REGION II
UNIVERSITY TRANSPORTATION RESEARCH CENTER

Final Report

Investigation of RFID Based Sensors for Sustainable Transportation Applications

Prepared by

Dr. Michael A. Carpenter
Assistant Professor
College of Nanoscale Science and Engineering University – Albany/SUNY
Albany, NY 12302
Tel: (518) 437-8686
Email: mcarpenter@uamail.albany.edu

January 21, 2011

Disclaimer

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Investigation of RFID Based Sensors for Sustainable Transportation Applications		5. Report Date January 21, 2011 6. Performing Organization Code
7. Author(s) Michael Carpenter, Albany/SUNY		8. Performing Organization Report No. 49111-09-20
9. Performing Organization Name and Address College of Nanoscale Science and Engineering University Albany/SUNYAlbany, NY 12302		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address University Transportation Research Center Marshak Hall, Room 910 The City College of New York New York, NY 10031		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Through support of a University Transportation Research Center Faculty Development Minigrant an investigation was made into the use of RFID based sensing technologies for transportation purposes. Transportation applications would potentially include the wireless detection of overweight trucks, remote and automated emissions monitoring of vehicles, corrosion of infrastructure and transportation security applications. Sustainable transportation would be improved through savings realized by a reduction in the cost of sensor technologies as well as the significant cost savings and environmental impacts realized by reducing the damage to roads and bridges by the efficient detection of overweight trucks, a reduction in the number of vehicles with emissions violations, in-situ detection of infrastructure corrosion to enable just in time maintenance and improved safety of mass transit. Commercially available RFID tags cost $0.1 and are being used in a wide range of applications including, shipping, warehouse management among others. Recently Wake Inc. has developed methods for incorporation of RFID tags into concrete structures for in-situ measurement of the curing process. While these tags cost more than $0.1, due to the enhanced packaging, they are able to measure the temperature of concrete structures to determine when the structure has cured. Typical protocols require that concrete "cure" for a mandatory 28 days so that its maximum strength is achieved.

However depending on the local temperatures, humidity, concrete volume etc., concrete may achieve this maximum strength in just several days. Thus, through the use of the RFID sensors, construction of transportation related infrastructure can proceed at a much faster pace and realize significant savings by reopening major routes, bridges or runways at earlier dates. While Wake Inc. has demonstrated this in several instances, including the Port Authority of New York and New Jersey, there are further improvements to be made to this technology by incorporating new sensing capabilities into RFID tags.

17. Key Words	18. Distribution Statement
RFID Based Sensors, RFID Tags, Overweight Trucks, Automated Emissions, Infrastructure, Transportation Security, Sustainable Transportation, Chemical Sensors.	

19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	19	

Form DOT F 1700.7 (8-69)

Through support of a University Transportation Research Center Faculty Development Minigrant an investigation was made into the use of RFID based sensing technologies for transportation purposes. Transportation applications would potentially include the wireless detection of overweight trucks, remote and automated emissions monitoring of vehicles, corrosion of infrastructure and transportation security applications. Sustainable transportation would be improved through savings realized by a reduction in the cost of sensor technologies as well as the significant cost savings and environmental impacts realized by reducing the damage to roads and bridges by the efficient detection of overweight trucks, a reduction in the number of vehicles with emissions violations, in-situ detection of infrastructure corrosion to enable just in time maintenance and improved safety of mass transit. Commercially available RFID tags cost ~$0.1 and are being used in a wide range of applications including, shipping, warehouse management among others. Recently Wake Inc. has developed methods for incorporation of RFID tags into concrete structures for in-situ measurement of the curing process. While these tags cost more that $0.1, due to the enhanced packaging, they are able to measure the temperature of concrete structures to determine when the structure has cured. Typical protocols require that concrete "cure" for a mandatory 28 days so that its maximum strength is achieved. However depending on the local temperatures, humidity, concrete volume etc., concrete may achieve this maximum strength in just several days. Thus, through the use of the RFID sensors, construction of transportation related infrastructure can proceed at a much faster pace and realize significant savings by reopening major routes, bridges or runways at earlier dates. While Wake Inc. has demonstrated this in several instances, including the Port Authority of New York and New Jersey, there are further improvements to be made to this technology by incorporating new sensing capabilities into RFID tags.

Due to the financial and time limitations of the minigrant program we performed a review of the current use of RFID sensing technologies for transportation applications with a focus on chemical sensors. The addition of this sensing capability to a RFID based sensor would have uses across many of the applications mentioned above. My research group has extensive expertise in developing tailored nanomaterials for optical based chemical sensing technologies. For much of this work the application relies on changes in the dielectric function of the material to induce a correlated optical response indicative of a chemical event. This same dielectric response change will induce a change in the impedance spectrum measured by the RFID tag reader. As such, much of the material work proceeding in my lab has the potential for use within an RFID based chemical sensor system and their optimization for this application has been a focus of our continued future work during this program. While the development of gold nanoparticle- metal oxide nanocomposite materials in my lab has been quite active, a limiting factor in incorporating these into an RFID based device is that they require an elevated temperature of at least 200^{o}C. However, as noted later in the report there has been recent work on incorporating low power heaters onto an RFID platform, this coupled with the development of metal oxide composite materials which require low operating temperatures offers further promise for their incorporation in future RFID sensing devices. Likewise, the development of optical based chemical sensing films has been an active area of work in my group during this program as well. Incorporation of optical devices into RFID platforms has been a limiting factor as well, as optical devices typically have power and size limitations which prevent their use within a low power RFID device. However, there has been recent work on this research front as well, and it will be noted in the report that with the miniaturization of optical devices, their integration into an RFID sensing platform is a very promising area of research.

This document is divided into three parts, 1) Providing reviews on chemical sensors based on RFID technology, 2) A summary of the fabrication and integration techniques for incorporation of chemical sensors onto an RFID platform, and 3)The measurement of pH response for an optical chemical sensor that is incorporated onto RFID platform.

