

Battery-Free Multivariable Sensors For Chemical, Biological, and Physical Detection



Radislav A. Potyrailo

GE Global Research

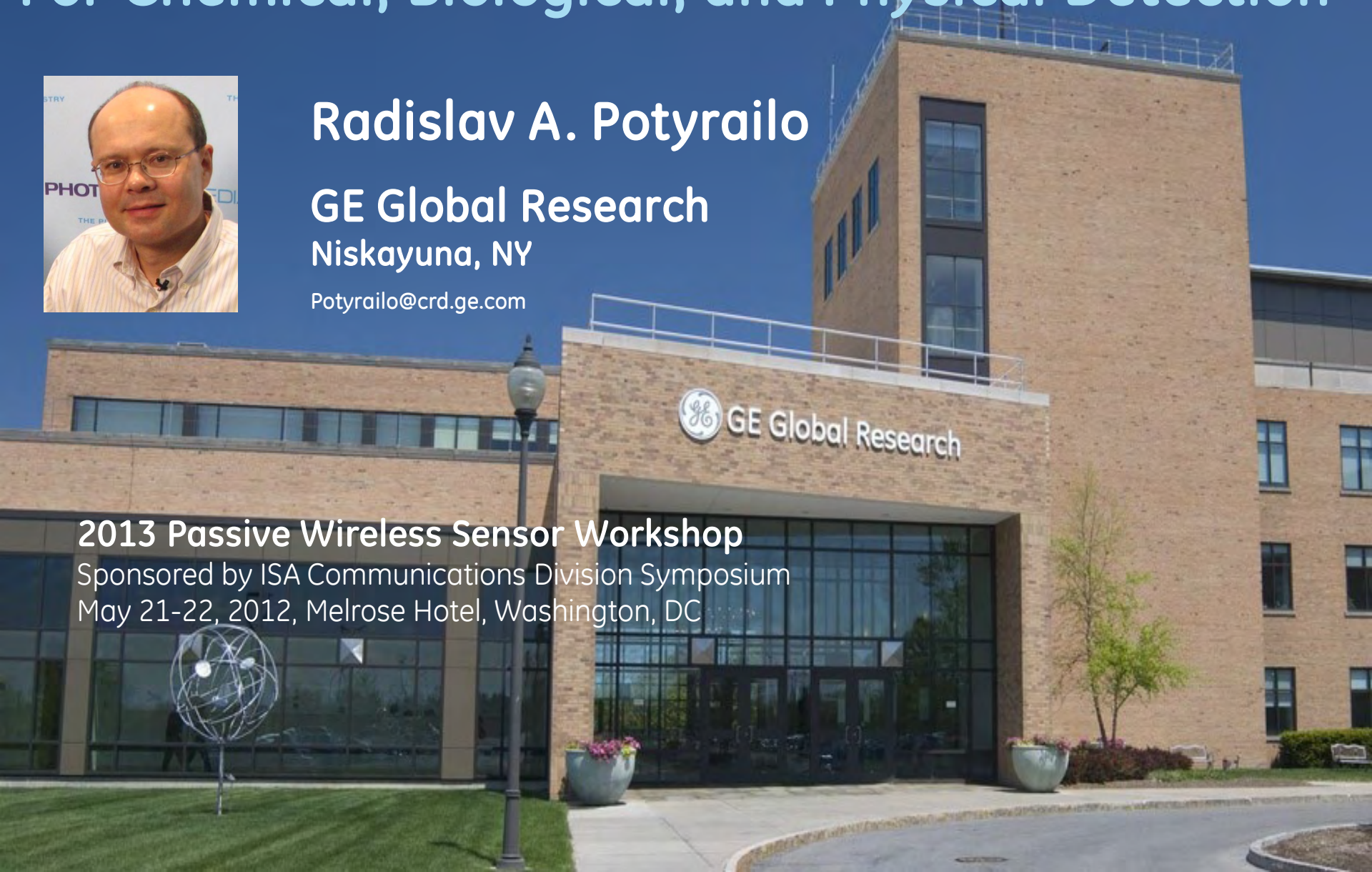
Niskayuna, NY

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2013 Passive Wireless Sensor Workshop

Sponsored by ISA Communications Division Symposium

May 21-22, 2012, Melrose Hotel, Washington, DC



General Electric Global Research

Niskayuna, NY



1,870 technologists

Technical Disciplines

Electrical	18%
Chemistry	18%
Computer Sci	17%
Mechanical	17%
Physics	9%
All Other	21%



Irving Langmuir
NOBEL PRIZE
CHEMISTRY (1932)



Ivar Giaever
NOBEL PRIZE
PHYSICS (1973)

GE Research across the world:
2,600 technologists

Technology driver #1: New performance requirements for diverse markets



Majority of modern demanding and high-value applications
require selective sensors

Technology driver #2: Potential impact

Markets

\$ Billions

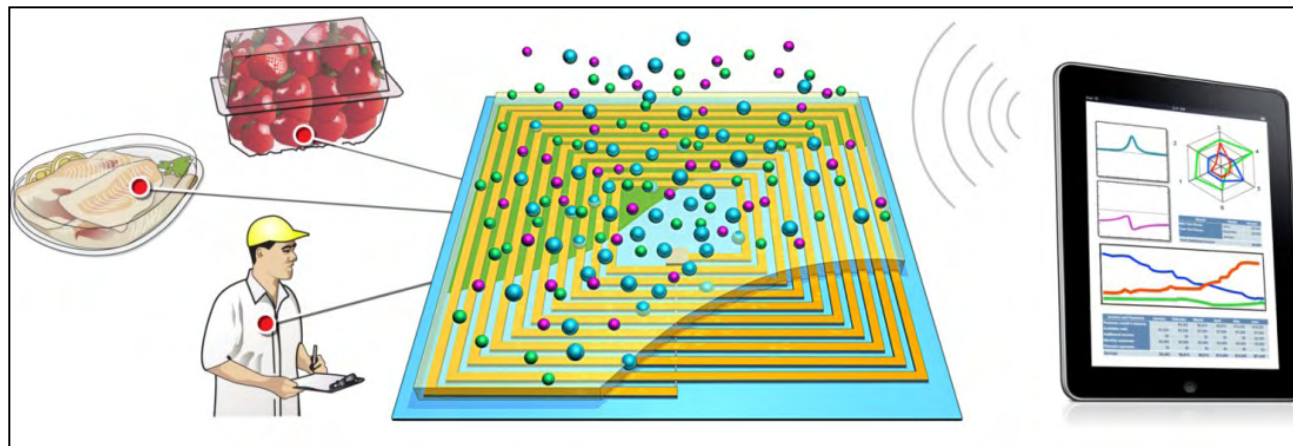
In vitro diagnostics	20
Clinical diagnostic instruments and reagents	10
Chemical sensors and biosensors	4
Pathogen sensors	0.5
Food safety testing products	0.25
Environmental monitoring	0.05

Weetall, *Biosens. Bioelectron.* **1999**

Alocilja, Radke, *Biosens. Bioelectron.* **2003**

Mongra, Kaur, *Digest J. Nanomat. Biostruct.* **2012**

Global Industry Analysts, Inc. **2013**



Potyrailo et al., *Chem. Rev.* **2011**

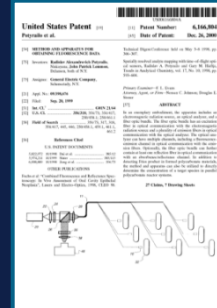
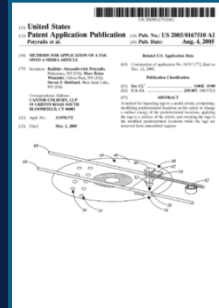
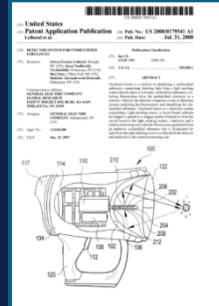
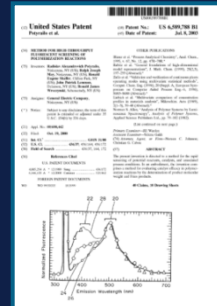
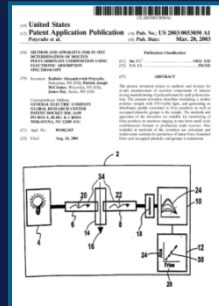
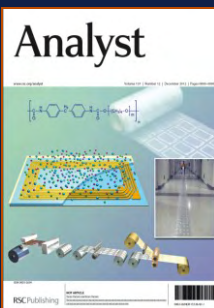
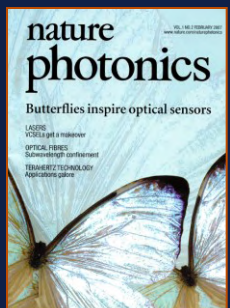
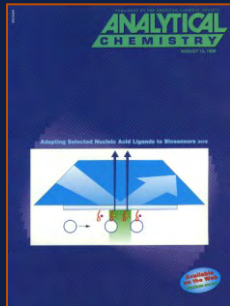


Potyrailo et al., *Biotechnol. Prog.* **2011**

Opportunities... and significant challenges
(sampling, sensor selectivity)

Technology driver #3: Imagination

Peer-reviewed results



Press coverage



scientific validation

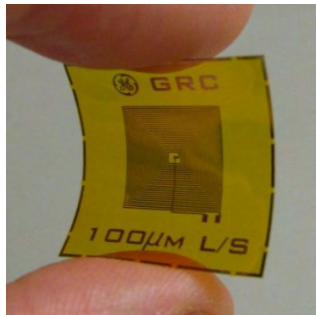
business value

new partnerships

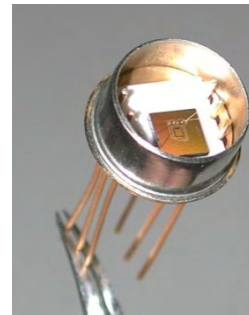
Requirements for an ideal sensor

Dynamic range
False positive rate
Initial cost
Long-term stability
Operation cost
Power consumption
Response speed
Response reversibility
Robustness
Selectivity
Sensitivity
Size
Sterilizability

