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A Passive Radio-Frequency Identification (RFID) Gas Sensor With Self-Correction Against Fluctuations of Ambient Temperature

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Abstract

Uncontrolled fluctuations of ambient temperature in the field typically greatly reduce accuracy of gas sensors. In this study, we developed an approach for the self-correction against fluctuations of ambient temperature of individual gas and vapor sensors. The main innovation of our work is in the temperature correction which is accomplished without the need for a separate uncoated reference sensor or a separate temperature sensor. Our sensors are resonant inductor-capacitor-resistor (LCR) transducers coated with sensing materials and operated as multivariable passive (battery-free) radio-frequency identification (RFID) sensors. Using our developed approach, we performed quantitation of an exemplary vapor over the temperature range from 25 to 40 °C. This technical solution will be attractive in numerous applications where temperature stabilization of a gas sensor or addition of auxiliary temperature or uncoated reference sensors is prohibitive.

Keywords

passive RFID sensor; gas sensing; temperature correction; multivariate data analysis

Introduction

Uncontrolled fluctuations of ambient temperature greatly reduce accuracy of gas sensors [1-3] in their intended field applications. Thus, present research efforts are focused on the development of techniques for temperature compensation of gas sensor responses [4, 5]. One approach is to add separate a temperature sensor to a gas sensor system and to use the response of the temperature sensor to correct for the temperature-induced drift of the gas sensor response. Representative examples of this approach include temperature corrections of individual chemoresistor [6] and chemicapacitor [7] gas sensors as well as chemoresistor [8] and chemicapacitor [9] gas sensor arrays. Another approach is to add a separate uncoated sensor as a temperature reference and to use its temperature-affected response to correct for the temperature-affected response of a sensor coated with a gas-sensing film. Representative examples of this approach include microcantilevers [10] and acoustic wave resonators [11].

While these techniques can be applied for both tethered and wireless sensors [12], for wireless sensors, they are becoming progressively difficult due to the limitations of available

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on-board power and difficulties of adding separate temperature sensors for compensation and heaters for temperature control. As a result, temperature-induced drift is one of the most serious problems in wireless sensors [13]. Understanding of temperature effects followed by their significant reduction is critical for building robust temperature-corrected transfer functions for sensor operation in the field to preserve sensor response sensitivity, selectivity, and stability.

We recently developed a strategy of using resonant inductor-capacitor-resistor (LCR) transducers coated with different sensing materials as multivariable sensors to improve selectivity of gas-phase detection [14, 15]. These sensors can be utilized as passive (battery-free) radio-frequency identification (RFID) sensors fabricated using different methods, including a conventional roll-to-roll process [16]. Although battery-powered wireless sensors communicate over greater distances than passive sensors, their relatively large (battery-limited) size and the need for periodic battery replacement [17, 18] are serious limitations in numerous applications including food and medical packaging [19, 20], single-use biopharmaceutical manufacturing [21], and wearable electronics [17, 22]. For these and other applications, passive sensors are attractive as long-lasting, cost efficient, easy-to-manufacture, and inconspicuous devices [15].

In our approach of passive RFID-based sensing, we convert ubiquitous 13.56 MHz RFID tags into inductively coupled sensors, acquire the resonance impedance spectrum of the RFID antenna, obtain digital sensor calibration parameters stored in an integrated circuit (IC) memory chip, perform multivariate analysis of measured resonance impedance spectrum, and extract the relation between the sensor response and the gases of interest [14, 23, 24]. We demonstrated that such individual sensors have self-correction ability against uncontrolled fluctuations of humidity [24-26], quantify an analyte in the presence of several interferences [15], and achieve part-per-billion and part-per-trillion [20, 26] limits of detection. These abilities is an attractive departure from the concept of sensor arrays where otherwise individual sensors suffer from humidity and other interferences [27-29].

Wireless or non-contact implementations of these sensors are applicable for numerous applications, for example for the rapid screening of multiple sensors embedded in food packaging [20], for the elimination of the need for de-contamination in homeland security applications [26], and for monitoring of pollutants of industrial and environmental importance [23]. However, in these and many other applications, there is a strong need to have a methodology for the self-correction against fluctuations of ambient temperature in a single sensor.

