Attempt at Home-Built STM with $LiNbO_3$ Scanner

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Timeline

[Early 2024] Insider information leaks that Freitas and Merkle have achieved mechanosynthesis experimentally, are hiding the information, and unknown bottleneck limits to **3 reactions/day**.

[Aug 2024] Simulations reveal silicon carbide can plausibly be built with 3-DoF scanning probes

[Sep 2024] Switch from theoretical to experimental side of atomically precise manufacturing

[Sep 2024] 3D printed low-cost, atomic resolution STM from “MechPanda”

[Dec 2024] Undergraduate research course in STM approved

[Jan 2025] Philip learns quantitative model for piezo creep

[Jan 2025] Philip learns LiNbO3 can eliminate creep to within measurement error

[Feb 2025] Philip learns of Wolkow et al. 2020 patent on LiNbO3 STMs

[Mar 2025] Philip solves the throughput problem of STMs theoretically, shows **50,000 reactions/day** is plausible in a single STM.

Lithium niobate wafers the student ordered ($130 for 10 piezo plates)

0.068 nm/V

Central problem: $LiNbO_3$ has 10% the piezo constant of PZT

Design Goals

Do not build an STM

- Low yield of mechanically cut, atomically sharp W tips. NaOH etching does not guarantee atomic sharpness. In practice, people use UHV field ion microscopy techniques to sharpen a W wire after NaOH etching.
- 3-DoF actuation is not needed to prove piezo creep has been solved. The fact that proportional-integral control is needed for the 1-DoF current-setpoint feedback loop, indicates that piezo creep has caused control issues.
- Current-distance spectroscopy can measure ~10 pm relative movements, when a tip enters the tunneling regime. So far, it’s never been done at 300 K, likely because piezo creep makes the data inaccurate. I(z) spectroscopy can be done without the ability to scan a surface.

Design Goals

Maximize range by maximizing voltage:

- 200 V: commercial SPMs based on PZT longitudinal stacks
- 1000 V: plausible for $LiNbO_3$ shear stacks
    - Dielectric breakdown of air (**limiting factor**)
    - Dielectric breakdown of $LiNbO_3$ (✅)
    - Voltage rating of commercially available power MOSFETs (✅)
    - Multiple existing designs for high-voltage amplifiers (✅)

Capacitive displacement sensor: sense <10 nm actuations without expensive laser interferometer

- Integrate compensation capacitor into the transimpedance amplifier
- Eliminate or calibrate away leakage currents above 1 pA
- Digital lock-in amplifier, 10 V amplitude, ~10 kHz frequency

Practical Issues: Piezo Stack Fabrication

Lead times for piezo shear plates

- 3 weeks, \$13/plate from Crystal Substrates (**best deal, but cannot sit idle for 3 weeks**)
- 8 weeks, \$50/plate from Boston Piezo Optics (❌)
- No commercially available PZT shear plates for comparison to $LiNbO_3$ shear plates

Multiple plates per stack

- More plates increases range, but also manual effort for fabrication
- Pre-cut notches, chamfers ensure plates all have the same crystallographic orientation. If this gets messed up, it’s an expensive mistake; the epoxy gluing process is irreversible.

Electrical connections

- Copper electrodes may need to be fabricated with electrochemical etching (**complexity!**)
- Conductive epoxy: very complex process to mix “two-part systems”, dispense, and cure
- End caps to prevent high-voltage surface of piezo plate from interfering with nearby parts

Practical Issues: Mechanical

Vibration isolation needed to measure displacements smaller than 1 μm

Thermal drift from electromagnetic stepper motors in Air-STM designs takes ~20 min to settle

Kinematic mount desired for strain-free, deterministic actuations (eliminate jitters of ~50 nm)

- Complexity of bonding alumina, sapphire, hardened steel to metallic housing with epoxy
- UHV-STM designs use shear piezo stacks, irreversibly epoxied to kinematic mount
- “Open STM” used longitudinal piezo stack with lubricated linear slide (UHV incompatible)

CNC aluminum desired for housing in the tip-sample loop

- Better rigidity, needed to maximize resonance frequency (improves vibration isolation)
- Lower coefficient of thermal expansion (less thermal drift)
- UHV incompatible, but acceptable for Air-STM design. Surrogate for BeCu or Mo.

