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FINAL REPORT

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I. Project Title

Development of a Sub-$200 Quantum Tunneling Current Measurement Device

II. Project Completion Date

January 12, 2019

III. Student(s), Department(s), and Major(s)

(1) Justin Jee, Departments of Physics & Electrical Engineering, Physics & Electrical Engineering

IV. Faculty Advisor and Department

Dr. Gregory Scott, Department of Chemistry

V. Cooperating Industry, Agency, Non-Profit, or University Organization(s)

California Polytechnic State University, San Luis Obispo

VI. Executive Summary

Abstract:

Scanning tunneling microscopy is a modern technique which creates images of atoms in a material surface, the invention of which won a 1986 Nobel Prize in Physics. The importance of a scanning tunneling microscope (STM) branches across many industries and fields of study, but a cost on the order of $100,000 makes it impractical for undergraduate lab courses. Development of an inexpensive STM gives chemistry, physics, materials engineering, and electrical engineering students at "Learn by Doing" schools hands-on experience with modern imaging techniques, inspiring them and further preparing them for a successful career. This project develops the crucial first step in creating an open-source STM for use in classrooms and research activities. In this step, the team creates a working apparatus that measures the quantum tunneling current from a piece of graphite to a tungsten tip and plots it as a function of scan head voltage on an oscilloscope. All plans, procedures, schematics, and drawings will be available on polytatom.com.

Device Chassis and Scan Head:

The device chassis is machined from a single bar of ½ inch thick and 2 inch wide aluminum using a band saw, drill press, 10-32 tap, and a flat file. The design is mindful of the potentially limited resources of academic institutions and can be made with a hacksaw and hand drill instead of the bandsaw and drill press. The 3D Printed scan head insulator can also be made from a steel washer, noting that the hardened steel is difficult to drill though and must be properly cooled while machining. An additional 3D printed holder for the transimpedance amplifier was created but its location allows significant noise into the signal. Ideally, the transimpedance amplifier should be placed closer the scan tip for minimal noise.

The mechanical approach system uses three ¼-80 fine adjustment screws and matching bronze bushings. Placement of the screws allows for adjustment distances of 317 µm per turn on the screws closest to the scan head, and 10.6 µm per turn on the furthest screw. With the addition of the piezo disk scan head's 160 nm/V resolution the device can move the tip at 0.1 nm distances required to establish tunneling currents.

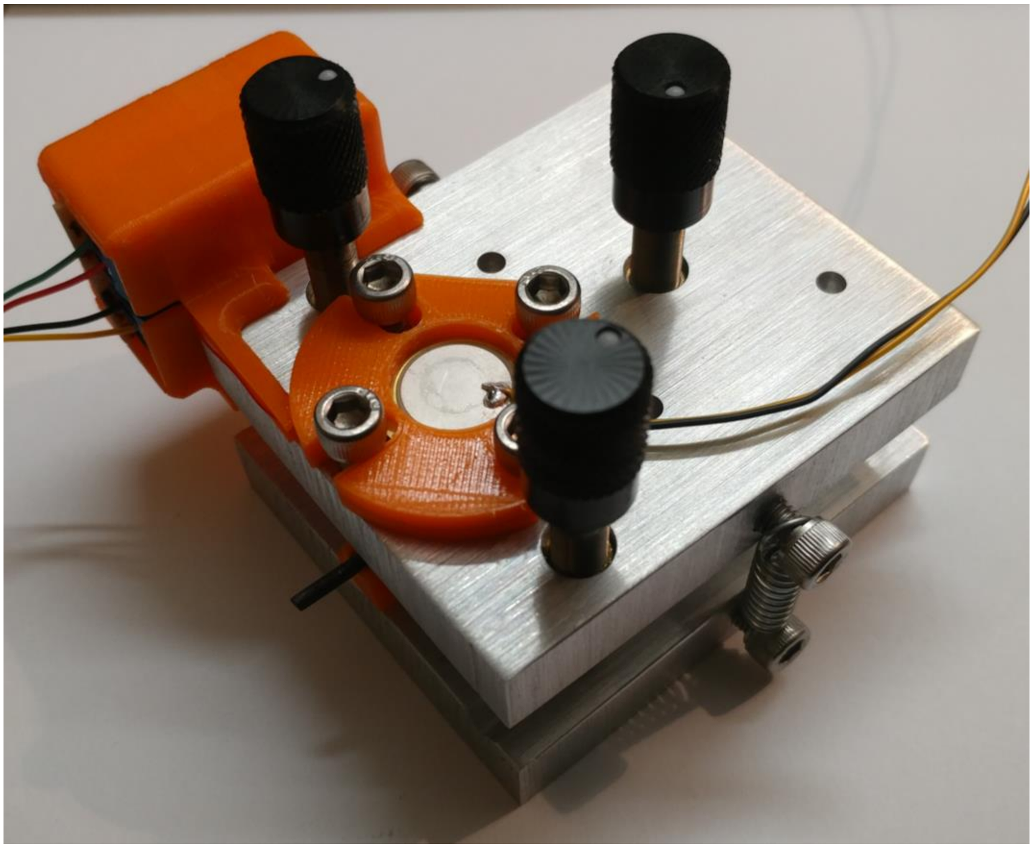


Figure 1: Fully assembled quantum tunneling current measurement device chassis with graphite in sample holder.

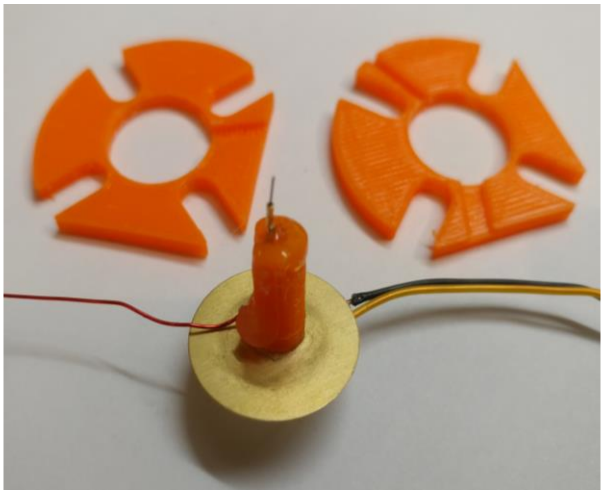


Figure 2: Scan head with tungsten tip (center) and two piece scan head insulator (left and right).