In this study, we developed an approach for the self-correction against fluctuations of ambient temperature of individual passive RFID gas sensors inductively coupled with a sensor reader without the need for a separate uncoated reference sensor or a separate temperature sensor. Using this approach, we performed quantitation of water vapor (selected as a relevant model vapor) from 0 to ~ 8500 ppm with the standard error of 212 ppm of water vapor over the temperature range from 25 to 40 °C.

Experimental

RFID gas sensors were constructed from available 13.56 MHz RFID tags as detailed earlier [14, 23, 24, 30]. Polyetherurethane (PEUT) was selected as a sensing material. The PEUT material was drop cast onto the sensing antenna from a PEUT solution in dichloromethane forming a ~ 50- μ m thick sensing film. Water vapor was selected as a model vapor for the demonstration of the principle of self-correction of individual multivariable vapor sensors against temperature fluctuations. Sensor was exposed to different water vapor concentrations at different temperatures such as 25, 30, 35, and 40 °C by placing the RFID sensor into an

environmental chamber with ~ 0.1 °C temperature control. Different concentrations of water vapor were generated and monitored outside the environmental chamber using a computer-controlled vapor-generation system using dry nitrogen gas as a blank gas and keeping the total flow rate constant at 0.45 L/min. Tested concentrations of water vapor were 0, 2807, 4210, 5614, 7017, and 8421 ppm (corresponding to 0, 9, 13, 18, 22, and 27 % of relative humidity (RH) at 25 °C) as determined at the smallest tested temperature using a reference humidity sensor (Model HS1101LF, Humirel, Inc.). Measurements of low (part-per-million) and high (% RH) concentrations of water vapor are important for different applications as described earlier [31-35]. Conversion of water vapor concentration from ppm to %RH at different temperatures can be easily performed as described elsewhere [36]. Exposures to five vapor concentrations were done in three replicates at each temperature. Vapor exposure steps were 4.5 min long with 9 min long exposures to the blank nitrogen gas. The duration between replicates was 16.5 min long.

Measurements of resonance impedance of the RFID sensors were performed with a network analyzer (Model E5062A, Agilent Technologies, Inc., Santa Clara, CA). Collected impedance data was analyzed using KaleidaGraph (Synergy Software, Reading, PA) and PLS_Toolbox (Eigenvector Research, Inc., Manson, WA) operated with Matlab (The Mathworks Inc., Natick, MA). Digital ID readings from RFID sensors were performed using handheld and computer-controlled SkyeTek readers (Westminster, CO) and a computer-controlled RFID Reader/Writer evaluation module (Model TRF7960 Evaluation Module, Texas Instruments).

Results and Discussion

A. Principle of self-correction against temperature fluctuations

The principle of operation of our multivariable RFID sensors and the self-correction against fluctuations of ambient temperature is illustrated in Fig. 1. We employ 13.56 MHz RFID tag-based sensors available from different manufacturers or with antennas fabricated in-house [24], deposit a sensing material onto a resonant antenna of the sensor [15], acquire the resonance impedance spectrum $\tilde{Z}(f)$ of the RFID antenna, and obtain digital sensor calibration parameters stored in an IC memory chip (Fig. 1A). Measurement of $\tilde{Z}(f)$ of the RFID sensor antenna and reading/writing of digital data from the IC chip are performed via mutual inductance coupling between the RFID sensor antenna and the pickup coil of a reader.

A simplified equivalent circuit of the multivariable RFID sensor is illustrated in Fig. 1B with inductance L_A , capacitance C_A , and resistance R_A of the sensing antenna coil and capacitance C_C and resistance R_C of the IC chip. A sensing film that affects C_A and R_A of the equivalent circuit is further applied onto the sensing antenna. The complex permittivity of the sensing film is described as $\epsilon'_r - j\epsilon''_r$ where the real part ϵ'_r is also known as dielectric constant and the imaginary part ϵ''_r is directly proportional to conductivity σ . Variations in ambient temperature and gas concentrations produce uncorrelated effects on L_A , C_A , R_A , C_C , and R_C of the equivalent circuit. These uncorrelated effects originate from the different materials (dielectric sensor substrate, metal sensor coil, dielectric sensing film, and semiconductor IC memory chip) and their different temperature- and gas-induced effects on the equivalent circuit of the sensor. These uncorrelated effects are quantitatively separated by the multivariable response of the sensor making possible temperature correction with the same multivariable gas sensor without the need for a separate uncoated reference sensor or a separate temperature sensor [37].

