R2-B.1: Orthogonal Sensors for Trace Detection

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<tr>
<th>Graduate, Undergraduate and REU Students</th>
<th>Name</th>
<th>Degree Pursued</th>
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<th>Month/Year of Graduation</th>
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<td>5/2019 (BS), 5/2024 (PhD)</td>
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<td>5/2020</td>
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II. PROJECT DESCRIPTION

A. Project Overview

In Year 6, we have dramatically improved the sensitivity and selectivity of our orthogonal sensors for the trace detection of explosives. The deliverable for this research project is a portable explosives trace detection (ETD) system, capable of continuously monitoring a wide variety of threat molecules in the vapor phase. Our ETD system is passive, non-invasive, and operates in a manner similar to a dog’s nose, where vapor is continuously drawn across sensors in a single pass, after which the vapors are expelled from the system. As the vapor is drawn across the active sensor, the energetic molecules are detected using microcalorimetry (i.e. the heat effect associated with the catalytic decomposition of the energetic molecule). The heat effect is monitored by measuring the electrical power difference between two microheaters required to maintain a constant temperature, as the temperature is scanned over a range from 50°C to 200°C. One microheater is coated with a metal oxide catalyst and the second is left uncoated. The catalyst-coated microheater senses any sensible heat effects plus any heat effects associated with decomposition of the explosive molecule whereas the second microheater senses any sensible heat effects, and thus, is the reference. The difference between the two signals (power difference) is the sensor response and is attributed to the energy released during decomposition.

Our sensing approach relies on the catalytic decomposition of the analyte and the heat effect associated with oxidation/reduction reactions that occur on the surface of the catalyst, which is much more specific, and when “printed” on ultrathin ceramic substrates, much more sensitive and selective to different explosive molecules than other techniques [1]. Specifically, we monitor the heat effects associated with oxidation/reduction reactions taking place at the catalyst surface when an energetic molecule decomposes. We have shown previously [1-3] that the decomposition of TATP takes place via catalytic decomposition as opposed to ordinary thermal decomposition as suggested by Chen and Bannister [4] and Dubnikova et al. [5, 6]. Several analytical methods have been successfully used to detect TATP at trace levels [7-10]; however, each has its own set of limitations. Many of these analytical techniques use large-scale equipment and require complex operational protocols. Colorometric sensor arrays [7] for example, have been used to detect TATP at the 2 ppb level, but this method requires swabbing, and thus is not amenable to continuous monitoring. One advantage of colorometric sensing, however, is that it is insensitive to the effects of
humidity, which can be problematic for the detection of TATP by other methods. MEMS based sensors can easily meet the requirements for portable detection, and thus, a number of techniques to detect explosives using MEMS sensors have been investigated. MEMS based sensors include metal-oxide-semiconductor (MOS) devices [8], bulk acoustic wave resonators [9], and differential thermal analyzers [10].

A low thermal mass version of our thermodynamic sensor was developed to improve the response time, selectivity and sensitivity to explosive molecules such as TATP and 2,4-DNT. In addition, a greater signal-to-noise ratio, and a reduced noise floor was achieved with these low thermal mass sensors relative to earlier versions of the sensor reported by Amani et al. [3]. To facilitate the hypothesis that a lower mass sensor would greatly benefit our approach, microheaters weighing less than 40 μg were fabricated. These sensors had a thermal mass that was almost 5000 times less than the solid-state sensors reported by Amani et al. [3]. The detection limits, and response times were greatly improved as a result. The evolution of our orthogonal sensors over the last year is significant, because not only did the response time dramatically improve, but the sensitivity and selectivity were dramatically improved, which was an unanticipated outcome of the research done in Year 6. This evolution and the corresponding responses of the three different sensor platforms are demonstrated in Figure 1, and will continue through the upcoming year as further reduction in mass continues. Using very thin, low mass yttrium stabilized zirconia (YSZ) substrates, detection of explosives in the ppb range is now possible at temperatures between 75°C and 200°C, whereas prior to using these very thin, low mass YSZ substrates, temperatures of 500°C or more were necessary to achieve responses in the ppb range. For example, the detection limits for TATP and 2,4-DNT using the latest sensor platform are 78 ppb and 2 ppb, respectively. We now believe that part per trillion detection is a real possibility in Year 7.