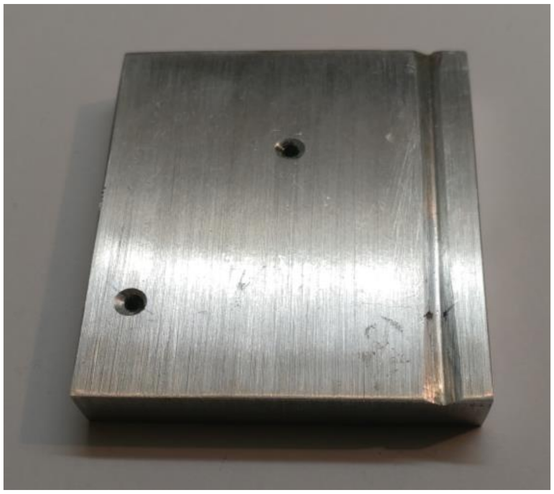


Figure 3: Device bottom plate.

Figure 3: Device top plate with fine adjustment screws and embedded bushings (top view)

Figure 4: Device top plate with fine adjustment screws and embedded bushings (bottom view)

Power Supply:

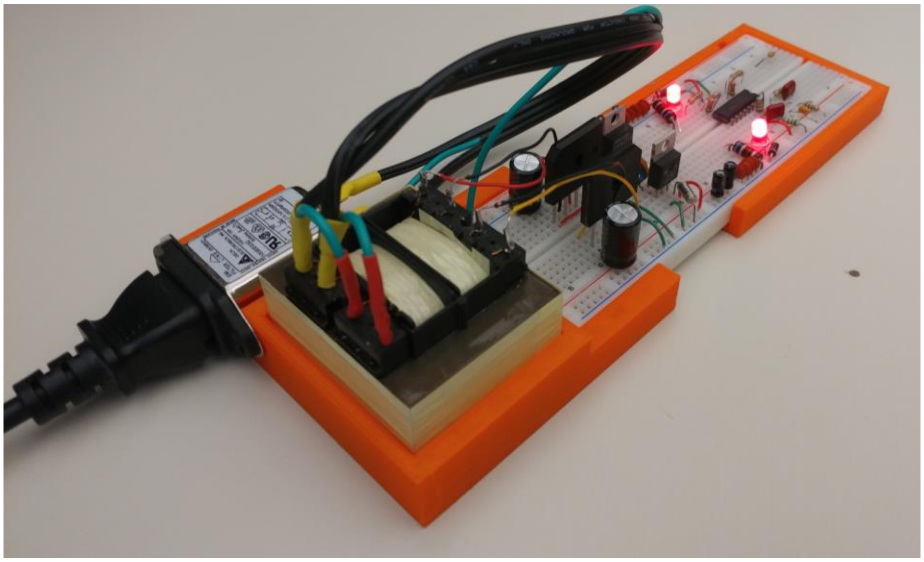


Figure 5: Power supply, piezo amplifier and notch filer on breadboard in 3D printed holder.

The device power supply must deliver power to four main circuits. For simplicity, all amplifiers operate off ±15 V rails and the tips bias requires a variable voltage of 0 to 5 V. Due to noise and cost concerns, a linear power supply architecture was chosen. In this type of supply, the 120 V 60Hz AC voltage from a wall outlet is rectified through a diode bridge network and regulated to the desired voltages. One major disadvantage of this system is the heat dissipated by the linear regulators, though the low current draw from the supplied circuits allowed for operating temperatures of about 44 °C as measured by an Etekcity Infrared Thermometer. Voltage ripple in the rails measured at 0.0046 $V_{Peak-Peak}$ for the +15 V and 0.0078 $V_{peak-peak}$ for the -15V.

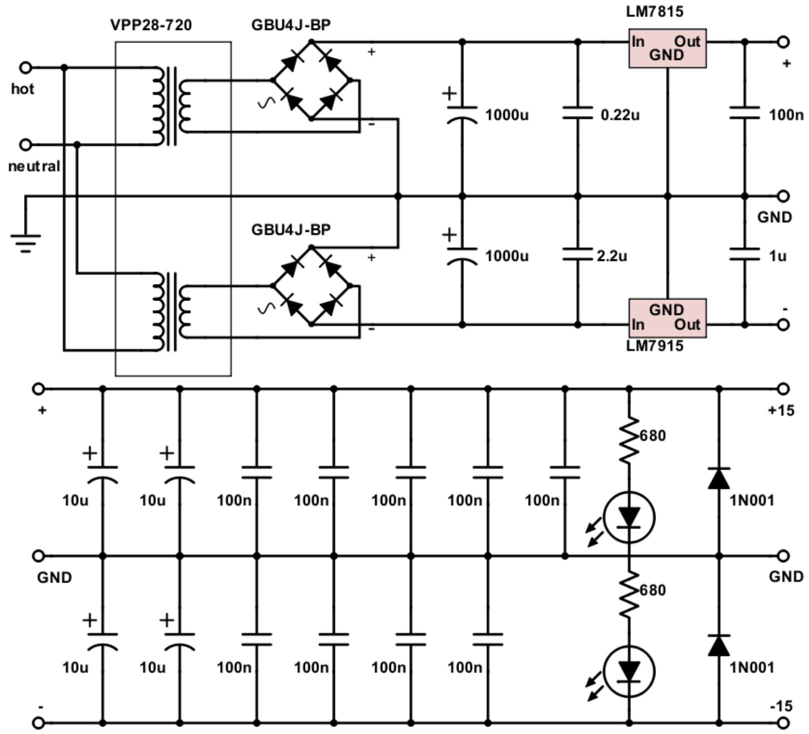


Figure 6: Linear power supply schematic. All resistors are ¼ W with 5% tolerance. Linear regulator filter capacitors are tantalum, polarized capacitors are electrolytic, and all other are ceramic.