To accurately measure gases in the presence of the uncontrolled temperature fluctuations, the real $Z_{re}(f)$ and imaginary $Z_{im}(f)$ parts of the impedance spectra $\tilde{Z}(f)$ are measured from

the resonant sensor antenna coated with a sensing film and several spectral parameters are calculated from the measured $Z_{re}(f)$ and $Z_{im}(f)$ as shown in Fig. 1C. These parameters include the frequency position F_p and magnitude Z_p of $Z_{re}(f)$, the resonant F_1 and antiresonant F_2 frequencies of $Z_{im}(f)$, and the impedance magnitudes Z_1 and Z_2 at F_1 and F_2 frequencies, respectively. Additional parameters can also be calculated (zero-reactance frequency, quality factor, etc). From the measured parameters, resistance, capacitance, and other parameters of the polymer-coated resonant antenna can be also determined.

Multivariate analysis reduces the dimensionality of the complex impedance response (from measured real $Z_{re}(f)$ and imaginary $Z_{im}(f)$ parts of the complex impedance spectra or calculated parameters F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 to a single data point in multidimensional space for selective quantitation of different gases and for the self-correction against fluctuations of ambient temperature.

B. Univariate analysis of RFID sensor response

For demonstration of our method for the self-correction against fluctuations of ambient temperature, we employed PEUT as a “classic” sensing material [38-43], previously used for detection of different organic vapors and water vapor. Chemical structure of PEUT is presented in Fig. 2. This material is a dielectric polymer with a glass transition temperature below room temperature [41, 44].

Examples of univariate responses of the RFID sensor such as F_p and Z_p responses are illustrated in Fig. 3 A, B. Measurements were performed at four temperatures (25, 30, 35, and 40 °C). At each temperature, the sensor was exposed to three replicate runs of five water vapor concentrations (2807, 4210, 5614, 7017, and 8421 ppm) spaced by the exposures to the dry carrier gas (nitrogen). These replicate measurements provided information about the reproducibility of sensor performance when different levels of the humidified gas were brought to the sensor at a flow rate of 0.45 L/min. At the experimental conditions of these studies, temperature equilibration was several tens of minutes (see Fig. 3 A, B). Thus, for modeling of sensor performance at different temperatures, we used sensor responses only from the second and third replicate runs.

The temperature changes from 25 to 30, 40, and 40 °C produced temperature-induced baseline frequency and impedance offsets. For example, the F_p frequency offset was ~100 kHz when the sensor was at 40 °C as compared to F_p response at 25 °C (see Fig. 3 A). Similarly, the Z_p impedance offset was ~ 5 Ohm upon temperature change from 25 to 40 °C (see Fig. 3 B). These baseline offsets were the result of the temperature effects on the sensor electronic circuitry and sensing film. Temperature effects on the sensor electronic circuitry were pronounced via the changes in the dielectric constant of the sensor substrate, resistance of the sensing coil, and capacitance and resistance of the IC memory chip. Temperature effects on the sensing material were pronounced via the changes in the dielectric constant of the sensing film.

The sensitivity of this RFID sensor to water vapor was expected to be temperature-dependent as was demonstrated earlier with numerous sensing materials [1, 6, 45-48]. The effects of temperature on the water-vapor sensitivity of the sensor are illustrated in Fig. 3 A, B. Upon the temperature increase, the changes in F_p and Z_p signals between the sensor response to dry and humidified carrier gas were proportionally reduced. The main factor in the temperature-affected vapor sensitivity of the PEUT dielectric sensing material used in these studies was the temperature dependence of the vapor-partition coefficient of PEUT.

