R2-B.3: Multi-Functional Nano-Electro-Opto-Mechanical (NEOM) Sensing Platform

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II. PROJECT DESCRIPTION

A. Project Overview

The development of a new technology platform capable of performing multiple chemical analyses in a miniaturized footprint is needed for the implementation of portable, field-based analytical tools for rapid and reliable trace detection. A new multi-functional detector technology, which is the subject of this report, would enable a low-cost, low-power, portable, and high-performance trace detection platform. This project addresses the four most important challenges associated with the development of miniaturized nanoelectromechanical systems (NEMS), sensors suitable for the implementation of portable, field-based analytical tools for rapid and reliable trace detection:

1) High resolution (100x that of conventional sensor technologies);
2) Transduction efficiency (efficient on-chip actuation and sensing of vibration in ultra-low volume nanomechanical structures with a unique combination of electrical, mechanical, and optical properties);
3) Selectivity (selective detection of a targeted group of chemicals with very low false positive and false negative rates); and
4) Low power consumption (~mW in active mode and zero standby power consumption (<10 nW) when the signal of interest is not present).

The aims of this project include:

- The development of multi-spectral and room temperature infrared (IR) thermal detectors that can far exceed the state-of-the-art performance of uncooled IR sensors, and rival those utilizing the bulky, heavy, expensive, and inconvenient cryogenically cooled semiconductor photodetectors in terms of detection speed and resolution: Time Constant, $\tau \approx \mu s$-$ms$, Noise Equivalent Power (NEP) $\approx pW/Hz^{1/2}$, Noise Equivalent Temperature Difference (NETD) $\approx mK$.
- The implementation of portable, field-based analytical tools for rapid and reliable trace detection.
• The heterogeneous integration of this multi-spectral detector technology with state-of-the-art Quantum Cascade Lasers (QCLs) will lead to disruptive improvement in field-deployable systems for IR signature detection and imaging.

• Our technology overcomes fundamental scientific and engineering development challenges, enabling the implementation of a new generation of multi-spectral uncooled IR detectors that provide near real-time detection, high sensitivity, and high specificity for a targeted group of explosives IR spectral signatures, resulting in very low false-positive and false-negative rates.

• By leveraging a technology developed in the PI's lab under the Defense Advanced Research Projects Agency (DARPA) Near Zero Power RF and Sensor Operations (N-ZERO) program, we demonstrate IR digitizing microsystems that can remain dormant, with near-zero power consumption, until awakened by specific IR spectral signatures associated with a threat. These completely passive digitizing IR sensor microsystems can harvest the energy contained in a specific IR spectral signature (i.e. IR emission peaks of energetic materials) to produce a digitized output bit capable of waking up short-duty cycle powered electronics for further signal analysis and communications. The implementation of sensors that consume power only when useful information is present will result in a nearly unlimited duration of operation for unattended sensors deployed to detect infrequent but time critical events (such as forest fires, earthquakes, territory intrusion, chemical warfare threats, etc.).

B. State of the Art and Technical Approach

The performance of a sensor system for multiple analyte detection can be improved by increasing the amount of chemically orthogonal information acquired by the sensor [1]. This can be achieved by recording the analyte induced variations of several independent physical, chemical, and electrical quantities such as mass, IR absorption spectrum, and temperature. Chemical sensors composed of multiple transducer modules have already been proposed. For example, chemical sensors based on gravimetric sensors, such as Quartz Crystal Microbalances (QCMs) [2-4], have shown significant advantages over other sensor technologies (e.g. conductance-based sensors, chem-FET, and optical sensors [5-7]) since QCMs use frequency as the output variable, which is one of the physical quantities that can be monitored with the highest accuracy [8]. Even though QCMs have been successfully employed as gravimetric sensors with limits of mass detection on the order of few nanograms, their large volume and inability to be directly integrated on silicon render them unattractive for the fabrication of sensor arrays composed of a large number of mechanical elements. Nanoelectromechanical systems (NEMS) beam resonators have also been exploited as transducers for the realization of extremely sensitive miniaturized gravimetric sensors [9, 10]. Although scaling the beam dimensions to smaller values inevitably yields a lower device mass and higher sensitivity, in most cases, these enhancements are offset by the reduced stability and power-handling of the nanomechanical device. This results in a limited gain of detection or resolution [11], which is the minimum value of analyte concentration that can be detected, and depends on the device sensitivity and the signal-to-noise ratio. Furthermore, the greatly reduced dimensions of these beam resonators render their transduction extremely difficult, requiring the use of cumbersome, complex, and power-inefficient read-out techniques, and limit the area dedicated to the absorption of the analyte in the environment.