Flexible



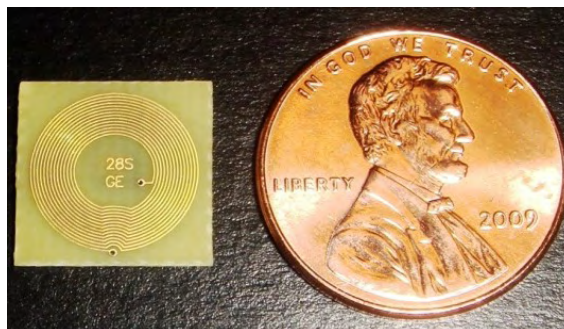
MEMS



Bio-inspired



Radio-frequency identification



Colorimetric



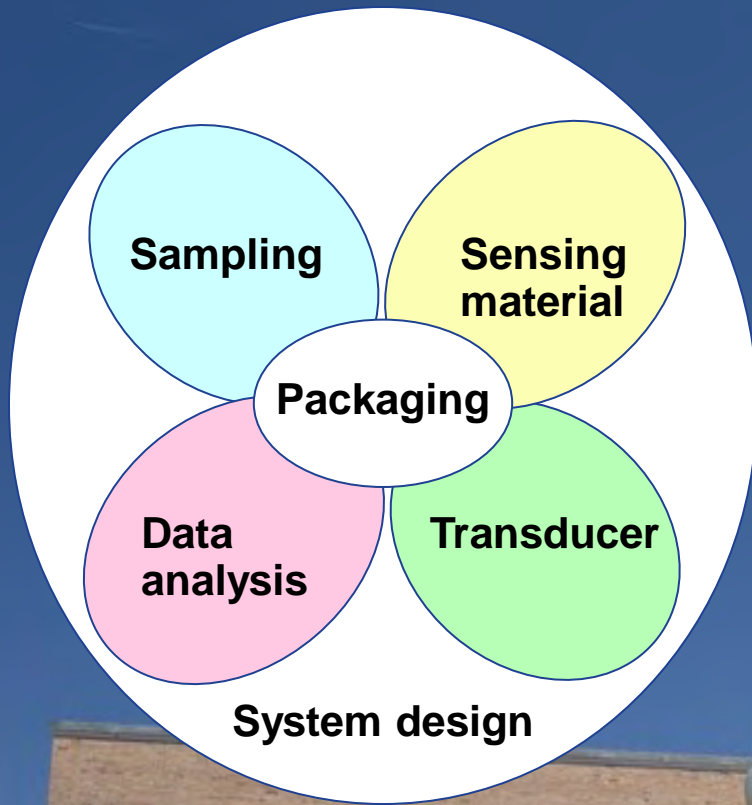
Diversity of sensor designs
to meet specific application requirements

Potyrailo, *Angew. Chem. Int. Ed.* **2006**, 45, 702-723

Potyrailo, Mirsky, *Chem. Rev.* **2008**, 108, 770-813

Potyrailo, Surman, Nagraj, Burns, *Chem. Rev.* **2011**, 111, 7315-7354

Potyrailo, Nak, *Annu. Rev. Mater. Res.* **2013**, 43, DOI: 10.1146/annurev-matsci-071312-121710



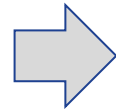
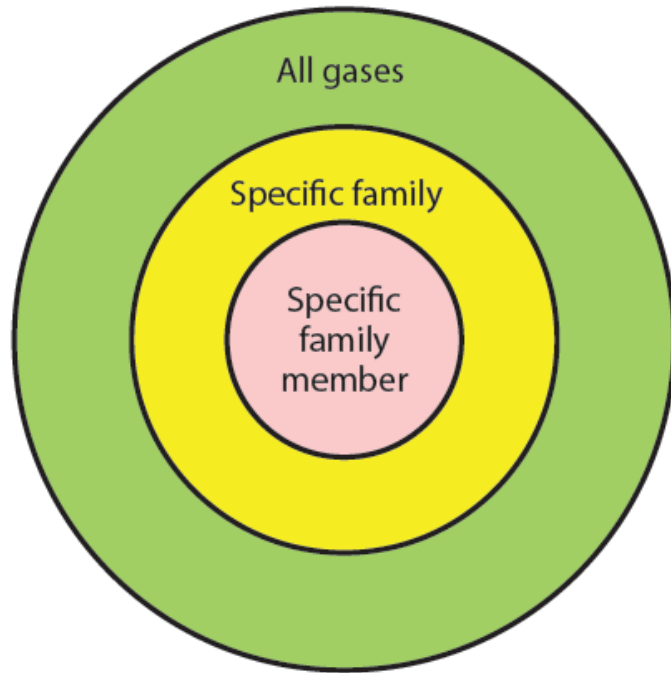
Chem/bio sensors development at GE Global Research

- Chemistry
- Materials science
- Materials characterization
- Micro-fabrication
- Electrical engineering
- Optical engineering
- Wireless communications

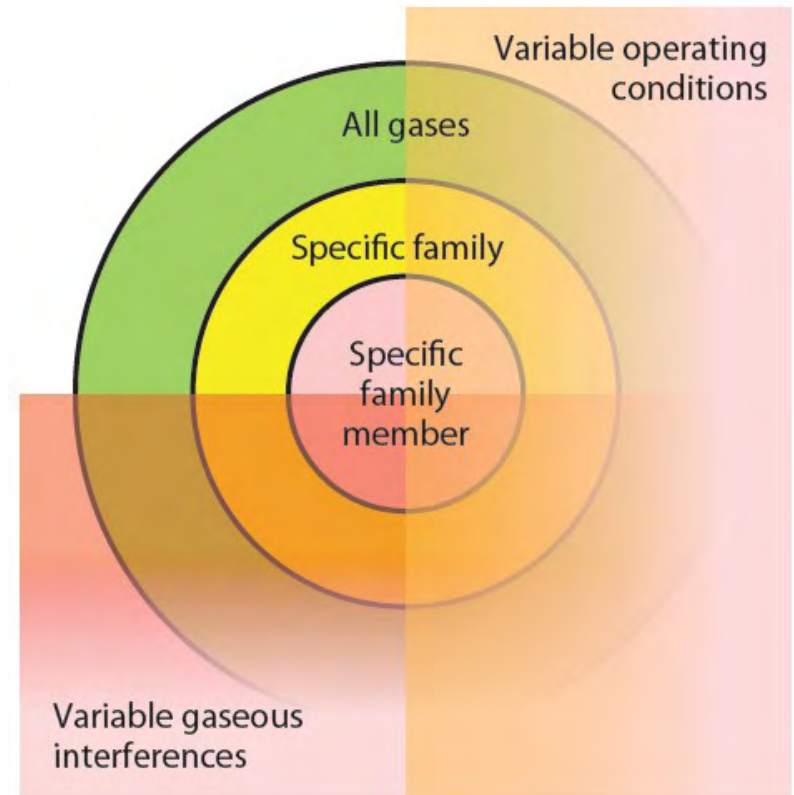


Maturing sensors from the lab to the field

Initial sensor development
in pristine laboratory conditions



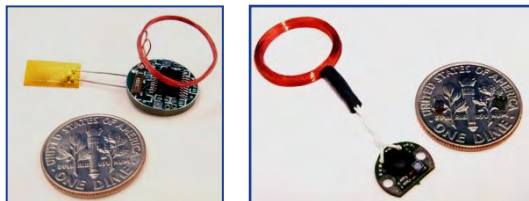
Advanced sensor development
for the field operating conditions



Majority of modern demanding and high-value applications
require selective sensors

Examples of passive sensors with custom IC chips with sensor inputs

Passive RFID sensors

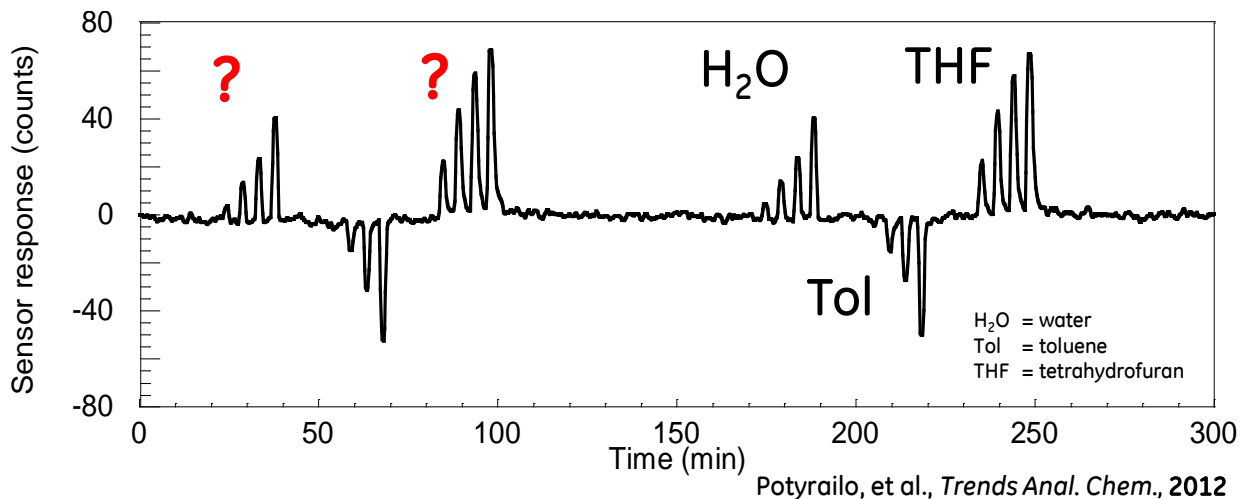
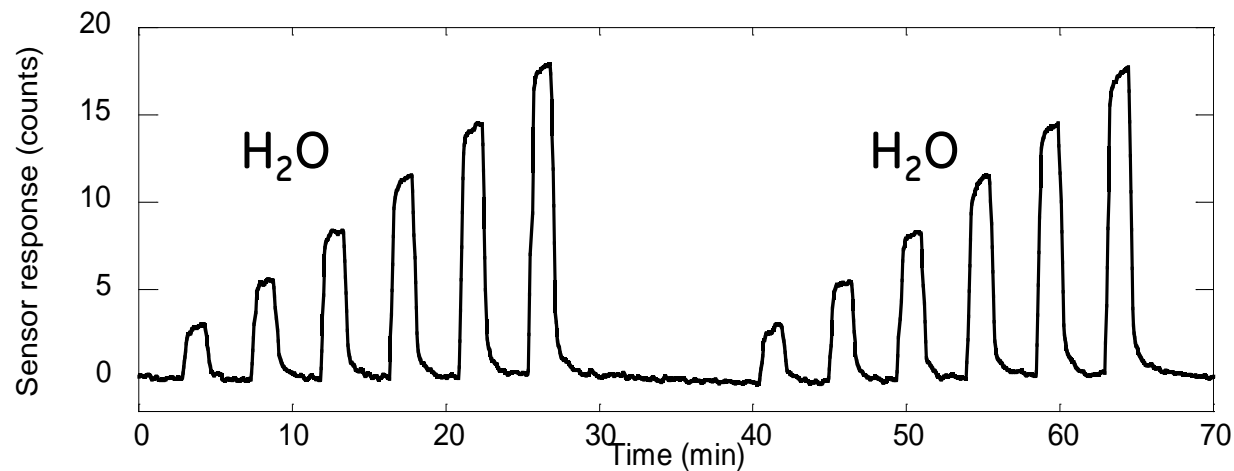


