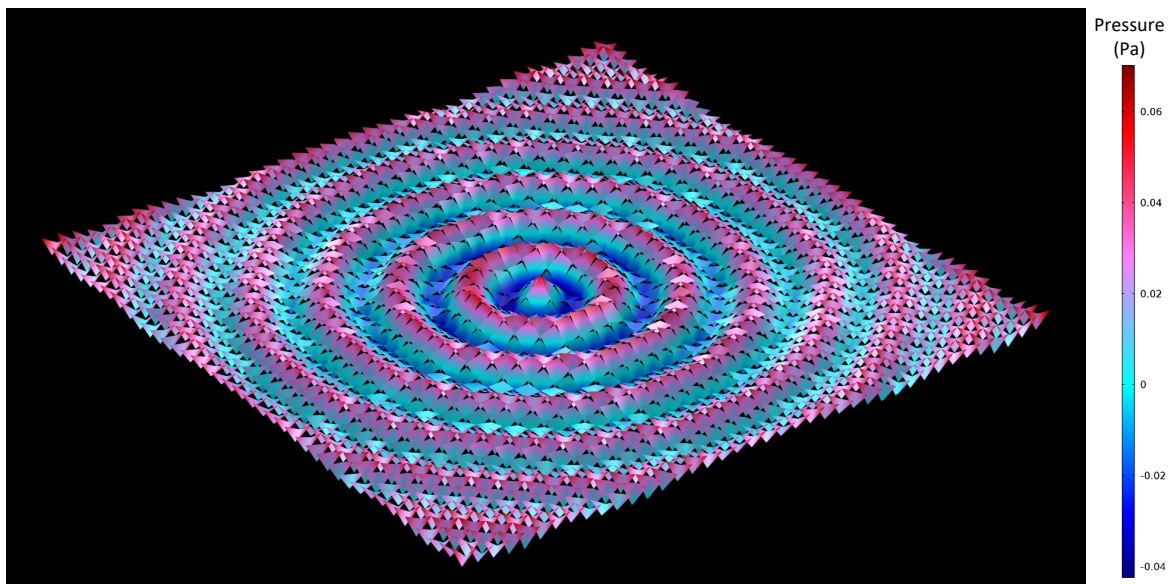
Rudy Haluza, advised by Dr. Charles Bakis
and Dr. Kevin Koudela



Cross-section of a 16-ply fiber-reinforced polymer laminate with voids (black), undulated glass fibers (light yellow), and polymer matrix (dark yellow) captured via optical microscope. The title features a pun referring to the woven fibers within the composite material and the composite image itself—comprising of 110 individual micrographs woven together.

The discontinuous butterfly effect

Ravi Kedarasetti, advised by Patrick Drew & Francesco Costanzo



Pressure field simulated using finite element implementation of the Navier-Stokes' equation. Discontinuous pressure elements make it easier to implement Vanka smoothers for multigrid preconditioners, which can immensely speedup simulations.

Surface Roughness of 3D Printed Filaments for Bone Tissue Engineering

Kazim Kerim Moncal, advised by Ibrahim Tarik Ozbolat

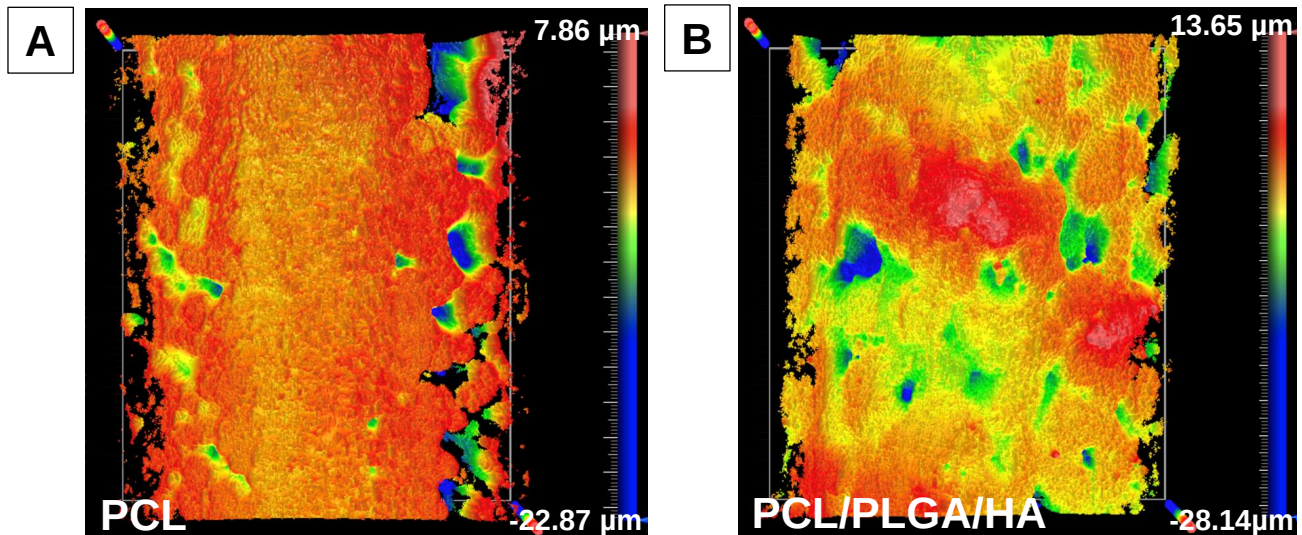
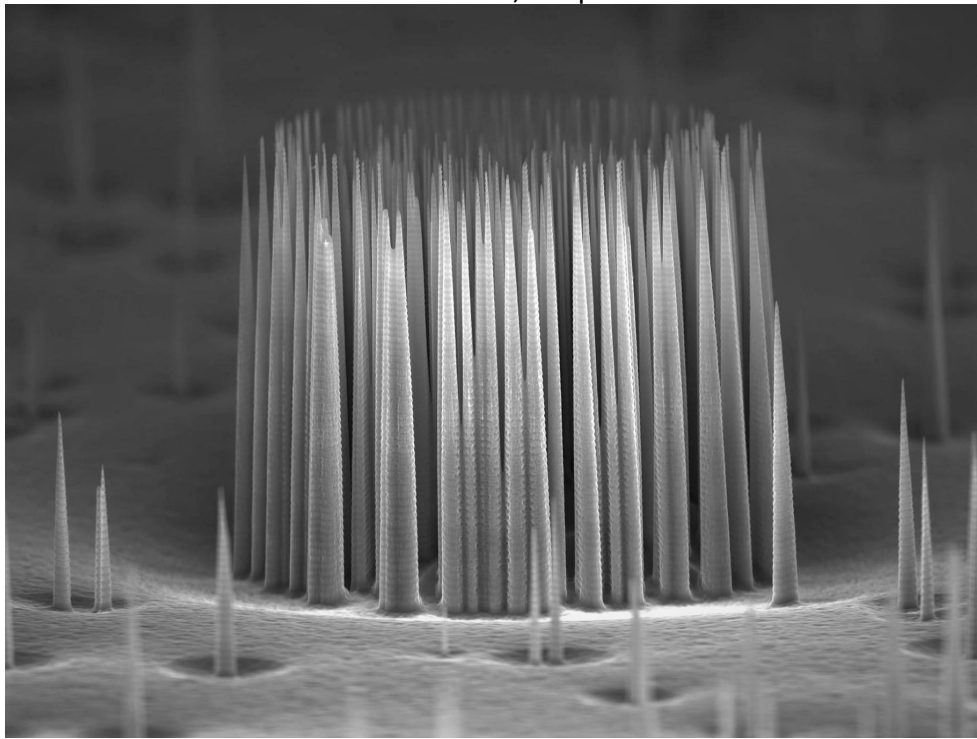