On the other hand, spectroscopy-based optical sensors such as IR detectors have also been utilized for chemical sensing thanks to their non-invasive nature and high selectivity. Among different IR sensing technologies (i.e. microbolometers, pyroelectric detectors, and thermoelectric detectors), uncooled IR detectors based on microelectromechanical systems (MEMS) resonators have emerged as one of the most promising technologies due to their unique advantages in terms of high sensitivity to external perturbation (extremely reduced overall volume) and low noise performance (intrinsically high quality factor, Q). MEMS-
resonant IR detectors based on gallium nitride (GaN) [12] and quartz [13] piezoelectric resonators have been recently demonstrated and have shown promising performance. However, volume scaling, performance, cost, and large scale production of these technologies are fundamentally limited by the lack of cost effective and low temperature deposition techniques capable of producing high quality piezoelectric quartz or GaN thin films on an arbitrary substrate (i.e. quartz and GaN thin-film production techniques are not compatible with conventional Complementary Metal Oxide Semiconductor (CMOS) process).

In summary, when a compact, portable, and low-power system is desirable, the current available solutions, composed of a multitude of different transducers, will be cumbersome and inefficient. In this context, the design of a multi-transducer sensor capable of efficiently transducing different physical, chemical, and electrical changes induced by a gas sample would be groundbreaking.

We propose to develop an innovative, Nano-Electro-Opto-Mechanical (NEOM) sensing technology platform which integrates, in a small footprint, some of the fundamental chemical analyses typically performed in a laboratory, such as gravimetric analysis, IR spectroscopy, and thermal analysis (see Fig. 1). The core element of the proposed technology is a Graphene-Aluminum Nitride (G-AlN) NEMS-resonant multi-transducer detector coupled with an array of QCLs for chip-scale IR spectroscopy and integrated with a nano hot-plate for thermal analysis. The fundamental advantage of NEMS resonant sensors over other existing sensor technologies is related to the unique combination of extremely-high sensitivity to external perturbations (due to their very reduced dimensions) and ultra-low noise performance (due to the intrinsically high quality factor, Q, of such resonant systems). The proposed technology overcomes fundamental scientific and engineering development challenges, enabling the implementation of a new generation of trace detectors that provide near real-time detection, high sensitivity, and high specificity for a targeted group of explosives, and resulting in very low false positive and false negative rates. Such disruptive improvement in field-deployable chemical sensor technology is made possible by key innovations made in gravimetric analysis, IR spectroscopy, and thermal analysis.

Figure 1: Schematic representation (not to scale) of the envisioned sensing technology platform.
C. Major Contributions

C.1. Major Work Conducted Before Year 6:

C.1.a. Graphene-AlN NEMS Resonators for IR and Chemical Sensing (Published in Nano Letters [14])

We experimentally demonstrated the remarkable manner in which graphene is able to mimic an ideal mass-less electrode, enabling piezoelectric NEMS devices to operate at theoretically “unloaded” frequency limits with improved electromechanical performance and reduced volume over an unprecedented range of operating frequencies: $0.2 \text{ GHz} < f_0 < 2.6 \text{ GHz}$ [14]. This represents a spectacular trend inversion in the scaling of piezoelectric electromechanical resonators, opening up new possibilities for the implementation of NEMS systems with unprecedented performance. We also demonstrated that G-AlN NEMS resonators have intrinsically high sensitivity to IR radiation without the need for additional absorbing materials [15] (which eliminates the loading effects of the IR absorber conventionally integrated on top of MEMS-based thermal detectors [12]). The achievement of high IR absorbance in NEMS resonant structures with reduced volume and improved electromechanical performance addresses one of the most fundamental challenges in the NEMS field, and could potentially lead to the development of fast (~ms) and high resolution (Noise Equivalent Power $\sim 1 \text{ pW/Hz}^{1/2}$, Noise Equivalent Temperature Difference $\sim 1 \text{ mK}$) uncooled IR detectors suitable for the implementation of high performance, miniaturized, and power-efficient IR imaging systems. Furthermore, we demonstrated an innovative chemical-sensing mechanism based on the effective transduction of the analyte-induced variations in the electrical conductivity of the graphene electrode employed to excite mechanical vibration in an aluminum nitride (AlN) NEMS resonator [16]. Analyte-induced variations in the graphene electrode conductivity can be efficiently detected by monitoring the corresponding induced variations in the device vibration amplitude without the need of direct electrical probing of the graphene-sensing layer. Thanks to this unique feature, two chemically orthogonal quantities, such as mass and charge of the analyte, can be simultaneously acquired by the proposed G-AlN NEMS resonant sensor.

C.1.b. Narrowband MEMS Resonant IR Detectors [18]

A new type of ultrathin plasmonic absorber that features narrow bandwidth (FWHM $\leq 17\%$) and near-perfect IR absorption ($\eta \geq 92\%$) was proposed and exploited for the first demonstration of narrowband AlN resonant infrared detectors suitable for standoff chemical detection in the MWIR range. An ultrathin (230 nm) plasmonic absorber (three-layer stack composed of a ground metal plate, a thin dielectric and an array of gold patches) is integrated on top of an AlN nano plate resonator (NPR) and used to confine the impinging IR radiation (in a narrow bandwidth around the wavelength of interest) in the deeply subwavelength NEMS structure, while simultaneously guaranteeing confinement of the radio frequency transduction electric field across the thin piezoelectric transducer. Despite the integration of the ultrathin plasmonic absorber on top of the AlN NPR, high electromechanical performance ($Q \sim 1600$ and $k^2 > 1.3\%$) is achieved. Moreover, an excellent thermal isolation ($\sim 1.6 \times 10^6 \text{ K/W}$ in vacuum) of the resonant thermal detector is achieved thanks to the use of carefully designed nanoscale (80 nm thick) metal anchors [17]. All these attributes lead to the demonstration of a narrowband (FWHM $\sim 795 \text{ nm}$, $\sim 17\%$) high-resolution (noise equivalent power, NEP $\sim 130 \text{ pW/Hz}^{1/2}$) uncooled IR detector tuned at 4.7 $\mu\text{m}$.