The inset of Fig. 3 B illustrates two additional sensor aspects such as (1) a reversible sensor response with the response/recovery times controlled by gas flow rate, cell dead volume, and

sensing film thickness and (2) the low noise level of the sensor. In our earlier work, the measured short term sensor noise (as one standard deviation, 1σ) was 60 Hz and 0.025 Ohm for F_p and Z_p , respectively [30]. In the present work, the noise level was reduced by at least two-fold.

Fig. 4 presents a summary of the temperature-induced baseline frequency and impedance offsets for all univariate parameters (F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2) employed in this study. Similarly, Fig. 5 summarizes the vapor-induced signal changes in F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 responses at different temperatures where the sensor was exposed to the highest water vapor concentration. This data is from the second and third replicate runs of the sensor; each data point is the mean of baseline values and the error bars represent one standard deviation 1σ . The sensor precision was $< 5\%$ RSD (relative standard deviation): most of the error bars of the F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 responses were smaller than the size of the data points. This diversity of individual responses F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 to temperature and water-vapor concentrations provided the foundation for the multivariate analysis as described in the next section.

C. Multivariate analysis of RFID sensor response

By applying multivariate analysis of sensor response, discrimination between temperature and vapor concentration effects was obtained. We applied principal components analysis (PCA) to produce a multivariate signature from the single sensor. PCA is a multivariate data analysis tool that projects the data onto a subspace of lower dimensionality with removed collinearity and displays variance in the data as weighted sums of the original variables (called principal components, PCs) [49]. The responses F_p , Z_p , F_1 , F_2 , Z_1 , Z_2 for different water vapor concentrations and temperatures were processed using PCA. Fig. 6 illustrates a PCA scores plot of the sensor response to variable concentrations of water vapor at four tested temperatures. Similar with the analysis of individual responses F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 , the multivariate sensor response was strongest at 25 °C as indicated by the distance between the data points associated with the sensor responses to different water vapor concentrations at 25 °C. The first two PCs of the built PCA model included more than 99% of the total variance from the data set.

Critical to the sensor ability for the self-correction against temperature fluctuations is the separation between the data points in the PCA scores plot when the data originated from the sensor response at different temperatures. This separation between the respective data points is due to the independent effects of temperature on the different components of the sensor equivalent circuit and the sensing film (see Fig. 1 B).

We further developed a model for prediction of water vapor concentrations at various temperatures using only a single sensor (see Fig. 7). Results of developed quadratic model are illustrated in Fig. 7 A. The predicted values of water vapor concentrations at various temperatures were calculated and compared with the actual measured values. As illustrated in a correlation plot in Fig. 7 B, the data points were close to a line corresponding to a slope of unity. The plot of residual errors of prediction (see Fig. 7 C) demonstrated a desired almost random data spread. The standard error of the quadratic model was 212 ppm of water vapor (i.e., 0.7 % relative humidity).

Conclusions

While implementation of ubiquitous passive 13.56 MHz RFID tags as inductively coupled sensors opens numerous opportunities, it is important to provide technical solutions for these sensors to operate in the field conditions of uncontrolled ambient temperature. This study demonstrated such an approach where multivariate analysis was applied for the self-

correction for temperature effects in the response to individual LCR transducers coated with sensing materials and operated as multivariable passive RFID sensors without the need for a separate uncoated reference sensor or a separate temperature sensor. Our current work is focused on design of a portable and cost-effective network analyzer system as a sensor reader [50, 51]. Results of those studies are forthcoming.