Figure. Surface roughness of 3D printed A) Poly (ϵ -caprolactone) (PCL) and B) PCL/Poly (D, L-lactide-co-glycolide) (PLGA)/ Hydroxyapatite (HA) Composite Filaments for Bone Tissue Engineering. (Interferometric optical profilometry (Zygo NexView 3D, Zygo Corporation, Middlefield, CT) was used to capture the surface roughness of the 3D printed filaments.)

Silicon Nanowire Forest

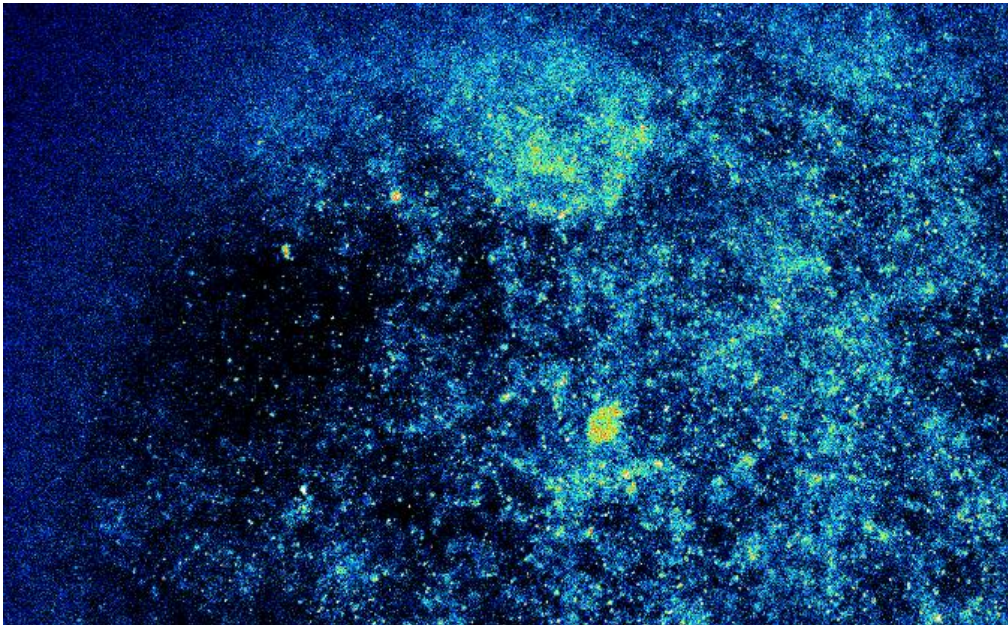
Daniel Schulman, Saptarshi Das



Scanning electron microscope image of a silicon nanowire “forest”. Particles and contaminants randomly redeposit on the silicon surface during Deep Reaction Ion Etching (DRIE) forming silicon nanowires thinner than the width of a human hair.

Particle Shadow Velocimetry

Christine Truong, advised by Jeff Harris



An image of a flow field taken with a high-speed camera. Using particle shadow velocimetry, rapidly-imaged snapshots of the flow can be used to determine its instantaneous velocity. The image has been processed to invert the intensity field and to remove background noise.