Inkjet-Printed Nanotechnology-Enabled Zero-Power Wireless Sensor Nodes for Internet-of-Things (IoT) and M2M Applications

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ATHENA Research Group

- 10 PhD students
- 5 MS students
- 5 GT-ORS Undergraduate Students
- 5 Visiting Faculty+Stuff (Japan, France, Italy, Spain, China)
- Strong collaboration with Georgia Tech Ireland - Athlone (visited Summer 2009)
- Featured in IEEE The Institute, Wall Street Journal, Discovery Channel, CNN, Boston Globe, CBS Smartplanet, Yahoo, EE Times, engadget.com, gizmag.com
- Co-founders of the RF-DNA anti-counterfeiting technology listed among the 25 technologies featured in the 20-year anniversary issue of the Microsoft Research Center
- http://www.athena-gatech.org
ATHENA Focus Areas

• RFID's, mmID's and RFID-enabled Sensors
• Inkjet-Printed RF electronics, antennas and sensors
• Nanotechnology-based "zero-power" wireless sensors
• Ubiquitous WSN's and Internet of Things
  • "Smart Skin" and "Smart Energy" Applications
  • Wearable and Implantable WBAN's
  • Flexible 3D Wireless " Smart Cube" Modules up to sub-THz
  • Multiform Power Scavenging and Wireless Power Transfer
  • Conformal ultra broadband/multiband antennas and antenna arrays
  • Paper/PET/Fabric-based Electronics
Selected Awards

- IEEE Fellow
- NSF CAREER Award
- IEEE MTT-S Distinguished Microwave Lecturer
- 2009 E.T.S. Walton Award from SFI
- 2010 IEEE APS Society P.L.E.Uslenghi Letters Prize Paper Award
- 2010 Georgia Tech Senior Faculty Outstanding Undergraduate Research Mentor Award
- 2009 IEEE Trans. Components and Packaging Technologies Best Paper Award
- 2006 IEEE MTT Outstanding Young Engineer Award
- 2006 Asian-Pacific Microwave Conference Award
- 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award
3D Integrated Platforms

Multi-mode Wireless Interface for Comm. and Energy Harvesting

Wireless Interface for Comm/Sensor/Power

Organic Substrate

Sensor node

Power management

Comm. node

Si-CMOS Substrate

Electronic Interface for Nanowire

Nanowire Sensor

Nanowire Energy Harvest

Nanowire Battery

Multi-mode Nanowire Interface for Sensing/Energy Harvesting/storing
Enabling Technologies in the future

- PET/Kapton
- Paper
- Fabric
- Nano
- LCP
- LTCC
- MEMS
- Thermal
- PWB
- 3D
Inkjet-Printed RF Electronics and Modules on Paper

- Module
  - Microcontroller Unit and Transceiver SoP Integration and Packaging
  - Inkjet-printing
  - Curing
  - Multilayer lamination

- Components
  - Energy Harvesting Devices (Solar, Piezo)
  - Power Management Unit
  - Temperature Sensor
  - Paper-based Substrates

- System
  - Identification
  - Localization & Position Tracking
  - Environmental Sensing and Monitoring

- Network
  - RFID ↔ WSN Communication
  - Multi-hopping Routing Protocol
Internet of Things - *at its most basic level*...
RFID Ink-jet Printed on Paper Using Conductive Ink

PAPER ELECTRONICS:
• Environmental Friendly and is the LOWEST COST MATERIAL MADE
• Large Reel to Reel Processing
• Compatible for printing circuitry by direct write methodologies
• Can be made hydrophobic and can host nano-scale additives (e.g. fire retardant textiles)
• Dielectric constant $\varepsilon_r \sim 3$ close to air’s
• Potentially setting the foundation for truly “green” RF electronics
RFID printed on paper: conductive ink

**PAPER:**
- Environmental Friendly and low cost 
  *(LOWEST COST MATERIAL MADE BY HUMANKIND)*
- Large Reel to Reel Processing
- Compatible for printing circuitry by direct write methodologies
- Can be made hydrophobic and can host nano-scale additives (e.g. fire retardant textiles)
- Dielectric constant $\varepsilon_r$ (~2) close to air’s

**INK:**
- Consisting of nano-spheres melting and sintering at low temperatures (100 °C)
- After melting a good percolation channel is created for electrons flow.
- Provides better results than traditional polymer thick film material approach.