Practical Issues: Electronics

Complexity of fabrication:

- DAC81404 considered for far-term design iteration, only available as QFN. Cannot be hand-soldered, requires reflow soldering.
- Do you buy all the bulky equipment and ventilation for soldering at your DIY home lab, or pay someone to assemble a one-off PCB in an external lab? The latter typically only happens for high-volume production (batch of 50 boards).

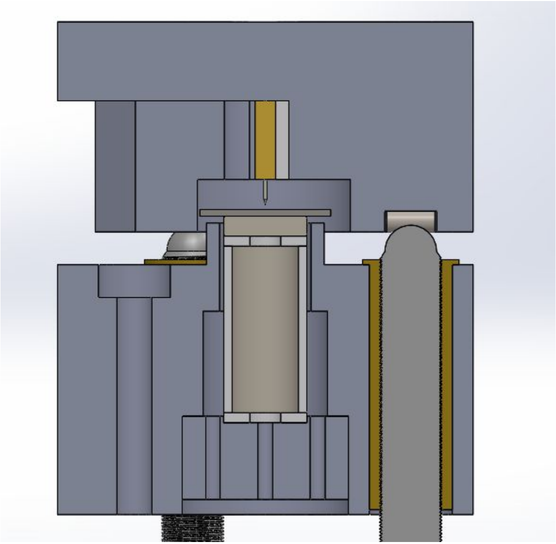
Electromagnetic interference degrades sensitivity of current + capacitance combined sensor

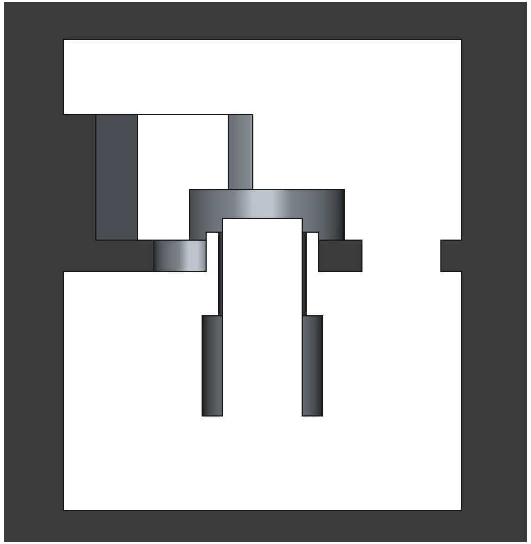
High-voltage electronics:

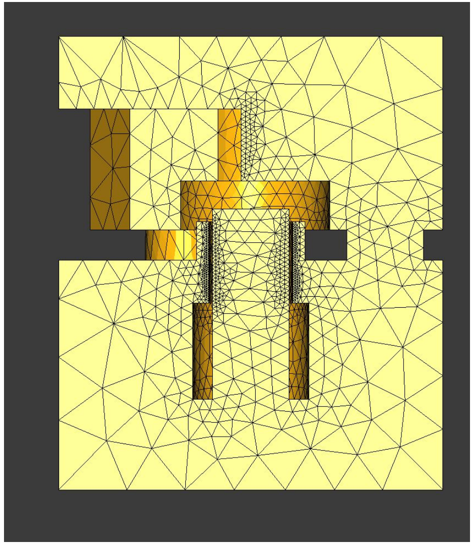
- Need a custom high-voltage, linearly regulated 1000 V supply
- High gain (100 V/V) means lower bandwidth in regulators and piezo drivers
- Part count for high-voltage amplifiers is enormous (e.g. multiple 1 W resistors)