Sensor responses to 78 ppb TATP for “free-standing” nickel wire microheaters and “free standing” thin film microheaters on ultrathin YSZ substrates are shown in Figure 2. In Year 6, we systematically reduced the thickness of the YSZ platform from 40 μm to 10 μm. The results of sensor testing with the systematic reduction in thermal mass and thickness are clearly evident in Figure 3. Here, the response time is decreased and the sensitivity to TATP is increased with decreasing substrate thickness and thermal mass. This was somewhat expected; however, an unexpected result was that the sensor selectivity had also improved with the systematic reduction in thermal mass and thickness as demonstrated in Figure 4(a). In Year 6, we also employed thinner metallization for the microheaters to reduce the thermal mass of our sensors even further. In addition to nickel microheaters, copper and palladium were investigated as microheater alternatives. One unexpected outcome of this work was the general catalytic effect associated with the palladium microheaters, which acted as a catalyst amplifier. In earlier work [2], we showed that Pd nanoparticles incorporated into a SnO matrix had a dramatic effect on sensor response to TATP. Figure 4(b) shows the response of thin film Pd and Cu microheaters to 20 ppm TATP. Here, the response using palladium microheaters was significantly better than the Cu microheaters due to this catalytic effect. In general, all of the improvements in sensor response, selectivity, and response time will greatly benefit the Department of Homeland Security (DHS) and its stakeholders by providing a complementary tool to the existing Homeland Security Enterprise (HSE) toolbox that could enhance current technologies used for the screening of explosives, such as computed tomography (CT), or be used as a stand-alone tool for highly-deployable advanced compound detection, such as drones and wearables.
Figure 1: Evolution of our orthogonal sensor (left) and corresponding responses using the three different sensor platforms to 20 ppm TATP at an operating temperature of 200°C (right).

Figure 2: Thermodynamic sensor responses to 78 ppb TATP. Response of a free-standing nickel wire microheater (left) and an ultrathin YSZ microheater (right).

Figure 3: Thermodynamic sensor responses of three different YSZ substrate thicknesses using 0.5 μm thick copper microheaters to 20ppm TATP (operating temperature was 175°C).
Our state of the art ETD system is fundamentally different from other trace detection systems. We are not aware of any other sensor platforms that incorporate a catalyst, specifically tuned for a target molecule to achieve the desired levels of sensitivity/selectivity necessary for the detection of threat molecules at trace levels. The approach used by Chen and Bannister for detecting explosives comes closest to our technology [4]. They were able to differentiate energetic (explosive) materials from non-energetic materials using micro-thermal analysis. Specifically, they used a micro-calorimetry approach for detection, where changes in a material as it was heated generated a thermal “fingerprint” due to decomposition. Our approach relies on catalytic decomposition and the heat effect associated with oxidation/reduction reactions that occur on the surface of the catalyst, which is much more specific, sensitive, and selective to different explosive molecules when “printed” on ultrathin ceramic substrates. Specifically, we monitor the heat effects associated with oxidation/reduction reactions taking place at the catalyst surface when an energetic molecule decomposes. In Year 6, we have continued to push the state of the art by employing thinner YSZ substrates (supports for the microheaters), dual-sided catalyst, and alternative metallization for the microheaters. As a result, we have demonstrated dramatic improvement in every sensor metric applicable to wearable smart sensors and drones for the rapid detection of threats (see Table 1). Here, the catalytic response, response time, power requirements, and energy requirements are summarized for the various sensor platforms investigated in terms of Year 6.
In Year 6, considerable progress in the area of high throughput sensing was made, which provided the ability to interrogate sizable volumes continuously and efficiently and thus could impact a multitude of potential modalities going forward for DHS. Throughputs as high as 70 cubic feet per minute have been investigated to detect TATP at the 20 ppm level. The methodology developed for unmanned aerial vehicles (UAVs) can be readily implemented into airport computed tomography (CT) tunnels for rapid and continuous analysis of luggage for explosive threats. This was originally developed for integrating with our sensors on the wing of a UAV, where sampling of convective flows over areas of suspicion was the motivation. In one version, our sensor package having a total thickness <250 μm was integrated with a modified planar “pitot tube.” This “pitot tube” package was fabricated from a piece of 40 μm thick YSZ with micro-machined channels for easy delivery of the analyte to and from the sensor platform. These microchannels permitted sampling of high flow rate streams and the planar design of the “pitot tube” insured laminar flow of the stream reaching the microheaters. Using the modified planar “pitot tube” design we were able to detect 20 ppm TATP at flow rates ranging from 250 SCCM to 70 ft³ per min. Figure 5 illustrates the response to 20 ppm TATP under very high flow rate conditions. Here, the reference does show the hydrodynamic and sensible heat effects on the sensor system under these high flow rate conditions but this signal is subtracted from the signal that includes the catalytic decomposition (i.e. detection plus sensible heating effects).