C.1.c. Ultra Narrowband IR Absorbers (Published in Advanced Optical Materials [24])

Different from previous demonstrations based on arrays of densely-arranged plasmonic nanostructures (e.g. squared patches or disks), this work investigates the use of sparsely-arranged cross-type nanostructure arrays to sustain localized plasmonic resonances and achieve high Q-factor absorption in an ultra-thin metal-
insulator-metal (MIM) structure. Our proposed configuration minimizes capacitive coupling between neighboring plasmonic nanostructures, enabling maximized field confinement within the top and bottom metal layers, while maintaining high absorptivity. At the same time, the axial XY-symmetry of the cross-type nanostructure and the vertical field confinement in the sub-wavelength thickness of the structure guarantee angle and polarization insensitivity. We demonstrated how mid-IR absorbers have high absorptivity (η>91%) with the narrowest absorption bandwidth reported to date (full width at half maximum FWHM~225 nm, 4.29% at λ=5.23µm), while maintaining angle (θ=0~60°) and polarization insensitivity [19]. The unprecedented performance of such batch-microfabricated and lithographically-defined ultrathin absorbers paves the way for the development of new classes of plasmonically-enhanced multi-spectral sensing and imaging microsystems for noninvasive chemical sensing and IR spectral signature detection.

C.1.d. Ultra-fast NEMS IR Detectors Based on 50 nm Thick AlN Nano-plate Resonators (NPR)[23]

NEMS IR detectors based on AlN NPRs have shown great potential in replacing conventional microbolometers for the next-generation high-performance uncooled IR detectors [2]. The performance of such resonant IR detectors in terms of thermal sensitivity, noise equivalent power (NEP), and response time (τ) can be improved by scaling the device volume while simultaneously maintaining high values of quality factor (Q) and transduction efficiency [20, 21]. In fact, thermal detectors based on 50 nm thick AlN NPRs have been reported by our group [22], showing two orders of magnitude improvement in the figure of merit compared to previous demonstrations (\( \text{FoM} = 1/(\text{NEP} \cdot \tau) \propto \eta \cdot C_0 \cdot TCF \cdot Q / t^2 \)), where \( \eta \), \( C_0 \), TCF and \( \tau \) are the IR absorption coefficient, static electrical capacitance, temperature coefficient of frequency and thickness of the resonant structure, respectively. However, the smallest devices (28×30 \( \mu m^2 \)) in [22] show limited \( Q \) values below 300 (~1/4 of the ones of larger devices), making them less capable in applications that require high resolution (due to the increased noise).

This issue is addressed in this work by mitigating anchor loss in such greatly-scaled 50 nm thick AlN NPRs. Nanoscale metal anchors (proposed in [20] for the first time) are employed instead of conventional AlN and metal anchors used in [22] to introduce higher acoustic impedance mismatch between the resonant body and the anchors, and therefore reducing the energy loss through the anchors. Such optimization in anchors not only boosts the \( Q \) from less than 300 to 1157 for the same design of resonant body in [21, 22], but also increases the thermal resistance (\( R_{th} \)) by ~2 orders of magnitude (due to smaller cross-sectional area of the anchors), resulting in a high-performance IR detector with both high resolution (NEP \( \sim 466 \ pW/Hz^{1/2} \)) and fast detection speed (\( \tau \sim 164 \ \mu s \)).

C.1.e. Spectroscopic Chemical Sensing Based on Narrowband MEMS Resonant Infrared Detectors [25]

Screening for hazardous materials in airports, public places, and government facilities is important to homeland security. The development of technology for fast standoff detection of highly explosive materials (HEMs) with high accuracy is decisive in early identification of terrorist threats. Chemical analysis methods based on molecular spectroscopy coupled with advanced multivariate statistical methods to identify chemicals from its spectrum are a powerful tool to detect chemicals at low concentrations. HEM detection using transmission spectroscopy relies on the detection of characteristic IR spectral absorption bands of specific functional groups such as \(-\text{NO}_2\), peroxide, and \(-\text{CN}\) that are indicative of explosive materials. Reliable detection of HEMs is possible by irradiating a sample with IR radiation and using a calibrated IR detector to quantify the transmitted IR intensity in the spectral bands of interest corresponding to these functional groups. This in turn depends on the concentration of the molecules: greater the concentration, lower is the intensity in those spectral bands.
We have previously demonstrated uncooled MEMS resonant IR detectors with narrow bandwidth (full width at half maximum, FWHM ≤ 17%) and near-perfect IR absorption (η ≥ 92%) based on AlN nano-plate resonators integrated with MIM plasmonic absorbers. In this work, we show that it is possible to use such a spectrally-selective IR detector for chemical sensing in liquid phase with a simple experimental setup including a blackbody and a liquid cell. In particular, we demonstrate the detection of the presence of a nitrile functional group (-C≡N) in a binary mixture of liquids through transmission spectroscopy. -C≡N has its characteristic stretching mode around 4.5 µm. When IR radiation matching this wavelength passes through a sample containing -C≡N bonds, the electromagnetic energy gets coupled to the vibrational resonant mode of the bond, resulting in reduced IR power exiting the sample at that wavelength. A set of samples with increasing concentration from 0.5% to 100% of benzonitrile mixed with hexane are used for calibration. The experiment shows a detectable range up to 61% and a minimum detectable concentration change of ~0.01%.