Potyrailo, et al., *Chem. Rev.*, 2011

Smartphone with NFC-based sensor

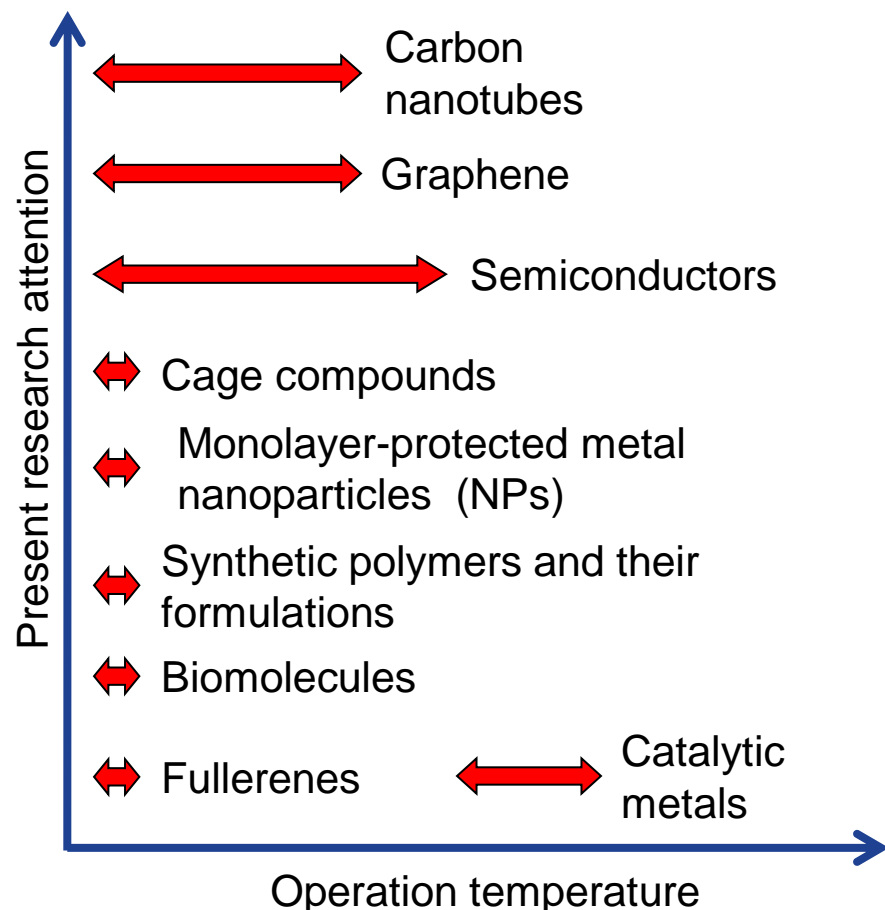


Photo by Potyrailo
from *Sensor + Test*, 2012

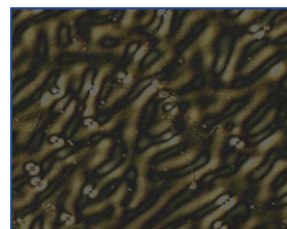


Excellent available sensors
for non-selective sensing using conventional univariate sensors with wireless readout

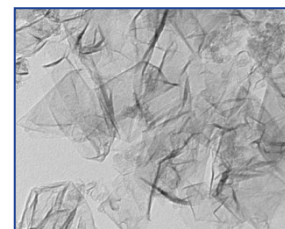
Diverse sensing materials for sensing



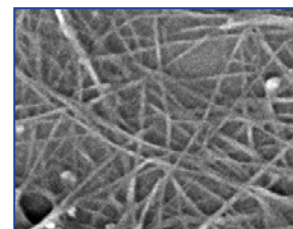
Polymers



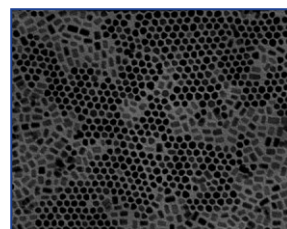
Graphene



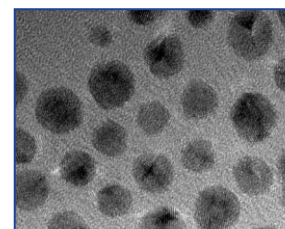
Carbon nanotubes



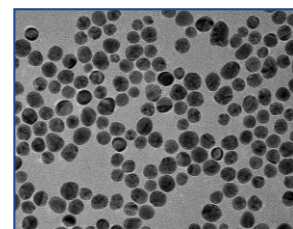
Quantum dots



Thiols – Au NPs



Peptides – Au NPs

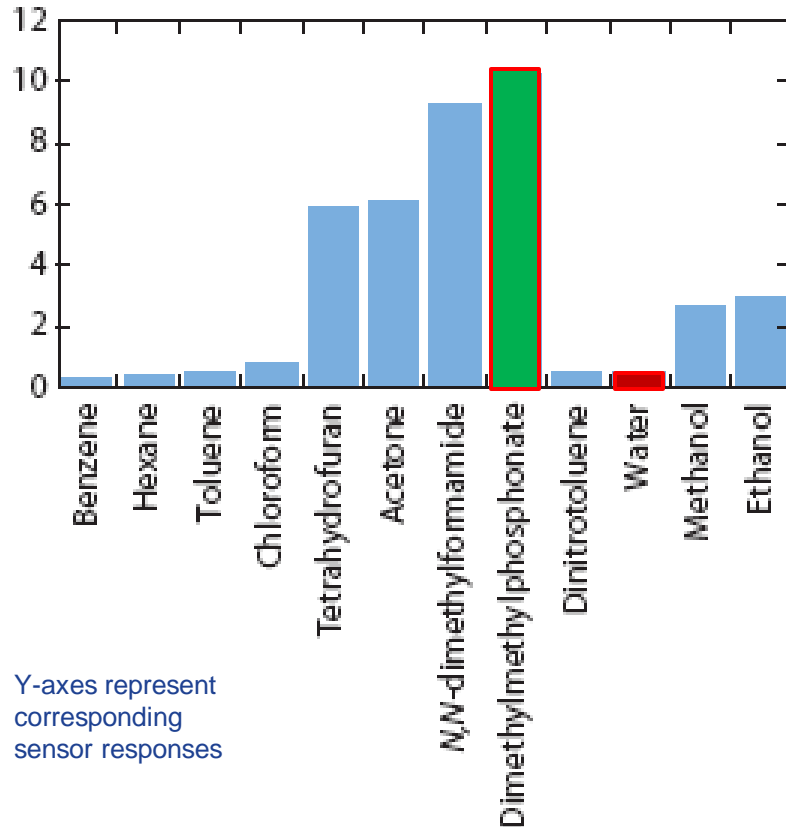


Potyrailo, Sivavec, *Anal. Chem.* **2004**, 76, 7023-7027
 Potyrailo, Leach, *Appl. Phys. Lett.* **2006**, 88, 134110
 Potyrailo, *Angew. Chem. Int. Ed.* **2006**, 45, 702-723
 Potyrailo, Mirsky, *Chem. Rev.* **2008**, 108, 770-813
 Potyrailo, Surman, Nagraj, Burns, *Chem. Rev.* **2011**, 111, 7315-7354
 Rumyantsev, Liu, Shur, Potyrailo, Balandin, *Nano Lett.* **2012**, 12, 2294-2298
 Nagraj, Slocik, Phillips, Kelley-Loughnane, Nak, Potyrailo, **2013**
 Potyrailo, Naik, *Annu. Rev. Mater. Res.* **2013**

GE's practical experience with major types of sensing materials:
 materials-agnostic sensor development