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<th>Energy</th>
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<tr>
<td>Ni Microheater†</td>
<td>~375 mW</td>
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<td>25s</td>
<td>9.38 J</td>
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<tr>
<td>Cu Microheater†</td>
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<td>No effect</td>
<td>6.25 J</td>
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<tr>
<td>Pd Microheater†</td>
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<td>6s</td>
<td>2.4 J</td>
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<tr>
<td>Dual-Sided Catalyst‡†</td>
<td>No effect</td>
<td>0.6 %</td>
<td>10s</td>
<td>3.75 J</td>
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<tr>
<td>20 um YSZ ‡</td>
<td>~316 mW</td>
<td>2.5%</td>
<td>7s</td>
<td>2.21 J</td>
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<tr>
<td>12.5 um YSZ ‡</td>
<td>~302 mW</td>
<td>3.2 %</td>
<td>5s</td>
<td>1.51 J</td>
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</table>

* Response time was arbitrarily determined to be time to reach 1mW differential response  
† All microheaters fabricated on 40 um YSZ substrate; 0.5 um conductor thickness  
‡ All microheaters fabricated with 0.5 um Cu as conductor

Table 1: Metrics for various sensor platforms for wearable and drones applications.
C. Major Contributions

Almost all of the milestones in Year 6 were related to transition; specifically, the transition to a portable ETD system. Toward this end, a MEMS-like version of our ETD sensor system was developed with unprecedented sensitivity and selectivity for explosives and narcotics. We have demonstrated that our ultrathin, low mass sensors can detect TATP, 2,4-DNT, and cannabidiol (CBD) at the ppb level. Detection of cannabinoids (CBC, CBD, etc.) are essential in the detection of illegal cannabis or tetrahydrocannabinol (THC). Structurally, CBD and THC are very similar with the only variation being a doubly bonded oxygen. Detection of CBD can be indicative of THC and thus, provides an important marker for the detection of cannabis at trace levels. Implementation of 10 μm thick yttrium stabilized zirconia as the substrate for thin film microheaters, has made detection beyond the part per trillion level a possibility. The surface area of the thin film microheaters deposited onto 10μm thick YSZ substrates combined with the reduced film thickness microheaters (0.5 μm) allowed us to achieve much lower thermal-mass without sacrificing catalytic surface area. In addition to the reduced thickness, the substrates have rather unique thermal properties (i.e. highly anisotropic thermal conductivity), and thus, produce very localized heating of the catalyst so that heat remains in the vicinity of catalyst without dissipating into the substrate. This lowers the power requirements and makes the response much more specific for a given temperature. Lastly, using the ultrathin YSZ substrates, detection of explosives in the ppb-ppt range is possible at temperatures between 75°C and 275°C, whereas without these YSZ substrates, temperatures of 500°C were required to achieve the same detection limits.

D. Milestones

Milestone 1: Fabrication of Orthogonal Sensors on Ultrathin YSZ Substrates (Q1- 2019)

- 1.1 (Q1-2019): Fabricate thin film microheaters for thermodynamic sensors on ultrathin yttrium stabilized zirconia (YSZ) substrates having thicknesses of 40μm, 20μm, 12.5μm, and 8μm. Ultrathin yttrium stabilized zirconia substrates will be supplied by industry partner (ENrG).
1.2 (Q1-2019): Fabricate Cu or Pd thin film microheaters for thermodynamic sensors having varying thickness (0.8 μm, 0.5 μm, 0.3 μm, 0.1 μm) on ultrathin yttrium stabilized zirconia substrates supplied by industry partner (ENrG).

1.3 (Q1-2019): Fabricate orthogonal sensors (conductometric/thermodynamic sensors) on ultrathin yttrium stabilized zirconia (YSZ) substrates.
   
   1.3.1: Fabricate Cu and Pd microheaters, metal oxide catalysts and thin film metal electrodes for thermodynamic/conductometric (orthogonal) sensors; oxide catalysts including SnO, CuO, ZnO, and FeO, as well as other metal oxides with multiple oxidation states.
   