1.0 Chemical Sensors

Recent work by Potyrailo et al. has shown that through the use of chip-less RFID technology, i.e. measurement of the analog based impedance spectrum of the RF signal from industrially available RFID tags, one is able to detect with a high degree of sensitivity and selectivity a range of chemicals. This has been demonstrated for a variety of solvents, such as ethanol, methanol, and water as well as the degree of milk spoilage within a milk carton.[1,2]

Potyrailo et al. has demonstrated an approach that adapted a single conventional radio frequency identification (RFID) tag for multianalyte chemical identification and quantitation. The RFID chemical sensors are made by coating a polymer film, which is used for adsorption of the target chemical, using conventional draw-coating process onto a standard 13.56-MHz passive RFID tag.[3,4,5,6] It is important to note that the tags used for these studies are readily available and have a minimal cost, $0.1. The polymer films are selected based on the target chemical and film material properties and are then coated onto the RFID tag using simple deposition techniques.[3]

The principles of target chemical detection and measurement are based on the mutual inductance coupling between the RFID sensor antenna and the pickup coil of the reader, and involve changes in the dielectric function and properties of the sensing film coated on the antenna. After the adaptation of a conventional RFID tag for chemical sensing by deposition of a sensing film on the antenna, the tag ID and the complex impedance of the antenna are measured with a conventional RFID reader and an impedance analyzer. While the cost of the individual tags is low, the readers can be a more extensive financial impact, with costs ranging into the 1000s of dollars. The measured digital ID provides information about the individual sensor whereas the measured complex impedance provides a multivariate response for chemical determination.[1- 6] This is an important characteristic of this technique, as both the digital tag ID is needed as well as the analog impedance spectrum, which adds both complexity and cost to the application.

1.1 Repositioning Effects[4]

The range of detection of these RFID devices is typically on the order of 1-5m, but is dependent on the power of the RFID reader. The sensing signal has also been prone to the position of the RFID tag and studies of the repositioning effects are carried out by controlling the relative position of the RFID sensor and the reader pickup coil. The repositioning states for this study involved a 5 mm step changes in both the horizontal (X-) and vertical (Z-) directions, ranging from 0 to 20 mm and back to 0 mm. Humidity detection is chosen as a model system for these studies. Two replicate exposures towards dry air and 45% relative humidity (RH) air are carried out for every position of the sensor. Figure 1 shows an example of the RFID sensor's responses to dry air and 45% RH at the origin (0, 0) position.

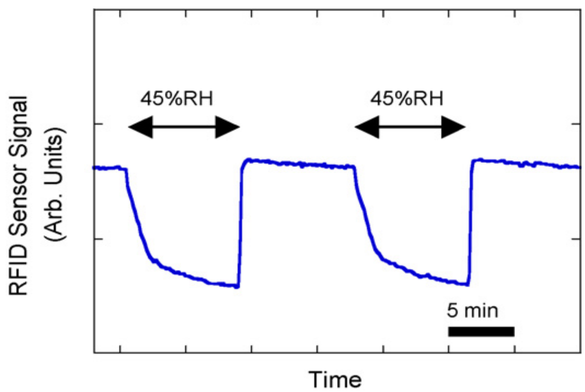

Fig 1. An example of the RFID sensor's responses to dry air and 45% RH at the origin (0, 0) position.[4]

Parameters from the measured complex impedance, which included the frequency and magnitude of the maximum of the real part of the complex impedance (F_p and Z_p), and the resonant and antiresonant frequency of the imaginary part of the complex impedance (F_1 and F_2) are calculated. From the experiment, it was found that all parameters of the complex impedance yielded a position-dependent analyte-quantitation. The position-induced effects were comprised of the baseline signal becoming offset due to exposure to dry air, and changes in the analyte magnitude response when exposed to 45% RH. Sensor noise, however, did not show any noticeable changes due to position. Table 1 shows a detailed summary of the position-induced effects of the sensor response.

	Z-effects	X-effects
F_1 shift	Sensor baseline increase Sensitivity to analyte decrease	Sensor baseline slightly increases Sensitivity to analyte does not significantly change
F_2 shift	Sensor baseline decrease Sensitivity to analyte increase	The sensor baseline does not significantly change Sensitivity to analyte does not significantly change
F_p shift	Sensor baseline increase Sensitivity to analyte does not significantly change	Sensor baseline slightly changes Sensitivity to analyte does not significantly change
Z_p shift	Sensor baseline decrease Sensitivity to analyte decrease	Sensor baseline slightly decreases Sensitivity to analyte does not significantly change

Table 1. Position-induced effects of the RFID sensor response.[4]

Although repositioning of the RFID sensor and pickup coil affected the quantitative responses of the sensor, Potyrailo's group managed to compensate for these repositioning effects by performing principal components analysis (PCA) of the measured parameters. Figure 2 shows the results of the PCA analysis, where position stability of the baseline signal and magnitude of the analyte response when subjected to dry air and 45% RH exposures respectively, can be observed. PCA analysis requires the input of a number of variables gleened from the sensor response data and then through a statistical analysis, patterns emerge and statistically reliable information can be determined. Figure 2 shows that after over 3500 samples the baseline drift due to repositioning and repeated exposures to humidified and dry air a reliable and repeatable sensing response can be achieved. For transportation applications a much larger change in environmental variables will likely be experienced by an RFID based chemical sensor (for instance emissions monitoring at a toll booth, subway, parking garage, train station,…). These include not only changes in the chemical environment, such as humidity, but also temperature and position. So it is clear from this initial previous work that a much more extensive study for reliability of the RFID based sensing studies would need to be completed to determine these limitations and the proper analysis algorithms to eliminate these types of environmental effects from the measurement.

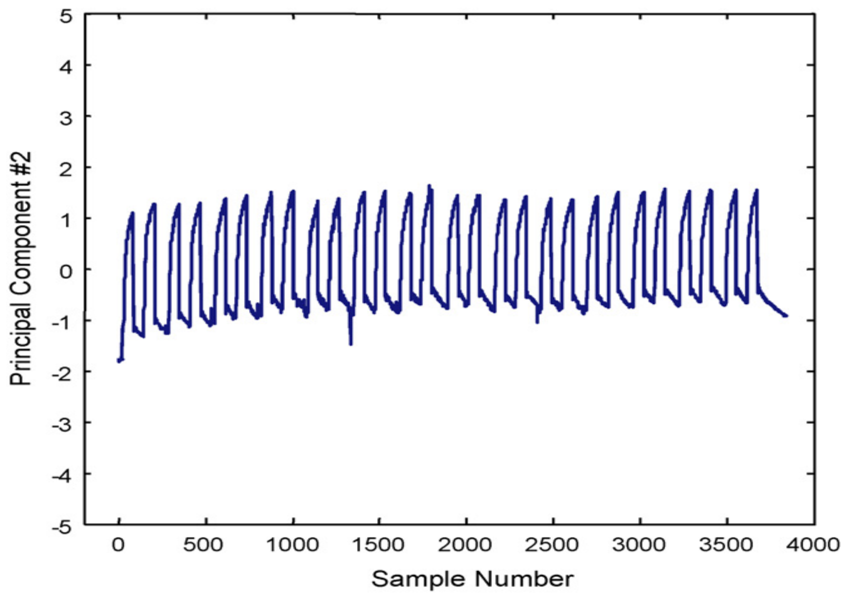

Fig. 2. Results of PCA analysis of the measured F_p, Z_p, F_1 and F_2 parameters for determination of position-independent analyte quantification.[4]