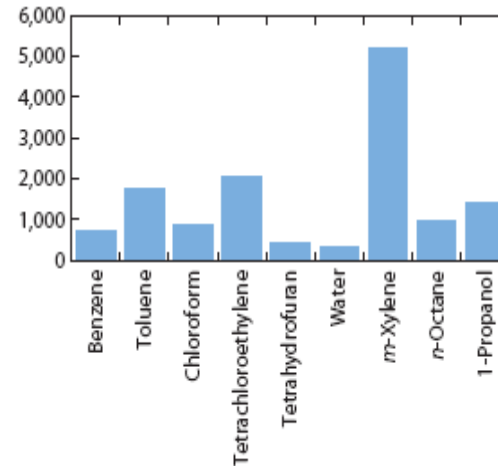
Understanding challenges in gas sensing

Carbon nanotubes

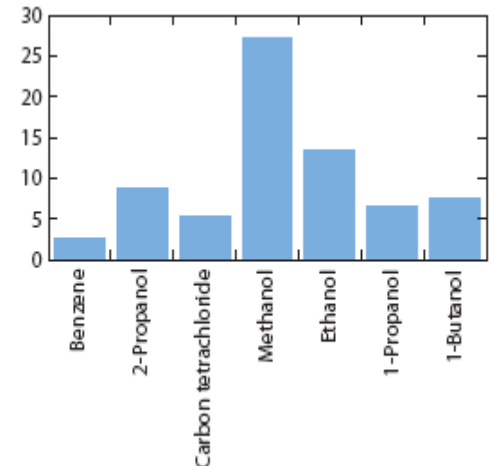


Y-axes represent corresponding sensor responses

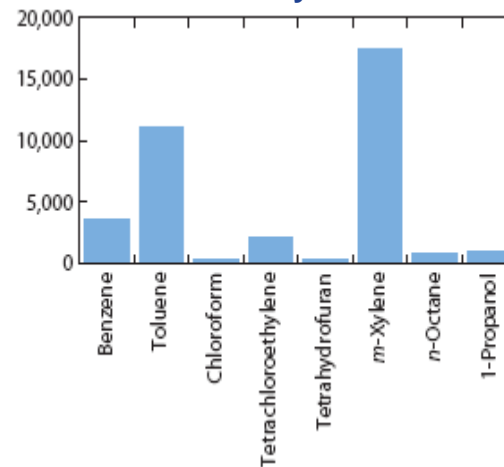
Dielectric polymers



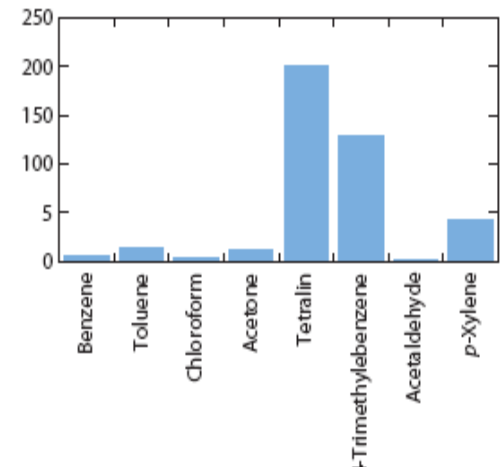
Conjugated polymers



Phthalocyanines

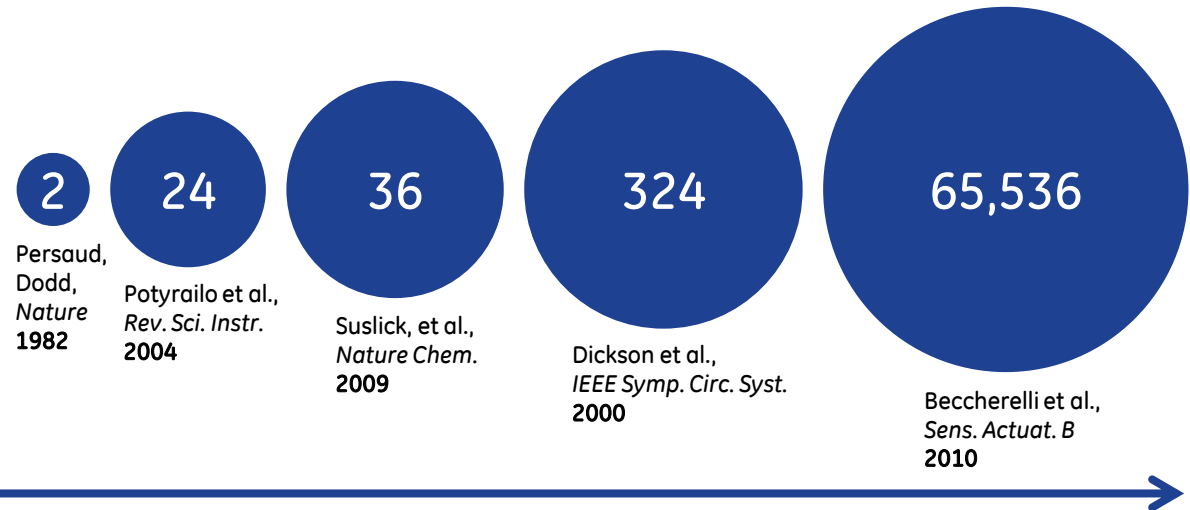
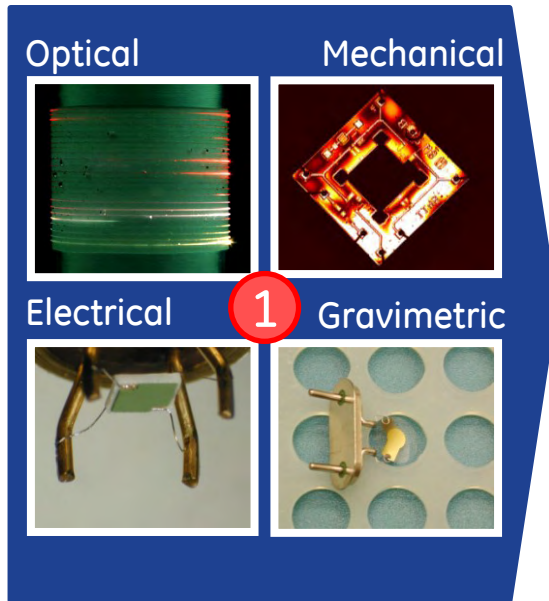


Metal-organic frameworks



Sensing materials suffer from non-selective response
Because of conflicting requirements for sensor selectivity and reversibility

Sensor arrays for selectivity improvement



Conventional individual sensors:

- Established data acquisition / analysis
- Conflicting selectivity vs. reversibility
- Sensor selectivity is “a lost battle”

Sensor arrays:

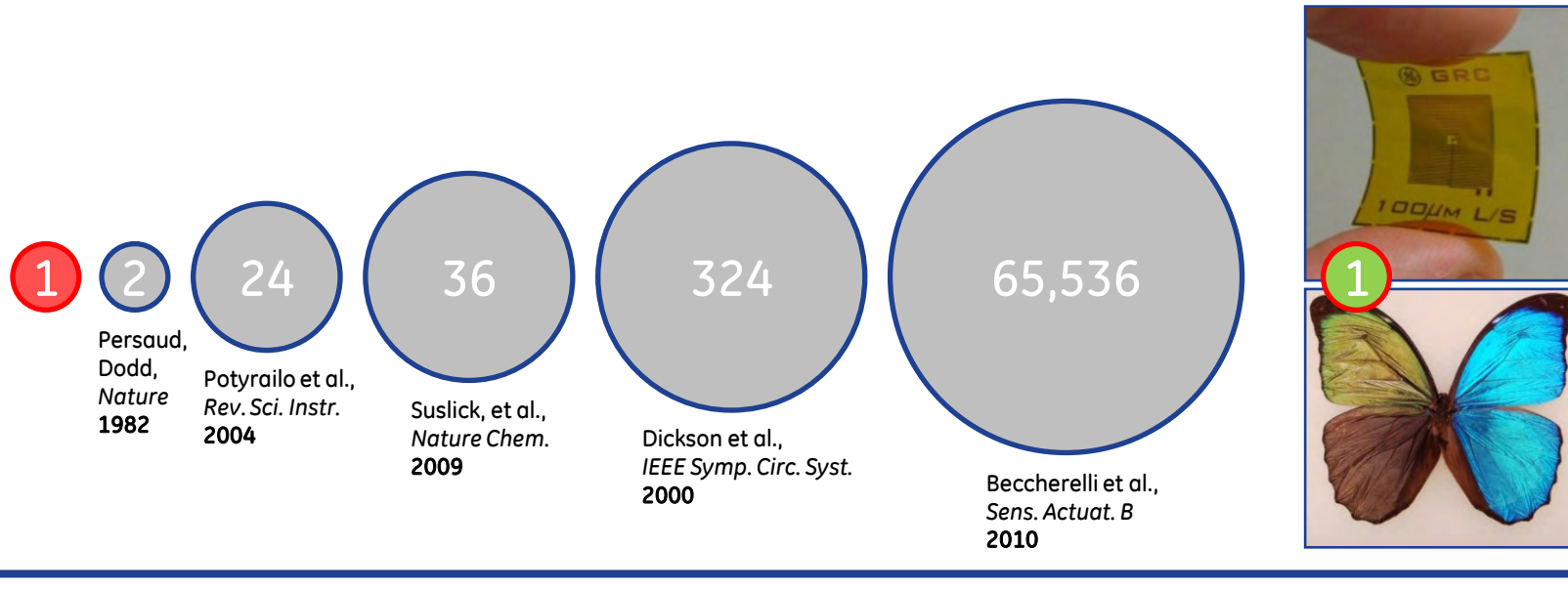
- Operate well in the absence of interferences
- Multiple number of noise sources
- Diverse sources of aging of sensors

Sensor arrays is the compromise to improve selectivity

Individual univariate sensors:

Potyrailo, Hieftje, *Fresenius' J. Anal. Chem.* **1999**, 364, 32-40
 Potyrailo, Wroczynski, Morris, Bradtke, *Polym. Degrad. Stab.* **2004**, 83, 375-381
 Potyrailo, Morris, *Appl. Phys. Lett.* **2004**, 84, 634-636
 Potyrailo, Morris, Wroczynski, *Rev. Sci. Instrum.* **2004**, 75, 2177-2186
 Potyrailo, Morris, Leach, Sivavec, Wisnudel, Boyette, *Anal. Chem.* **2006**, 78, 5893-5899

GE's strategy: individual multivariable sensors



Individual multivariable sensors:

- Simplified manufacturing
- Reduced number of noise sources
- Simplified device packaging
- More predictable sensor aging

Individual multivariable sensors for tailored response selectivity

Individual multivariable sensors:

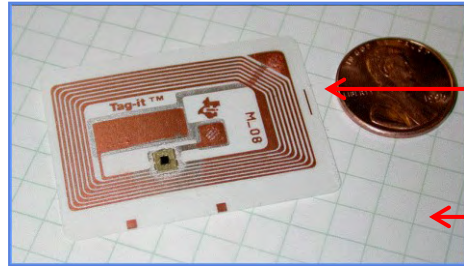
Potyrailo, Morris, *Anal. Chem.* 2007, 79, 45-51

Potyrailo, Ghiradella, Vertiatchikh, Dovidenko, Cournoyer, Olson, *Nature Photonics* 2007, 1, 123-128

Numerous granted GE patents and GE patent applications

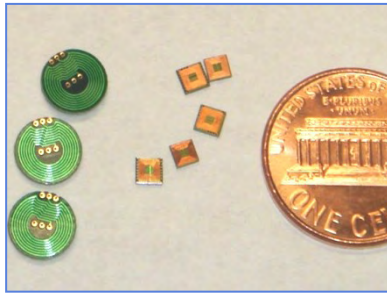
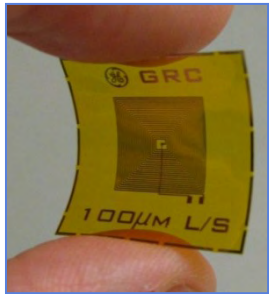
GE's multivariable sensors: operation principle

Diverse transducer manufacturing approaches: flexible, printed, etc.



Integrated circuit memory chip

antenna

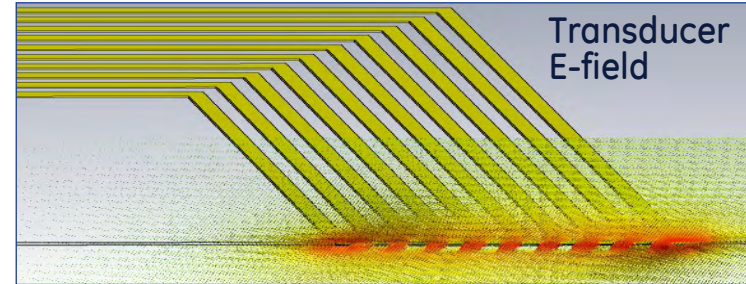


Common platform for:

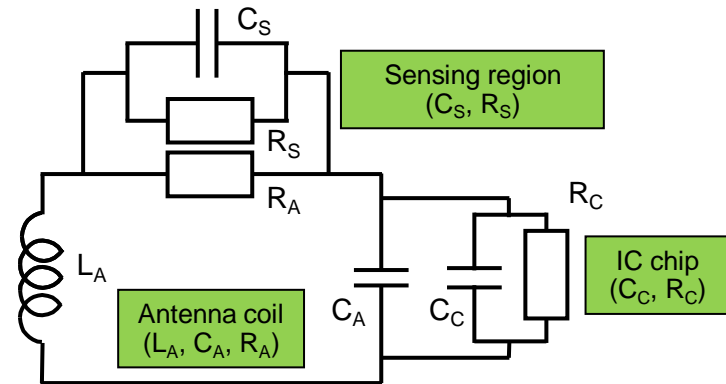
- Phys/chem/bio sensors
- **Asset tracking**
- Storage of sensor calibrations

Transducer E-field interacts with ambient environment or sensing film

Sample (Gas, Liquid, Solid)