C.2. Work conducted in Year 6:

C.2.a. Chip-Scale MEMS-CMOS Multispectral Infrared Chemical Sensor

In the past decade, IR spectroscopy has become a key technique in laboratory environments for accurate and non-disruptive analysis of chemical composition [26]. More recently, there has been a growing demand for exploring such IR spectroscopy technique beyond the traditional laboratory settings. In fact, the on-going trend in sensor development toward compact size, power efficiency, and reliable measurement has accompanied the increasing effort to implement ultra-miniaturized IR spectrometers, in lieu of the conventional IR spectrometers that are bulky, costly and power inefficient. The implementation of compact IR spectrometers can enable fast and accurate chemical composition analysis on-the-go, allowing for the IR spectroscopy technique to be easily accessible in diverse applications such as mobile food quality analysis and on-the-spot security screening.

One of the key elements for such miniaturized IR spectrometers is a high performance multispectral IR detector array with a chip-scale form factor and IR detection performance on par with the conventional uncooled IR detector technology. In this context, resonant IR detectors are the ideal candidates thanks to the fast response and high resolution enabled by their low noise performance, high thermal sensitivity and the use of frequency shift as the output parameter for high measurement accuracy [27]. Aluminum nitride (AlN) resonant IR detector technology is particularly favored due to its unique advantages of volume scaling and compatibility with CMOS for on-chip frequency read-out [28]. In fact, an AlN IR detector using silicon nitride as the dielectric IR absorbing material and a CMOS oscillator for direct frequency read-out has been reported [28]. Nevertheless, the use of such broadband IR absorbers prevents development of ultra-miniaturized IR spectrometers, as the system inevitably needs additional elements such as lasers or filters for spectral analysis.

Plasmonic absorbers, on the other hand, are characterized by the lithographically controlled peak absorption wavelengths and a high absorbance. Metal-insulator-metal (MIM) metamaterial IR absorbers, for instance, feature near-unity IR absorption and high spectral resolution while maintaining angle and polarization insensitivity, which satisfy the stringent criteria for compact spectroscopic applications [29]. Furthermore, the ultrathin form factor enabled by the subwavelength plasmon excitation and nanofabrication techniques allows for the seamless integration with the existing IR detector technologies [30-32].

In this work, we demonstrate the first complete prototype of an ultra-miniaturized (total chip area ≈ 1.53 mm²) multispectral IR chemical sensing microsystem comprising an array of plasmonically-enhanced MEMS IR detectors and a CMOS IC readout. The monolithic integration of lithographically-tunable plasmonic IR absorbers overcomes the fundamental limitation of low IR absorption performance (small angular
acceptance, low optical throughput and narrow spectral range) of the existing compact IR spectrometers based on photodiodes and Fabry-Perot interferometers [33-34]. Finally, the demonstrated fast (<100 ms per spectral scan), low power (∼1.07 mW), and high resolution (NEP ∼ 402 pW/Hz^1/2) IR detection capability allow us to successfully discriminate the characteristic IR transmission spectra of unknown chemicals using the proposed sensing microsystem.

The sensor consists of five densely-packed MEMS resonant IR detectors wire-bonded to a CMOS read-out IC (Fig. 2). The CMOS IC includes a self-sustained oscillator and an on-chip 3-bit decoder capable of addressing each detector through a switch bank [35]. The core element of the IR sensor is a thermally-sensitive AlN nano-plate resonator with an integrated nearly-perfect plasmonic absorber with lithographically-defined absorption wavelengths in mid-wavelength IR (MWIR) regime. The resonant structures designed to vibrate at the same frequency are thermally-isolated from the substrate by nanoscale metallic anchors. The absorbed IR power causes a large and fast increase of the device temperature due to the high thermal resistance and extremely low thermal capacitance of the freestanding nanomechanical structure. The IR-induced temperature rise leads to a shift in the center frequency of the piezoelectric resonator due to its intrinsic temperature coefficient of frequency (TCF), which is monitored via the high stability oscillator CMOS IC.