1.2 Combined Effects of Plasticizers and Temperature[6]

The work of Potyrailo et al. has had a focus on using polymeric coated RFID sensors and as an absorbent layer for the target chemicals of interest. The preparation of the polymer coatings, including plasticizer type and the corresponding annealing temperature have an effect on the polymer's sensing performance. Studies of the combined effects of polymeric plasticizers and annealing temperature were done by using a model system comprising of a 6 x 8 array of polymer-coated RFID sensors. This array of sensors is made from a solid polymer electrolyte Nafion, which was formulated with five different phthalate plasticizers, namely dimethyl phthalate, butyl benzyl phthalate, di-(2-ethylhexyl) phthalate, dicapryl phthalate, and diisotridecyl phthalate. A sensing film without any plasticizer is used as the control sensing film. These sensing films are coated onto the RFID sensors and exposed to different temperatures ranging from 0 to 140˚C.

Figure 3 shows the impedance and frequency response differences (ΔZ_p and ΔF_p) before and after an hour of annealing from each sensor in air as a function of different annealing temperatures and sensor compositions. The most stable film composition after annealing corresponded to the smallest ΔZ_p and ΔF_p responses. Boiling point for each plasticizer used in the experiment is compared with the ΔZ_p and ΔF_p responses from sensors exposed to the highest temperature of 140˚C, as shown in Table 2.

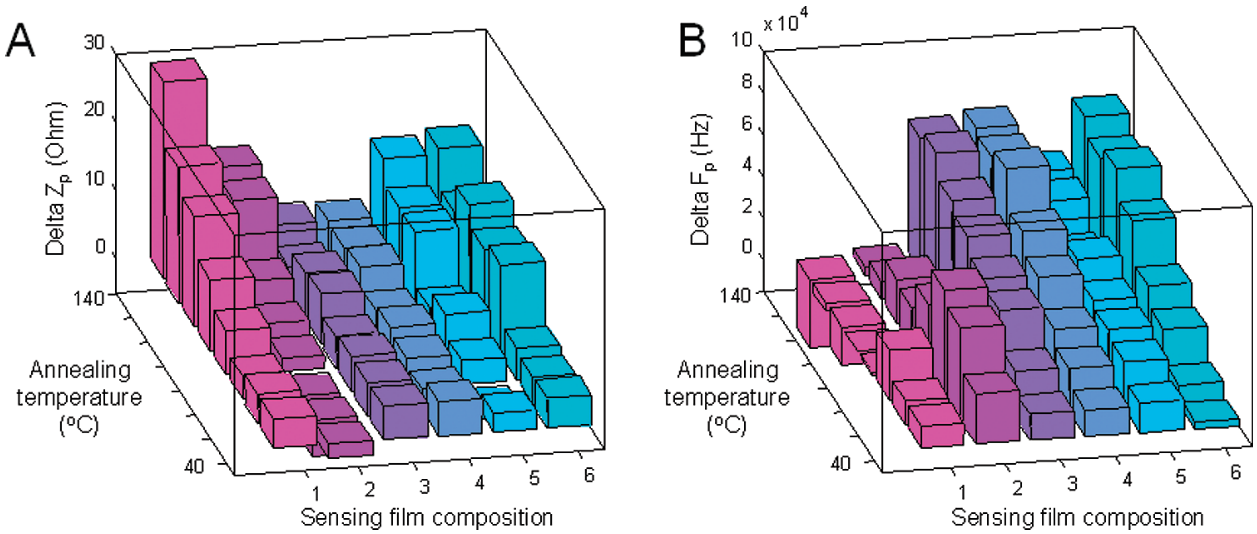

Fig. 3. (A) Impedance (ΔZ_p), and (B) frequency (ΔF_p) response before and after an hour of annealing from each sensor as a function of different annealing temperature and film composition, where the film compositions are: (1) control without plasticizer, (2) dimethyl phthalate, (3) butyl benzyl phthalate, (4) di-(2-ethylhexyl) phthalate, (5) dicapryl phthalate, and (6) diisotridecyl phthalate.[6]

composition	plasticizer type	boiling point, °C	sensor response ΔZ_p (ohm)	sensor response ΔF_p (Hz)
1	control (without plasticizer)		28.781	−32590
2	dimethyl phthalate	284	15.667	3940
3	butyl benzyl phthalate	370	6.781	64200
4	di-(2-ethylhexyl) phthalate	384	6.715	66880
5	dicapryl phthalate	230	15.351	44020
6	diisotridecyl phthalate	260	16.375	68880

Table 2. Parameters and temperature stability (as boiling point) of different sensing film compositions.[6]

The sensors response stability and gas selectivity patterns at different temperature were evaluated as well. Evaluation of the vapor responses stability is carried out by exposing the array of temperature-annealed sensing films to two analytes: water (H_2O) and acetonitrile (ACN) vapors, at a concentration (partial pressure) of 0.4 of the saturated vapor pressure (P_o). Figure 4 shows the ΔZ_p and ΔF_p responses to H_2O and ACN at an annealed temperature of 40 and 110°C. It can be observed that all sensing materials responded strongly towards H_2O as compared to ACN, which may be due to the difference in the dielectric constants ($\epsilon_{H2O} = 80$, and $\epsilon_{ACN} = 37$). As Nafion is known to absorb water and other polar molecules the adsorption property differences between these two chemicals, combined with their difference in dielectric constant likely also contributed to the RFID response difference. What is interesting to note however, is that by modifying the polymer preparation conditions the response characteristics can be changed. PCA analysis of the sensing films responses to H_2O and ACN suggested that different annealing temperature and plasticizers may change the diversity of the sensing films with a positive or negative effect, as shown in Figure 5 by the increase or decrease of the H_2O-ACN Euclidean distances. Dimethyl phthalate plasticizer is found to improve the response diversity of the sensing films to H_2O and ACN. Thus, this is further evidence that the tailored properties of the polymer coatings can have a profound effect on the RFID chemical sensor's sensing characteristics. For particular applications this materials optimization step will be important for providing the required sensing characteristics given a particular sensing environment.