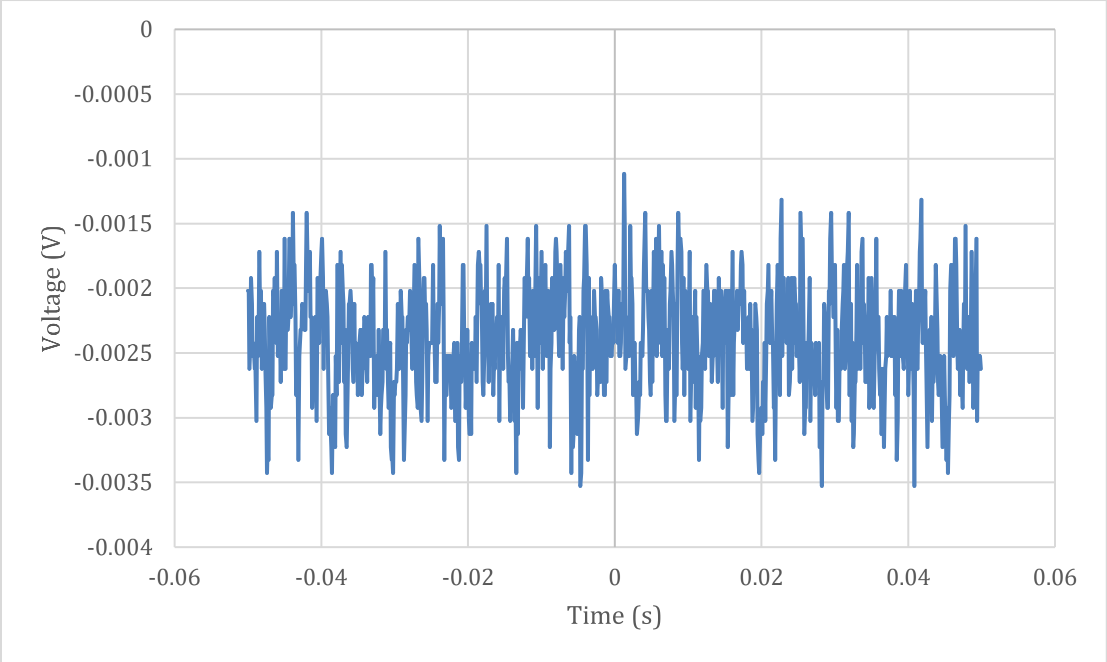


Figure 7: +15V rail noise measurement. Measured on a Keysight MSOX2022A oscilloscope in AC coupling mode. Rail RMS value is +14.998 V with no draw from external circuitry.

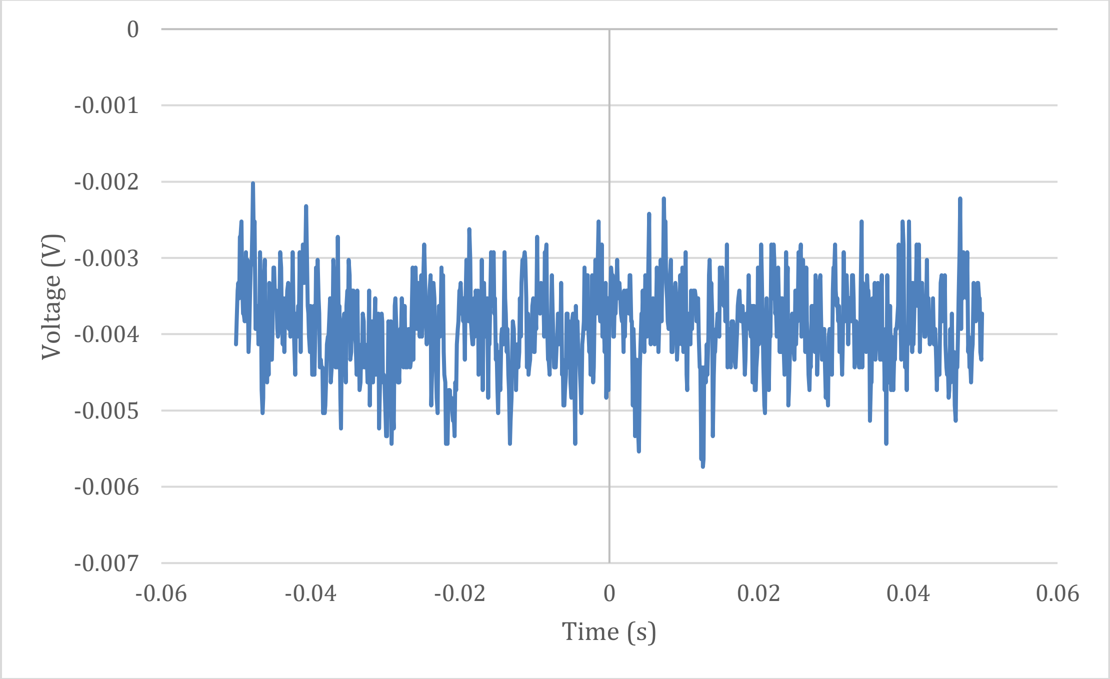


Figure 8: -15V rail noise measurement. Measured on a Keysight MSOX2022A oscilloscope in AC coupling mode. Rail RMS value is -15.002 V with no draw from external circuitry.

Signal Amplification:

