Liquid Metal Printed 2D ITO for Nanophotonic Applications

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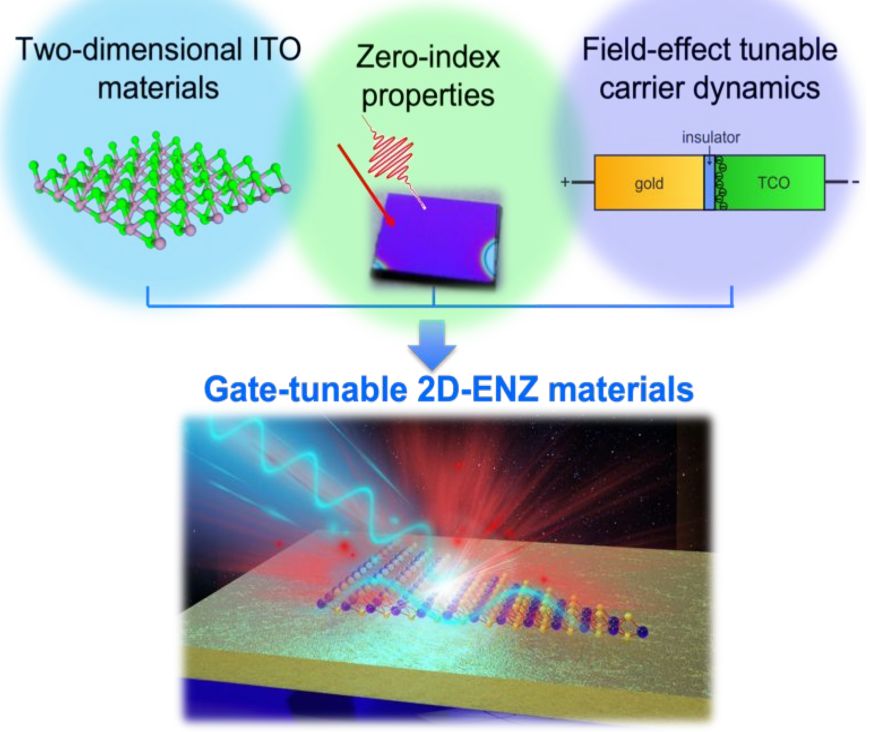
Motivation

Objectives

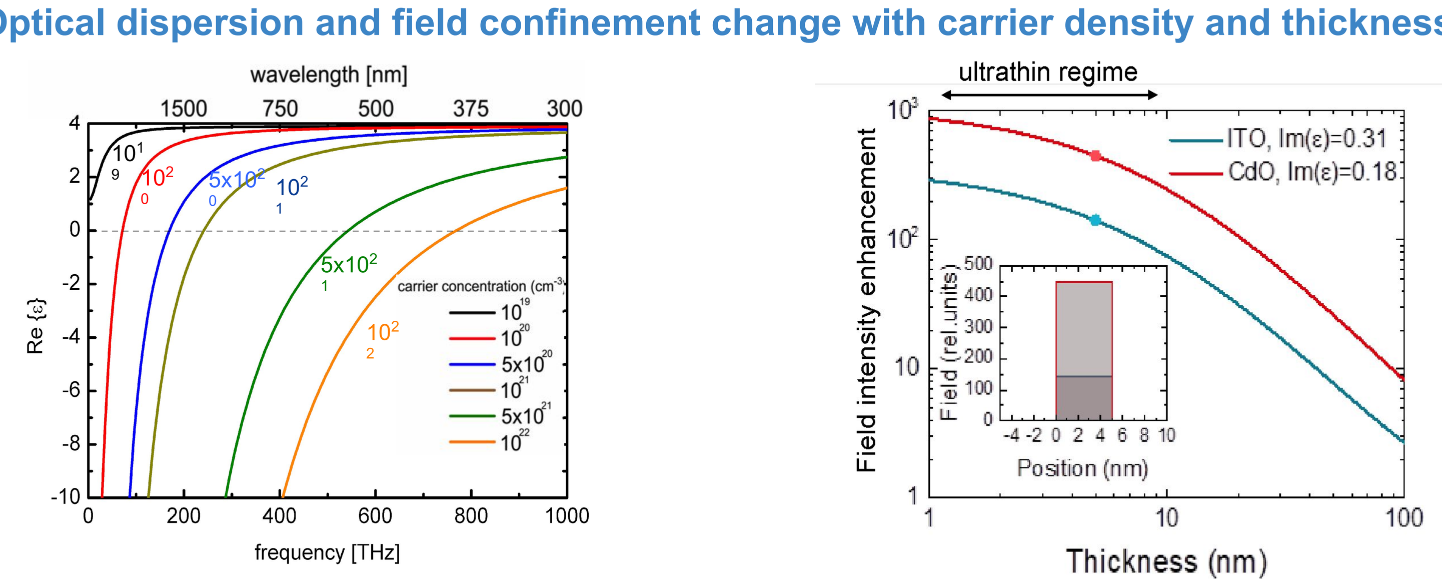
- Investigate liquid metal printing methods which consistently produce mm/cm-scale areas of nanometer-thin Indium Tin Oxide (ITO).
- Perform an optical characterization of ultrathin ITO film, using reflection and transmission intensities to obtain *n* and *k* for different thicknesses.
- Characterize the field effect modulation of 2D ITO under various biasing schemes, and tunability of nonlinear phenomena at epsilon-near-zero (ENZ) regime.