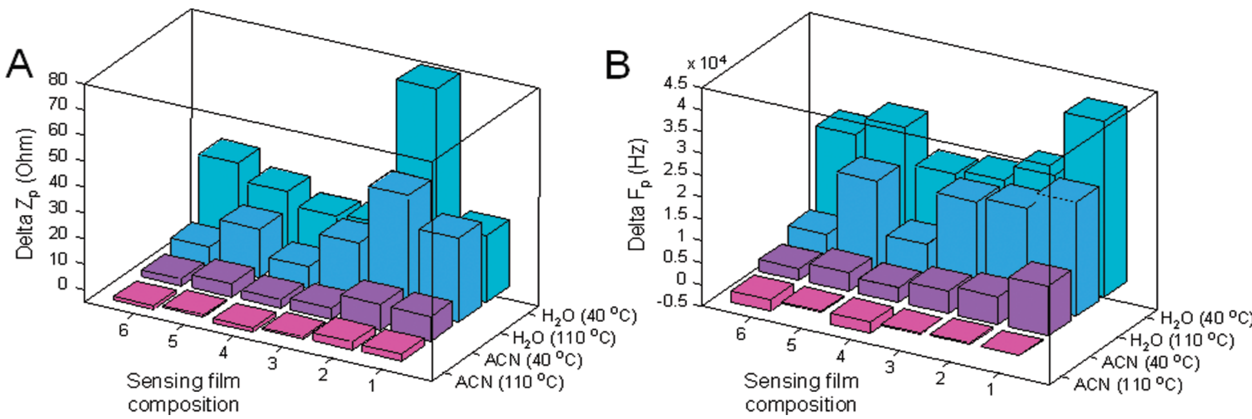

Figure 4. RFID sensor ΔZ_p and ΔF_p responses to H_2O and ACN at an annealed temperature of 40 and 110°C. Sensing film compositions are: (1) control without plasticizer, (2) dimethyl phthalate, (3) butyl benzyl phthalate, (4) di-(2-ethylhexyl) phthalate, (5) dicapryl phthalate, and (6) diisotridecyl phthalate.[6]

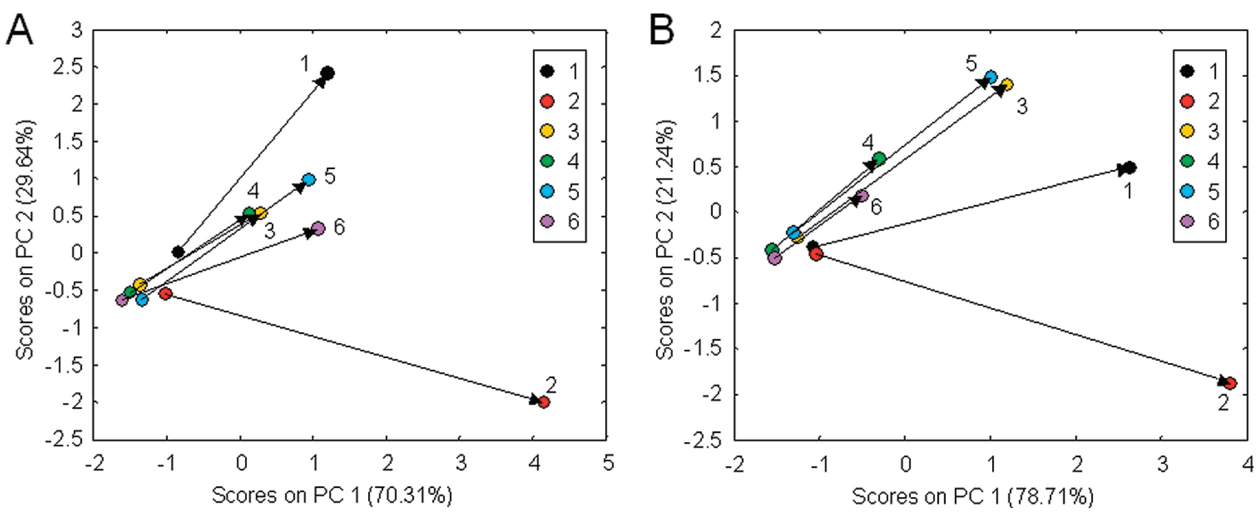

Figure 5. PCA analysis of the measured F_p, Z_p, F_1 and F_2 responses of RFID sensors with different sensing films to H_2O and ACN upon annealing at (a) 40°C, and (b) 110°C. Arrows indicate the H_2O-ACN Euclidean distances and the direction of responses. Arrows begin at the response of the sensing film to ACN and end at the response of the sensing film to H_2O.[6]

1.3 Evaluation of Radiated Emission and EMC Immunity[5]

Potyrailo's group had evaluated their RFID sensors for radiated emission and electromagnetic field immunity. The sensors are found to be able to operate within regulated emission levels and are not affected by common electromagnetic interferences. Therefore, if a particular sensing environment is exposed to emission levels that are within regulated levels, this will not have an effect on the RFID sensors performance.

1.4 Applications of a Coated RFID Tag Based Chemical Sensor[5]

Potyrailo's group had adapted and tested the RFID sensors for sensing applications that included:

1. RFID food freshness dosimeter

2. RFID dosimeter for exposure to toxic industrial chemicals (TIC)

This application tested the RFID response characteristics towards ammonia, one of the TICs with a high hazard index. The sensor was coated with a PANI polymeric sensing film, which acted as a dosimeter. The sensor is exposed to 10 minutes of different concentrations of ammonia (4, 8, 14, 20, 28, and 40 ppm). Figure 6 shows the F_2 (antiresonant frequency of the imaginary part of the complex impedance) response for ammonia gas. It can be observed that there is a measurable change in the response. The inset of Figure 6 shows the calibration curve for the ammonia response. Higher sensitivity of response is obtained for lower ammonia concentrations (0 – 10 ppm), higher sensitivity of response is seen whereas for higher concentrations of ammonia, lower sensitivity of response is observed. The detection limit of the sensor is calculated to be 80 ppb. The stable response of the RFID sensor and capability to detect parts per billion of concentrations of TICs made it important for industrial safety, homeland protection, and other applications.

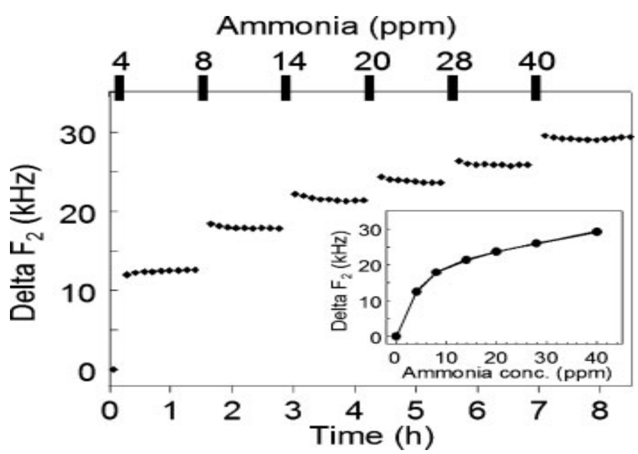

Figure 6. F_2 (antiresonant frequency of the imaginary part of the complex impedance) response for ammonia gas at different concentrations of ammonia. Inset, calibration curve for the RFID ammonia dosimeter.[5]

3. RFID sensor for toxic volatile polar and nonpolar vapors

Periodic exposure of 3 toxic volatile vapors, including trichloroethylene (TCE), methanol (MeOH), and toluene (Tol) at different concentrations (partial pressures) of 0.04, 0.07, 0.10, 0.15, and 0.20 P/P_o was done over 20 hours of exposure time. The RFID sensor is deposited with polyurethane polymeric coating. Figure 7 shows the Z_p (magnitude of the real part of the complex impedance) response over 4 replicate sets of exposure. From the figure, it can be concluded that the sensor shows good response reproducibility and very rapid response and recovery times of the sensor to the vapors (less than 1 min for TCE, MeOH, and Tol).