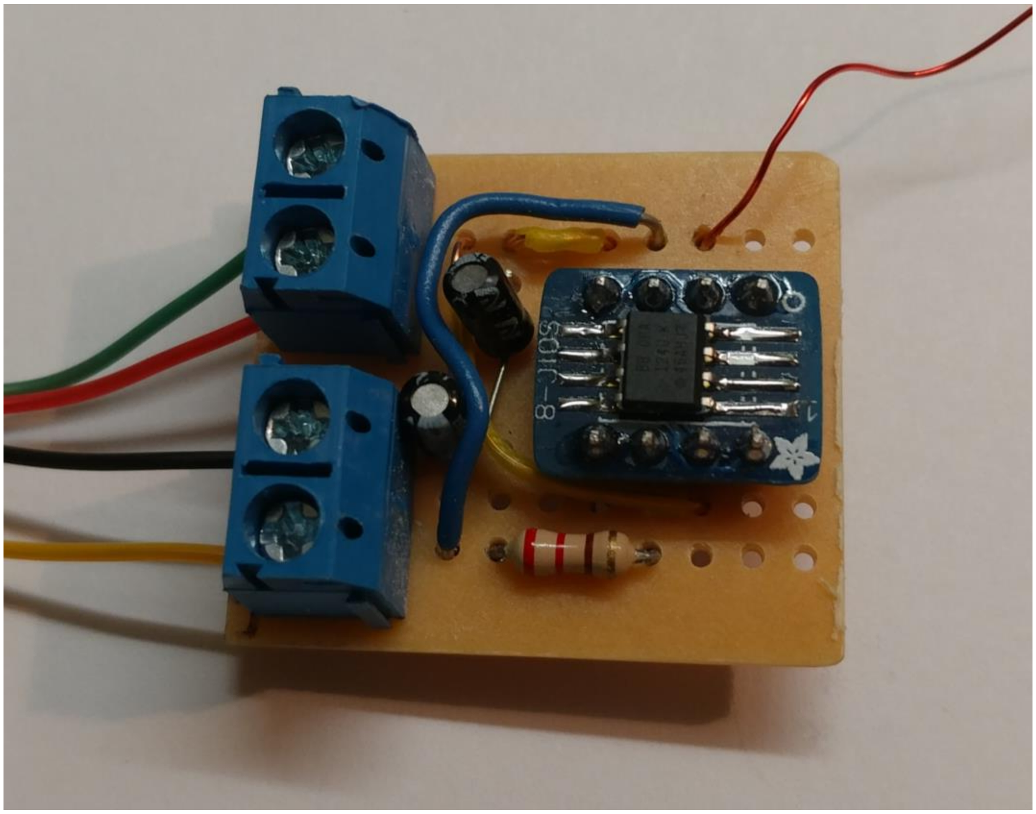


Figure 9: Transimpedance amplifier circuit. Two ceramic capacitors and feedback resistor are soldered underneath the board.

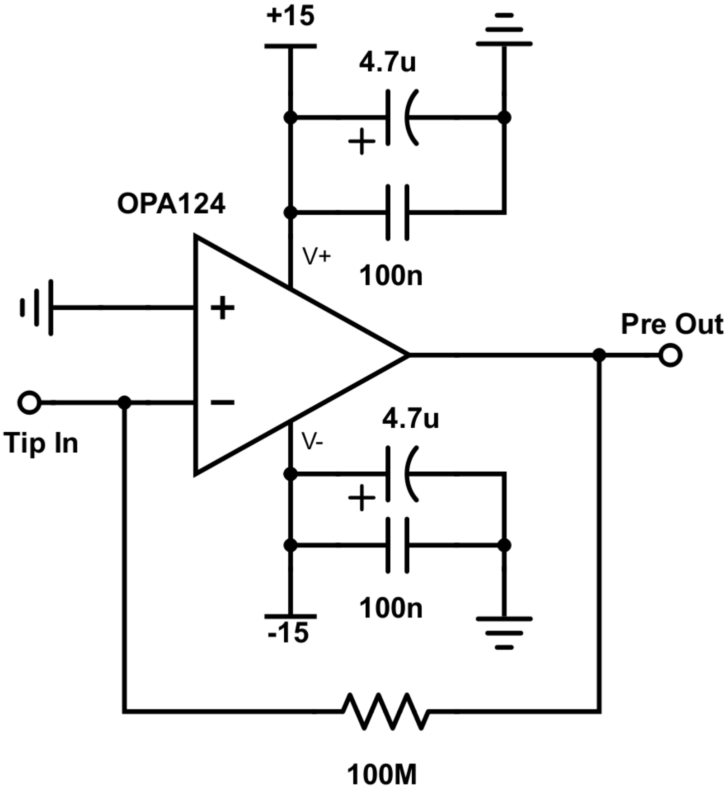
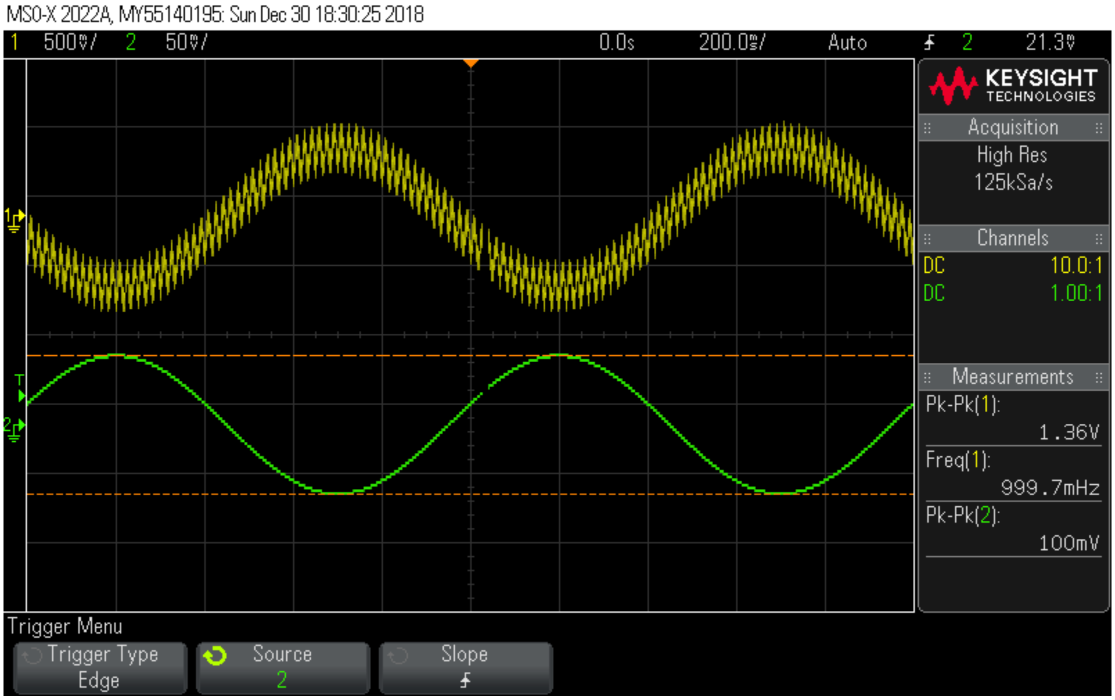


Figure 10: Transimpedance amplifier schematic. All resistors are ¼ W 5%. Polarized capacitors are electrolytic and all other capacitors are ceramic.

Current to voltage conversion and an amplification of 10^8 is achieved using an OPA124 based transimpedance amplifier. Due to the signal wire length, magnetic fields from the power grid (lights, measurement equipment, power strips, etc.) induce small currents which are amplified to significance by the amplifier.