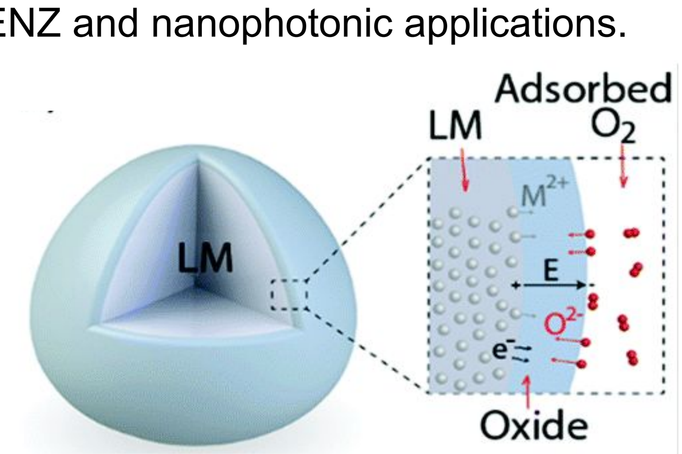
Optical Phenomena of Epsilon-Near-Zero (ENZ) Materials

- Strong EM wave confinement.
- Extreme optical nonlinearity and electrical tunability.
- Integration with metasurfaces to enable optical phase and amplitude modulation, leading to beam steering, tunable focusing, etc.

Optical dispersion and field confinement change with carrier density and thickness:



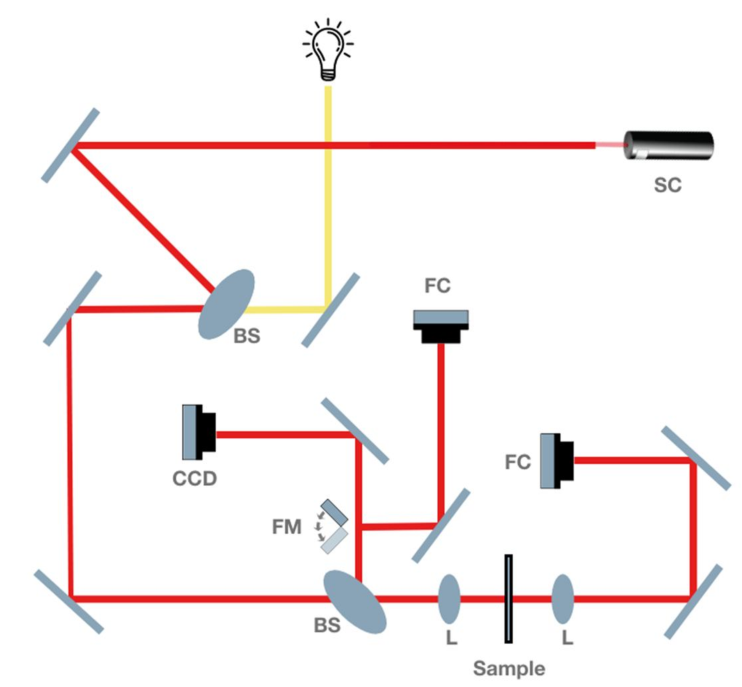
- **Field intensity enhancement** for thin-film ITO is unexplored in the sub 10-nm region; increases of 1-2 orders of magnitude are expected as compared to 100nm.
- Additionally, **low-temperature, low-cost (material and equipment) methods of thin film fabrication** enable further use in nanophotonic and ENZ applications. Low-temperature and low-cost fabrication makes these films ideal for scalable ENZ and nanophotonic applications.