Figure 2: (a) Overview of chip-scale multispectral infrared chemical sensors including: a circuit diagram of the Pierce-like multiplexed oscillator with the integrated 3-bit on-chip decoder; a scanning electron microscopic image of the IR detector array (the yellow inset shows a close-up view of the patch-type nanostructures of plasmonic absorber and the red inset shows a cross-section of an IR detector); an image of the sensor consisting of the CMOS chip (area ∼ 1.05 mm^2); and the MEMS IR detector array (area ∼ 0.48 mm^2). (b) Measured admission curve of an AlN IR detector and its modified Butterworth-Van Dyke model fitting. (c) Measured TCF (∼29.5 ppm/K) of the AlN IR detector. (d) Measured Allan deviation (ADEV) as a function of gate time, which corresponds to a noise spectral density (f_n) of ∼ 2.34 Hz/Hz^1/2 at the optimal gate time (f_n = ADEV/√(gate time)). (e) Measured IR absorbance. Consistently high absorbance >0.93 and narrow FWHM <890nm were measured across the five fabricated IR detectors.
The proposed sensor was fabricated via a standard 4-mask microfabrication process for the MEMS resonant IR detector array with an additional electron beam lithography step for the integrated plasmonic absorbers. The multiplexed CMOS readout circuitry was taped-out in the ON Semiconductor (www.onsemi.com) 0.5-μm CMOS process. The electromechanical performance of the fabricated MEMS resonant IR detectors was tested using an Agilent E5071 network analyzer, showing a high mechanical quality factor \( Q = 1778 \) and electromechanical coupling coefficient \( k_t^2 = 1.78\% \) (Fig. 2b). Furthermore, the intrinsically high temperature coefficient of frequency of the resonator \( \text{TCF} = 29.5 \text{ ppm/K} \) was measured on a temperature-controlled RF probe station (Fig. 2c).

The fabricated sensor was powered by a DC source \( V_{\text{DD1}} = 1.79 \text{ V} \) and its output signal was monitored over time with Agilent 53230A frequency counter. Each detector in the array was sequentially activated by the decoder to support self-sustained oscillation with a consistent output frequency \( f_s \approx 241 \text{ MHz} \) and a low noise performance (Allan deviation \( \approx 7.4 \text{ Hz} \)), leading to an ultra-low detection limit \( \text{NEP} \approx 402 \text{ pW/Hz}^{1/2} \) (Fig. 2d). The current drawn from the power supply was measured to be 600 μA resulting in a low power consumption of \( \approx 1.07 \text{ mW} \) for the whole microsystem. The reflectance spectra \( R \) of the fabricated sensor was measured using a Bruker V70 Fourier transform infrared (FTIR) spectrometer coupled with a Hyperion 1000 IR microscope. The absorbance spectra \( A \) of the fabricated devices were then calculated assuming a negligible transmitted power through the 70 nm optically-thick Pt reflector \( A = 1 - R \). The large spectral range in MWIR \( \lambda_0 = 3\text{~}6 \mu\text{m} \) was measured thanks to the monolithic integration of the MIM IR absorbers with lithographically-controlled peak absorption wavelengths (Fig. 2e). The results also show consistently high absorbance \( \eta \) up to 99.4% and a narrow FWHM down to 620 nm (Fig. 2e).

The sensor was then placed inside a vacuum chamber and its frequency output was monitored using the frequency counter (as illustrated in Fig. 3a). A calibrated blackbody at 600°C (mechanically chopped at \( \approx 1 \text{ Hz} \) was used as the broadband IR radiation source. The sensor was illuminated with the IR radiation transmitted through a 0.108-mm thick zinc selenide liquid cell, containing either 100% acetone or hexane, and the calcium fluoride IR window of the vacuum chamber (Fig. 3a). The measured frequency shift of each IR detector in the array was normalized to that induced by the IR radiation without liquid cell to remove the effect from the variation of IR power of blackbody across the tested spectral bands (Fig. 3b,c). The IR-induced frequency shifts obtained by the proposed sensor successfully capture the spectral characteristics of the chemicals measured by the benchtop FTIR spectrometer. The demonstrated spectroscopic analysis in a significantly miniaturized form factor based on the proposed technology clearly emphasize the potential capability of the implementation of ultra-compact IR spectrometers.
C.2.b. Threshold-Triggered MEMS-CMOS Infrared Resonant Detector with Near-Zero Standby Power Consumption

The demand for low-cost and low-power microsystems for spectrally-selective IR sensing has been rising with the proliferation of Internet of Things (IoT) for applications such as security surveillance and natural disaster monitoring [36]. However, a key technical challenge preventing the deployment of large-scale sensor networks has not been addressed yet because of the continuous power consumption of active electronics in the sensors built with existing technologies. Recent studies thus have been focused on reducing the standby power consumption of environmental sensors with a hope of decreasing or even eliminating the maintenance cost associated with the frequent battery replacements [31, 37-40]. In this context, zero-power IR sensors that utilize the energy in the signal of interest to operate without consuming any electrical power have recently been proposed and experimentally demonstrated [31]. Such a new class of IR sensor relies on a micromechanical photoswitch (MP) to generate a digitized wake-up signal for triggering an alarm when an above-threshold signal of interest is present, otherwise remain completely dormant [40]. However, unlike conventional IR sensors, they lack the ability to measure the exact value of an above-threshold IR power. Therefore, using MP(s) as the only IR sensing element is not sufficient for tracking the progress and determine the severity of an IR radiation related event. For example, first responders (e.g. firefighters) could understand the situation of a fire accident and get better prepared if the size of the fire and growth rate are reported by pre-deployed sensors. The integration of an additional IR sensor with MP is thus desirable for having an analog output while maintaining zero power consumption in standby when the input is lower than a predetermined IR threshold.