   1.3.2: Optimize heat treatment of catalysts (time at temperature) for maximum sensor response.
   
   1.3.3: Fabricate thin film microheaters, metal oxide catalysts and thin film metal electrodes on ultrathin yttrium stabilized zirconia substrates having thicknesses of 40 μm, 20 μm, 12.5 μm, and 8 μm.
   
   1.3.4: Fabricate Cu thin film microheaters and Cu thin film electrodes for orthogonal sensors having a total thickness <1 μm.

Milestone 2: Demonstrate Orthogonal Sensors Fabricated on Ultrathin YSZ Substrates (Q1-2019/Q2-2019)

2.1 (Q2-2019): Test orthogonal sensors fabricated on ultrathin yttrium stabilized zirconia (YSZ) substrates using different explosives; peroxide based and nitrogen based explosives (TATP, 2,4 DNT).

2.2 (Q2-2019): Test orthogonal sensors fabricated on ultrathin yttrium stabilized zirconia (YSZ) substrates using different drugs/narcotics (CBD, THC).

2.3 (Q2-2019): Demonstrate improved response times and lower power requirements for orthogonal sensors fabricated on ultrathin yttrium stabilized zirconia (YSZ).

2.4 (Q2-2019): Demonstrate new detection limits for orthogonal sensors fabricated on ultrathin yttrium stabilized zirconia (YSZ). Our target is a part per trillion detection limit.


3.1 (Q2-2019/Q3-2020): Design new CAD drawings of microheater patterns having line widths and line spaces of 50 μm, 25 μm, and 10 μm to minimize lateral heat dissipation.

3.2 (Q2-2019/Q3-2020): Fabrication of thin film microheater arrays utilizing new CAD designs.

3.3 (Q2-2019/Q3-2020): Evaluate sensors (sensor metrics) utilizing thin film microheater arrays.
   
   3.3.1: Evaluate cross talk (heat transfer) from one thin film microheater to another using IR imaging techniques; i.e. effect of line width and line space for different designs (50 μm, 25 μm, 10 μm line width and line space).
   
   3.3.2: Fabricate and pattern different catalysts on select microheaters in array (SnO, CuO, FeO).
   
   3.3.3: Demonstrate microheater arrays using various analytes; measure sensor metrics including response time and power requirements in addition to sensor sensitivity and selectivity.
3.4 (Q3-2020/Q4-2020): Test sensors fabricated with arrays of microheaters patterned with different catalysts; analytes include explosives and narcotics.
  
  3.41: Test sensor arrays fabricated on ultrathin yttrium stabilized zirconia (YSZ) substrates using different explosives and drugs; (TATP, 2,4 DNT, CBD).
  
  3.42: Develop new interconnect schemes for thin film microheater arrays to maximize number of microheaters in array.

3.5 (Q3-2020): Algorithm development for identification of analyte to minimize false positives and negatives; and energy budget and optimize duty cycle.

**Milestone 4: Field Test Sensor Arrays on Ultrathin YSZ at Naval Research Lab (Q3-2020)**

4.1 (Q3-2020): Integrate thin film microheater arrays into our portable trace detection system.

4.2 (Q3-2020): Test our portable trace detection system with integrated microheater arrays in our lab using a variety of explosives.

4.3 (Q3-2020): Travel to Naval Research Laboratory's Vapor Test Bed for confirmation of detection limits and demonstrate sensor response in the presence of select interferents using NRL’s proprietary vapor generator so analytes w/ interferents can be delivered in a highly controlled manner.

**Milestone 5: Integration of Sensor Arrays for Drone and CT Applications Using High Throughput Design (Q4-2020)**

5.1 (Q4-2020): Finalize design for high throughput sensing using thin film microheater sensor arrays on ultrathin YSZ substrates.

5.2 (Q4-2020): Fabricate sensors with modified “pitot tube” design for high throughput sensing; concept relies on micro-machining channels and vias within the ultrathin YSZ substrates.
  
  5.21: Optimize size and pattern of vias and microchannels within the ultrathin YSZ substrates for effective sampling of high flow rate vapor streams.
  
  5.22: Deliver micro-machined channels and vias within the ultrathin YSZ substrates of varying thickness (40 μm, 20 μm, 12 μm, 8 μm).

5.3 (Q4-2020): Demonstrate sensor arrays with modified “pitot tube” design using micro-machined channels and vias within the ultrathin YSZ substrates for high throughput sensing.
  