Sensor Equivalent circuit



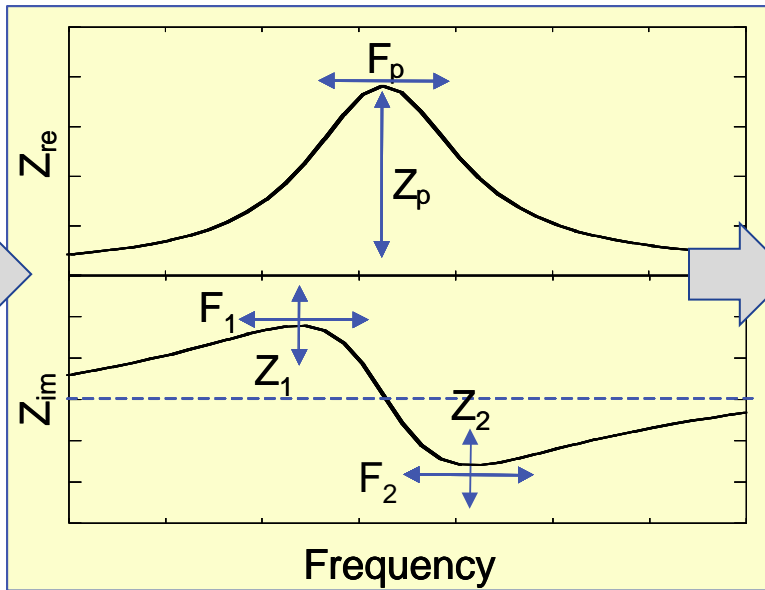
16-bit sensing resolution
resides in sensor reader, not in disposable sensor

Potyrailo, Morris, *Anal. Chem.* **2007**, 79, 45-51

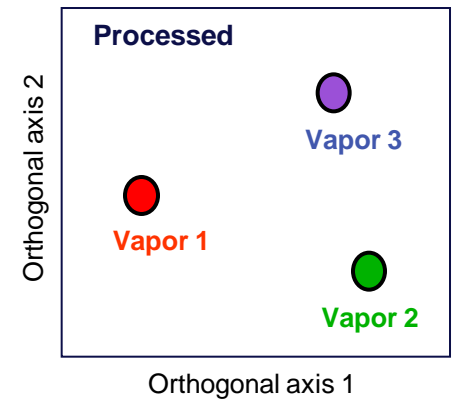
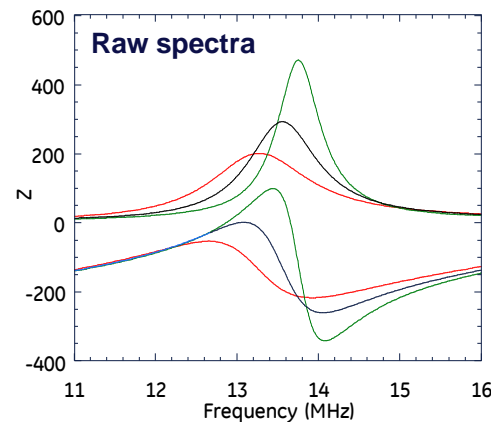
Potyrailo, Morris, Sivavec, Tomlinson, Klensmeden, Lindh, *Wirel. Commun. Mob. Comput.*, 2009, **9**, 1318-1330
and numerous granted GE patents and GE patent applications

GE's multivariable sensors: operation principle

Measured multiple parameters of resonance impedance spectrum

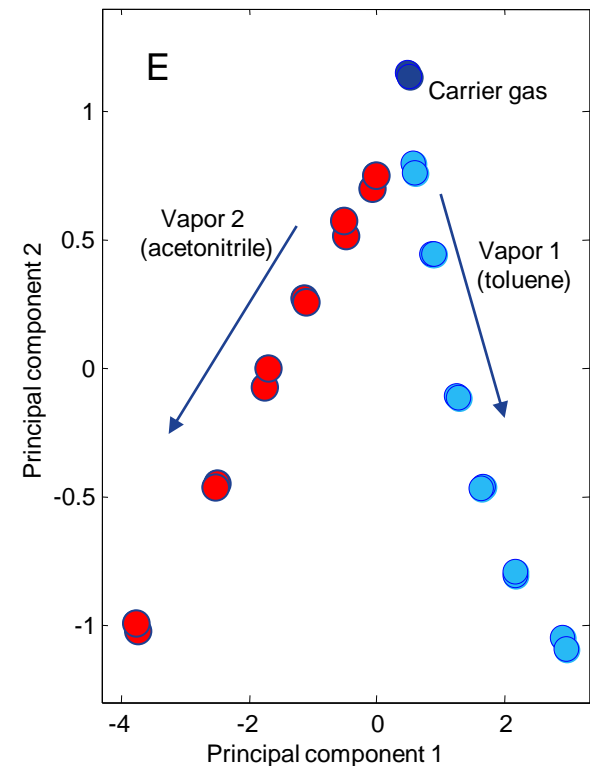
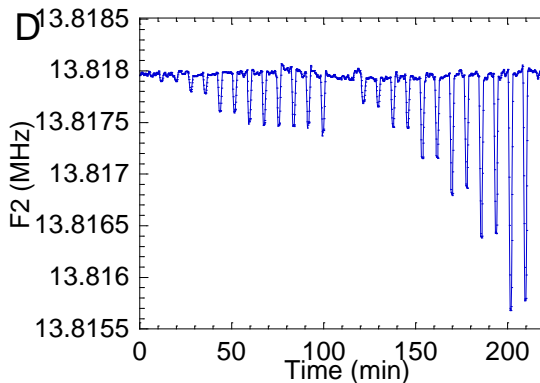
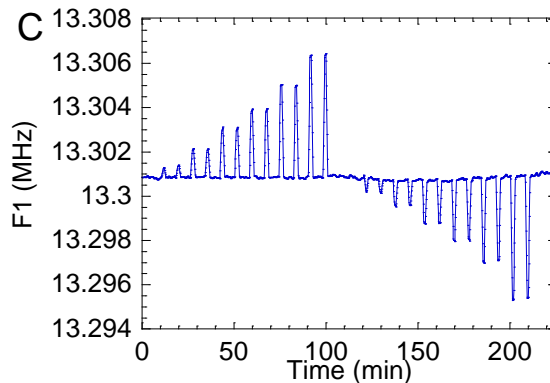
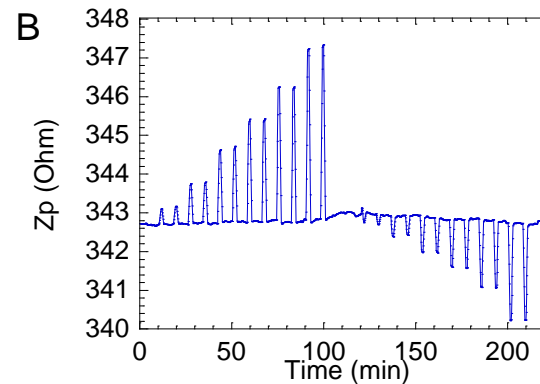
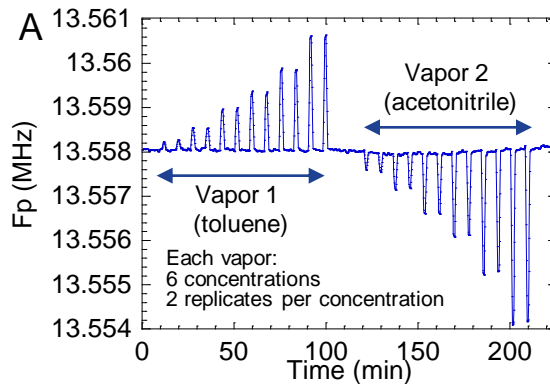
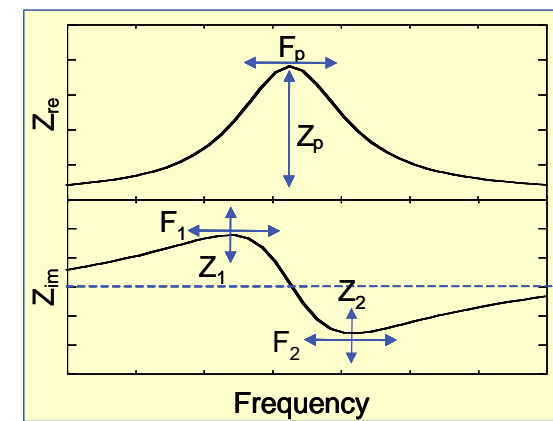


Multivariate data analysis provides orthogonal responses from a single sensor



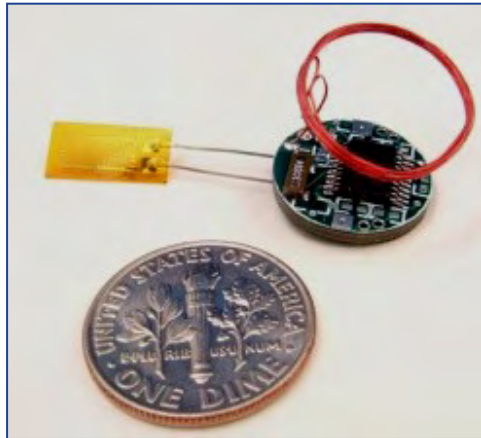
GE-developed data acquisition + analysis tools –
to enhance selectivity of individual sensors