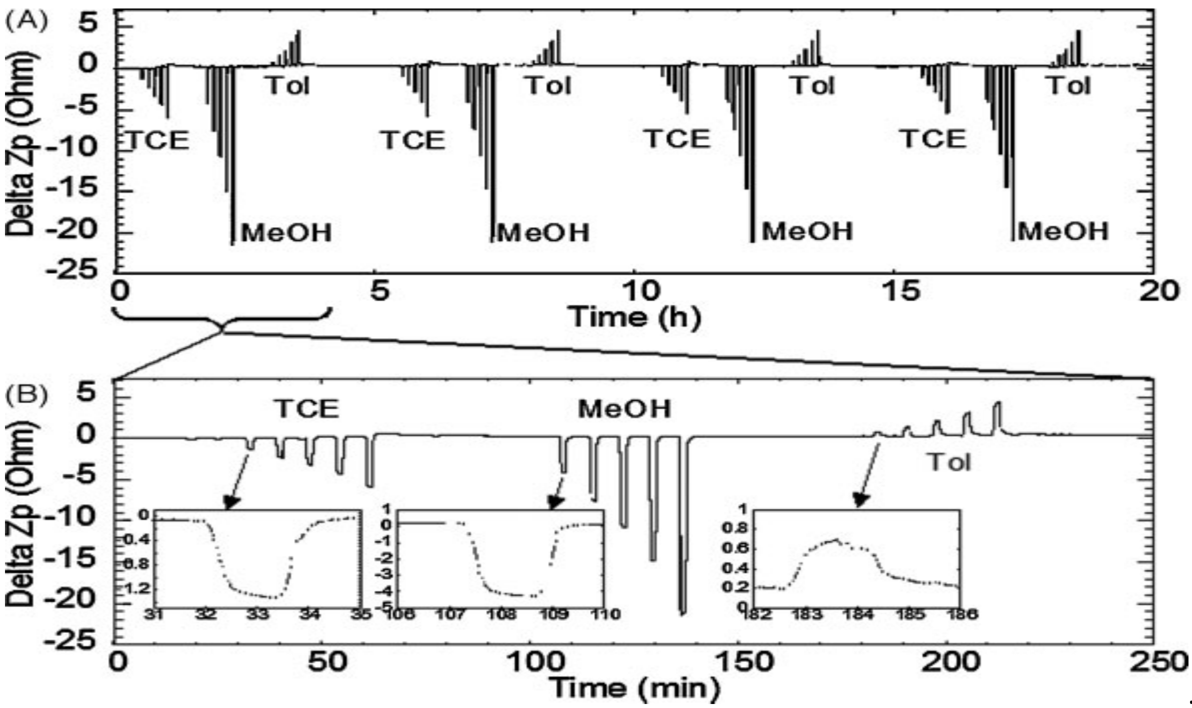

Figure 7. (A) Z_p response over 4 replicate sets of exposure to the 3 tested vapors at different concentrations. (B) Rapid response and recovery times of the sensor to the 3 tested vapors. Inset, less than 1 min of response and recovery times for 0.04 P/P_o of TCE, MeOH, and Tol.[5]

The results obtained by Potyrailo et al. as described above show that the technique of coating the RFID tag's antenna with a tailored material, various polymers in each of the above cases, enables the detection of a variety of chemicals with a high degree of sensitivity as well as promise of selectivity (determined through PCA analysis). This work is promising for a variety of applications including transportation, however a wealth of future work is needed to determine this techniques long term stability, sensitivity and selectivity within sensing environments that mimic field applications more accurately.

2.0 Integration of Chemical Sensors onto an RFID Platform

Rather than coating a passive RFID tag with a material that adsorbs the chemical of interest, causing a measurable change in the corresponding impedance spectrum, another technique which would make the use of RFID technology more accessible is to develop low power chemical sensing devices which can be incorporated into an RFID platform. In this case the sensing signals would be transmitted by the RFID tag when the tag is remotely probed for information. Therefore a key development is sensitive and selective chemical sensors, which not only have low power requirements, but also can be integrated onto a flexible material platform.

Development of a flexible tag microlab (FTM), which involved the fabrication of the RFID flexible tag and the integration of ultra-low power gas sensors on it, has been recently reported.

2.1 RFID flexible tag[7,8,9]

The RFID flexible tag involves the fabrication of the flexible substrate with all components needed for the FTM built onto it. Figure 8 shows the outline of the process design for flexible substrates fabrication. The material used in this process is the DuPont™ Pyralux® AP 8525R double-sided, copper-clad laminate, or also known as Kapton. The Kapton material is 50 µm thick and the copper layer is 18 µm thick on each side. In this process, femtosecond laser ablation was carried out to open the vias and windows in Kapton. Photolithography and wet etching are done to form the copper interconnections of the two metal levels. And, lastly, the vias are filled to make electrical contacts required for this device structure.

Figure 8 shows the prototype of the FTM with its main functional blocks labeled. The implemented system here is a semi-active tag with a passive read-out, and a battery powered sensing devide. The reading distance is about 15 cm.