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References

1. Zellers ET, Han M. Effects of Temperature and Humidity on the Performance of Polymer- Coated Surface Acoustic Wave Vapor Sensor Arrays. *Anal Chem.* 1996; 68:2409–2418. [PubMed: 8686930]
2. Tchoupo GN, Guiseppi-Elie A. On Pattern Recognition Dependency of Desorption Heat, Activation Energy, and Temperature of Polymer-Based Voc Sensors for the Electronic Nose. *Sens Actuators B.* 2005; 110:81–88.
3. Peng N, Zhang Q, Lee YC, Huang H, Tan OK, Tian J, Chan L. Humidity and Temperature Effects on Carbon Nanotube Field-Effect Transistor-Based Gas Sensors. *Sensor Lett.* 2008; 6:796–799.
4. Joo S, Brown RB. Chemical Sensors with Integrated Electronics. *Chem Rev.* 2008; 108:638–651. [PubMed: 18184017]
5. Hierlemann A, Gutierrez-Osuna R. Higher-Order Chemical Sensing. *Chem Rev.* 2008; 108:563–613. [PubMed: 18198903]
6. Hossein-Babaei F, Ghafarinia V. Compensation for the Drift-Like Terms Caused by Environmental Fluctuations in the Responses of Chemoresistive Gas Sensors. *Sens Actuators B.* 2010; 143:641–648.
7. Avramov-Zamurovic S, Lee RD. A High-Stability Capacitance Sensor System and Its Evaluation. *IEEE Trans Instrum Meas.* 2009; 58:955–961.
8. Hobson RS, Clausi A, Oh T, Guiseppi-Elie A. Temperature Correction to Chemoresistive Sensors in an E-Nose-Ann System [1]. *IEEE Sensors J.* 2003; 3:484–489.
9. Oikonomou P, Botsialas A, Goustouridis D, Valamontes E, Sanopoulou M, Raptis I. Compensation of Temperature Variations in Chemcapacitive Gas Sensing Systems. *Sensor Lett.* 2012; 10:736–741.
10. Han J, Wang X, Yan T, Li Y, Song M. A Novel Method of Temperature Compensation for Piezoresistive Microcantilever-Based Sensors. *Rev Sci Instrum.* 2012; 83:art. no. 035002.
11. Fu JL, Ayazi F. Dual-Mode Piezo-on-Silicon Resonant Temperature and Humidity Sensor for Portable Air Quality Monitoring Systems. *Proc IEEE Sensors.* 2010:2131–2135.
12. Oprea A, Courbat J, Bârsan N, Briand D, de Rooij NF, Weimar U. Temperature, Humidity and Gas Sensors Integrated on Plastic Foil for Low Power Applications. *Sens Actuators B.* 2009; 140:227–232.
13. Diamond D, Coyle S, Scarmagnani S, Hayes J. Wireless Sensor Networks and Chemo-/Biosensing. *Chem Rev.* 2008; 108:652–679. [PubMed: 18215076]
14. Potyrailo RA, Morris WG. Multianalyte Chemical Identification and Quantitation Using a Single Radio Frequency Identification Sensor. *Anal Chem.* 2007; 79:45–51. [PubMed: 17194120]
15. Potyrailo RA, Surman C, Nagraj NN, Burns A. Materials and Transducers toward Selective Wireless Gas Sensing. *Chem Rev.* 2011; 111:7315–7354. [PubMed: 21899304]
16. Potyrailo RA, Burns A, Surman C, Lee DJ, McGinniss E. Multivariable Passive RFID Vapor Sensors: Roll-to-Roll Fabrication on a Flexible Substrate. *Analyst.* 2012; 137:2777–2781. [PubMed: 22358260]
17. Pantelopoulos A, Bourbakis NG. A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis. *IEEE Trans Syst Man Cybern C.* 2010; 40:1–12.