On the other hand, MEMS resonant IR detectors (RIDs) have shown unique advantages such as high thermal sensitivity and low noise performance [27]. The relatively low power consumption and miniaturized form...
factor of MEMS resonant IR detectors making them ideal candidates for the integration with MP. Among different resonant IR sensor technologies AlN piezoelectric nano-plate IR detectors stand out as the most promising technology for fast detection and CMOS integration thanks to the mature thin film deposition process for AlN at room temperature [23]. Furthermore, it has been shown that plasmonic absorbers [24] can be seamlessly integrated with AlN nano-plate resonant IR detector for spectrally-selective sensing in the mid-IR range [17, 18], which is an essential functionality for non-dispersive IR spectroscopy and the discrimination between various IR sources.

For the first time, we show a system-level implementation of a zero-power MP interfaced to an AlN RID to enable accurate measurement and monitoring of an IR signature with above-threshold variation in intensity (i.e. burning of toxic chemicals and hot spot formation in power electronics).

The proposed microsystem is composed of a single transistor oscillator based on a narrowband uncooled MEMS AlN RID, a MP with matching IR absorption band, and an ultra-low leakage CMOS load-switch (Fig. 4). The first core element is a threshold-triggered MP [31] which selectively harvests the energy from impinging IR radiation in the specific band of interest to mechanically close the switch contacts. Any IR radiation with an intensity lower than the predefined threshold will not trigger the microsystem. Thanks to the physical gap in between the two contacts in the MP (Fig. 4), standby power consumption is eliminated. The second core element is a high performance MEMS RID based on a AlN nano-plate resonator integrated with a plasmonic absorber. When the targeted IR radiation is incident on the detector, the plasmonic absorber converts the electromagnetic energy to heat. The confined heat results in a temperature increase and frequency shift in the nano-plate resonator due to the high thermal isolation (enabled by the nanoscale metallic anchor) and the temperature coefficient of frequency (TCF) of the AlN nano-plate resonator. The resonant frequency decreases when the temperature of the resonator increases [23]. A CMOS single-transistor Pierce oscillator circuitry built around the resonator is used to sustain the oscillation and monitor the resonance frequency (Fig. 4).

Figure 4: (a) A schematic of the proposed sensor system consists of an oscillator based on an AlN resonant IR detector (RID) that is powered through a MP-controlled load-switch; and a schematic of the threshold-triggered output of the proposed sensor system. The oscillator is turned on by the MP when the power of incident IR radiation was increased to a pre-determined threshold and frequency change is shown with changing IR intensity. (b) A circuit diagram of the proposed sensor microsystem. (c) Photographs of PCBs and MEMS chips that are later on electrically connected inside a vacuum chamber.
The thermo-mechanical coupling of both MEMS devices is enhanced by the integration of near-perfect metal-insulator-metal plasmonic absorbers. The lithographically-defined size and periodicity of the patches on the absorber set the wavelength and bandwidth of the absorption peak. In this work, the absorbers are designed to operate around ~ 3.5 μm, which corresponds to the IR emission of hot nitrogen dioxide (NO₂) released from burning wood. The absorbers are designed to have an active area of 150 × 150 μm² in the MP and 60 ×144 μm² in the RID (Fig. 4).

The oscillator circuit is activated by the MP with the help of an ultra-low leakage CMOS load-switch [41] (Fig 4). The load-switch is used to handle the relatively high current required by the oscillator (The current handling of MP is limited to ~200 µA). The MP is connected to the control pin of the load switch while a SourceMeter is set to supply 1.5 V and measure the current across the port.

The sharp sub-threshold slope of the MP ensures the gate voltage of the load-switch to be well below the threshold voltage of transistor in order to have a near-zero leakage current. A pull-down resistor is used to hold the logic signal at zero volts when the MP is open and also limit the current through the MP when it is triggered on. Once the MP is triggered to close, the 3.5 V is supplied to the Pierce oscillator circuitry (which the resonator is directly wire-bonded to), and the frequency is recorded from voltage output with a frequency counter.

The fabrication steps of the MP and the AlN RID are covered in [31] and [18], respectively. The fabricated AlN RID and MP were connected together with the load-switch in a vacuum chamber. A blackbody IR source with a narrow-band filter (around 3.5 μm with 0.5 μm bandwidth) were used to emulate the emission from gases in the mid-IR range. The devices under test were exposed to filtered IR radiation through an IR-transparent window made of calcium fluoride (CaF₂) in the lid of the vacuum chamber. Additional CaF₂ lens was placed between the window and the blackbody to increase the IR power density while maintaining the radiation area large enough to cover both IR sensitive devices. The temperature of the blackbody (i.e. delivered power) was increased over time to simulate an evolving IR source with characteristic emission at 3.5 μm (with a bandpass filter placed in front of the blackbody). The absorption spectrum and full width at half maximum (FWHM) of the fabricated plasmonic absorbers were measured in Fourier transform infrared (FTIR) spectrometer showing absorbance >98% and FWHM <650nm for the MP, and absorbance >94% and FWHM <700nm for the AlN RID at ~3.5 μm.