Results

Finite element method simulations of Dan Berard’s incomplete second iteration

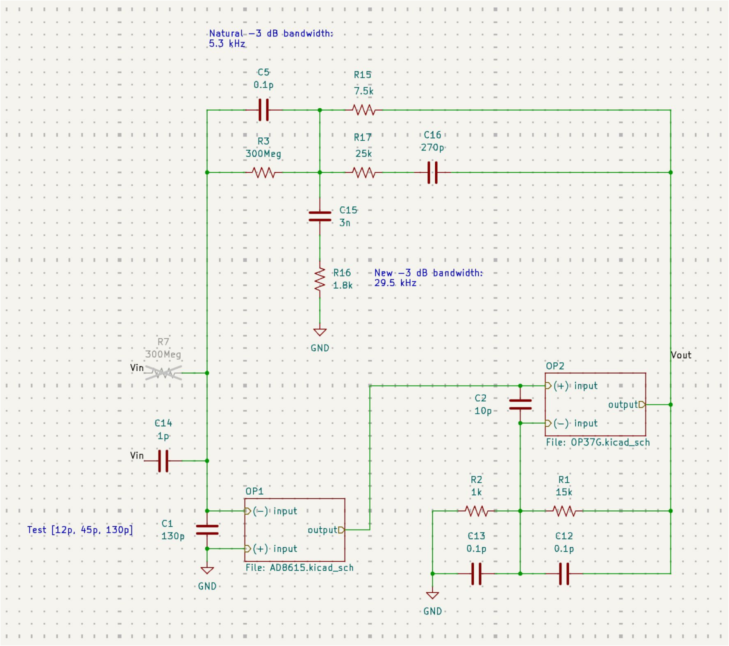


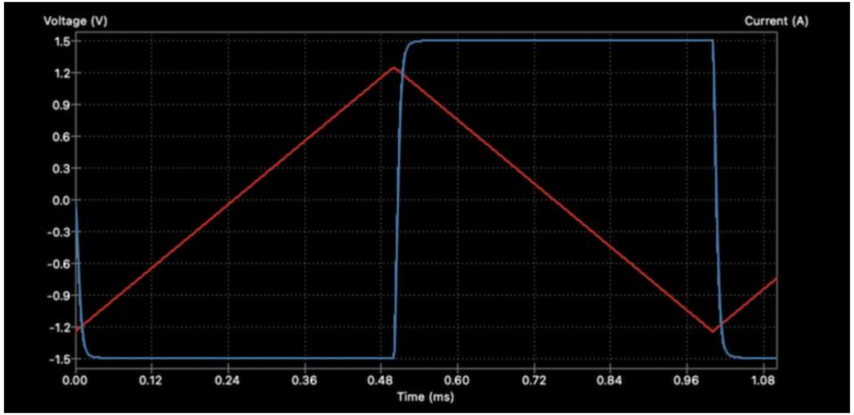




Results

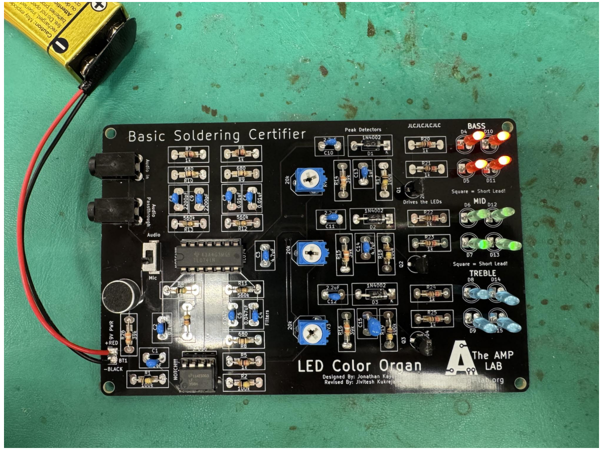
Proposed redesign of the “fast low-noise transimpedance amplifier”