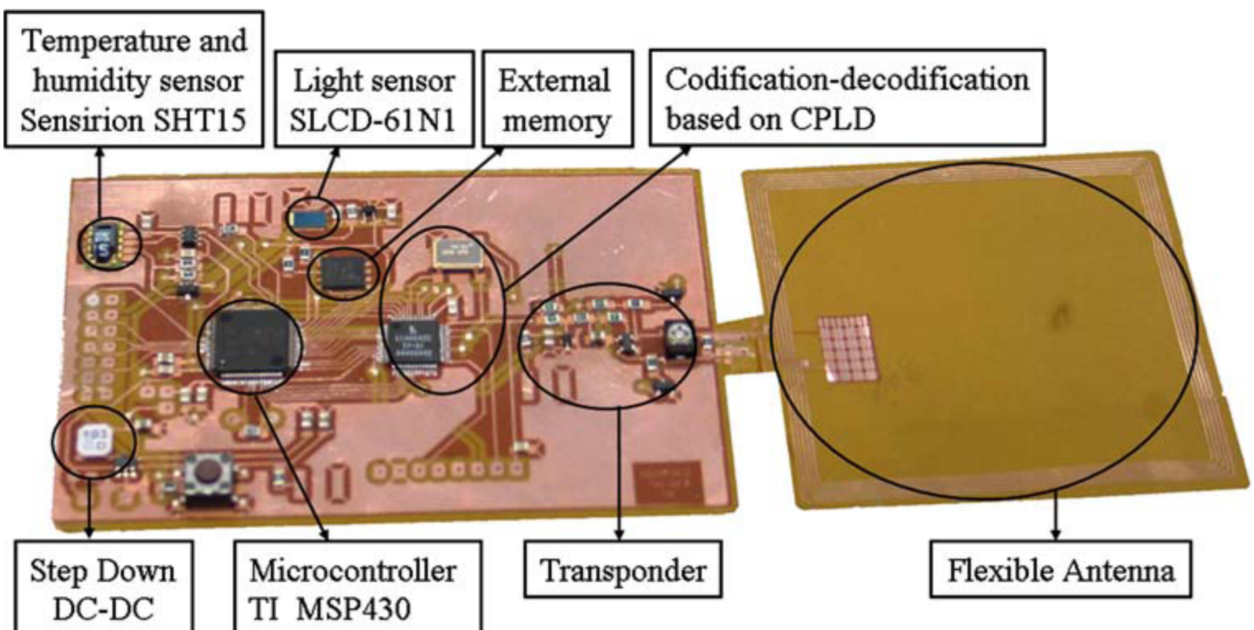

Figure 8. Prototype of the FTM with its main functional blocks labeled.[8]

2.2 Integration of ultra-low power gas sensors

Integration of metal oxide (MOX) based sensors on the flexible tag requires specific assembling techniques and protection of the chips from the environment due to mechanical reliability and power consumption problems. MOX based chemical sensors have been used for decades both in a thick and thin film format, and more recently MOX nanowires have been extensively used for development of novel low power chemical sensors.[10,11,12] Furthermore, the use of MOX thin films doped with gold nanoparticles has been shown to be a promising optical based sensing method.[13,14] The design and fabrication of an ultra-low power hot plate (ULPHP) satisfied the ultra-low power consumption issue, reduced die dimensions for tag flexibility, and is compatible with the encapsulation on the flexible substrates.[7,8,9,15] The integration of a low power hot plate into an integrated RFID sensor opens up the possibility of using a variety of MOX based chemical sensing platforms, as many of these require the MOX sensing element to be operated at temperatures between 200 and 400^{o}C. Critical to this design then, is not only the low power requirement but also the design of low thermal conducting material junctions between the hot plate and the integrated sensing platform.

Two encapsulation methods have been reported, including ACA flip-chip bonding and chip on flex wire bonding. The procedures for the integration of ULPHP using the ACA flip-chip bonding method[7,8] involves window opening by femtosecond laser ablation, patterning of the electrical contacts, ACA flip-chip for assembly and polymer casting and curing for encapsulation (as shown in Figure 9). For chip on flex wire bonding[7], the MOX sensor is directly mounted on and electrically connected to the flexible substrate (Figure 10). Reliability of the connection between the MOX sensor and flexible substrate can be increased by using stiffener as a rigid support. Cap has been used to protect the membrane of the sensor during the integration of the ULPHP.

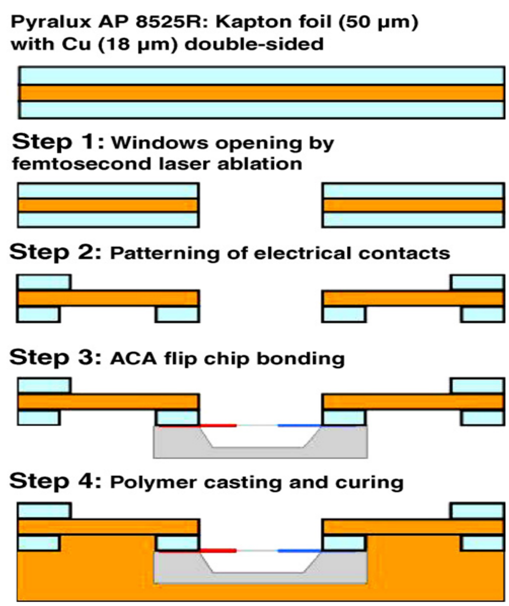

Figure 9. Process design for the MOX integration using the ACA flip-chip bonding technique.[7,8]

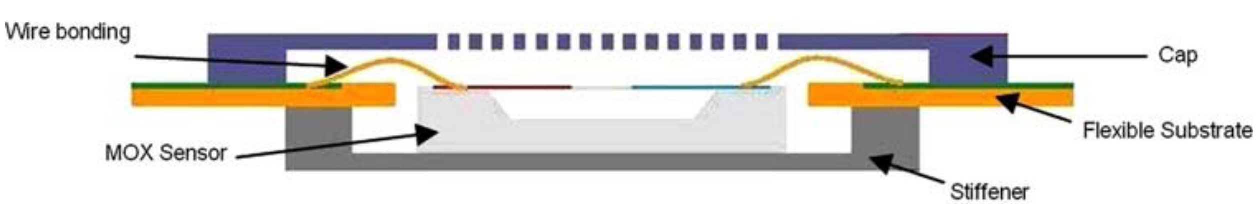

Figure 10. Schematization of the chip on flex structure.[8]

Comparisons between these two encapsulation methods have been done.[7,8] The ACA flip-chip bonding process is a simple, cheap, and mechanically and electrically reliable process. On the other hand, although the chip on flex wire bonding approach produces a very reliable mechanical structure as well, it is a more complex process as compared to the ACA flip-chip bonding process, which does not required any caps or stiffeners. However, the chip on flex bonding approach has an advantage over the ACA flip-chip approach. Its bonding wires have better conductivity in terms of low series resistance and maximum allowed current as compared to the specifications of the ACA materials. The chip on flex bonding would be useful in applications that required high currents. It is also useful to produce highly reliable tags that are needed for harsh environments. The developments noted above are critical towards the integration and use of RFID based sensing technologies across a variety of application areas. While the work of Potyrailo et al. is important, the use of multi-element sensing arrays which incorporate more than one type of transduction method allows for a higher degree of both sensitivity and selectivity. The flexible tag microlab would enable the incorporation of MOX sensing methods, which if incorporated within an array using polymer coated RFID tags would likely enable a wider range of target chemicals to be detected in a simultaneous fashion.