Figure 5: (a) The measured admittance curve (red line) of AlNIR detector and its MBVD model fitting (blue line). (b) The measured Allan deviation versus measurement time of the oscillator. (c) Response of the sensor system when both the photoswitch and the resonator are exposed to an increasing IR radiation at 3.5 μm. The recorded current flow through the MP. (d) The frequency shifts with respect to the first data point recorded after MP is activated.
The electromechanical performance of the fabricated RID (Fig. 5a) is characterized with a Vector Network Analyzer (VNA). The quality factor and electromechanical coupling coefficient is extracted to be $Q \approx 1000$ and $k^2 \approx 1.57$% using Modified Butterworth Van Dyke (MBVD) model fitting. The resonator was wire-bonded to a printed circuit board (PCB) containing the oscillator circuit with an ATF-551M4 E-pHEMT GaAs transistor and several discrete electrical components ($R_s=100 \text{k}\Omega$, $R_b=100 \Omega$, $C_1=1 \text{pF}$, $C_2=10 \text{pF}$, $C_3=10 \text{pF}$ in Fig. 4b). The Allan deviation of the oscillator was measured with a frequency counter under various gate times (Fig. 5b). Based on the extracted noise spectral density ($f_n$), a noise equivalent power (NEP) $\approx 746.4 \text{pW/Hz}^{1/2}$ is calculated by $\text{NEP}=f_n/R_s$, where $R_s (R_s=R_cR_kTCFf_0)$ is the responsivity of the RID.

The transistor circuitry requires $\approx 9 \text{mA}$ to self-sustain the oscillation, which corresponds to a power consumption of $\approx 3.15 \text{mW}$. The load-switch ensures proper handling of the relatively high current without creating any damage in the MP. The inclusion of the ultra-low leakage CMOS load-switch introduces a near-zero ($3.01 \text{nW}$) power consumption in standby (due to the 0.86 nA leakage in the load-switch).

The oscillator was triggered by the MP when the IR power was increased to 3.41 mW/cm$^2$ corresponding to an absorbed power of 440 nW in the MP. The same input IR power (i.e. filtered blackbody radiation at 3.5 $\mu$m) results in an absorption of 177 nW in the resonator (calculated based on the absorption spectrum and area of the RID). Fig. 5c shows the measured MP current variation in time where the switch turned ON when the MP threshold was reached (i.e 440 nW) and kept conducting current in response to further increased input power. The resonant frequency of the RID was monitored by a frequency counter connected to the output of the oscillator (Fig. 5d). The IR-induced frequency shift after the triggering of MP was recorded showing the dormant time period with zero output and active time period with analog read-out capability. The linear frequency shift is expected due to the linearly increased IR intensity along time. (A stabilization time for the blackbody to change its temperature was given between the measurements and each data point was averaged over 5 seconds.)

D. Milestones

- We demonstrated the first prototype of a miniaturized MEMS-CMOS chemical sensor based on an array of multispectral plasmonic-MEMS resonant IR detectors and a low-power CMOS IC for direct frequency read-out. The monolithic integration of ultrathin narrowband plasmonic absorbers and the high performance resonant IR detectors eliminate the need of bulky components for spectral discrimination and allow for ultra-miniaturization of IR spectrometer. The excellent resonant IR detection capability ($\text{NEP} \approx 402 \text{pW/Hz}^{1/2}$) and the plasmonic-enabled high spectral resolution ($\eta > 93\%$, FHWM < 890 nm), combined with the multiplexed CMOS read-out IC prove a great potential for the implementation of a new class of miniaturized IR spectroscopy microsystems, suitable for a fast and accurate chemical composition analysis on-the-go. It is worth noting that, the multispectral IR sensor array developed in this work can be readily adopted in mature nondispersive infrared (NDIR) sensor technology for gas sensing. Packaged and calibrated sensor array along with a gas chamber and broadband IR source will need to be assembled together for the demonstration of a minimum system suitable for field test.

- We demonstrated a microsystem for zero-power IR sensing based on the integration of a micromechanical photoswitch (MP) with an AlN MEMS resonant IR detector (RID). The resulting MEMS-CMOS RID is capable of measuring the above-threshold intensity of an IR signature with zero standby power. The MP in the composed microsystem can selectively harvest the energy from impinging IR radiation to power up the RID part: When the absorbed IR power exceeds 440 nW the MP automatically connects the RID circuit to a power source showing a high-resolution IR detection capability ($\text{NEP} \approx 746.4 \text{pW/Hz}^{1/2}$) in the active state. When the IR power is lower than the threshold, the microsystem stays dormant with near-zero power consumption (3.01 nW). Such a threshold-triggered IR detector is
expected to extend the capabilities of the emerging dormant, yet always-alert sensor networks for various demanding IoT applications.