The ONLY group able to inkjet-print carbon-nanotubes for ultrasensitive gas sensors (ppb) and structural integrity (e.g. aircraft crack detection) non-invasive sensors
Characteristics:

- Piezo-driven jetting device to preserve polymeric properties of ink
- 10 pL drops give $\approx 21 \mu m$
- Drop placement accuracy $\pm 10 \mu m$ gives a resolution of 5080 dpi
- Drop repeatability about 99.95%
- Printability on organic substrates (LCP, paper ...)

High resolution inkjet printed copper (20 $\mu m$)

SEM Images of a Layer of Printed ink, Before and After a 15 Minute Cure at 150°C
Novel Method for Inkjet Cu

- 15x cheaper than metallic nanoparticles
- Uniform, non-porous films
- Can be deposited on glass and wafers (Future integration w/ CMOS)
- Zero oxidation
Printed Dielectrics For Multi-Layer Passives/Actives

• Inkjet Multi-Layer Process
  – Metal/Dielectric/Via layers (All Printed)
  – Post-Processing on-chip antennas/interconnects
  – MEMS
  – MIM Caps
  – Transistor Gates
  – Substrate Surface Energy Modification
Inkjet Printing on Si/Glass

Surface modification enables inkjet printing on silicon/glass that was not possible before.
Inkjet Printing on Si/Glass

Cu as well as some other metals such as Au, Ag, Pd, Ni and Co can be printed on Si/glass in our novel approach by combining inkjet printing technology and electroless deposition.

A Cu pattern printed on glass slide
Wireless Sensor Module: 904.2 MHz

- Single Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.2 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation
- Maximum Range: 1.86 miles

[Diagram of wireless sensor module with circuit and antenna]
Wireless Sensor Module: 904.5 MHz

- Double Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.5 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation
- Maximum Range: < 8 miles

Wireless ASK modulated Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer

Antenna Radiation Pattern showing high gain
SenSprout: Inkjet-Printed Soil Moisture and Leaf Wetness Sensor

Features:
Inkjet-printed capacitive sensor for soil moisture and rain detection

Applications:
Irrigation optimization, quality control of high-value fruit, and land-slide detection in mountains

Leaf Wetness Sensor (Rainfall and frost detection)

Microcontroller

Soil Moisture Sensor

Monopole Antenna (Communication, RF Energy Harvesting)
A.Traille, A.Coustou, H.Aubert, S.Kim and M.M.Tentzeris, “Monolithic Paper-Based & Inkjet-Printed Technology for Conformal Stepped-FMCW GPR Applications”, accepted for Podium Presentation to the 2013 European Microwave Week, Nurnberg 2013
UWB Inkjet-Printed Antennas on Paper: Is it possible?
Inkjet Printing on LCP: Up to mm-Wave Frequencies

![Graph showing return loss vs. frequency](image1)

![Image of printed structure](image2)

![Graph showing S11 vs. frequency](image3)

![Image of fabricated device](image4)
Working prototype
3D-”Magic Cube” Antennas

• Typical RFID/Wireless Sensor antennas tend to be limited in miniaturization by their length
• What if used a cube instead of a planar structure to decrease length dimension?
• Interior of cubic antenna used for sensing equipment as part of a wireless sensor network
• Can lead to the implementation of UWB sensors and the maximization of power scavenging efficiency, potentially enabling truly autonomous distributed sensing networks
Experimental Set-Up

ORIENTATION #1: Tx and Rx co-polarized

ORIENTATION #2: Tx and Rx orthogonal

ORIENTATION #3: Tx and Rx random

Transmit Module

Receive Module

TX

RX

Orientations
Min/Max Distance Ratio for All Orientations

- Maximum Whip-Whip Distance is 0.12 miles
- Maximum Cube-Cube Distance is 0.116 miles

More variability with orientation for the whip antenna (65% vs. 95% for the cube antenna)
Isotropic Radiator

Radiation Pattern of 915MHz Printed Antenna Folded Around FSS Cube

Horizontal Orientation

Vertical Orientation

Georgia Institute of Technology

ATHENA
Omnidirectional Broadband CP Antenna

The first CP Antenna with 30%+ AR Bandwidth (10x better than state of the art)
Also: omni, flex independent
“Autonomous” Wireless Sensor Node Powered by RF Energy Harvesting

Features:
• A dipole antenna + rectifier for 550MHz (Digital TV) harvests ~100uW from TV tower 6.5km away
• MSP430 + CC2500 for sensing and communication
• Dynamic duty cycle control software for maximize scarce energy intake
Ambient RF: How much is out there?