MSO-X 2022A, MY55140195: Sun Dec 30 18:30:25 2018

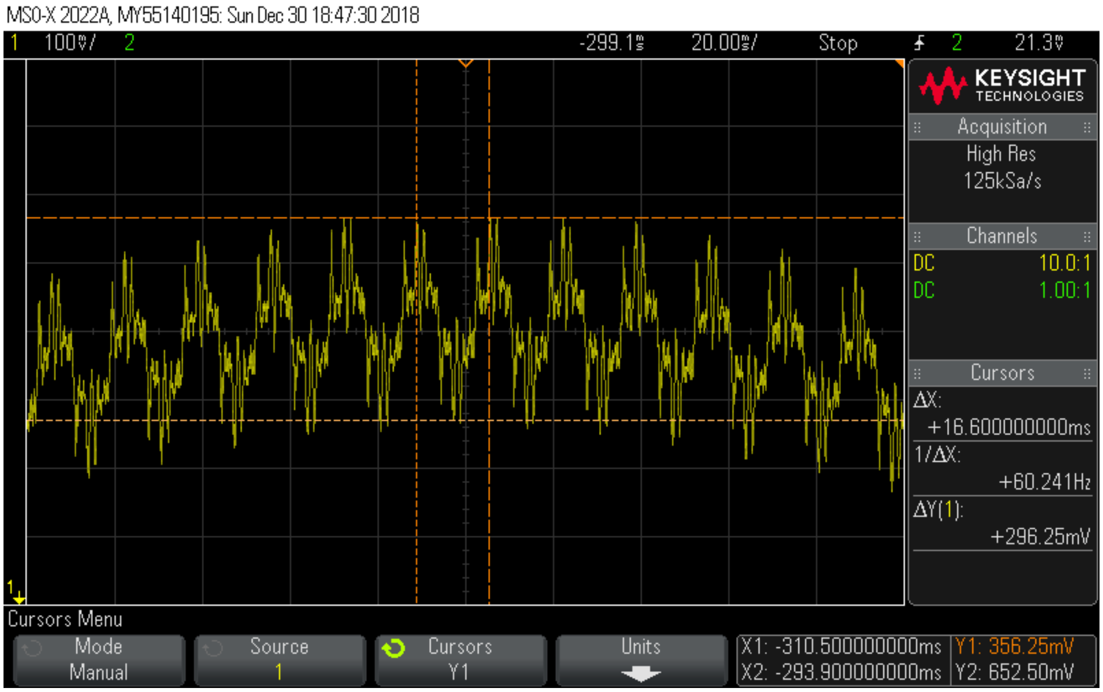
1 500mV/ 2 50mV/ 0.0s 200.0ms/ Auto 2 21.3mV

Acquisition: High Res 125kSa/s

Channels: DC 10.0:1, DC 1.00:1

Measurements:
Pk-Pk(1): 1.36V
Freq(1): 999.7mHz
Pk-Pk(2): 100mV

Figure 11: Test of transimpedance amplifier. A 1 Hz 100 $mV_{peak\text{-}peak}$ sinusoid was dropped across a 10 MΩ resistor applying a 10 $nA_{peak\text{-}peak}$ signal to the amplifier input. The 1.36 $V_{peak\text{-}peak}$ output signal confirms a gain of over 10^8 as required.


MSO-X 2022A, MY55140195: Sun Dec 30 18:47:30 2018

1 100mV/ 2 -299.1ms 20.00ms/ Stop 2 21.3mV

Acquisition: High Res 125kSa/s

Channels: DC 10.0:1, DC 1.00:1

Cursors:
ΔX: +16.600000000ms
1/ΔX: +60.241Hz
ΔY(1): +296.25mV

X1: -310.500000000ms Y1: 356.25mV
X2: -293.900000000ms Y2: 652.50mV

Figure 12: Noise measurement of transimpedance amplifier setup as described in Figure 11. 60 Hz noise is reflective of parasitic currents magnetically induced in the signal wire. Noise measures 296.25 $mV_{peak\text{-}peak}$.

A notch filter was built to decrease the 60 Hz noise however this solution is not ideal as it also introduces noise and alters the signal from the tunnel current. The best solution is to move the transimpedance amplifier as close to the tip as possible.

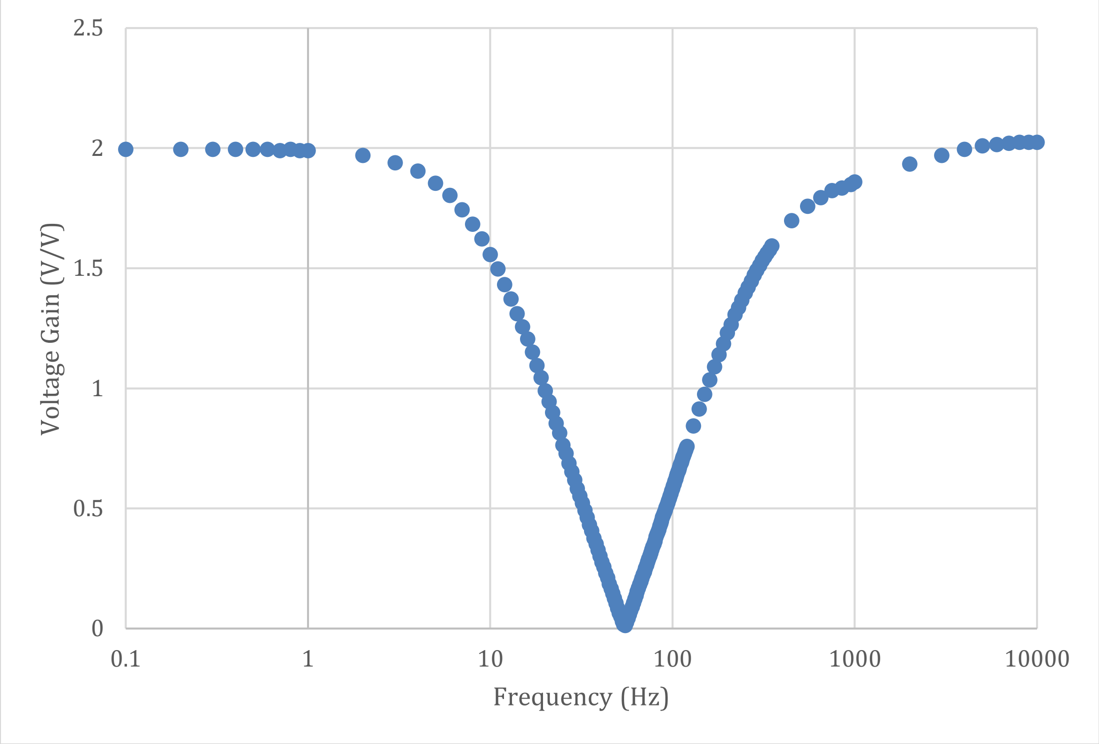


Figure 13: Notch filter frequency response to a $1V_{peak\text{-}peak}$ sinusoid at varying frequencies. Vertical axis represents the input voltage divided by the output voltage.