3.0 Incorporation of Optical Chemical Sensor (Optrode) onto RFID Platform[16]

Optoelectronics is an active research field that is continually reducing the size and power requirements of optical sources, spectrometers and detectors and in doing so removes these constraints for integration into a range of sensing related systems. In particular, Steinberg et al. have developed an optical chemical sensor (optrode) to be incorporated onto a passive, battery-free RFID platform. A wireless tag, or vicinity integrated circuit card (VICC) connected to a reader which has a chemical sensor, optoelectronic and chemical interfaces, antenna, and RFID processor built onto it. The optical chemical sensing function of the optrode is demonstrated through the measuring of pH on the optrode's chemical interface. The pH measurement is done by using a pH sensitive thin sol-gel film that is comprised of a pH sensitive indicator dye, bromocresol green (BCG). Figure 11 shows the absorption spectrum of the immobilized BCG thin film measured with a UV-Vis spectrophotometer.

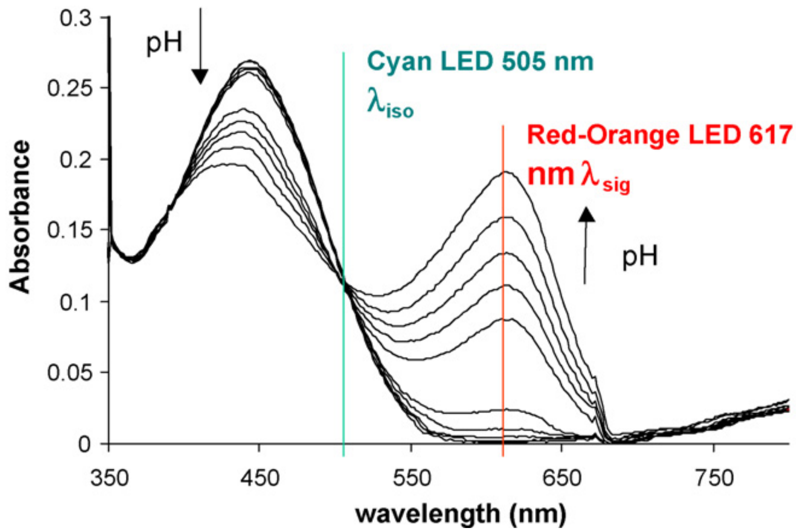

Figure 11. Absorption spectrum of the immobilized BCG thin film after exposure to different pH buffer solutions, measured with a UV-Vis spectrophotometer.[14]

Upon exposure to different pH values of solution of phosphate buffers, the absorbance of the model BCG thin film is measured with a spectrophotometer at a wavelength of 619 nm. These pH responses are as shown in Figure 12. The film shows colorimetric response to pH between 5.0 – 8.5 pH.

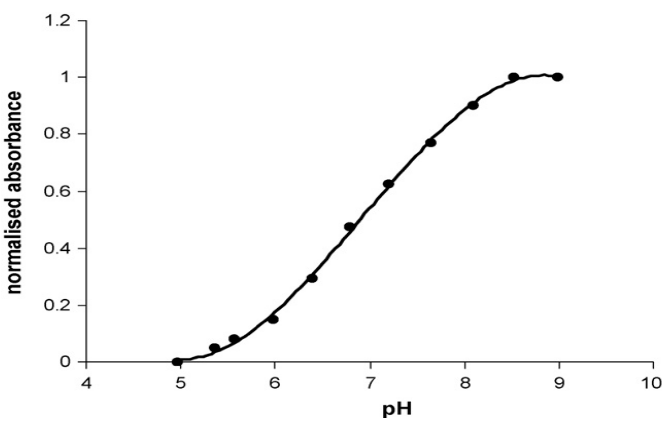

Figure 12. Normalized absorbance of the immobilized BCG thin film measured at 619 nm using UV-Vis spectrophotometer.[14]

The optoelectronic interface of the VICC is made of light sources that include a silicon photodiode and two LEDs to measure the pH of the thin film at two different wavelengths. It is the first RFID chemical sensor that uses dual wavelength optical absorption as the transduction principle. Thus, VICC is used to measured the transmittance of the thin film at 617 nm (red-orange) referenced to 505 nm (cyan). Absorbance of the film can be calculated from the normalized transmittance. Figure 13 shows the normalized transmittance and calculated absorbance curves. The pH sensitive range for this measurement is between 5.2 – 8.3 pH, slightly narrower as compared to the range determined from the spectrophotometer. This might be due to the lower dynamic range of the VICC's optoelectronic interface. Other than this, the results show good correlation between the measurements obtained from the spectrophotometer and VICC. The recent work of Carpenter et al. has shown the promise of using the photoluminescence properties of quantum dots as a sensing signal for the detection of hydrocarbons.[17] As the development of low power optoelectronics field continues to progress it is expected that RFID integrated photoluminescence based sensing techniques will also become a viable device. The work by Steinberg et al. proves the possibility of the integration of an optical chemical sensor onto a passive RFID tag, providing for future applications such as smart packaging, personal diagnostics (wearable sensor badges for personal chemical and biological exposure and contamination monitoring), and other industrial or medical related applications.

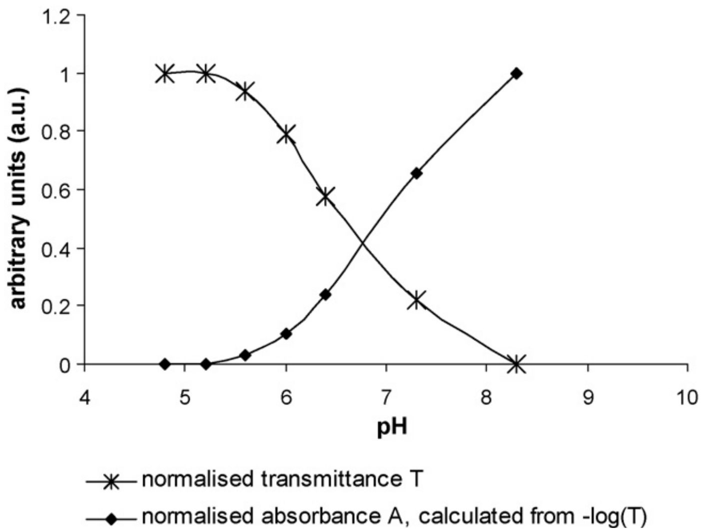

Figure 13. The normalized transmittance and calculated absorbance curves of the immobilized BCD thin film measured using VICC.[14]