- Ambient RF: Atlanta
  - Digital TV
  - 3G, 4G, DVBH
  - GSM

- Ambient RF: Tokyo
  - Analog TV
  - Digital TV
  - Mobile Phone, MCA
Energy Harvesting circuit to capture power from air

- **EH Circuit performance**
  - 12 µ-watts of wireless power -> 1.8V DC out
  - 17 µ-watts of wireless power -> 2.2V DC Out
  - 25 µ-watts of wireless power -> 3.3V DC out

- **EH Circuit design includes**:
  - Converts microwatts of wireless power to over 3V of DC output signal
  - No batteries - Uses Capacitor to wireless power
  - Powers up microcontroller for power management and sensing applications

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Energy Harvester performance in field

- At 6.5 km from source
- RF-DC charges output capacitor to 4.1-4.2V in 3 mins
- Needs just 28 microwatts of wireless channel power in air to give 4.2V

Introduction

In the new area of the Internet of Things, the focus of this work is about...

Wearable Electronics

Health Monitoring

Physical Activity Monitoring

Rehabilitation Methods Improvements

Safety

Instantaneous data elaboration
EBG Ground Plane

- Reflection phase characteristic method
- Illuminate plane wave to the EBG ground plane
- Monitoring phase of the reflected wave ($S_{11}$)

Fig. 6. (a) Antenna Geometry
(b) Layout of EBG surface company logo
Communication Range Improvement

- Communication range is improved
  - Original chip antenna: 18.3 m
  - The proposed antenna: 82.8 m
- Range is increased by a factor of four

Fig13. Communication range measurement
Proposed Microfluidic RFID Tag

• Microfluidic-integrated RFID antenna
  – Utilizes capacitive microfluidic gap to load antenna
  – Change in fluid $\varepsilon_r$ causes change in $f_r$
  – RFID chip provides digital backscatter modulation
Inkjet Microfluidic Fabrication

1. Laser Etch Channels
2. Print Metallization
3. Print Bonding Layer
4. Bond Channels

Fluid Channel
RFID Chip
Capacitive Gap

10 mm
Inkjet Microfluidic Fabrication

• Laser engraved channels
  – Etch acrylic
  – Vary laser power/focus
  – Depths as low as 50 um

• Bonded channels
  – Ultra-thin bonding layer
  – No channel clogging
Inkjet Microfluidic Varactor

- Fabricate capacitor to extract gap impedance
- Requires 1 uL of fluid
- Load capacitor with:
  - 1-Hexanoh (Er = 3)
  - Ethanol (Er = 15)
  - Water (Er = 73)
Inkjet Microfluidic Varactor

![Graph showing capacitance vs. frequency for different fluid mixtures.]

- Empty 1
- Empty 2
- Hexanol
- Ethanol
- Ethanol:Water 90:10 w%
- Ethanol:Water 80:20 w%
- Ethanol:Water 50:50 w%
- Water

Frequency [GHz] vs. Capacitance [pF]
Beacon Oscillator

- Solar powered inkjet printed stand alone beacon oscillator
- Green environmentally friendly technology
- Localization application
• The carrier frequency: 874.65 MHz
• Low phase noise: -68.27 dBc/Hz @ 10kHz from the carrier frequency
  -123.6 dBc/Hz @ 1MHz from the carrier frequency
Parylene Coating for Protection

- The antenna covers 900 MHz & 2.4 GHz
- Linearly polarized
- Parylene C type is deposited (about 1μm)
- Hydrophobic & waterproof surface is created
Parylene Coating for Protection

- No performance degradation after water contact
Inkjet-Printed Passives - Waveguide

- Substrate Integrated Waveguide (SIW)
  - High system integrity
  - Innumerable applications on organic paper substrate in mmWave area (ex: Radar, traveling wave antenna, etc)
Inkjet-printed Via on Vertical Via Hole

- A vertical via hole on thick substrate (> 500 µm):
  - Crack formation due to the sintering process and the gravity
Stepped-via Fabrication