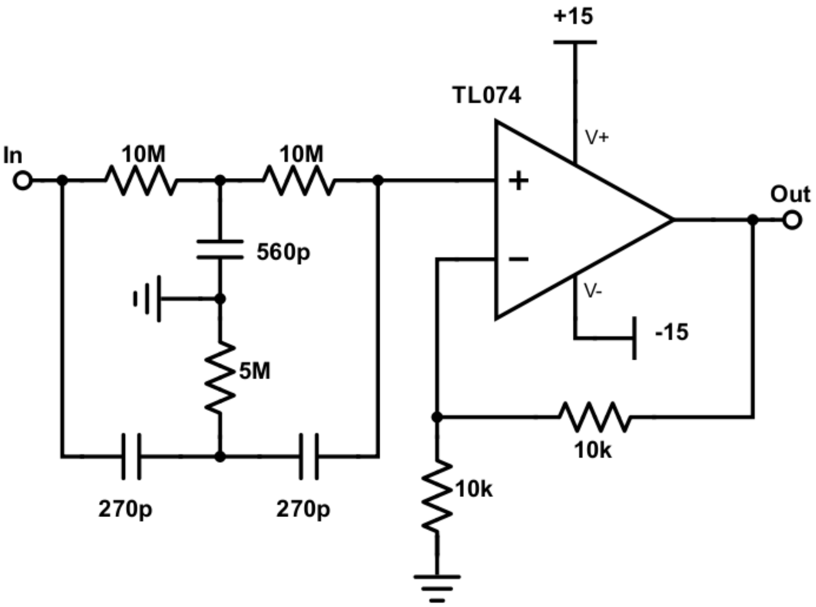
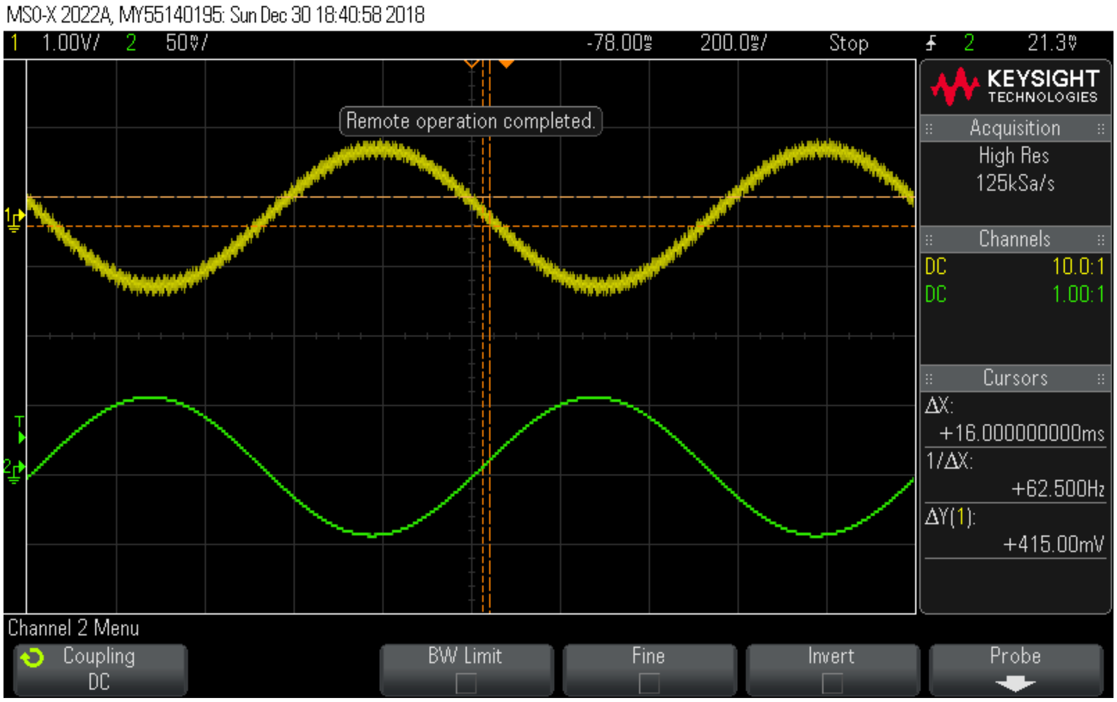
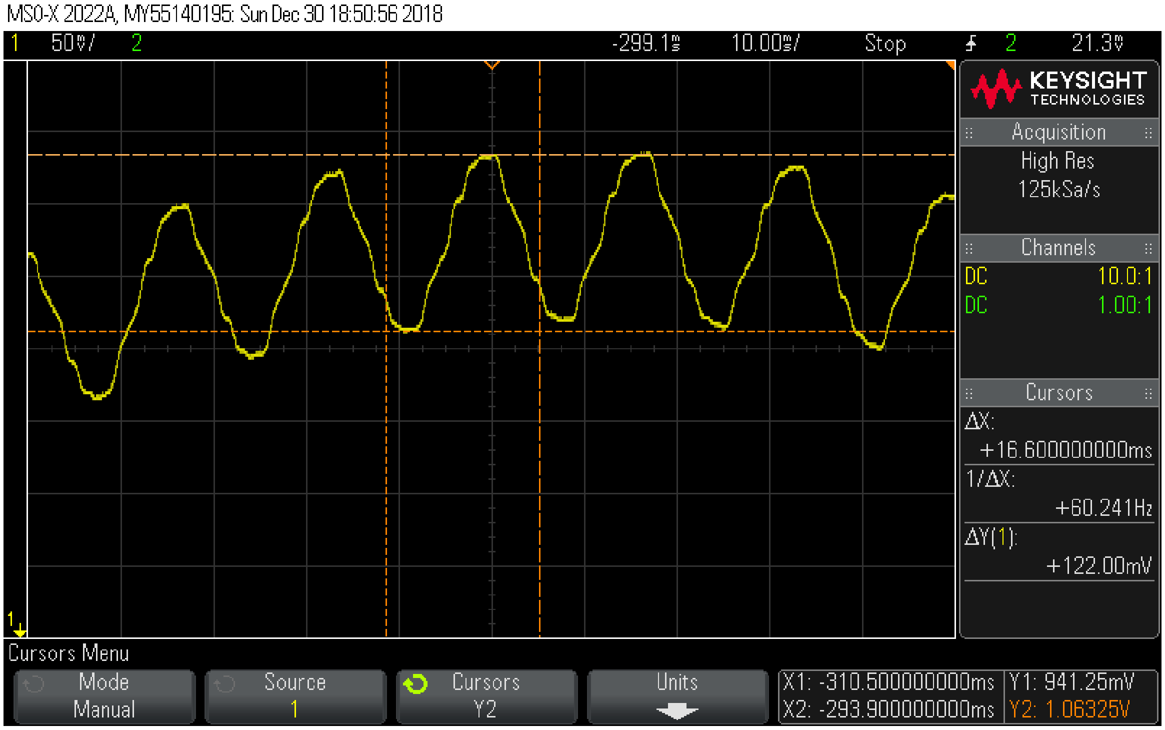