18. Patel S, Park H, Bonato P, Chan L, Rodgers M. A Review of Wearable Sensors and Systems with Application in Rehabilitation. *Journal of NeuroEngineering and Rehabilitation*. 2012; 9:article 21.
19. Tao H, Brenckle MA, Yang M, Zhang J, Liu M, Siebert SM, Averitt RD, Mannoor MS, McAlpine MC, Rogers JA, Kaplan DL, Omenetto FG. Silk-Based Conformal, Adhesive, Edible Food Sensors. *Adv Mater*. 2012; 24:1067–1072. [PubMed: 22266768]
20. Potyrailo RA, Nagraj N, Tang Z, Mondello FJ, Surman C, Morris W. Battery-Free Radio Frequency Identification (RFID) Sensors for Food Quality and Safety. *J Agric Food Chem*. 2012; 60:8535–8543. [PubMed: 22881825]
21. Potyrailo RA, Surman C, Monk D, Morris WG, Wortley T, Vincent M, Diana R, Pizzi V, Carter J, Gach G, Klensmeden S, Ehring H. RFID Sensors as the Common Sensing Platform for Single-Use Biopharmaceutical Manufacturing. *Meas Sci Tech*. 2011; 22:art. no 082001.
22. Kim D-H, Lu N, Ma R, Kim Y-S, Kim R-H, Wang S, Wu J, Won SM, Tao H, Islam A, Yu KJ, Kim T-i, Chowdhury R, Ying M, Xu L, Li M, Chung H-J, Keum H, McCormick M, Liu P, Zhang Y-W, Omenetto FG, Huang Y, Coleman T, Rogers JA. Epidermal Electronics. *Science*. 2011; 333:838–843. [PubMed: 21836009]
23. Potyrailo RA, Morris WG, Sivavec T, Tomlinson HW, Klensmeden S, Lindh K. RFID Sensors Based on Ubiquitous Passive 13.56-Mhz RFID Tags and Complex Impedance Detection. *Wirel Commun Mob Comput*. 2009; 9:1318–1330.
24. Potyrailo RA, Surman C, Morris WG, Go S, Lee Y, Cella JA, Chichak KS. Selective Quantitation of Vapors and Their Mixtures Using Individual Passive Multivariable RFID Sensors. *IEEE International Conference on RFID, IEEE RFID*. 2010:22–28.
25. Surman, C.; Morris, WG.; Potyrailo, RA. Quantitation of Toxic Vapors in Variable Humidity Atmosphere Using Individual Passive Radio Frequency Identification (RFID) Sensors. Elsevier Science; 12th International Meeting on Chemical Sensors; Columbus, Oh. 2008. Talk SADA 12
26. Potyrailo RA, Nagraj N, Surman C, Boudries H, Lai H, Slocik JM, Kelley-Loughnane N, Naik RR. Wireless Sensors and Sensor Networks for Homeland Security Applications. *Trends Anal Chem*. 2012; 40:133–145.
27. Pang P, Guo Z, Cai Q. Humidity Effect on the Monolayer-Protected Gold Nanoparticles Coated Chemiresistor Sensor for Vocs Analysis. *Talanta*. 2005; 65:1343–1348. [PubMed: 18969951]
28. Dovgolevsky E, Konvalina G, Tisch U, Haick H. Monolayer-Capped Cubic Platinum Nanoparticles for Sensing Nonpolar Analytes in Highly Humid Atmospheres. *J Phys Chem C*. 2010; 114:14042–14049.
29. Konvalina G, Haick H. Effect of Humidity on Nanoparticle-Based Chemiresistors: A Comparison between Synthetic and Real-World Samples. *ACS Appl Mater Interfaces*. 2012; 4:317–325. [PubMed: 22121824]
30. Potyrailo RA, Surman C, Go S, Lee Y, Sivavec T, Morris WG. Development of Radio-Frequency Identification Sensors Based on Organic Electronic Sensing Materials for Selective Detection of Toxic Vapors. *J Appl Phys*. 2009; 106:124902.
31. Basu S, Chatterjee S, Saha M, Bandyopadhyay S, Mistry KK, Sengupta K. Study of Electrical Characteristics of Porous Alumina Sensors for Detection of Low Moisture in Gases. *Sens Actuators B*. 2001; 79:182–186.
32. Kapa P, Pan L, Bandhanadham A, Fang J, Varahramyan K, Davis W, Ji HF. Moisture Measurement Using Porous Aluminum Oxide Coated Microcantilevers. *Sens Actuators B*. 2008; 134:390–395.
33. Islam T, Kumar L, Khan SA. A Novel Sol-Gel Thin Film Porous Alumina Based Capacitive Sensor for Measuring Trace Moisture in the Range of 2.5–25 Ppm. *Sens Actuators B*. 2012; 173:377–384.
34. Ong KG, Grimes CA, Robbins CL, Singh RS. Design and Application of a Wireless, Passive, Resonant-Circuit Environmental Monitoring Sensor. *Sens Actuators A*. 2001; 93:33–43.
35. Wang X, Larsson O, Platt D, Nordlinder S, Engquist I, Berggren M, Crispin X. An All-Printed Wireless Humidity Sensor Label. *Sens Actuators B*. 2012; 166–167:556–561.
36. Lide, DR., editor. *CRC Handbook of Chemistry and Physics*. CRC Press; Boca Raton, FL: 1993. p. 74