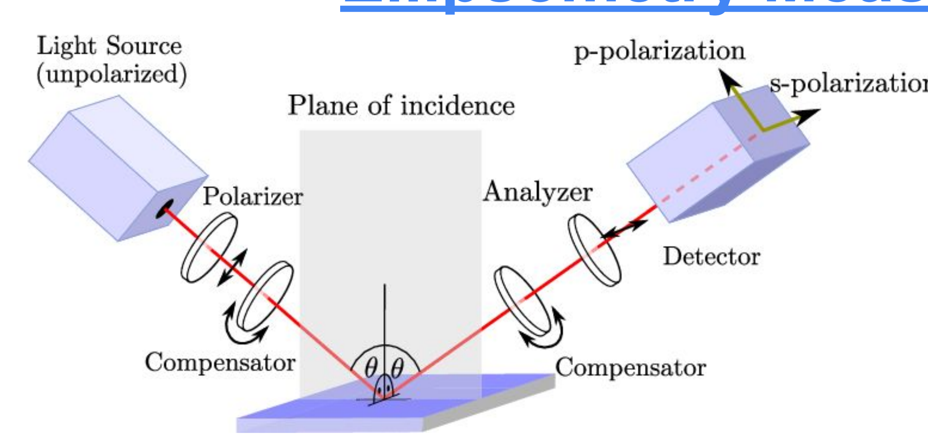
Self-limiting Cabrera Mott oxidation allows formation of atomically-thin oxide films. In comparison to vacuum deposition methods, this process is notably lower-cost and lower-temperature.

Optical Characterization

- Reflected and transmitted intensity from supercontinuum white light laser measured.
- To measure points of interest with areas smaller than the laser spot size, light is focused down to ~5 μm.
- Navigation to points of interest performed with reflected incoherent white light on a visible camera.