Figure 14: Notch filter schematic. This notch filter is flawed in many respects. The 560 pF should be 540 pF and 1% resistors should be used instead of 5%.


MSO-X 2022A, MY55140195: Sun Dec 30 18:40:58 2018

Remote operation completed.

Figure 15: Transimpedance amplifier signal after filtering. The transimpedance amplifier test from Figure 11 was repeated and the output was fed into the notch filter.


MSO-X 2022A, MY55140195: Sun Dec 30 18:50:56 2018

X1: -310.500000000ms Y1: 941.25mV
X2: -293.900000000ms Y2: 1.06325V

Figure 16: Noise measurement of test described in Figure 15. Noise is reduced to 122 $\mathrm{mV}_{\text{peak-peak}}$.

Conclusion:

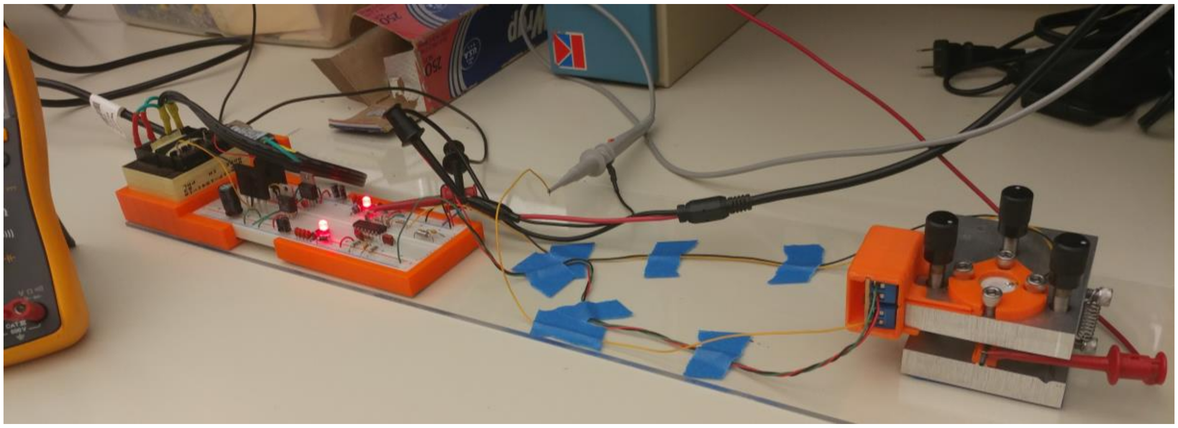


Figure 17: Fully operational device prototype with attached probes for taking measurements below.

The finished prototype was able to establish a tunneling current and amplify the current to a voltage measurable on an oscilloscope. Although a signal was established and there was a strong dependence of signal voltage on tip height, the expected exponential dependence was not observed. Noise from currents induced in the wire connecting scan tip to the transimpedance amplifier was the main source of trouble for this device. Until the noise issue is resolved, automated tip approach is unachievable and the device cannot be made into a scanning tunneling microscope. The first step to resolving the noise issue is to redesign the device chassis to bring the amplifier closer to the tip. The power supply should also be optimized for improved performance and lower voltage ripple. This prototype, along with other more expensive do it yourself scanning tunneling microscope projects, proves the ability to create an inexpensive solution for undergraduate labs and hobbyists.

Moving forward, a new team of students will develop this device into a fully functional scanning tunneling microscope for our senior projects. I will be focusing my time on writing the device firmware and GUI. By the end of June 2019, all progress will be posted to Polyatom.com.

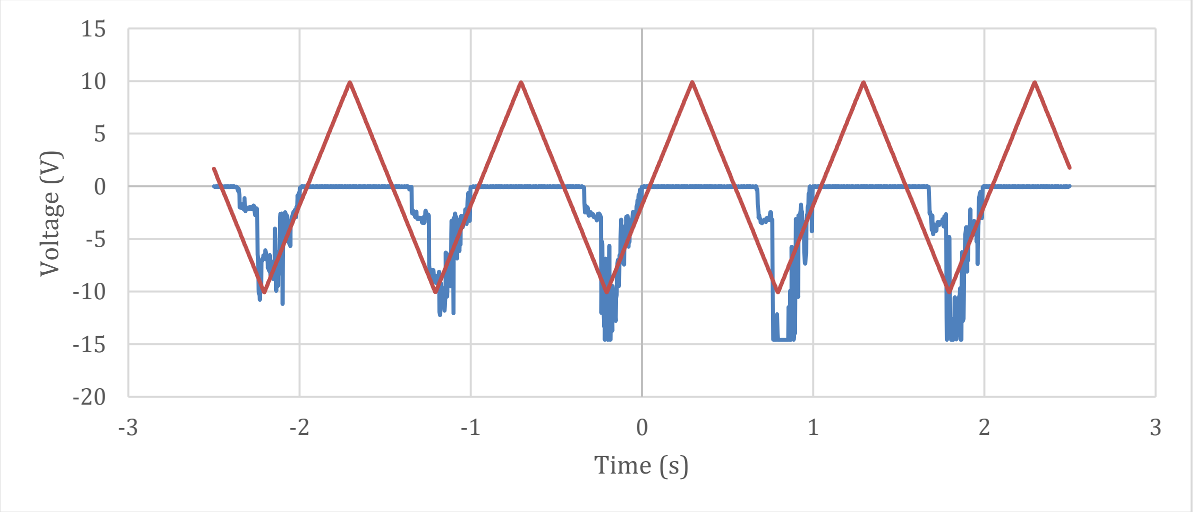


Figure 18: Measured tip current after transimpedance amplifier (blue) and scan head input waveform (orange). A negative piezo voltage corresponds to the tip approaching the sample. The transimpedance amplifier inverts the signal, leading to the downward voltage responses shown.

