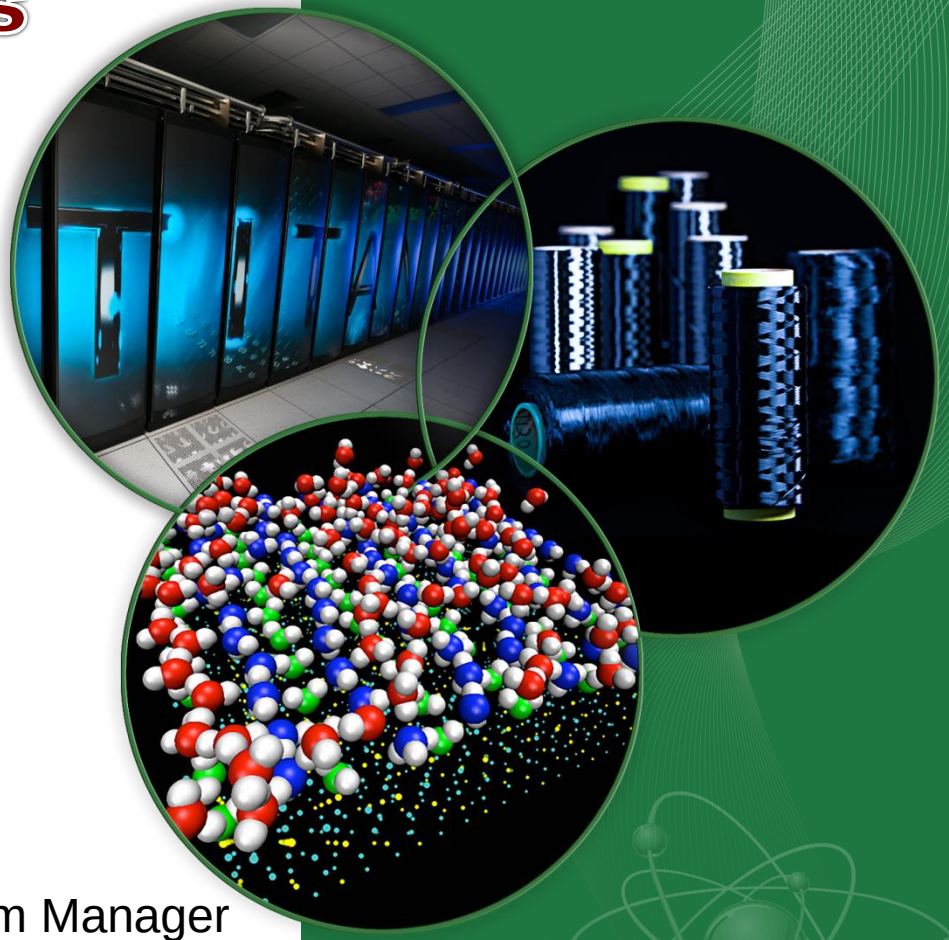
On Low-cost, Ubiquitous Sensors Networks; Applications in the Energy and Environmental Sector



By

Tim McIntyre
Energy & Environmental Sensors Program Manager
Electrical & Electronic Systems Research Division
15 December 2015

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE National Laboratory

Outline

The Challenge

- Integrated energy systems - a transactional economy
  - Electricity grid modernization and response
  - Building automation beyond LEED
  - Adaptive manufacturing
  - Smart and secure vehicles
- Environmental observatories
  - SPRUCE, NGEE Arctic, Tropics, Urban??

The Role of Low-cost Sensors

- Real-time observation – process dynamics
- Multi-scale observation – micro-biome → ecosystem
- Integrated multi-variate observation → Model V&V