(i) Laser drilling: Top

(ii) Drilled via hole: Top

(iii) Laser drilling: Bottom

(iv) Drilled via hole: Bottom

(v) Inkjet printing & Sintering

(vi) Fabricated stepped via hole
Stepped Via Hole: Top view

- **Substrate**: PMMA (polymethyl methacrylate)
- **Thickness**: 1 mm

### Radii Table

<table>
<thead>
<tr>
<th>Radius</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₁</td>
<td>1.00</td>
</tr>
<tr>
<td>R₂</td>
<td>0.63</td>
</tr>
<tr>
<td>R₃</td>
<td>0.40</td>
</tr>
<tr>
<td>R₄</td>
<td>0.25</td>
</tr>
<tr>
<td>R₅</td>
<td>0.16</td>
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</table>

### Via Geometry

- Geometry of stepped via hole and SEM images: Top view

### SEM Images

- (a) Radii table
- (b) Via geometry
- (c) SEM images
GATech-FIU Ideas

• GATech and FIU inventions address all the above problems of traditional SCMR in order to develop a WPT that is:
  – Highly efficient (mid-range)
  – Compact in size
  – Misalignment insensitive
  – Broadband
WPT Techniques

**Inductive Coupling**
- Operates at \( f_0 \)
- Very poor efficiency

**Resonant Inductive Coupling**
- Operates at \( f_0 = f_r = 1/\sqrt{LC} \)
- Poor efficiency
- Larger efficiency than inductive coupling due to RLC circuit resonance

**SCMR System**
- Operates at \( f_0 = f_{Q_{\text{max}}} = f_r = 1/\sqrt{LC} \)
- Large efficiency due to \( f_r = f_{Q_{\text{max}}} \)
- TX and RX elements naturally exhibit maximum Q-factor at a specific frequency \( f_{Q_{\text{max}}} \)

- \( L \) is the inductance of each element; the schematic assumes that each element has only a distributed inductance (this is true for loop elements)
- \( C \) is the external capacitance added to resonate the elements
- Other SCMR elements (e.g., helices, spirals, split ring resonators) can have both distributed inductance and capacitance
Misalignment Insensitive
Highly Efficient WPT

Source Element
TX 3D loop resonator

Load Element
RX 3D loop resonator

Normalized Efficiency

0 10 20 30 40 50 60 70 80 90

0

0.2

0.4

0.6

0.8

1

Angle(°)

Standard SCMR
Embedded TX + Loops RX
All Embedded

Provisional patent # 61/658,636
Distance = 7 cm

Provisional patent # 61/662,674
Design 2: Embedded 3-D loops
Each 3-D loop comprises of three connected orthogonal loops

- The RX and TX resonator elements as well as the source and load elements are 3-D continuous loops.
- Each 3-D loop comprises of three connected orthogonal loops.
- The source and load loops are embedded inside the TX and RX resonators, respectively.
- This type of system has a spherical symmetry and therefore, it is expected to have misalignment insensitive performance.
Design 2- Embedded 3-D loops

Angular Azimuth Misalignment

![Graph showing efficiency vs azimuth misalignment angle for Design 2. The graph compares simulation and measurement results. At azimuth misalignment angles of φ = 0°, φ = 45°, and φ = 90°, the efficiency percentage is plotted.]
Preliminary Implantable Results

- 60x-80x better than inductive coupling
- SRR-based shapes enabled miniaturization below $\lambda/200$
Solar Antennas

- Silicon in PV cell used as an antenna substrate
- Novel Slot type Antenna
- Gain 2-4dBi
- Directive Pattern
Motivation

**CHALLENGE**

Battery limits usability and autonomy

An alternative source of energy is required to power up the device

**GOAL**

Power up an RFID node to allow communication from the body to the reader without the use of battery

AVOIDING BATTERY REPLACING IN RFID BODY AREA NETWORK
Wearable Tag Antenna Design

Bent antenna electromagnetic model of the foot

Far Field Radiation Pattern

2.7 dBi @ 397 MHz

Measured and Simulated Return Loss
Circuit Implementation

Logo Antenna

Port to Antenna

RF Transmitter

Connection to Transformer

Diode Bridge

Storage Capacitor

MAX666 Voltage Regulator

MAX666

Piezo Element

Transformer MAX666

TXE-433-KH2

Antenna

4.7 pF

1 MΩ

1.3 MΩ

1.3 KΩ

Vcc

Piezo Element

25:1

Transformer

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Antenna
Capacitor voltage:
- Max 666 output voltage
- V waveform of C and Regulator