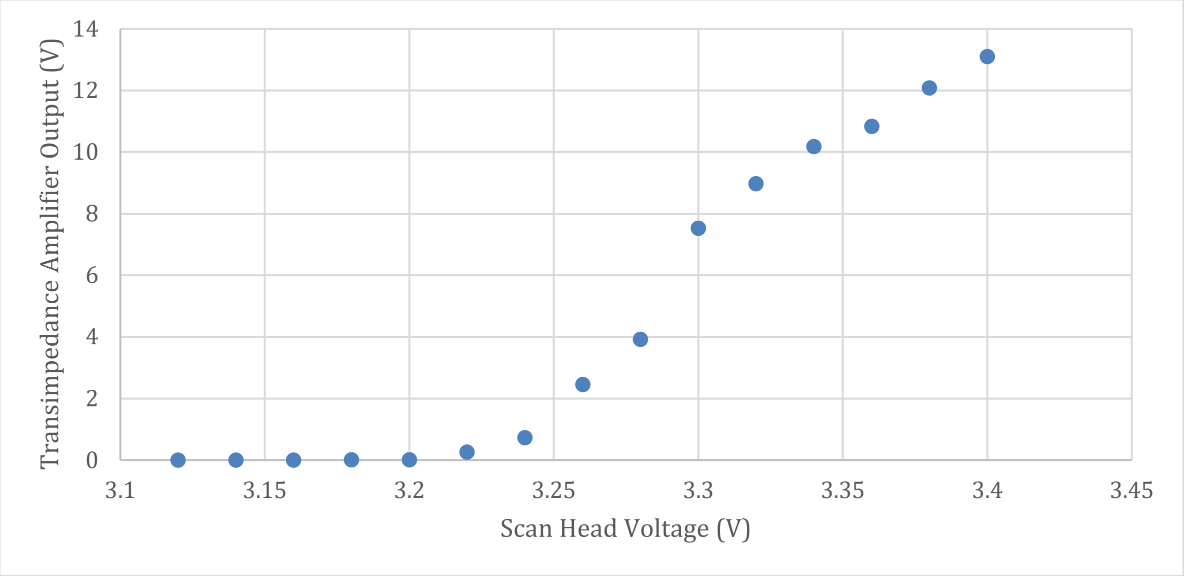


Figure 19: Scan of tip approaching graphite sample at 0.02V (3.2 nm) increments. Sample was biased at 0.512 V and measurements were taken in sets of 5 and averaged.

VII. Major Accomplishments

(1) Developed quantum tunneling current measurement device with manual approach mechanism.

(2) Fabricated and tested prototype device.

(3) Constructed plan for resolving noise issues and turning device into a low-cost scanning tunneling microscope.

VIII. Expenditure of Funds

Date	Vendor	Part Number	Item	Qty	Cost
1/10/2018	Sparkfun	ROB-09238	Stepper motor with cable	1	
		ROB-12859	Big Easy Driver	1	
					$ 41.05
2/12/2018	Texas Instruments	MSP-EXP432P401R	MSP432 Launchpad	3	
					$ 45.96
5/12/2018	Digikey	490-7711-ND	Murata piezo disk	10	
		36-369-ND	Keystone Electronics Standoff	10	
		LM7915CT	Voltage Regulator -15 V	2	
		LM7815ACT	Voltage Regulator +15 V	2	
		P2.0KW-1BK-ND	2k 1W Resistor	1	
		1N4148FS-ND	Diode	2	
		2N3906-APCT-ND	BTJ Transistor	1	
		296-7190-5-ND	TL072 Operational amplifier	10	
		237-1072-ND	Triad Magnetics Transformer	1	
					$ 50.58
6/6/2018	McMaster-Carr	97424A590	Ultra-fine thread thumb screw	4	
		92185A988	316 stainless steel screw, 10-32 (25)	1	
		98625A950	0.313" long brass bushing	3	
		95783A071	4.5mm nylon hex standoff	4	
		9214A035	18-8 stainless steel washer (25)	1	
		8975K477	6061 aluminum bar, 0.5"x0.5"x2'	1	
					$ 117.91
10/20/2018	Coast Electronics	276-0170	Printed circuit board	1	
		276-0159	Dual IC board	1	
					$ 6.98
10/20/2018	Harbor Freight	95142	Plastic Drop Cloth	1	
		68238	Toolbox with organizer	1	
					$ 18.29
10/30/2018	McMaster-Carr	98625A960	0.438" Long brass bushing	4	
		97424A650	Ultra-fine thread thumb screw	4	
		98952A402	Aluminum Male-female standoff	4	
					$ 95.26
11/7/2018	fisher scientific	AA10408G6	Tungsten wire (10m)	1	
					$ 45.90
12/9/2018	Coast Electronics	Resistor	10K 1/4W resistors	21	
		276-0410	2-position terminals	1	
					$ 11.94
12/20/2018	ACE Hardware	Fasteners	3mm screws	9	
					$ 4.85
Total					$ 438.72

IX. Impact on Student Learning

Many months were spent reading books and articles to understand scanning tunneling microscopy and the history of the instrument. From this I learned how to effectively locate information and apply it to product development. It was also necessary for me to learn how to manage my time to accomplish a task over such a large span of time (as compared to labs or internships) and how much a setback can affect the timeline of a project. In addition to learning a great amount about scanning tunneling microscopy, I have also discovered an enjoyment for developing low cost instrumentation. Most importantly, I gained insights into person deficiencies when attempting self-guided research projects. I am happy to have realized these issues before starting my senior project and am especially thankful that I can address them before heading off to graduate school.