37. Potyrailo, RA.; Surman, C. Temperature Independent Chemical and Biological Sensors. US Patent Application. 20120161787. 2012. available at <http://www.uspto.gov>
38. Josse F, Lukas R, Zhou R, Schneider S, Everhart D. Ac-Impedance-Based Chemical Sensors for Organic Solvent Vapors. *Sens Actuators B*. 1996; 35–36:363–369.
39. Hierlemann A, Zellers ET, Ricco AJ. Use of Linear Solvation Energy Relationships for Modeling Responses from Polymer-Coated Acoustic-Wave Vapor Sensors. *Anal Chem*. 2001; 73:3458–3466. [PubMed: 11476248]
40. Fontecha J, Fernández MJ, Sayago I, Santos JP, Gutiérrez J, Horrillo MC, Gràcia I, Cané C, Figueras E. Fine-Tuning of the Resonant Frequency Using a Hybrid Coupler and Fixed Components in Saw Oscillators for Gas Detection. *Sens Actuators B*. 2004; 103:139–144.
41. Razan F, Zimmermann C, Rebière D, Déjous C, Pistré J, Destarac M, Pavageau B. Radio Frequency Thin Film Characterization with Polymer-Coated Love-Wave Sensor. *Sens Actuators B*. 2005; 108:917–924.
42. Then D, Vidic A, Ziegler C. A Highly Sensitive Self-Oscillating Cantilever Array for the Quantitative and Qualitative Analysis of Organic Vapor Mixtures. *Sens Actuators B*. 2006; 117:1–9.
43. Jin C, Zellers ET. Limits of Recognition for Binary and Ternary Vapor Mixtures Determined with Multitransducer Arrays. *Anal Chem*. 2008; 80:7283–7293. [PubMed: 18771277]
44. Smith AL, Shirazi HM. Quartz Microbalance Microcalorimetry: A New Method for Studying Polymer-Solvent Thermodynamics. *Journal of Thermal Analysis and Calorimetry*. 2000; 59:171–186.
45. Potyrailo RA, Golubkov SP, Borsuk PS, Talanchuk PM, Novosselov EF. A Ph Indicator Based Ammonia Gas Sensor: Studies of Spectral Performance under Variable Conditions of Temperature and Humidity. *Analyst*. 1994; 119:443–448.
46. Hierlemann A, Ricco AJ, Bodenhöfer K, Dominik A, Göpel W. Conferring Selectivity to Chemical Sensors Via Polymer Side-Chain Selection: Thermodynamics of Vapor Sorption by a Set of Polysiloxanes on Thickness-Shear Mode Resonators. *Anal Chem*. 2000; 72:3696–3708. [PubMed: 10959952]
47. Potyrailo RA, Szumlas AW, Danielson TL, Johnson M, Hieftje GM. A Dual-Parameter Optical Sensor Fabricated by Gradient Axial Doping of an Optical Fibre. *Meas Sci Technol*. 2005; 16:235–241.
48. Jafari MJ, Azim-Araghi ME, Barhema S. Effect of Chemical Environments on Palladium Phthalocyanine Thin Film Sensors for Humidity Analysis. *J Mater Sci*. 2012; 47:1992–1999.
49. Beebe, KR.; Pell, RJ.; Seasholtz, MB. *Chemometrics: A Practical Guide*. Wiley; New York, NY: 1998.
50. Potyrailo, RA. Wearable Organic Electric Film RFID Sensors for Monitoring of Airborne Toxicants, Grant 1r01es016569-01a1 from National Institute of Environmental Health Sciences Irg: Isd. 2009. Project Start Date: 2009-09-15; Project End Date: 2011-07-31 (<http://www.novoseek.com/article/GRANTS/774931/>)
51. Potyrailo, RA.; Ashe, JM.; Morris, WG.; Surman, CM. Field-Portable Impedance Reader and Methods for Making the Same. US Patent Application. 20120004851. 2012. available at <http://www.uspto.gov>