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Integrated Energy Systems

AMIE demonstration project at ORNL Industry Day
September 23, 2015

Sensors Skunkworks

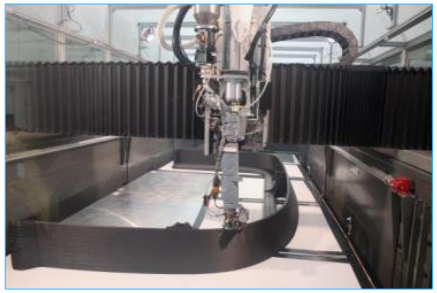
Building Technologies

Vehicle Technologies

Advanced Manufacturing

AMIE demonstration project

Sustainable Electricity



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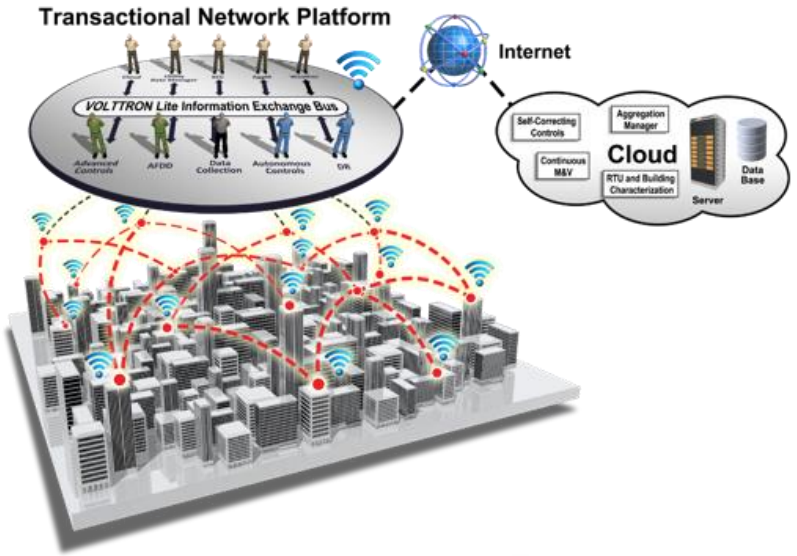
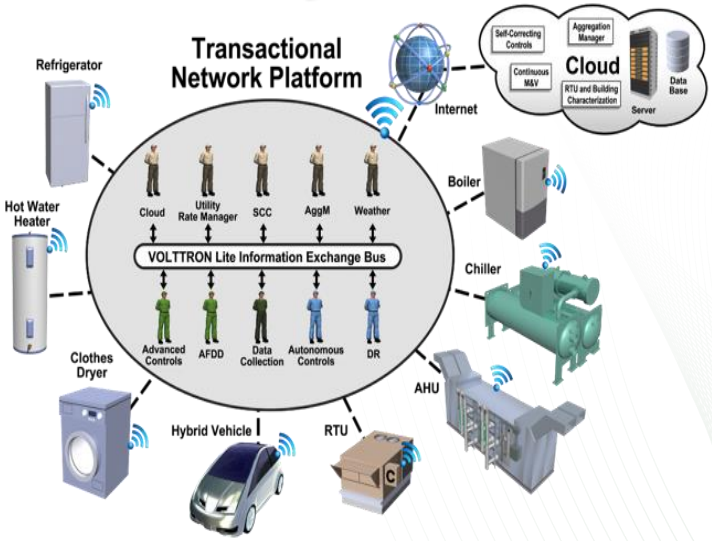
Transactional Network

- The transactional network enables energy saving retrofit solutions AND the networked systems to transact with the grid to mitigate variable distributed renewable energy sources
- Initially, the transactional concept is demonstrated using networked RTUs
- In the future, the concept can be extended to network other building systems, interaction between buildings and electric vehicles
- Work is being done at three labs
  - Oak Ridge
  - Pacific Northwest
  - Lawrence Berkeley





