NDnano
Notre Dame Nanoscience and Technology

NDnano Summer Undergraduate Research
2024 Project Summary

1. Student name & home university: **Daniel Noronha, University of Notre Dame**

2. ND faculty name & department:
   - **Gregory Snider, Electrical Engineering**
   - **Alexei Orlov, Electrical Engineering**

3. Summer project title: **Adiabatic Capacitive Logic & Clocking Systems for Ultra-Low Power Electronics**

4. Briefly describe new skills you acquired during your summer research:

I learnt how to program two 2-port Vector Network Analyzers (Keysight E5080B and Copper Mountain Technologies S5065) in Python with Jupyter Notebooks using SCPI commands to automate data collection and processing. I also learnt how to perform SOLT/TRL calibration (and add my own standards) using an impedance standard substrate and GSG RF probes that were also used to measure MEMS resonators. Additionally, I learnt how to import/export Touchstone S-parameter data in ADS software for curve-fitting to a simulated circuit model and improved my MATLAB skills in data processing and plotting. Finally, I was trained on using a wire bonder (WestBond 7476E) and 3D laser confocal microscope (Olympus LEXT OLS4100) for imaging in the cleanroom.

5. Briefly share a practical application/end use of your research:

Aluminum Nitride (AlN) MEMS resonators (microelectromechanical systems) can be used for ultra-low power clocking systems. When used in conjunction with reversible adiabatic capacitive logic, they facilitate achieving high frequency clock signals (in the GHz range) while only dissipating a fraction of the energy that conventional CMOS circuits would dissipate as heat. Currently, heat dissipation in CMOS circuits is one of the biggest issues with existing technology as it limits the maximum clock frequency microprocessors can achieve without overheating, thus limiting computational performance. AlN MEMS resonators recycle most of the energy received from an oscillator and use it in a reversible clocking scheme to minimize dissipated heat so that we can achieve much higher clock frequencies with the same heat dissipation as existing CMOS or achieve much lower heat dissipation at the same clock frequency.

6. 50- to 75-word abstract of your project:

AlN MEMS lamb wave contour mode resonators store energy electromechanically from AC excitation using the material's piezoelectric properties. My testing has verified that their resonant wavelength equals twice the interdigitated electrode pitch, thus allowing for precise control over their resonant frequency (with known AlN phase velocity). Further experimentation confirms that the Q factor (indicating the sharpness/quality of resonance peaks) is roughly proportional to the length of the electrodes, with clear positive correlation observed.

7. References for papers, posters, or presentations of your research:

- M. S. McConnell, "Adiabatic Reversible Computing: Measurement of Heat Dissipation using Nanothermocouples and Fabrication of MEMS Power Clocks," Ph.D. dissertation, Univ. of Notre Dame, Notre Dame, IN, USA, Dec. 2018.

- E. Calayir, "Heterogeneous Integration of AlN MEMS Contour-Mode Resonators and CMOS Circuits," Ph.D. dissertation, Carnegie Mellon Univ., Pittsburgh, PA, USA, Jul. 2018, doi: 10.1184/R1/6719777.v1.

One-page project summary that describes problem, project goal and your activities / results:

The goal of my project this summer was to design, fabricate, and test Aluminum Nitride MEMS resonators to determine how a resonator's geometry affects its electrical characteristics (resonant frequency and Q factor) so that we can use the most efficient resonator design as a power clock for a digital logic circuit running reversible adiabatic capacitive logic at a given resonance clock frequency in a Bennett clocking scheme. Our target is to maximize the Q factor and minimize equivalent motional resistance of the resonators at a specified frequency.

MEMS Resonator Design

My resonator design created this summer consists of interdigitated electrodes of Aluminum seated on a suspended Aluminum Nitride plate. It was exported as a 2-layer GDS file from KLayout and included several changes from my design last spring. One of these was including an Aluminum ground plane on the top layer and changing pad sizes to facilitate 150µm pitch GSG RF probe testing as opposed to wire-bonding which was used when testing prior samples. *Figure 1a* shows my entire (positive photoresist) mask design, where the pink areas represent regions where Aluminum is to be etched and purple areas show where Aluminum Nitride will be etched. *Figure 1b* shows a closeup of an individual resonator.