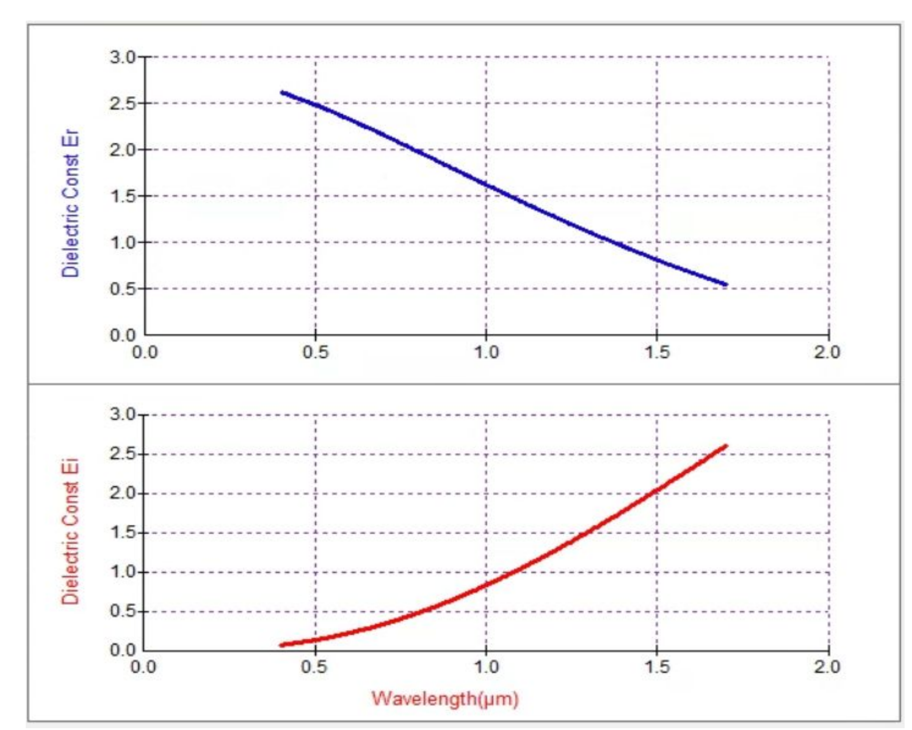
Ellipsometry Measurements

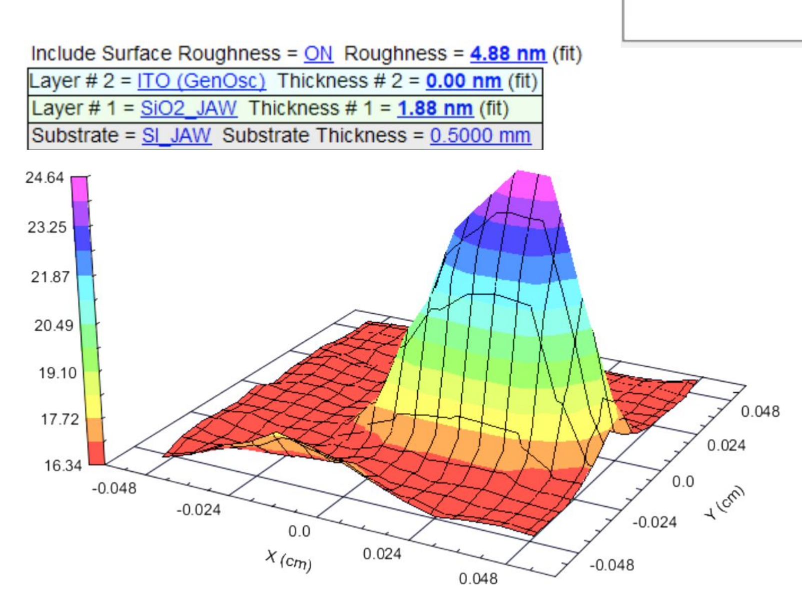


- Polarized light sent to sample at incident angle; returning reflected light compared to existing models to help determine thickness.
- Most useful for measurements of large ITO film regions.

Complex Permittivity

- No ENZ wavelength pictured; most likely at wavelength outside of ellipsometer range.
- Comparing to bulk ITO models, the predicted thickness is ~ 3x larger than the verified thickness, suggesting a stronger reflection effect with thinner ITO layers.