Example of multivariate response (F_p , Z_p , F_1 , F_2) of sensor

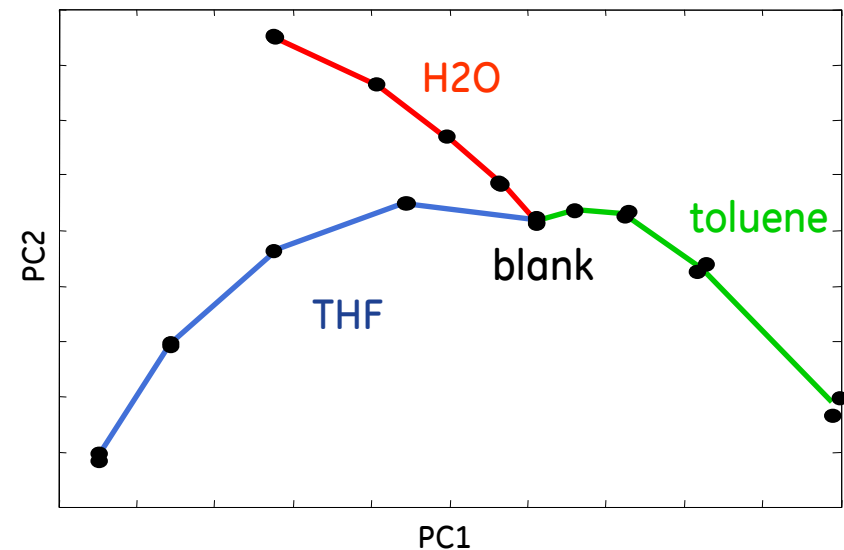
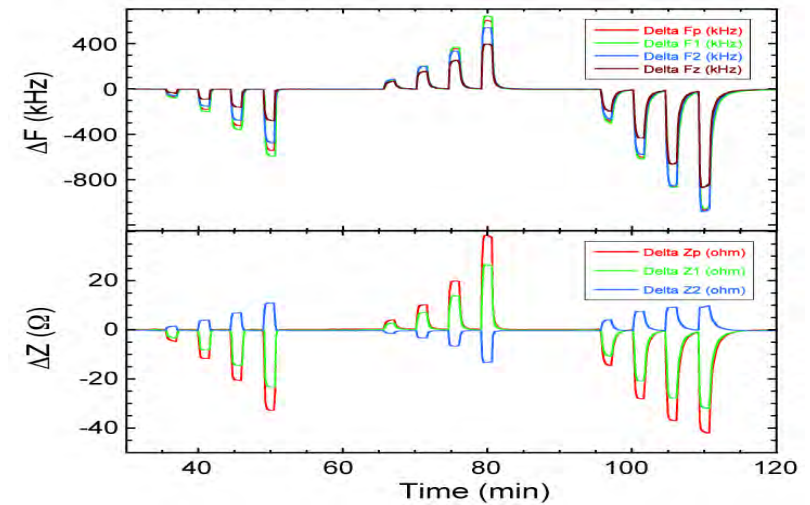
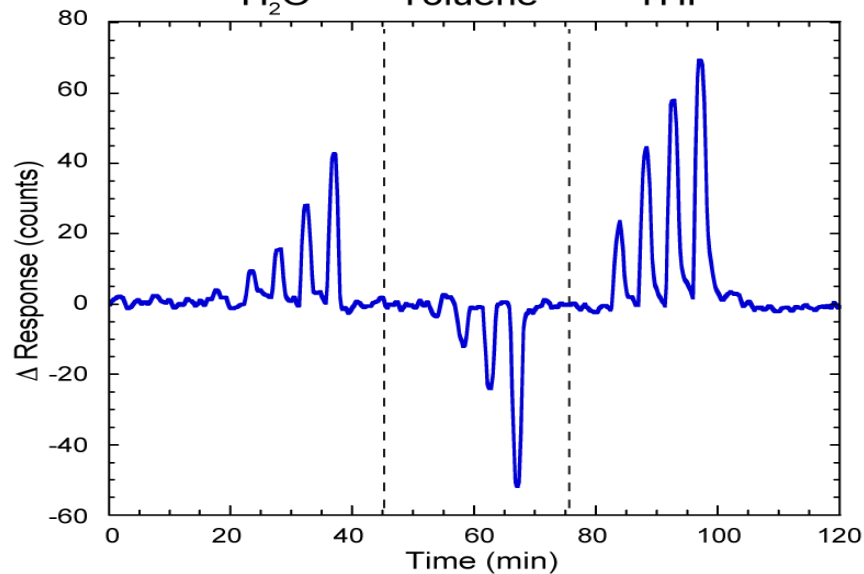


One sensor selectively detects individual vapors

Conventional vs. multivariable sensors

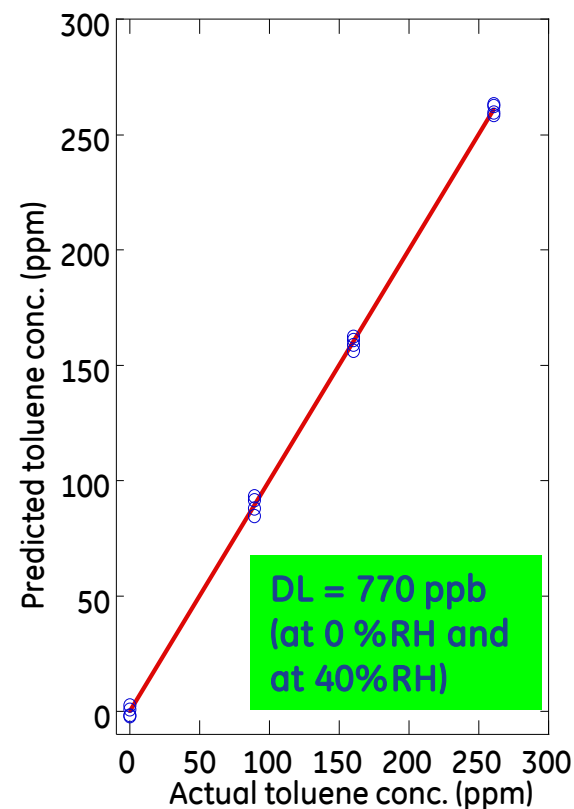
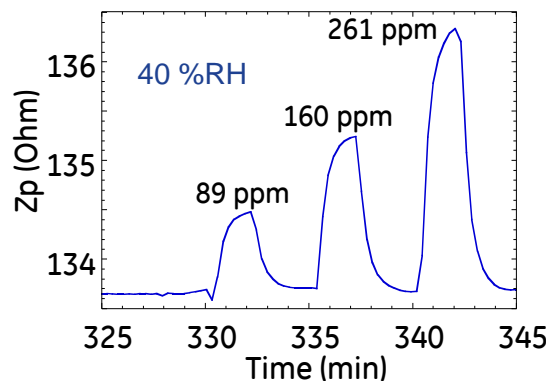
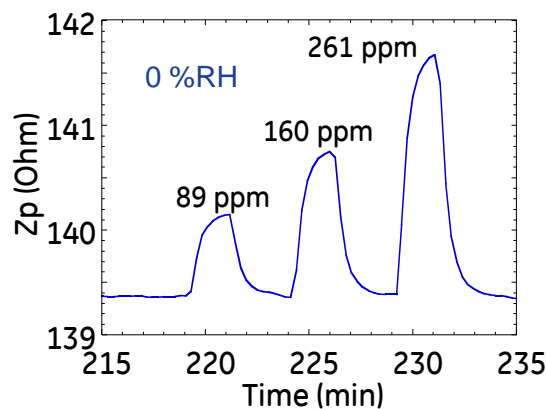
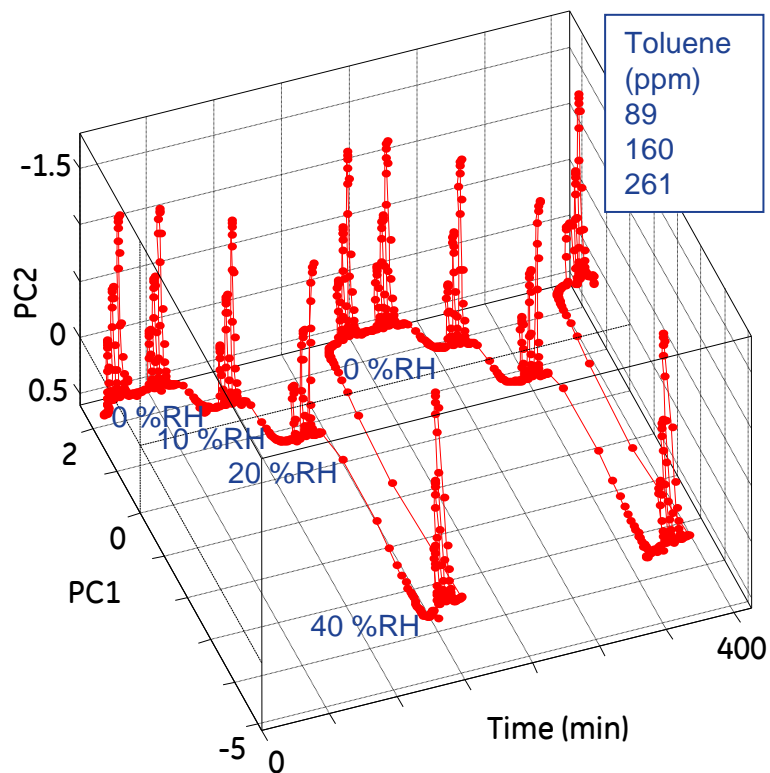


H₂O Toluene THF



- Selectivity cannot be achieved with univariate sensors
- Multivariable sensors provide required sensing selectivity

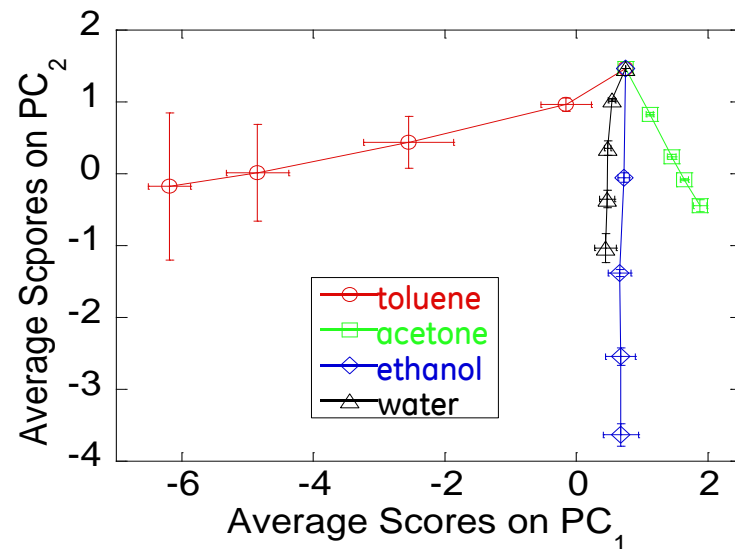
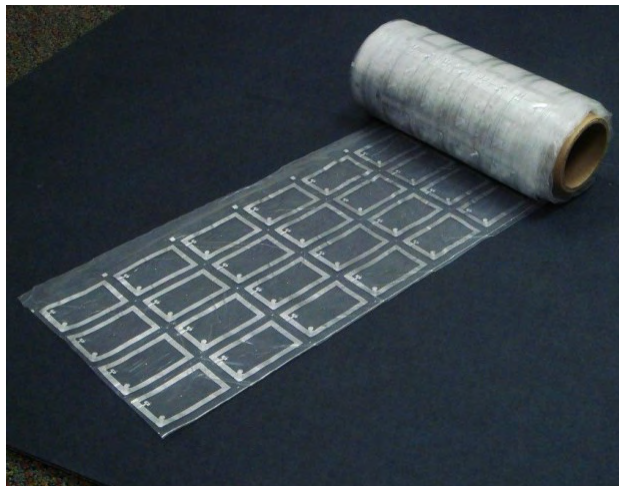
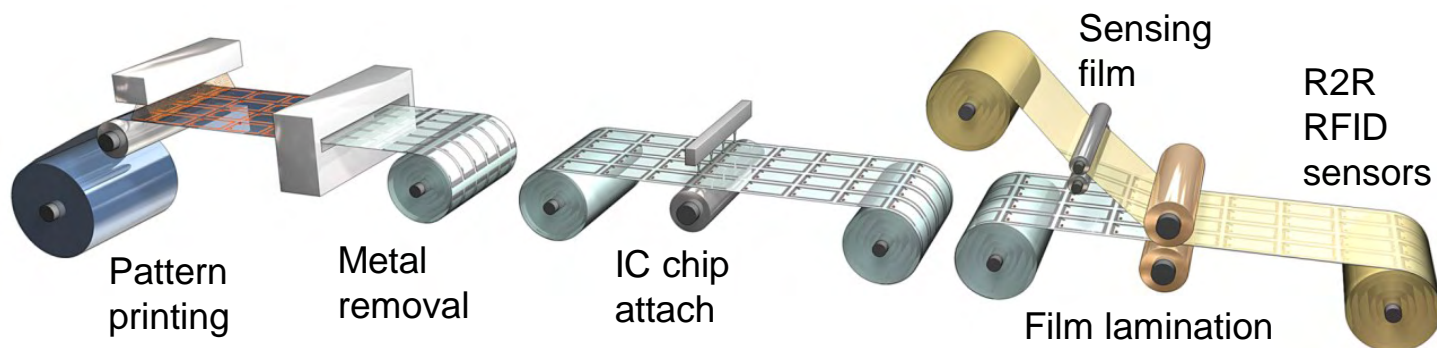
Rejection of interferences