Biographies

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Cheryl Surman (Bratu) is a Senior Scientist at General Electric Global Research Center in Niskayuna, New York. She received her B.S. in Chemistry and Biology from Valparaiso University in Valparaiso, Indiana, in 1997 and her Ph.D. in Bioanalytical Chemistry from Rensselaer Polytechnic Institute in 2006. She has ~15 years of experience in the development of various analytical techniques including 5 years of experience in online process control. In addition, Dr. Surman has extensive background and practical experience in chemometric techniques and combinatorial methods. Prior to joining GE, she worked at UOP, LLC, developing data-analysis techniques for process control and combinatorial screening of heterogeneous catalysts. At GE, Cheryl played a major role in the development of new sensing materials and an optical sensor array system for GE Water Technologies that has been awarded with the 2010 Prism Award for photonics innovation by SPIE and Photonics Media. Her current research is in the area of radio frequency identification (RFID) chemical, biological, and physical sensors. She has 20+ technical publications and 20+ filed patents.

Figure 1.

Principle of operation of passive multivariable RFID sensors and their self-correction against fluctuations of ambient temperature. (A) Sensor layout with a resonant antenna coated with a gas-sensing film and an IC memory chip. (B) Equivalent circuit of an RFID sensor. (C) Measured impedance spectrum, $Z_{re}(f)$ and $Z_{im}(f)$, and examples of parameters for multivariate analysis: the frequency F_p and magnitude Z_p of the maximum of the real part of impedance, the resonant F_1 and anti-resonant F_2 frequencies of the imaginary part of impedance, and magnitudes Z_1 and Z_2 at the resonant and anti-resonant frequencies.

Figure 2.
Chemical structure of PEUT employed in fabricated RFID sensors.

Figure 3.

Examples of individual univariate responses (A) ΔF_p and (B) ΔZ_p of the sensor upon exposure to five water vapor concentrations (2807, 4210, 5614, 7017, and 8421 ppm) at four temperatures (25, 30, 35, and 40 °C) and control steps of (C) water vapor concentrations and (D) temperature. At each temperature, three replicate measurements of exposures to five water vapor concentrations were performed. Inset in (B) illustrates a reversible response and a low noise level of the sensor. Actual temperature and vapor concentrations were measured using reference sensors as detailed in the Experimental Section.

Figure 4.

Temperature-induced baseline frequency and impedance offsets: (A) frequency offsets F_p , F_1 , and F_2 , (B) impedance offsets Z_p , Z_1 , and Z_2 . The data is from the second and third replicate runs of the sensor; each data point is the mean of baseline values and the error bars represent one standard deviation 1σ . Most of the error bars of the F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 responses are smaller than the size of the data points.

Figure 5.

Vapor-induced sensor signal changes at different temperatures where the sensor was exposed to the highest water vapor concentration: (A) frequency shifts F_p , F_1 , and F_2 , (B) impedance shifts Z_p , Z_1 , and Z_2 . The data is from the second and third replicate runs of the sensor; each data point is the mean of baseline values and the error bars represent one standard deviation 1σ . Most of the error bars of the F_p , Z_p , F_1 , F_2 , Z_1 , and Z_2 responses are smaller than the size of the data points.

Figure 6.
PCA scores plot of multivariate sensor response to variable concentrations of water vapor at four tested temperatures.

Figure 7. Single RFID sensor quantifies water vapor independently of temperature. (A) Developed quadratic model of multivariate sensor response. (B) Actual vs. predicted values of water vapor concentrations at four different temperatures. (C) Plot of residual errors of prediction of water vapor concentrations at four different temperatures.