Transmitted signal captured by the RTSA:
- One Word Transmission

Circuit Implementation

<table>
<thead>
<tr>
<th>ENERGY PROVIDED BY THE PUSHBUTTON</th>
<th>stored in the capacitor</th>
<th>848.4 µJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNUTILIZED ENERGY</td>
<td>below 2.7 V capacitor voltage, the active RFID tag stops transmitting</td>
<td>17.1 µJ</td>
</tr>
<tr>
<td>AVAILABLE ENERGY</td>
<td>848.4µJ - 17.1 µJ</td>
<td>831.3µJ</td>
</tr>
<tr>
<td>ENERGY REQUIRED BY THE CIRCUIT FOR A ONE-WORD TRANSMISSION</td>
<td>POWER needed for 50 ms operation: 9mW</td>
<td>450 µJ</td>
</tr>
</tbody>
</table>
Human motion powered wireless tag

Nike logo printed antenna performance

Tag circuit

Step powered RFID communication

Diode Bridge
Storage Capacitor
Diode Bridge

Logo Antenna

RF Transmitter
Port to Antenna

MAX666 Voltage Regulator
Connection to Transformer
Logo Antenna

Nike logo printed antenna performance

Simulation, RF on Foot
Foot in shoe measurements

Pilot and Sync. Bits
10-bit ID
8-bit Data

Step powered RFID communication
Introduction

Enabling Technology has to be

- Power Autonomous
- Unobtrusive

Objective of this project → design a wearable, partially self-powered health monitoring and indoor localization shoe-mounted sensor module
Localization: Overview

Personal Area Network

«Smart Tile» mapped matrix of NFC tags embedded in the floor for localization purposes

Partially self-powered shoe-mounted NFC reader
Dual-Band Wearable Adidas-Shaped Antenna

- Unobtrusive wearable antenna design
- Dual Band: 900 MHz and 2.4 GHz
- Deposited nano particle silver ink on organic substrate (photo paper) technology
System Architecture Description

- Temperature Sensor
- TI NFC Reader Board (Transceiver + MCU + Antenna)
- Dual-band (900 MHz and 2.4 GHz) Adidas-shaped Antenna
- NFC tags embedded into the floor for localization purposes
Comparison Between Simulated and Measured Return Loss

Return Loss (dB)

Simulation | Measurement

Freq (GHz) 0.4 0.65 0.9 1.15 1.4 1.65 1.9 2.15 2.4 2.65 2.9
Mag. S11 (dB) -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0
Simulated Antenna Radiation Patterns

- Excellent performance in term of radiation pattern for both 900 MHz and 2.4 GHz standards, considering the presence of the foot
- Gain > 3dB
Localization: NFC system test

- Test → moving the tag from position 1 to 8 (shown in the figure) the maximum reading distance has been measured. The reader is placed at the center of the tile either vertically and horizontally.
Why 6LoWPAN?

- IPv6 over Low-power Wireless Personal Area Networks -> native support of the IPv6 protocol stack on the end device
- A low-power communication protocol based on the IEEE 802.15.4 PHY and MAC layer
- Backed up by an active IETF Working group with real prototypes
- The network, transport and application layers of the 6lowPAN protocol stack (right) are the same as those of the IPv6 stack (left) and the necessary changes exist in the adaptation layer on top of the IEEE 802.15.4 medium access control and physical layer.
RF Wireless Pressure Transducer

- Fewer components
- Smaller system size
- Less power consumption
Carbon Nanotubes as Gas Sensor

- CNTs structure can be conceptualized by wrapping a one-atom-thick layer of graphite into a seamless cylinder.
- Single-walled CNTs and Multi-walled CNTs
- A diameter of close to 1 nanometer, with a tube length that can be many thousands of times longer.
- CNTs composites have electrical conductance highly sensitive to extremely small quantities of gases, such as ammonia (NH3) and nitrogen oxide (NOx).
- The conductance change can be explained by the charge transfer of reactive gas molecules with semiconducting CNTs.

Fabrication of CNTs film:
- Vacuum Filtering, dip coating, spray coating, and contact printing, requiring at least two steps to achieve the patterns.
- Can it be inkjet-printed? Yes, if you can develop the recipe!
Silver electrodes were patterned before depositing the SWCNT film, followed by a 140°C sintering.

The electrode finger is 2mm by 10mm with a gap of 0.8mm. SWCNT film was 2mm by 3mm.