Response to interferences
is designed to be out-of-plane of response to target vapor

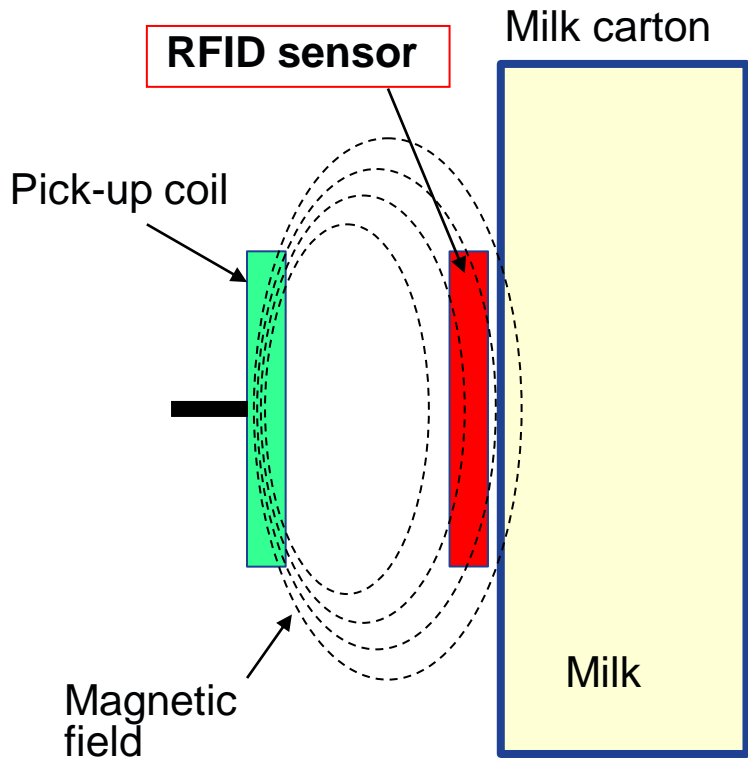
Potyraiilo, Nagraj, Surman, Boudries, Lai, Slocik, Kelley-Loughnane, Naik, *Trends Anal. Chem.* 2012, 40, 133-145

Roll-to-roll fabrication of RFID sensors on flexible substrate

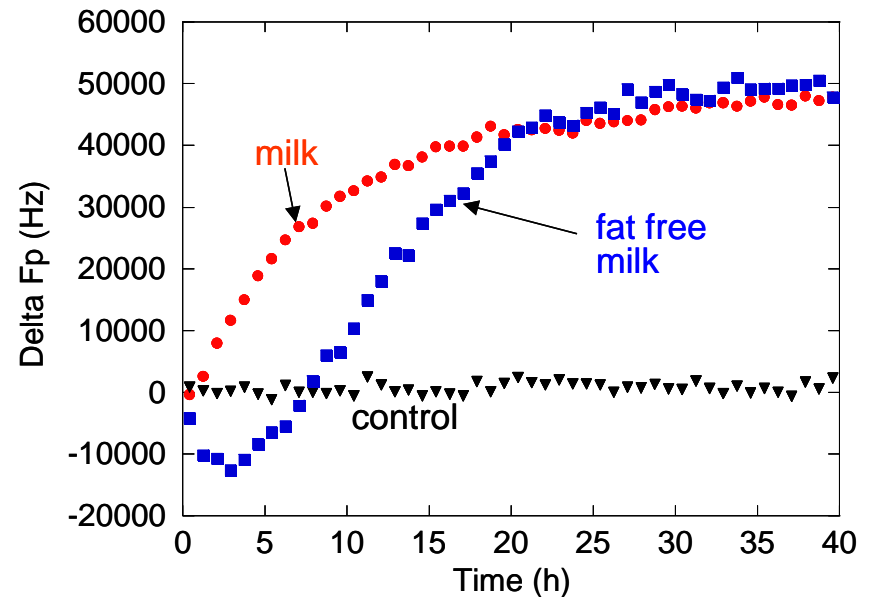


Manufactured ~ 5000 sensors
with Avery Dennison RFID Division

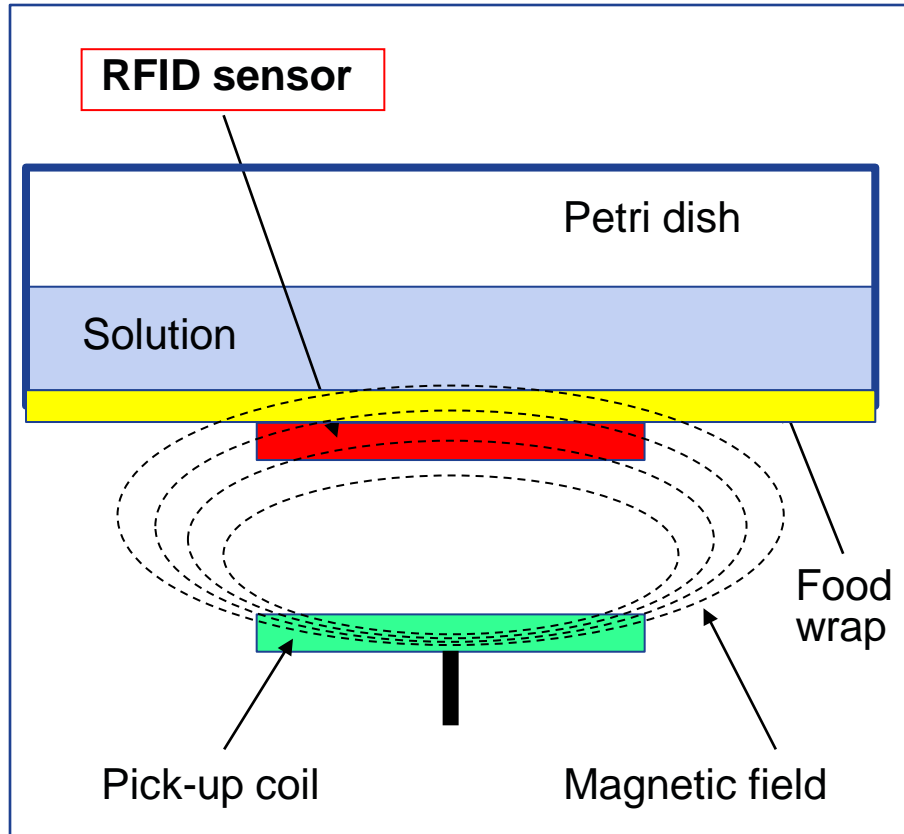
Determination of milk freshness



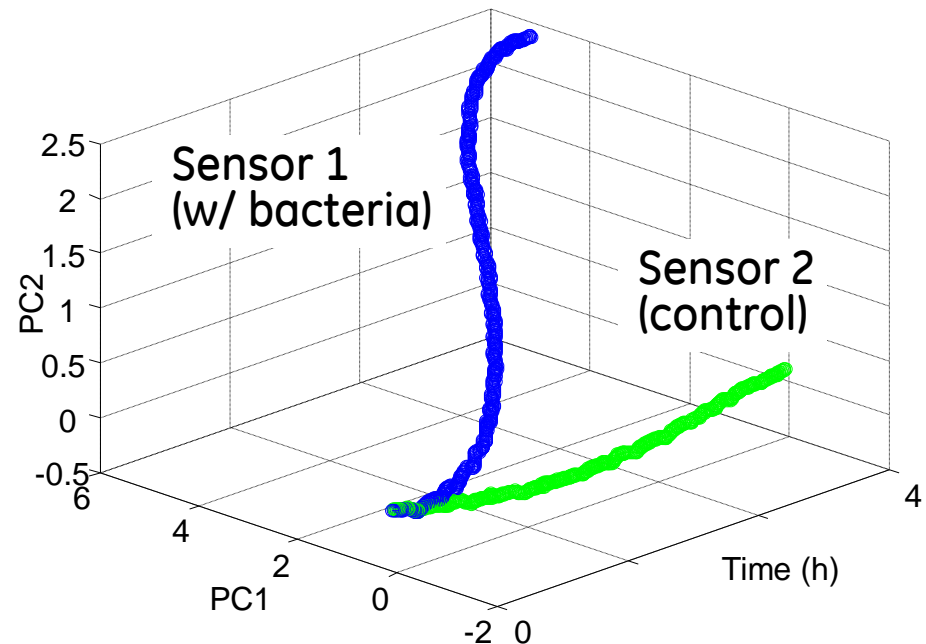
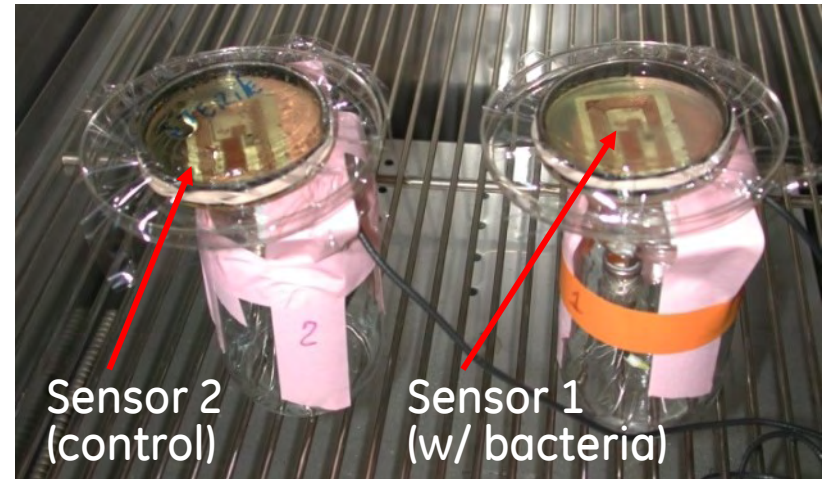
Non-invasive detection through the wall of milk carton