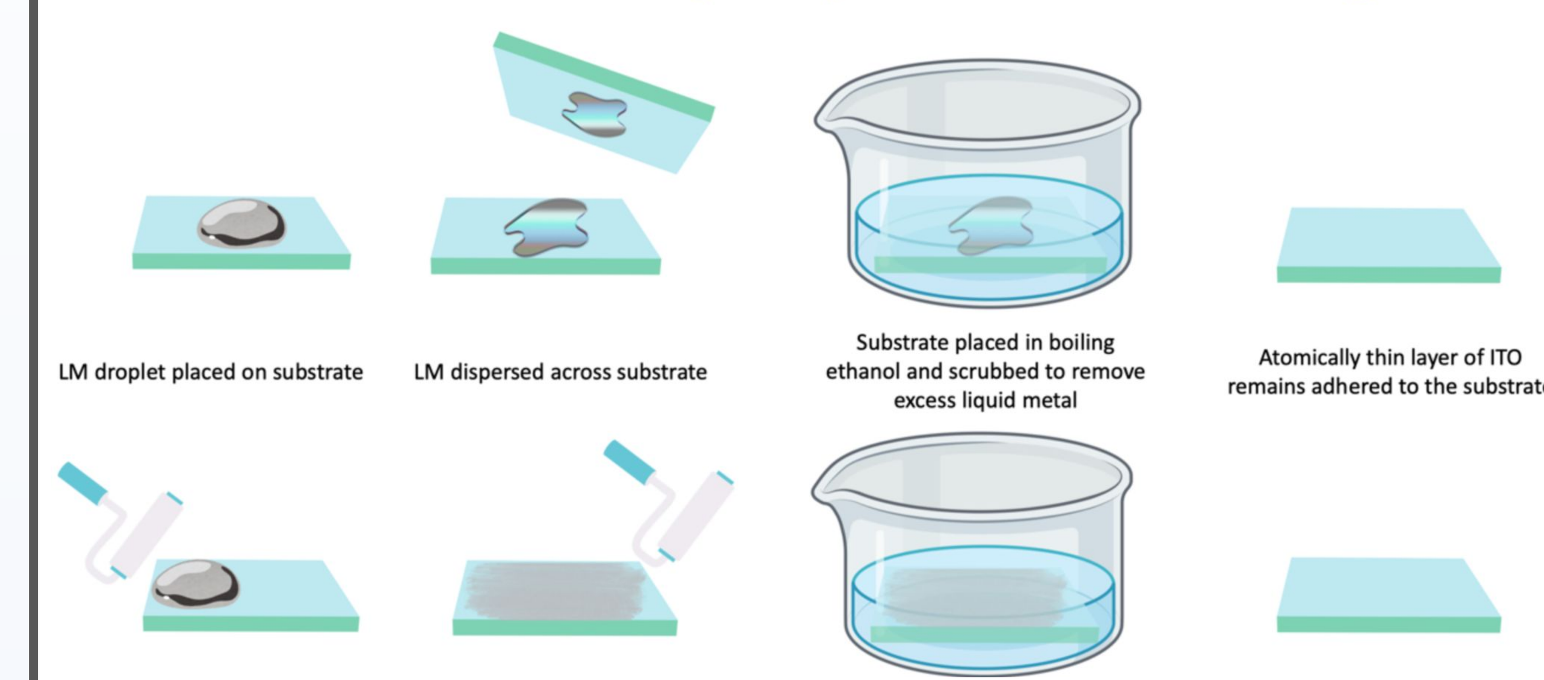


Ellipsometry on TJ S3 1 mm 100um step 01 on 2D ITO.

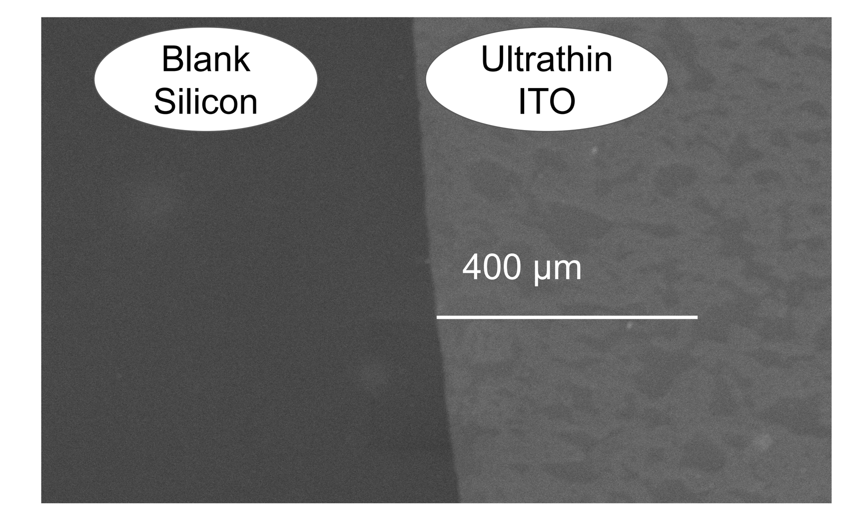
Observe higher Ψ values in certain areas, it may suggest regions where the ITO is thicker, has a higher refractive index, or where the surface is smoother and more uniform. Conversely, areas with lower Ψ values might indicate thinner ITO layers or rougher regions where light scattering reduces the reflection contrast between s- and p-polarized light.

