Advanced Membrane Mechanics in Imaging Devices

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Science is based on observation, gaining information about the physical world in order to understand or create. Imaging and microscopy are crucial observation tools for all experimental scientists. Advances in technology have pushed imaging capabilities beyond that of an optical microscope with techniques such as magnetic resonance imaging (MRI) and scanning electron microscopes (SEM). Yet, there is still room for improvement in sensitivity and resolution. Specifically, there is a disconnect between the advanced mechanical systems that are available and the systems that are actually used in imaging devices. By employing the best that microfabrication techniques can offer, I can push the boundaries of observation to a new level. After all, why wouldn't scientists use state-of-the-art tools for state-of-the-art research?

One such imaging technique is magnetic resonance force microscopy (MRFM). MRFM is an exploitation of spin mechanics that couples oscillating spins to a small, 4 μm diameter, magnetic tip suspended on a physical resonator, as seen in Figure (1). Spin is the angular momentum of a particle spinning about its own axis, which creates a small magnetic dipole. This coupling will drive the resonator, increasing its amplitude. This interaction can map an image of matter with high precision [1].

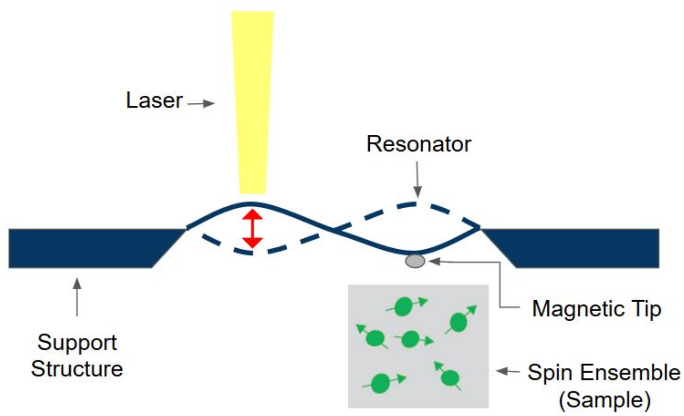

Figure 1: MRFM schematic (not to scale). The spins can be sensed or controlled through coupling with the magnetic tip. I measure the motion of the resonator via laser interferometry.

MRFM is a sub-field of MRI which uses similar concepts to analyze matter in the body in a non-invasive manner. The field of MRFM has progressed (a lot) in the past two decades, achieving single spin resolution [1]. Advances in micro-electrical mechanical systems has increased the sensitivity of MRFM systems, although there is room for improvement in sensitivity, imaging resolution, and coupling efficiency. Currently, MRFM assemblies use silicon cantilever or nanowire resonators that resonate at low frequencies, have high mechanical loss, and are highly damped. These properties put a restriction on the sensitivity and resolution that MRFM devices can achieve. Conversely, silicon nitride membrane resonators are more advanced mechanical systems that resonate at higher frequencies, have less mechanical loss, and are less damped than cantilever or nanowire devices. These thin-film resonators have high internal stress and low mass, allowing them to oscillate very fast (upwards of 400 kHz) and for millions of cycles without being affected by their environment. Due to these properties and low optical absorption of the SiN, these resonators can be optically measured or controlled and interact with small forces.

SiN membrane resonators can also be patterned with a periodic structure to reduce mass and create environment isolation [2,3,4]. Periodic structures oscillate only at certain natural frequencies that are dependent on the mass and internal stress. If the periodic structure is changed so does the natural frequency. Thus, by introducing a defect in the periodic structure, the defect will resonate at a frequency that the rest of the membrane will not. This creates mechanical isolation, reducing the amount of mechanical energy that is dissipated into the surrounding environment. These periodic structures, called phononic crystals (PnC), increase the quality factor (Q) of the membrane resonator, which is a measure of how underdamped a resonator is [2]. High Q resonators have better sensitivity than low Q resonators.

I have been working with the Regal group at the University of Colorado Boulder to fabricate and integrate these PnC membrane resonators into a MRFM experiment. I hope these membrane resonators will expand the possibilities of MRFM by reducing mass and increasing the natural frequencies of the resonator. When a resonator has an oscillating force act on it at its natural frequency, there is an established resonance. At resonance, the resonator's oscillations are amplified, instead of damped. With the introduction of these resonators, the force sensing of MRFM can be advanced, making MRFM a stronger candidate for imaging techniques on the nano-scale and single-spin levels.

PnC resonators are difficult to design and fabricate due to the extremely thin and fragile structure, as seen in Figure (2). To fabricate the resonator, I use a combination of photolithography, electron beam lithography, reactive ion etching, and chemical etching to define and release each membrane. I have been able to fabricate two different types of PnC membrane resonators that each have higher frequency and Q than typical silicon cantilevers and nanowires.

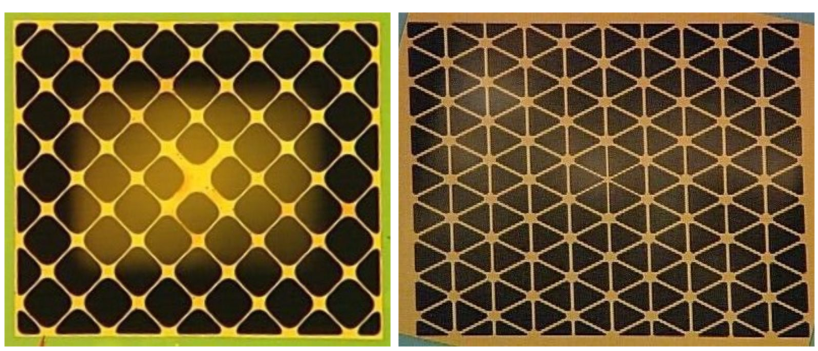

Figure 2: (Top Left) Fabricated 'Square-cell' PnC membrane type resonator. (Top Right) Fabricated 'Sankey-style' PnC membrane type resonator, adapted from [3].

Moving forward, my undergraduate honors thesis is focused on introducing these resonators into an MRFM assembly, making MRFM a strong candidate for imaging at a force sensitivity below attonewtons, the SI unit of force on the order of 10^{-18}. Utilizing these advanced micro-mechanical systems will allow for an increase in sensitivity in magnetic resonance imaging techniques, allowing scientists to image molecules and matter at the nanoscale level in a non-invasive manner. Further, as we increase our ability to gather information from the resonator coupling with the spins, we also increase our ability to control the spins through coupling. Thus, while these membrane resonators can be applied to imaging devices, they could also be used to increase control in the initialization of quantum spin states. This could allow quantum computing to be further developed. There exists many more possibilities for integration of the most advanced mechanical devices to cutting edge research.

In my work to fabricate and integrate these membrane resonators, I have gained practical experience in my role as a researcher. From clean room techniques to optics table practices, the hands on experience will help me in my future endeavours as a research scientist. My technical reading and writing skills have improved and will continue to improve. However, the most important part of my research experience has been satisfying my scientific curiosity and getting to play in the lab with really interesting concepts and equipment. I have no doubt that the lessons and experiences I have learned will only propel me further in my education as I continue on into graduate school and towards my dream of becoming a professor working on integrating atomic and quantum physics into practical applications.

References

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