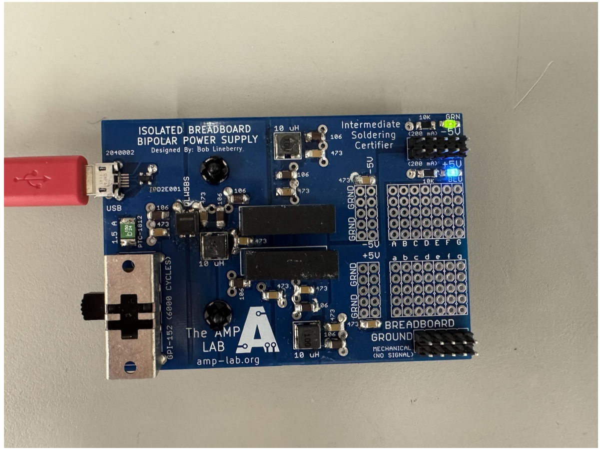


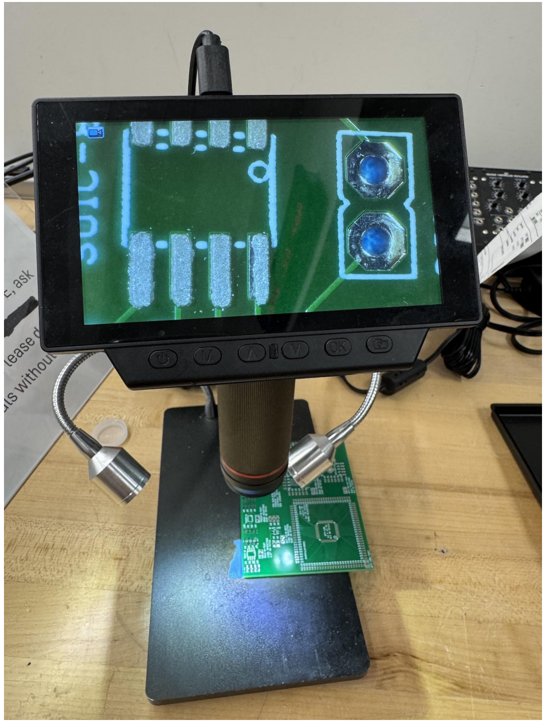


Results

Reflow soldering and hand soldering at the AMP Lab

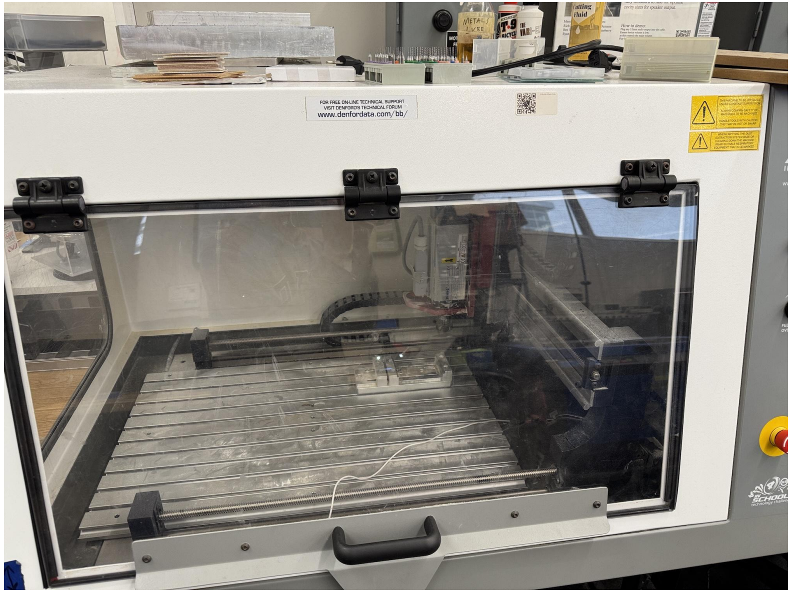


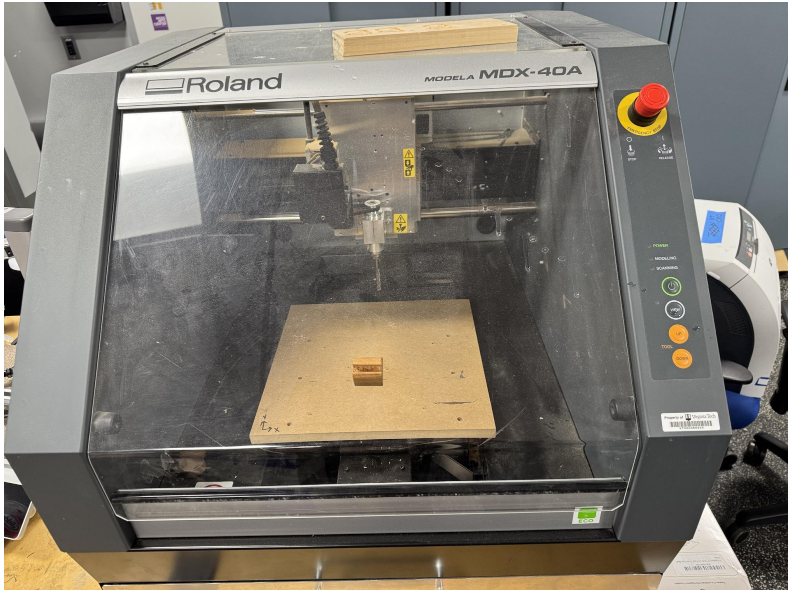




Results

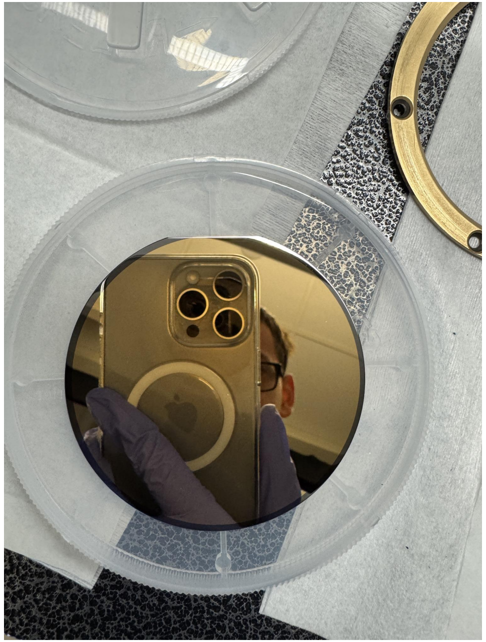
Fixed a non-operating CNC machine (and working on 2nd)

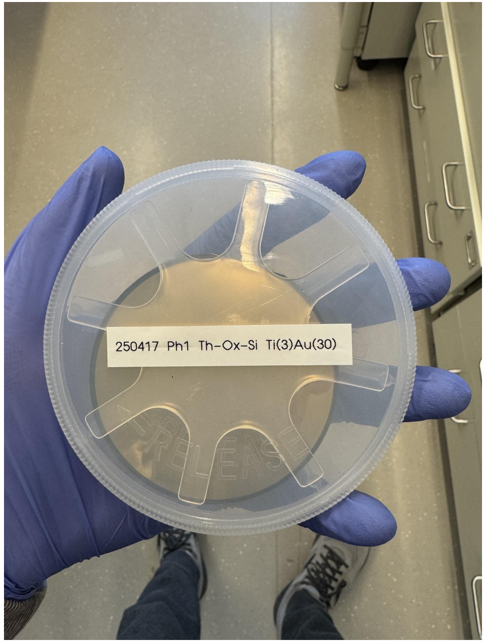




Results

Gold sputtering under 10^{-8} torr vacuum, reproducing what Dan Berard did





Discussion

Internal conflict over regaining motivation to work on backend software for atomistic simulations (CAD for molecules)

Neither 100% theory, nor 100% experiment. It’s a combination of both now.

Discussion

Suffered from side effects of being the 2nd person to explore an uncharted design space of creep-free designs. 1st person(s) (Wolkow et al. patent) didn’t fabricate the STM; only elaborated on the highest-level design considerations.

We’re at the point similar to when EUV lithography settled on tin as the element for the laser source. Now, we have to solve the strange, unusual technological demands, like pushing the limits of high-voltage linear amplifiers.

Discovered strange, bad design practices in the use of bypass/decoupling capacitors and instrumentation amplifiers to solve electromagnetic interference. Want more time to explore this with FEM field solvers and SPICE simulations. Not willing to use expensive ($300–$7000) and bulky commercial electronics modules.

Conclusion

After finalizing design requirements, several missing prerequisites were discovered. Used last month of semester to build these skills:

- Soldering low-volume PCBs with surface-mount parts
- CNC machining parts out of aluminum or harder metals; design-for-manufacture before sending order to online CNC service
- Using a two-component epoxy system to bond ≥2 parts (not a trivial task)
- Experience with high-vacuum systems and vacuum hygiene

Will take multiple months of full-time work to make the $LiNbO_3$ STM a reality.

Conclusion

Project repository: https://github.com/philipturner/home-built-stm

Favorite sentence: *Complexity is the nemesis of progress.*