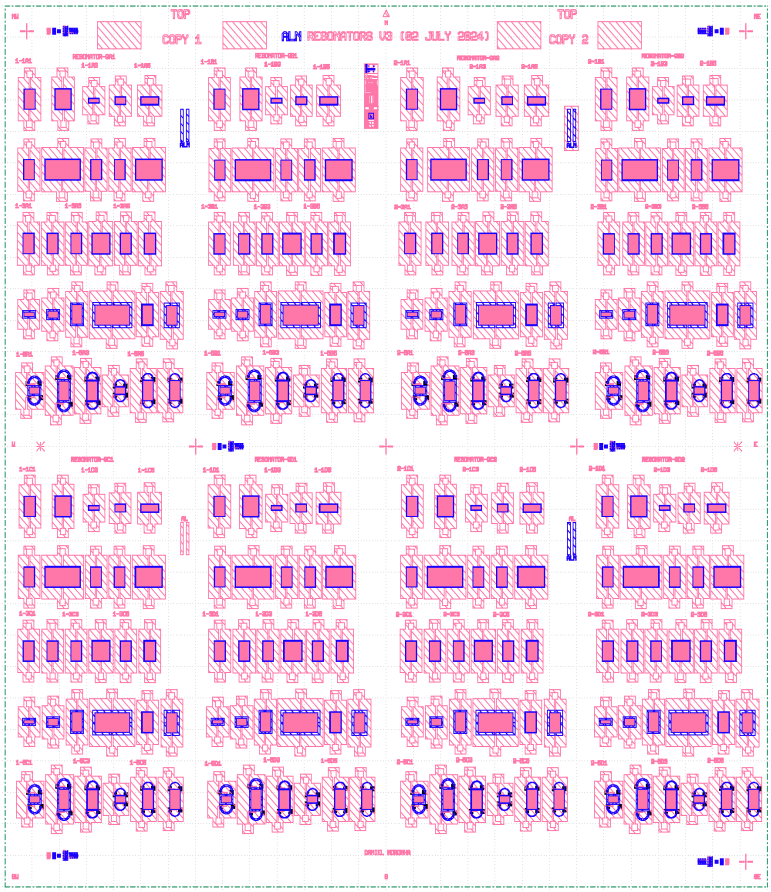

Figure 1a. Complete AlN Resonator Layout GDS in KLayout

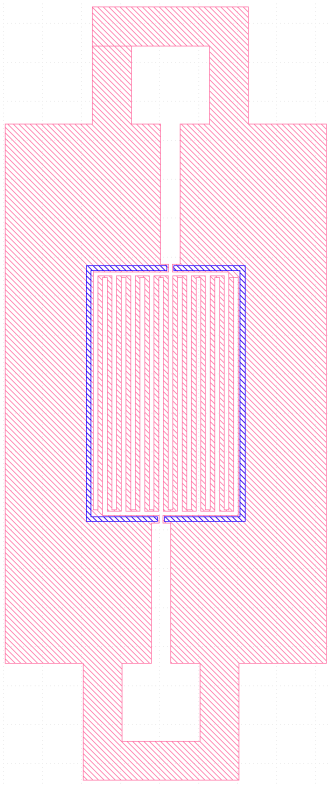

Figure 1b. Individual AlN Resonator Closeup

The overall design consisted of 112 resonator variants (2 copies), spanning 14mmx14mm with varied electrode lengths, widths, and counts to investigate how different aspects of resonator geometry affect the Q factor. The white regions above represent the Aluminum ground plane and signal electrode/pad regions. Electrode pitches were chosen based on the lamb wave wavelength in a contour mode resonator. This was expected to be twice the electrode pitch, allowing us to estimate the resonant frequency using the equation $v_p = f_{res}\lambda$, where v_p is a known constant for a given film. To speed up future designs, I wrote a Python macro to parameterize all the necessary resonator dimensions using one of KLayout's parametrized cells (PCells) and the KLayout Python API.