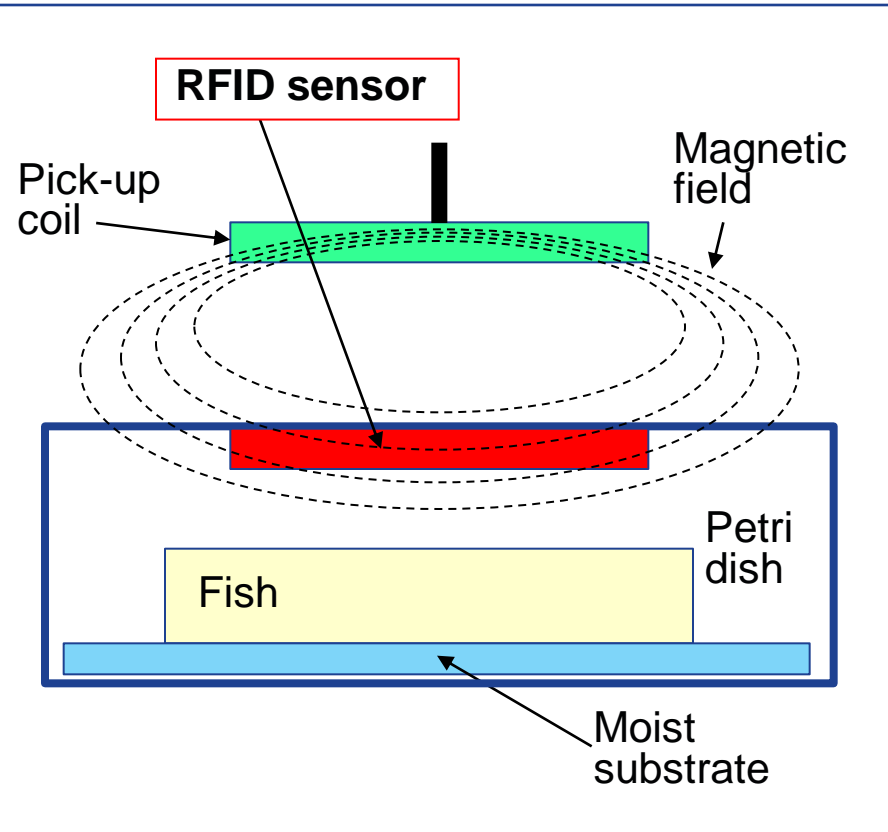
Monitoring of *E. coli* bacterial growth



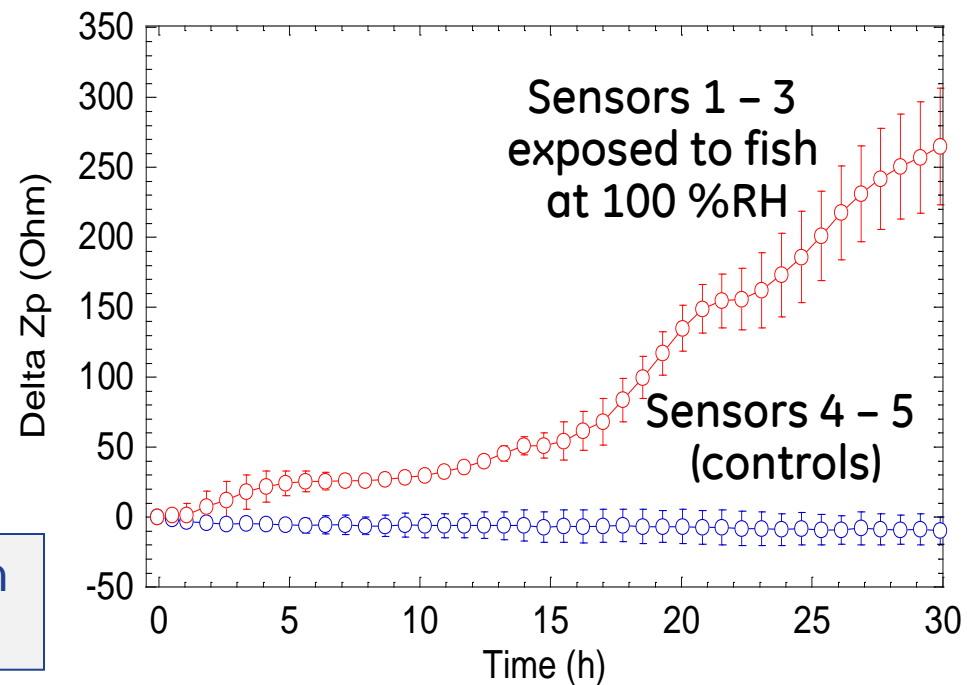
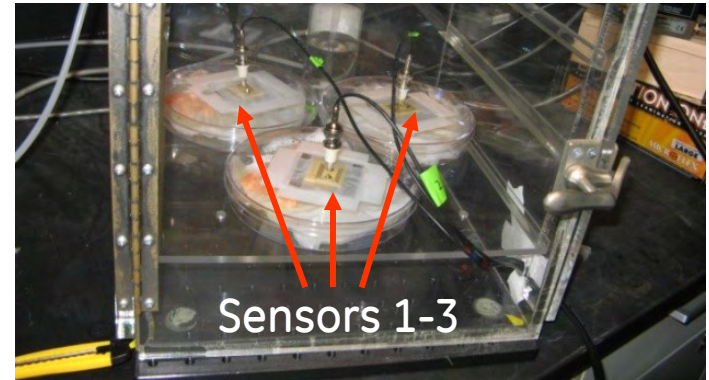
Multivariable sensor response facilitates rejection of interferences



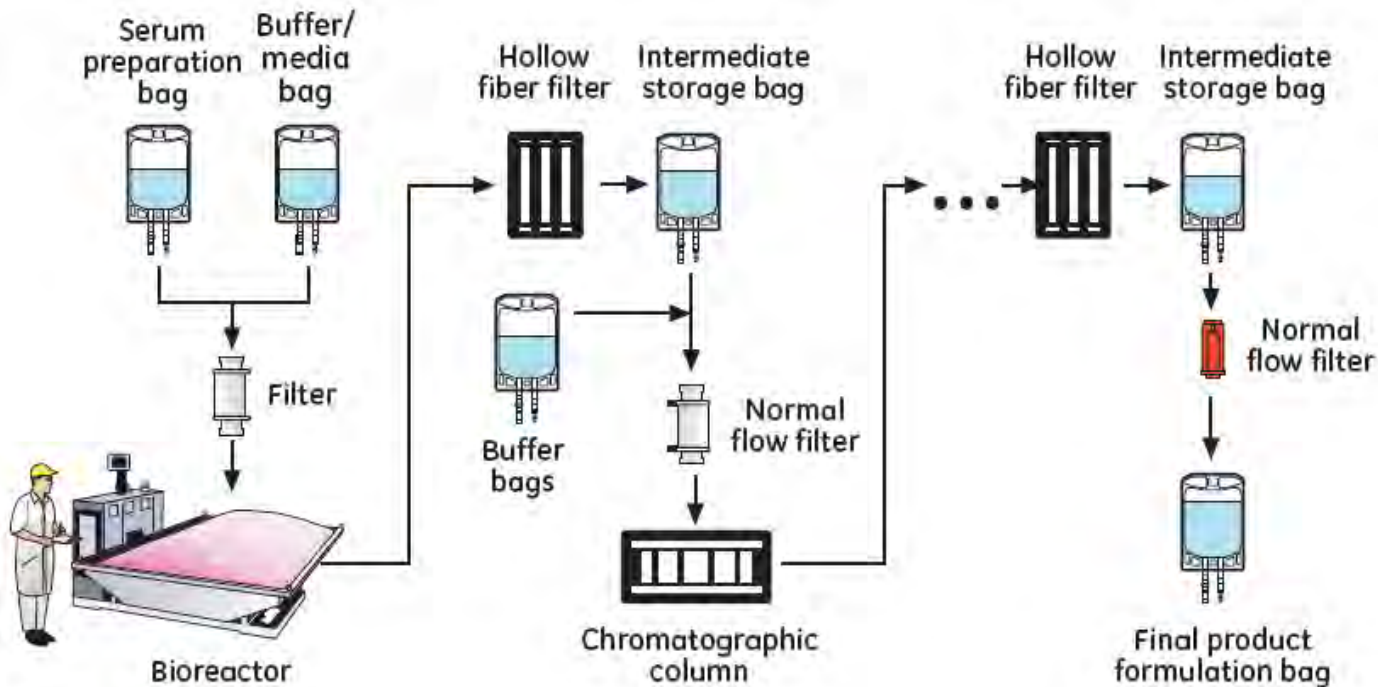
Monitoring of fish freshness



Polymer-coated sensors for early detection of changes in food condition



Passive RFID sensors: monitoring platform for bioprocess



RFID sensors integrated
in bioprocess
components



RFID sensor

Passive multivariable temperature, conductivity, and pressure sensors for
single-use biopharmaceutical manufacturing components

Potyrailo, Monk, Morris, Klensmeden, Ehling, Wortley, Pizzi, Carter, Gach, *IEEE RFID* **2010**, 1-7.

Potyrailo, Wortley, Surman, Monk, Morris, Vincent, Diana, Pizzi, Carter, Gach, Klensmeden, Ehling, *Biotechnol. Prog.* **2011**, 27, 875-884.

Potyrailo, Surman, Monk, Morris, Wortley, Vincent, Diana, Pizzi, Carter, Gach, Klensmeden, Ehling, *Meas. Sci. Tech.* **2011**, 22, art. no 082001

TOP FIVE benefits of individual multivariable sensors vs. sensor arrays

- Simplified manufacturing
- Reduced number of sources of noise
- Simplified device packaging
- More predictable sensor aging
- Reduced sensor footprint and power consumption



Acknowledgments

GE Global Research

Jeff Ashe
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Andy Burns
Jim Cournoyer
Lauraine Denault
Jon Dieringer
Evan Downey
Kevin Durocher
Steve Go
Mike Larsen
Yongjae Lee
Frank Mondello
Laurie Le Tarte
David Monk
Bill Morris
Nandini Nagraj
Manuel Palacios
Matthew Pietrzykowski
Brenda Peck
Tim Sivavec
Cheryl Surman
Alton Tang
Ihor Tokarev

GE Healthcare

Staffan Klensmeden
Hanno Ehring
Tim Wortley
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“Vision without funding is just a hallucination” Henry Ford