My research focuses on the study of piezoelectric Micro Electromechanical Systems (MEMS) and developing structures for new applications. My work combines micro-fabrication techniques and integrated circuit (IC) design to create a monolithically integrated MEMS-CMOS system. I have developed these systems for radio frequency (RF) applications and more recently I am working on the IC design and material research for gas and infrared (IR) sensing.

I started this work in August 2013 when I joined Dr. Ioannis Kymissis' research lab, the Columbia Lab for Unconventional Electronics (CLUE). The project, initially funded by DARPA, was to develop a low power alternative for RF filters and oscillators on CMOS to be used in receivers. High quality energy storage devices, called passives in the field, are crucial for the implementation of these RF components. Quality factor (Q) is the metric used to define the energy storage efficiency. The higher the value of Q, the more selective the resonator is at a specific frequency. CMOS foundries offer passives in their technology packages, comprised of inductors and capacitors. These are large in area and experience high losses, resulting in costly processes and a low Q of approximately 10. An alternative to the electrical components is acoustic wave devices, e.g. quartz crystals and acoustic wave devices. Acoustic devices using piezoelectric materials have a higher energy storage capability at resonance, which allows them to exhibit lower losses and, in turn, demonstrate a higher Q (between 100-10000). The selection of resonance frequency will depend on the electrode pitch for surface acoustic wave (SAW) or on the thickness for bulk acoustic wave (BAW). In my research, I focus on BAW structures. Although these piezoelectric devices are widely used in today's communication systems as duplexers, they are not part of the CMOS process and technology packages. Having these devices off-chip requires the use of wire bonding and flip chip techniques to connect the device to the CMOS chip. These techniques add parasitic resistances and capacitances (commonly called parasitics) and increase the chip area. The induced parasitics and higher chip area dramatically increase the power consumption and cost of the devices. BAWs, however, can be directly integrated with CMOS circuitry which makes them an attractive option for overcoming the interconnect parasitics, reducing the area required, and amortizing the packaging.

Two structures have been studied and fabricated in my research, both comprising a metal-piezoelectric-metal structure with zinc oxide (ZnO) serving as the piezoelectric material. The solidly mounted resonator (SMR) uses a distributed Bragg reflector to mechanically isolate the metal-piezoelectric-metal structure, while the thin film bulk acoustic wave resonator (FBAR) uses an air gap for this purpose. While much of these structures are physically and electrically similar, the FBAR shows smaller losses due to virtually no substrate leakage. The low substrate leakage makes the FBAR more appealing for purely RF applications.

Starting with a stand-alone device on glass, I measured and obtained an electrical model using Advanced Design System (ADS) for the device to be used later on for the IC design. The approximately 300C thermal budget of CMOS was a challenge for the ZnO growth, where high temperatures and pressures are required for a high quality crystalline film. Depositing a gold seed layer before RF Sputtering at temperatures <150C did enable me to obtain a highly c-axis oriented <002> film. This directionality of the crystal was characterized with X-Ray Diffraction before we built devices and measured their insertion loss (IL) to obtain Q.

We designed and taped out two IC chips in two different technologies and foundries: IBM 180nm and TSMC 65nm. The circuit design included a Pierce structure, normally used with quartz crystal oscillators for MEMS integration, and some small test structures such as ring oscillators. BAWs have been demonstrated to work on CMOS previously, but I have expanded the application to die processing rather than full wafer. Die processing allows maximum use of Multi Project Wafers (MPWs) in research environments, where using full wafers is costly and wasteful for developing processes. Besides the constraints of the thermal budget, CMOS adds concerns such as Electro-Static Discharge (ESD) protection, surface roughness, die handling and beading of chemicals on the small surface that I addressed in my work. Ultimately, I was able to measure a fully integrated MEMS-CMOS oscillator and characterize it with phase noise and power spectrum measurements. These results can be seen in our publication for JMEMS June 2017 tittled "Monolithically Integrated CMOS-SMR Oscillator in 65nm CMOS Using Custom MPW Die-Level Fabrication Process."

As previously mentioned, I have begun to apply these structures for sensing. My recent work then studies the improved sensing ability of piezoelectric MEMS using the superior parasitic performance provided in a monolithically integrated CMOS system created using die processing. MEMS using BAW structures offer a new way of measuring temperature and IR radiation, through measurements of total optical energy, overcoming the obstacles associated with narrow bandgap semiconductor detectors. It is possible to obtain a higher sensitivity device than previously demonstrated systems, using the FBAR, with the addition of an absorbing susceptor by taking advantage of ZnO's higher temperature coefficient of frequency (TCF). While the FBAR's higher thermal sensitivity makes is more useful for IR sensing, the SMR is still preferred for mass sensing applications. Mass sensing applications include gas sensing applications where a susceptor layer, tuned for a specific gas, is added. Depending on the material's selectivity it will catch particles and adhere them to the surface until it saturates, this process is also known as mass loading, as particles accumulate the acoustic path the wave hs to travel becomes longer effectively lowering the resonant frequency of the device. By characterizing the frequency shifts due to thermal change or mass loading we can determine how much incident IR or what concentration of a certain odor or gas is in the environment. These sensors promise to be low power and highly sensitive due to the high Q of the resonator and because we are working at such high frequencies (1.5-2GHz), where by the Sauerbrey equation, we can derive that thermal sensitivity is linearly proportional to the frequency and for mass loading sensitivity has a square relationship to the frequency.

In summary, die processing opens the possibility of exploring new applications with just slight changes to the IC and device designs. Improvements on previous work are expected as this technology is applied to infrared, gas and liquid sensing applications. I am currently working on the design of an IC for multi-sensing capabilities.