MEMS Resonator Fabrication

I completed my fabrication of two samples in the ND nanofabrication facility (a class 100 cleanroom) over two and a half days. It involved 2 deposition steps, 2 lithography steps, and 5 etching steps. Aluminum deposition was done using an Oerlikon e-beam evaporator, while SiO_2 was deposited by plasma enhanced chemical vapor deposition (PECVD). Both lithography steps were completed using direct write laser lithography (375nm i-line) in the new Heidelberg MLA150 with SPR-700 positive photoresist and AZ-917 developer. Apart from the final Xenon Difluoride isotropic Silicon etch, all other etches were done in a Plasmatherm 790 Reactive Ion Etcher (RIE) using recipes that I had previously characterized in my research over previous semesters. The process started with a bare 4" Si wafer that had a 1µm AlN film deposited by sputtering at Carnegie Melon University. I then cleaved this sample into ~20mmx20mm pieces and performed surface cleaning before proceeding. *Figure 2* shows my fabrication steps, while *Figures 3, 4, and 5* show one of the completed chips (regular camera image), 2D optical, and 3D laser confocal micrographs of a completed Aluminum Nitride MEMS resonator respectively.

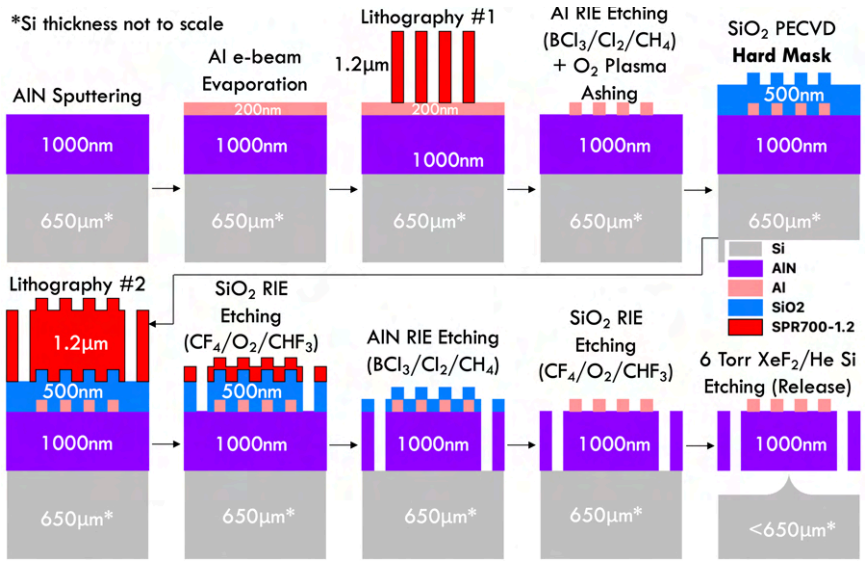

Figure 2. AlN MEMS Resonator Fabrication Process Steps

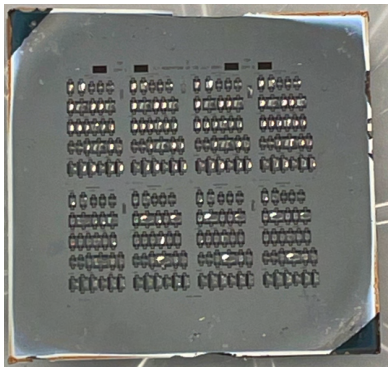

Figure 3. Completed MEMS Resonator Chip Image

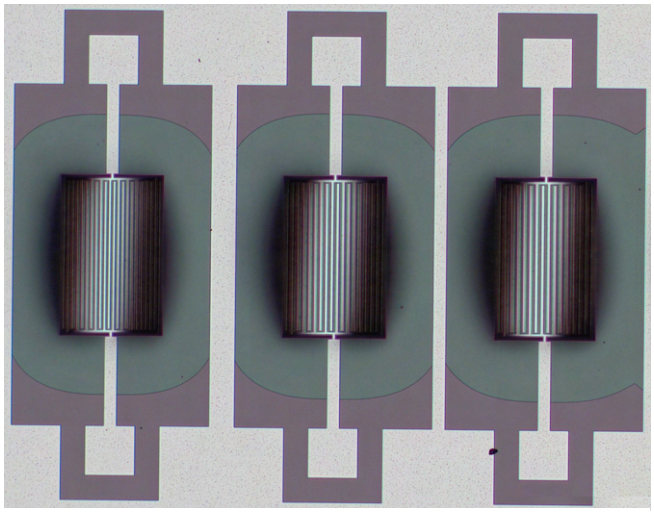

Figure 4. 2D Optical Micrograph (5x) of Fabricated MEMS Resonators

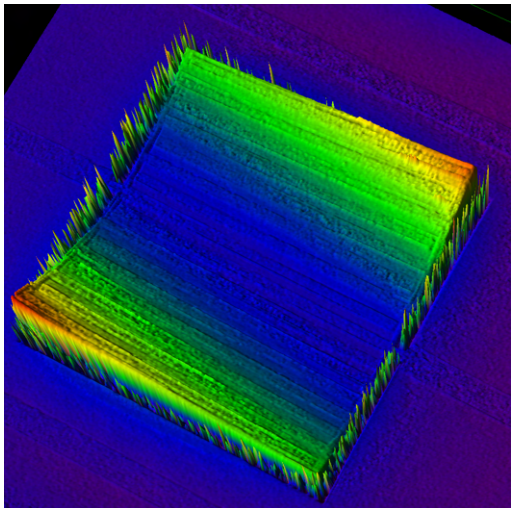

Figure 5. 3D Laser Confocal Micrograph (20x) of Suspended AlN MEMS Resonator Plate

MEMS Resonator Testing Setup, Results, and Analysis

The two fabricated MEMS resonator samples were tested using both wire-bonding and 150µm GSG RF probes (with a probe station) on separate samples. RF probe testing yielded better results as it minimized the effects of parasitic inductances and capacitances that could not be eliminated from bond wires. It was also a much quicker and more repeatable testing method. *Figures 6 and 7* show the two testing setups, with the wire-bonding setup using SMA launches on a 50Ω impedance-controlled RF PCB that I had designed earlier for another project.