4.0 Conclusions

There has been a wealth of recent work related to RFID based chemical sensing technologies. Readily available passive RFID tags which have minimal cost have been proven to be a sensitive and selective chemical sensor when the antenna is coated with a polymer based coating. It is important to note that both the digital and the analog signals from these devices are required to be read in order to identify the tag ID as well as to interpret the impedance spectrum for identification of the target chemicals. While the individual RFID tags are cheap, the associated electronics and software required to read the chemical sensing signal will have a cost on the order of 1000s of dollars. By tailoring the coating on the RFID tag it is conceivable to selectively detect a range of target chemicals. While polymers have been used and demonstrated to date on RFID tags, metal oxide coatings should also be investigated for their use in these types of sensors. While metal oxides typically require a micro heater, recent work has shown a variety of metal oxides, ceria, titania and ZnO, which are both catalytically active at ambient to modestly elevated temperatures as well as being a productive coating for use in chemical sensors. The sensing mechanism for a metal oxide coating on a RFID tag would be the same as in a polymer, as the target chemicals adsorb and react on the metal oxide coating the dielectric function will change, thus causing a measurable change in the impedance spectrum. Rather than coating an RFID tag to produce a viable chemical sensor, new developments in low power chemical sensing platforms have also been recently integrated onto an RFID system. The sensing data produced from either metal oxide based chemical sensors or an optical based chemical sensing platform, is stored and transmitted by the RFID device when remotely read. These three different types of chemical sensing structures with an underlying RFID integrated device structure will broaden the type of sensing applications that can be accessed, as well as enable the development of broad sensing networks across complicated environmental grids. While RFID based sensing technologies show great promise, in order for it to benefit a variety of transportation related applications there are a number of studies still to be performed. From a sensing standpoint there is much work to be done to demonstrate the detection limits for target gases of interest to the transportation industry. These tests need to be done as a function of the wide range of environmental factors these sensors would experience with respect to temperature, humidity and cross contaminants. While this report has focused mainly on chemical sensors, there are clearly a range of physical sensors, including temperature, stress, weight, traffic counts ect…, that could be integrated into a RFID platform and detailed tests need to be performed to prove these are viable as well. Lastly, while the individual RFID tags are cheap, the readers have a non-negligible financial commitment. Depending on the application, many readers will be required to complete the sensing network. A detailed cost benefit analysis, that is beyond the scope of this report, will need to be completed to determine if a sensing network within a subway or a rail system, toll booths, or any number of other transportation related application, is worth the financial commitment to an RFID based sensing system.

References:

[1] R. A. Potyrailo, H. Mouquin, W. G. Morris, "Position-independent Chemical Quantitation with Passive 13.56 MHz Radio Frequency Identification (RFID) Sensors', Talanta, **75**, 624 (2008).

[2] R. A. Potyrailo, W. G. Morris, "Multianalyte Chemical Identification and Quantitation Using a Single Radio Frequency Identification Sensor", Anal. Chem., **79,** 45 (2007).

[3] Potyrailo, R.A., and Morris, W.G. *Multianaltye chemical identification and quantitation using a single radio frequency identification sensor*. Anal. Chem. **2007**, 79, 45-51.

[4] Potyrailo, R.A., Mouquin, H., and Morris, W.G. *Position-independent chemical quantitation with passive 13.56-MHz radio frequency identification (RFID) sensors*. Talanta. **2008**, 75, 624-628.

[5] Potyrailo, R.A., Morris, W.G., Sivavec, T., Tomlinson, H.W., Klensmeden, S., and Lindh, K. *RFID sensors based on ubiquitous passive 13.56-MHz RFID tags and complex impedance detection*. Wirel. Commun. Mob. Comp. **2009**, 9, 1318-1330.

[6] Potyrailo,R.A., Surman, C., and Morris W.G. *Combinatorial screening of polymeric sensing materials using RFID sensors: combined effects of plasticizers and temperature*. J. Comb. Chem. **2009,** 11, 598-603.

[7] Abad, E., Zampolli, S., and etc. *Flexible tag microlab development: gas sensors integration in RFID flexible tags for food logistics*. Sensors and Actuators B. **2007**, 127, 2-7

[8] E. Abad, B. Mazzolai , A. Juarros , D. Go´mez, A. Mondini, I. Sayhan, A. Krenkow, Th. Becker. *Investigation of fabrication and encapsulation processes for a flexible tag microlab*. Microsyst Technol. 2008, 14, 527–534.

[9] Zampolli, S., Elmi, I., and etc. *Ultra-low-power components for an RFID Tag with physical and chemical sensors*. Microsyst Technol. 2008, 14, 581–588.

[10] Strelcov, Evgheni; Dmitriev, Serghei; Button, Bradley; Cothren, Joshua; Sysoev, Victor; Kolmakov, Andrei, "Evidence of the self-heating effect on surface reactivity and gas sensing of metal oxide nanowire chemiresistors", Nanotechnology **19**, 355502/1-355502/5 (2008).

[11] Hernandez-Ramirez, Francisco; Prades, Joan Daniel; Barth, Sven; Romano-Rodriguez, Albert; Mathur, Sanjay; Tarancon, Albert; Casais, Olga; Jimenez-Diaz, Roman; Rodriguez, Jordi; Pellicer, Eva;, "Fabrication of nanodevices based on individual SnO2 nanowires and their electrical characterization", Metal Oxide Nanostructures and Their Applications **3**, 3-30 (2010)

[12] R. Mukundan, E. L. Brosha, F. H. Garzon, "Mixed potential sensors: From understanding to applications", ECS Transactions, **1**, 95 (2006)

[13] P. H. Rogers, M. A. Carpenter*Particle Size Dependence of Nanocomposites for Plasmonic-Based All Optical Sensing Applications*, Journal of Physical Chemistry C, **114**, 11033 (2010)

[14] P. H. Rogers and M. A. Carpenter*Characterization of Surface Plasmon Peak Shifts and Dampening in Au-YSZ Nanocomposites,* Proceedings of the SPIE (2009 Fall Meeting)

[15] F. Rastrello,1 P. Placidi, and etc. *Thermal Transient Measurements of an Ultra-Low-PowerMOX Sensor*. Journal of Sensors. 2010.

[16] Steinberg, I.M., and Steinberg, M.D. *Radio frequency tag with optoelectronic interface for distributed wireless chemical and biological sensor applications*. Sensors and Actuators B: Chemical. 2009, 138, 120-125.

[17] Z. Zhao, T. M. Dansereau, M. A. Petrukhina, M. A. Carpenter *Nanopore Array Dispersed Semiconductor Quantum Dots as Nanosensors for Gas Detection*, Applied Physics Letters, **97**, 113105 (2010)