Liquid Metal Printing

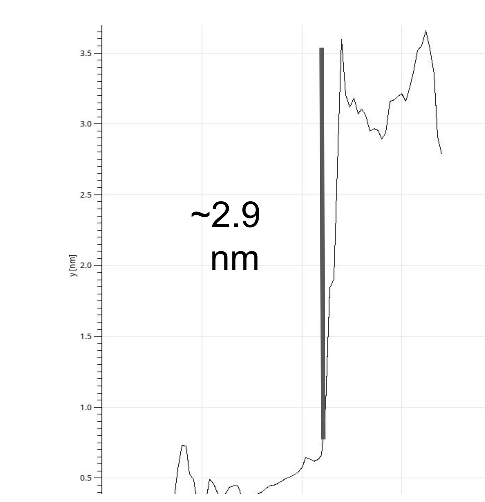
2D ITO Fabricated by Liquid Metal Printing



- Liquid Indium-Tin alloy (95:5) deposited onto silicon wafers at 200°C.



SEM image demonstrating near mm-scale areas of multiple layers of thin film ITO.

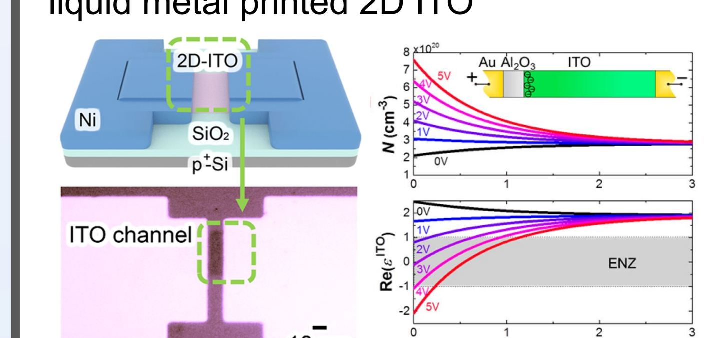


AFM image demonstrating atomically-thin layers of ITO.

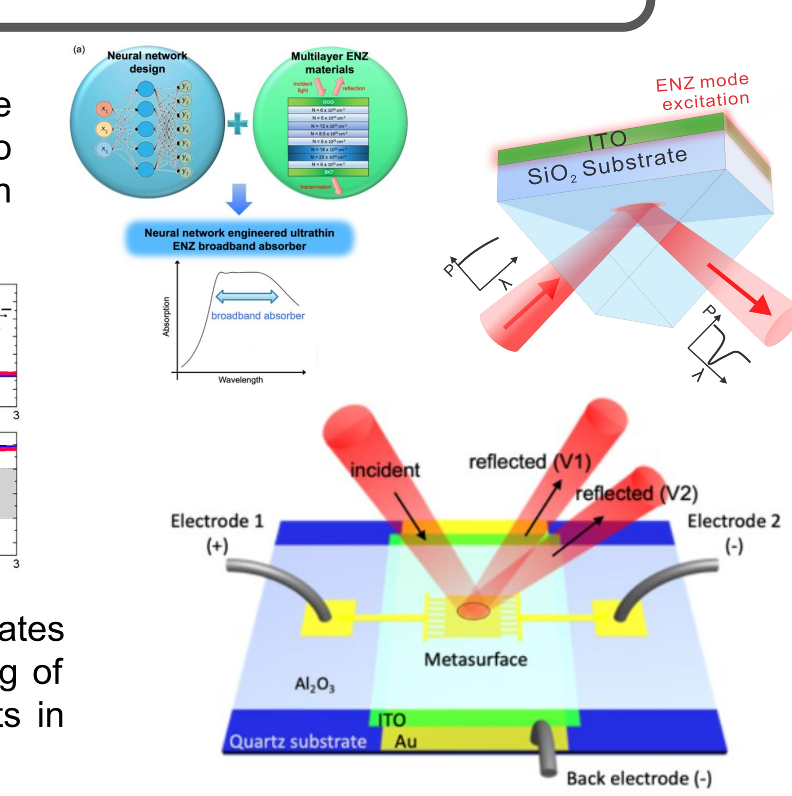
Future Work

Electrical Tunability

Ongoing project in collaboration with the Nomura group at UC San Diego, who have created thin film transistors with liquid metal printed 2D ITO



Electrical bias dynamically modulates carrier density, enabling real-time tuning of the permittivity and corresponding shifts in the ENZ wavelength regime.



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