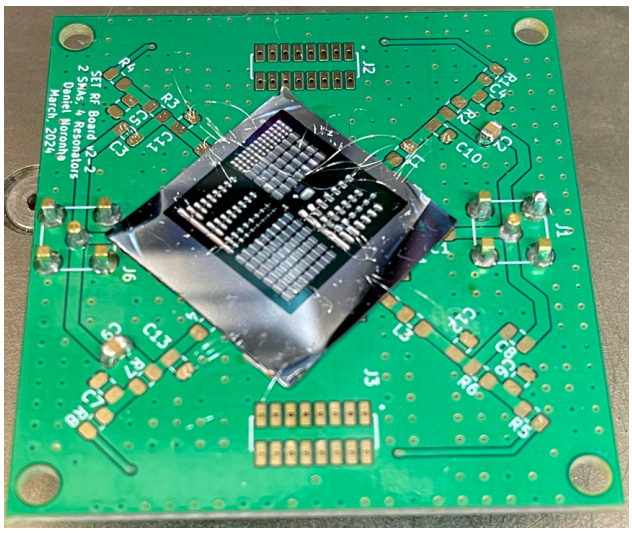

Figure 6. Wire Bonding Test Setup on 50Ω RF PCB

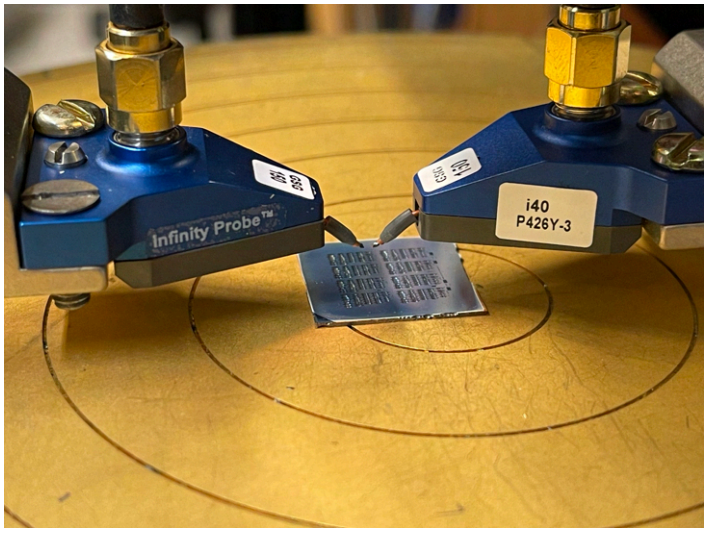

Figure 7. GSG RF Probe Test Setup with Probe Station

The primary measurement instrument used was a 2-port Vector Network Analyzer that measured the four scattering (S) parameters in the S matrix: S_{11}, S_{12}, S_{21}, S_{22}, which indicate reflection from and transmission through the resonator being tested. 2-port SOLT (short-open-load-thru) calibration was performed using an impedance standard substrate for RF probe testing to eliminate systematic errors and parasitic effects due to the test setup itself. The instrument was programmed in Python (Jupyter Notebooks) with SCPI commands to automate s2p data collection. Using one of my MATLAB scripts, the S matrix was transformed to a Y matrix (admittance) and Z matrix (impedance). The transmission admittance (Y_{21}) was then transferred to Keysight's Advanced Design System (ADS) software and the identified resonance peak was curve fit to a Butterworth-Van Dyke RLC resonator model as shown in *Figure 8*.

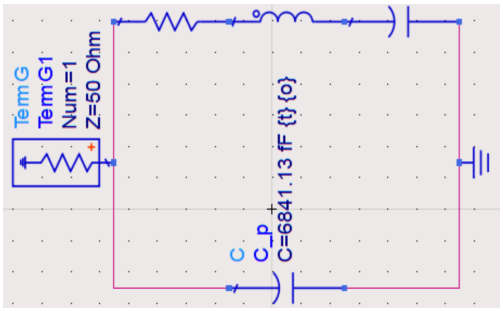

Figure 8. ADS BVD 1-port resonator model simulated for curve fit.
GND was replaced with another TermG element for 2-port curve-fitting.

Overall, the fabrication process was successful with an extremely high yield as all of the 32 resonators tested produced resonance peaks when measured. Moreover, the peaks observed matched theoretical calculations almost exactly. The average phase velocity calculated for over 10 resonators was around 10875m/s and all tested resonators had a phase velocity within ±1% of that value. This value was calculated using $v_p=f_{res}\lambda$, where f_{res} was the measured peak frequency and λ was calculated as twice the interdigitated electrode pitch (twice the period/distance between the same point on two adjacent electrodes) from the GDS design dimensions.

After establishing the phase velocity of the AlN film as a known constant, we determined that the resonant frequency of all measured resonators was inversely proportional to the resonator pitch. More specifically, it agreed very well with the equation $f_{res}=(v_p/(2W_p))$, where W_p is the resonator pitch and v_p is the average AlN phase velocity (~10875m/s). Another pattern observed across multiple resonators was that the interdigitated electrode length was roughly proportional to the Q factor obtained by curve fitting in ADS. Curve-fit simulation data was transferred back to MATLAB for processing and plotting. Two such examples of observed patterns are shown below. The pair of *Figures 9a and 9b* and shows that when all other dimensions are kept the same, but resonator pitch is halved from 6µm to 3µm, resonant frequency doubles from ~455MHz to ~910MHz. The pair of *Figures 10a and 10b* show that when all other dimensions are kept the same, but length is tripled (from 100µm to 300µm), the curve fit Q factor (calculated as $2\pi f_{res}L/R$) roughly triples as well.