E. Future Plans/Project Completion (Year 7):

By exploiting our deep scientific knowledge of uncooled infrared detectors and zero-power microelectromechanical systems, we propose to develop wireless miniaturized human detectors with near-zero standby power (< 10 nW) for applications in perimeter protection, such as airports and harbors. We will develop an ultra-miniaturized (coin size), low-cost and easily retrofitted wireless infrared (IR) sensor capable of continuously monitoring the appearance of thermal radiation from human body, without consuming any power in standby (i.e. when human bodies are not present). The wireless IR sensor wakes up (i.e. drains power from the battery) only upon detection of the presence of humans nearby to transmit a radio frequency signal indicating the location of the human activity event. The miniaturized wireless IR sensor will be easily retrofitted to hide in the wall of underground caves and tunnels and, thanks to the complete elimination of the standby power consumption, it will be able to wirelessly reveal thousands of intrusion events without ever replacing the sensor coin battery (life time extended to ~10 years, limited by the battery self-discharge).

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

- A new uncooled multi-spectral IR detector technology, suitable for standoff chemical detection in the MWIR range. (The engine exhaust plumes of jets and vehicles contain several gases with emission spectra in the MWIR range that can be used as specific signatures for detection.)
- IR digitizing microsystems that can remain dormant, with near-zero power consumption, until awakened by specific IR spectral signatures associated with a threat. These completely passive digitizing IR sensor microsystems can harvest the energy contained in a specific IR spectral signature (i.e. IR emission peaks of energetic materials) to produce a digitized output bit capable of waking up short-duty cycle powered electronics for further signal analysis and communications.

B. Potential for Transition

- Multi-spectral uncooled IR detectors that provide near real-time detection, high sensitivity, and high specificity for a targeted group of explosives IR spectral signatures, resulting in very low false-positive and false-negative rates.
- We plan to establish a partnership in Year 7 with United Technologies Corporation (UTC) to transition the technology to commercial products tailored for specific Border Protection applications. Along with UTC research center we have identified a collaboration topic on intrusion/presence detection (as part of an integrated wireless sensor systems) for an indoor space (e.g. buildings, caves, and tunnels).

C. Data and/or IP Acquisition Strategy

The PI holds intellectual property for the technology relevant to the project: United States Patent 9,419,583 (awarded on August 16, 2016) and United States Patent 9,425,765 (awarded on August 23, 2016). A PCT application (No. PCT/US2016/048083) and U.S. Provisional Patent Application (No.: 62/794,568) have been filed for the zero-power infrared sensor technology. These patents include claims related to the NEMS technologies developed under this program.
D. Transition Pathway

- Awarded with internal funding for technology transfer (GapFund360), the project targets the development of battery-less IR sensor tags for reliable occupancy sensing in indoor environment, which is suitable for many DHS-related applications such as airport security.
- Potential commercialization partners (Pendar Technologies, Analog Devices, and Boeing) have already been engaged with performance testing and transition development work.
- The PI holds intellectual property of the technology relevant to the project.
- Prototypes of the technology are being fabricated at Northeastern University for use and testing.
- The proof of concept will be shared with the identified potential customers to explore technology transition: the Department of Homeland Security (DHS), the Defense Advanced Research Projects Agency (DARPA), Analog Devices, Inc., Qualcomm, Pendar Technologies, Boeing, and Avago.

E. Customer Connections

- DHS: CBP Long Beach, Logan Airport
- United Technologies Corporation (UTC): Joseph Mantese
- DARPA Microsystems Technology Office: Ronald Polcawich, Benjamin Griffin, and Whitney Mason
- Air Force Office of Science Research: Kenneth Goretta, Gernot Pomrenke, and Harold Weinstok
- Analog Devices, Inc.
- Qualcomm
- RF Micro Devices, Inc.
- Pendar Technologies
- Avago

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Course, Seminar, and/or Workshop Development:
   a. 2018 Fall semester course: Introduction to MEMS
2. Student Internship, Job, and/or Research Opportunities:
   a. Research assistantship for two graduate students
3. Training to Professionals or Others:
   a. PhD student training (one student participated in IEEE Women in Engineering)
B. Peer Reviewed Journal Articles


C. Peer Reviewed Conference Proceedings


D. New and Existing Courses Developed and Student Enrollment

<table>
<thead>
<tr>
<th>New or Existing</th>
<th>Course/Module/Degree/Cert.</th>
<th>Title</th>
<th>Description</th>
<th>Student Enrollment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Course</td>
<td>Course</td>
<td>Introduction to Microelectromechanical Systems (MEMS)</td>
<td>This course provides an introduction to microelectromechanical systems including principles of sensing and actuation, microfabrication technology for MEMS, noise concepts, and packaging techniques. It covers a wide range of disciplines, from electronics to mechanics, material properties, microfabrication technology, electromagnetics, and optics. Students will study several classes of devices including sensors and RF components. The last third of the semester will be largely devoted to design projects, involving design of MEMS devices to specifications in a realistic fabrication process.</td>
<td>35</td>
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E. Technology Transfer/Patents

1. Inventions Disclosed
   a. Zero-Power Infrared Sensor Tags for Occupancy Sensing, NEU Reference Number: INV-19013

2. Patent Applications Filed (Including Provisional Patents)
V. REFERENCES