  5.31: Demonstrate high flow rate sensing at flow rates up to 100 CFM.
  
  5.32: Demonstrate detection limits, response times, false alarm rates etc. for high throughput sensing in a CT tunnel environment.

5.4 (Q4-2020): Final device packaging of sensor arrays using micro-machined channels and vias within the ultrathin YSZ substrates for high throughput sensing.

5.5 (Q4-2020): Finalize interconnect schemes for sensor arrays used for high throughput sensing.
  
  5.51 (Q4-2020): Demonstrate ability to detect explosives in head space of a CT tunnel in real time; i.e. typical timeframe to x-ray baggage.
E. Future Plans/Project Completion (Year 7)

We have been working with several commercialization partners, funded through the FlexTech Alliance for the past six months, to develop and commercialize a new class of ultra-thin flexible circuits that will enable high performance silicon electronics to be directly packaged with emergent solid-state lithium battery (SSLB) technology on 1mm thick alumina substrates. In short, we received a $2.8M award in September 2018 to develop a sensor platform for drone applications whereby monolithic sensors are integrated with thin film batteries to produce a battery with integrated processing and sensor systems (BIPASS). This effort will enable the integration of the power module, sensor, signal processing, and telemetry electronics all into a package with total thickness <250 μm; enabling its use in small drones, wearables, and other volume/weight-sensitive detection platforms. Furthermore, with only small changes to the catalyst materials, we will be able to detect a number of other analytes, such as toxics, NOx, and narcotics, thus providing enabling capabilities to the military and first responders.

Recently, we submitted a white paper to the FlexTech Alliance, for another $1.4M, involving some of the same commercialization partners as well as new partners, including FLIR. The white paper was well received and a full proposal to develop and demonstrate a novel, lower power, thin film array of chemical sensors that can detect a broad spectrum of compounds in real time as part of an early detection warning system was submitted. If successful, this $1.4M project will piggyback on our earlier award from the FlexTech Alliance to make a sensor system that could be deployed as a wearable smart sensor, affixed to a smart tag, or form a Smart Skin on robots/drones for the rapid detection of threats and other compounds. The “smart skin” sensing platform will employ multiple thin film microheaters fabricated on ultrathin yttria-stabilized zirconia (YSZ) ceramic substrates. Some of these microheaters will be coated with different catalysts to form “active” sensor elements and some will remain uncoated and will serve as references.

The ultimate transition product from our research is a portable ETD system, capable of continuously monitoring a wide variety of threat molecules in the vapor phase. We will continue the process of shrinking the “footprint” of our portable ETD system in Year 7, which is attractive to many of the stakeholders of our research, including the U.S. Navy. The Navy has been a potential end user of our technology since its inception, the transition to a handheld version of our orthogonal trace detection system for first responders and ground troops. This was original objective of the project, since establishing a Cooperative Research and Development Agreement (CRADA) with the US Navy (NCRADA-NUWCDIVNPT-13-801) in 2013, and was based on our ability to develop a MEMS version of our orthogonal trace detection sensor. This CRADA was in place through July 2018 and the development effort with the Navy continues to today. We are in the process of finalizing a new CRADA with the US Navy that is broader in scope and that will extend beyond July 2021. The new CRADA is slated to begin in June 2019 and will focus on the design, development, and testing of semiconductor based sensors and/or MEMS sensors with semiconductor substrates. It will also emphasize the integration of power modules, thin film sensors, signal processing and telemetry electronics relevant to MEMS platforms.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

Previously, we have shown that we can detect a variety of analytes at trace levels utilizing a lower mass-sensing platform. The systematic reduction in mass was accomplished by replacing microheaters deposited on 1mm thick alumina substrates with “free-standing” 0.5 μm thick copper micorheaters deposited onto ultrathin YSZ substrates. As a result the required operating temperatures were lowered from 350-500°C to
145°C without sacrificing sensitivity. This translates into a drastically reduced energy budget, one of the hurdles in making a truly portable ETD system. The enhanced surface area relative of the free-standing “free-standing” 0.5 μm thick copper microheaters allowed us to achieve unprecedented levels of detection (parts per trillion). To date, detection limits of 150 ppb for TATP, 2 ppb for 2-4, DNT, and 3 ppt for CBD have been achieved. As we continue to reduce the mass of our microheaters further, detection limits beyond the ppt level may be possible with our sensor platform.