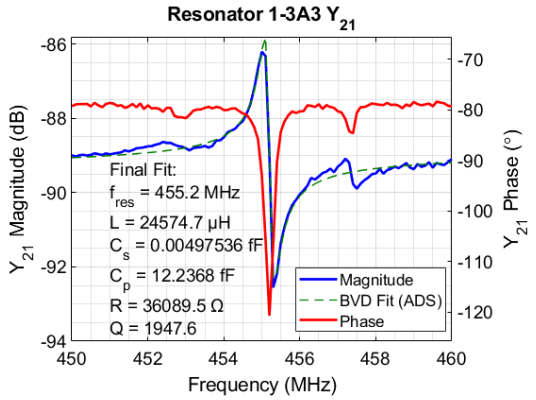

Figure 9a. Curve-Fit Resonance Peak from 6µm Pitch Resonator

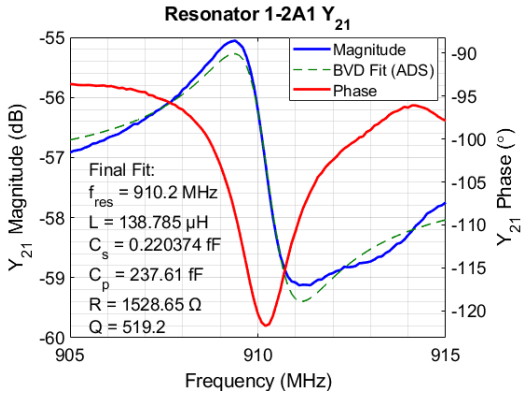

Figure 9b. Curve-Fit Resonance Peak from 3µm Pitch Resonator

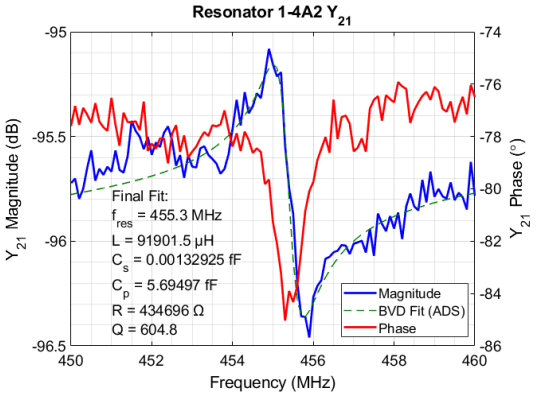

Figure 10a. Curve-Fit Resonance Peak from 100µm Electrode Length Resonator

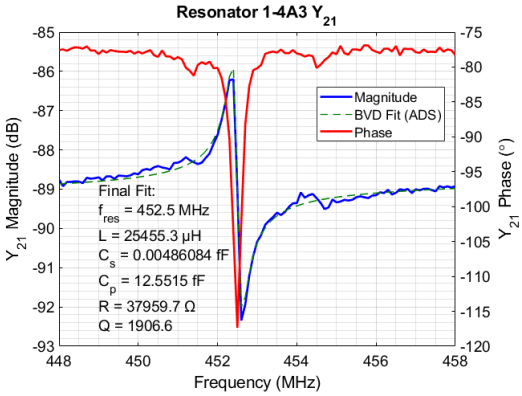

Figure 10b. Curve-Fit Resonance Peak from 300µm Electrode Length Resonator

The effect of interdigitated electrode count (number of periods) was not conclusively determined, possibly due to stress bending of the plate (see *Figure 5*) having a significant effect for large electrode counts or plate widths. In future designs, I will attempt to reduce this effect by adding a second anchor to the top and bottom of the plate. Based on the results shown above, I will also increase electrode lengths further to maximize Q and reduce anchor widths (given that the fabrication process has proven reliable) to minimize anchor loss in the next design iteration. Centering the anchors could also improve symmetry. Another goal is to more closely understand the relationships between curve fitting parameters like R and L, to improve R specifically and not just the L/R ratio that in part defines Q. Eventually, the resonators will be tested with an RC load to simulate transistor gate capacitance and evaluate the real-world performance of the resonators and their suitability in applications as MEMS power clocks.