1.1mm overlapping zone to ensure the good contact between the SWCNT film and the electrodes.
Gas Detection

$$P_r = P_i + 2G_i + 2G_r - 40\log_{10}\left(\frac{4\pi}{\lambda}\right) - 40\log_{10}(d) + \eta$$

Tag Antenna @ 686MHz
$$Z_{ant} = 42.6 + j11.4 \, \text{Ohm}$$

SWCNT Film @ 868MHz
- Z = 51.6 - j6.1 Ohm in air
- Z = 97.1 - j18.8 Ohm in NH3

Power reflection coefficient changes from -18.4dB to -7.6dB. At reader’s side, this means 10.8dBi increase of the received power level.

By detecting this backscattered power difference, the sensing function is fulfilled.
Inkjet-Printed Graphene/CNT-Based Wireless Gas Sensor Modules

1. Chemical Absorption
2. Changing Material Properties
3. Measureable Electrical Quantities

Gas Sensor Technology

Charge Transfer

Graphene

CNT
Inkjet-Printed Graphene/CNT-Based Wireless Gas Sensor Experiment

- Prototype

- Set-up
The in-house developed novel sensor material demonstrates:
- **6% normalized resistance change** within 15 minutes of exposure to a concentration of 500 ppm of NH$_3$.
- excellent recovery time with **over 30% of material recovery** observed within 5 minutes without exposure to high temperature or any UV treatments.
Inkjet-Printed CNT-Based Wireless Gas Sensor Experiment

-Sensitivity of 21.7% and 9.4% was achieved for 10 ppm NO2 and 4 ppm NH3, respectively at 864 MHz.

-MWNT-based gas sensor demonstrates fast response to both gases (few seconds); the sensitivity achieved at 864 MHz is 24.2% for NO2 and 12.7% for NH3 in just 2 minutes’ time. Note that after testing, the sensor exposed to NH3 shows more rapid recovery.
Inkjet-Printed CNT-Based Wireless Gas Sensor Experiment

<table>
<thead>
<tr>
<th>Concentration (ppm)</th>
<th>Sensitivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10ppm NO2</td>
<td>21.7</td>
</tr>
<tr>
<td>4 ppm NH3</td>
<td>9.4</td>
</tr>
<tr>
<td>864MHz NO2</td>
<td>24.2</td>
</tr>
<tr>
<td>864MHz NH3</td>
<td>12.7</td>
</tr>
<tr>
<td>2.4GHz NO2</td>
<td></td>
</tr>
<tr>
<td>2.4GHz NH3</td>
<td></td>
</tr>
</tbody>
</table>

Note that after testing, the sensor exposed to NH3 shows more rapid recovery.

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Structural Health Monitoring

Infrastructure Health Monitoring needs
- Early warning system - microstrain
- Real Time
- Remote/autonomous sensing
- Low cost -> large scale deployment

Additional Areas
- Energy – Wind, Hydro, Oil/Gas extraction
- Airline
Smart Skin Strain Sensor

- Novel antenna based smart skin detects strain and cracks on structures it is mounted on
- Immune to iPhone effects
- Antenna sends back strain response using EPC Gen-2 Standard backscattered wireless signal
- Strain sensor used no batteries
- Range <30 feet

Solar Powered Smart Skins for Structural Health Monitoring

- Novel Antenna based smart skins detect strains and cracks in civil structures
- Remotely interrogated using novel RF reader
- Reader uses 2.9 GHz to remotely interrogate tag. Tag returns strain information using 5.8GHz for better strain sensitivity
- Uses Solar Powered Frequency doubling mechanism for long range
Solar Powered Smart Skins for Structural Health Monitoring

- Latest prototypes show capability to detect 20 μ-strain
- Range extended to 10 meters through the use of Solar Power
Power Scavenging

- **Power Scavenging Technologies:**
  - Mechanical Motion
    - Power Density: $4 \mu\text{w/cm}^2$
    - Resonance: Hz
  - Thermal
    - Seebeck or peltier effect
    - Power Density: $60 \mu\text{w/cm}^2$
  - Wireless
    - Power Density $\leq 1 \mu\text{w/cm}^2$
  - Solar
    - Power Density: $100 \text{ mw/cm}^2$
    - Does Not require differential

936 MHz: $-41 \text{dBm (0.08}\mu\text{w)}$