Our ETD system will assist the DHS enterprise in a number of ways, including: (1) It could assist the manufacturers of commercial detection systems that do not currently have the capability to detect peroxide-based explosives; and (2) it would give the manufacturers of CT and other detection systems, the capability to screen for low-density compounds, such as TATP, one of the major challenges for DHS. By incorporating our ETD system into a checkpoint CT, a true 3-D sensing capability will be possible (i.e. three orthogonal sensor modalities brought together to mitigate false positives and negatives). Our ALERT research project specifically addresses the issue of false positives and negatives by employing orthogonal sensor modalities that are somewhat unique. Both of these would have to respond at the same temperature (as the sensor is scanned) for confirmation that an explosive was present. This built-in redundancy results in a very unique response; therefore, we will be able to detect a wider range of threats to public safety, without compromising sensor reliability due to false positives and negatives. For example, a potential interferent for TATP using our sensor platform is acetone, which is the decomposition product of TATP in the absence of any catalyst [1, 11], however, the catalytic decomposition of TATP using SnO or CuO results in hydrogen peroxide formation and not acetone [2, 3, 11]. Thus, those interferents anticipated in the absence of a catalyst may not affect selectivity, nor be an issue using our ETD system, since hydrogen peroxide is the more prevalent decomposition product.

B. Potential for Transition

There is considerable potential for transition using our orthogonal sensors for the trace detection of explosives (and narcotics) in future screening systems. This includes mounting or embedding our sensors onto the surface of a UAV wing with a low vertical profile (low drag) or small areal footprints for wearable sensors for firefighters and first responders. The detection of volatiles, explosives, and narcotics are the target analytes for these applications. In other applications, such as the CT tunnel environment, screening the head space (vapor space) around baggage for explosives in the time it takes to X-ray baggage is possible with the high flow rate version of our sensor, which is attractive to the CT manufacturers. We have been working with several commercialization partners, funded through the FlexTech Alliance, to develop and commercialize a thin film MEMs-like version of our sensor. Our partners, including FLIR, will help us develop a thin film array of chemical sensors that can detect a broad spectrum of compounds in real time as part of an early detection warning system. This “smart skin” sensing platform will employ multiple thin film microheaters fabricated on ultrathin YSZ substrates. Each microheater will be coated with a different catalyst to form “active” sensor elements and one will remain uncoated and serve as a reference. In this way, a broad spectrum of threat molecules can be detected in real time. This will of course require new sensing protocols and algorithms to be developed for the thin film sensor arrays, but will add considerably to sensor selectivity, which was cited as a potential weakness in our technology in the Year 5 Project Report.

C. Data and/or IP Acquisition Strategy

We have filed 7 disclosures this past year, many of which were subsequently filed as provisional patents. As we work with our partners to push the envelope for detection including new analytes and new detection protocols and algorithms, more opportunities for IP will arise over the next year.
D. Transition Pathway

In addition to the interaction with our commercialization partners (weekly conference calls) and working with the Flextech Alliance, our technology is being showcased across a much larger cross section of the sensor and electronics community. We still plan to do mock field trials of our sensor in a CT tunnel environment to test for explosives in the vapor while scanning luggage for solid explosives. The manufacturers of CT scanning equipment are very interested in adding capability to existing CT platforms to detect volatile explosives, such as TATP, which cannot be readily detected using CT. We will also be presenting our sensor work at a Nanotechnology Conference (TechConnect World Conference 2019) on June 17, 2019 in Boston, MA.

E. Customer Connections

<table>
<thead>
<tr>
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<th>Institution</th>
<th>Email</th>
<th>Phone</th>
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<td>401 874-5482</td>
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IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Interactions and Outreach Minority Serving Institution Students or Faculty
   a. We teamed with Professor Abdennaceur Karou from North Carolina Central University to develop a proposal for ORISE and the ALERT 2019 DHS Summer Research Team Program for Minority Serving Institutions. The proposal was entitled “TATP Nanosensor: The Role of the Catalyst and the Electron Reservoir in Transducing a Strong Signal during the Decomposition of the Explosive.”

B. Peer Reviewed Journal Articles


Pending –

C. Other Presentations

1. Seminars

2. Poster Sessions

3. Student Theses or Dissertations Produced from this Project

D. Technology Transfer/Patents

1. Inventions Disclosed

2. Patent Applications Filed (Including Provisional Patents)

V. REFERENCES


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