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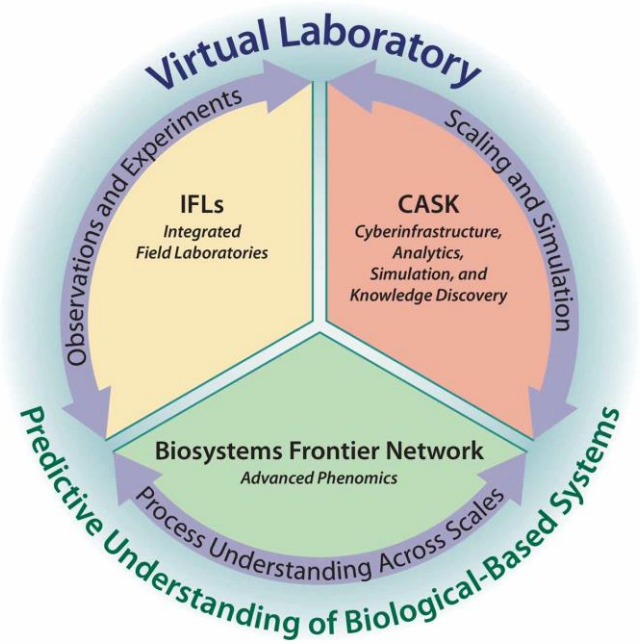
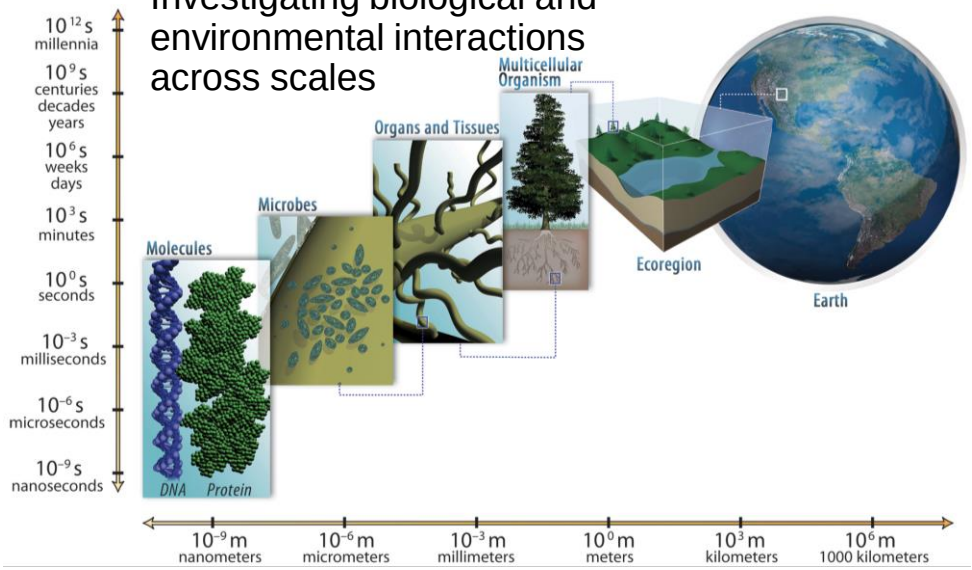
Environmental Intelligence Thrusts

Sensors Skunkworks



- Sensing
  - Multi-modal, multi-scale
  - Environmentally robust
  - Low-power, zero-power
  - Observation-relevant sampling theory – spatial, temporal
- Embedded computing
  - Achieve data reduction
  - Power-efficient (balance between measurement and transmit)

Investigating biological and environmental interactions across scales



- Communications
  - Analogy to industrial wireless
  - Wireless network protocols – perhaps a new protocol to support diversity and extent of sensor networks
  - Robust backhaul
  - Power harvesting and power management – radio/cellular/light/flow/thermal/etc.

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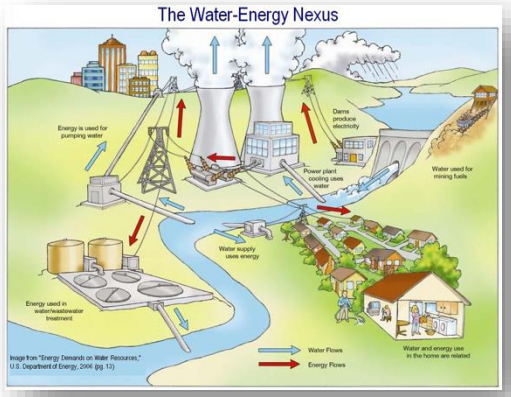
Environmental Intelligence Thrusts

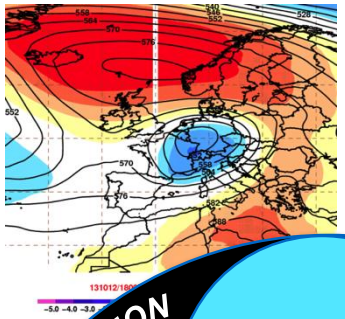
Sensors Skunkworks

Environmental Visualization with Integrated Observation Networks (EnVisION)

Characterizing environmental responses to changing climate

- Linked large-scale observations
- Sub-surface responses
- Plant-microbe interfaces



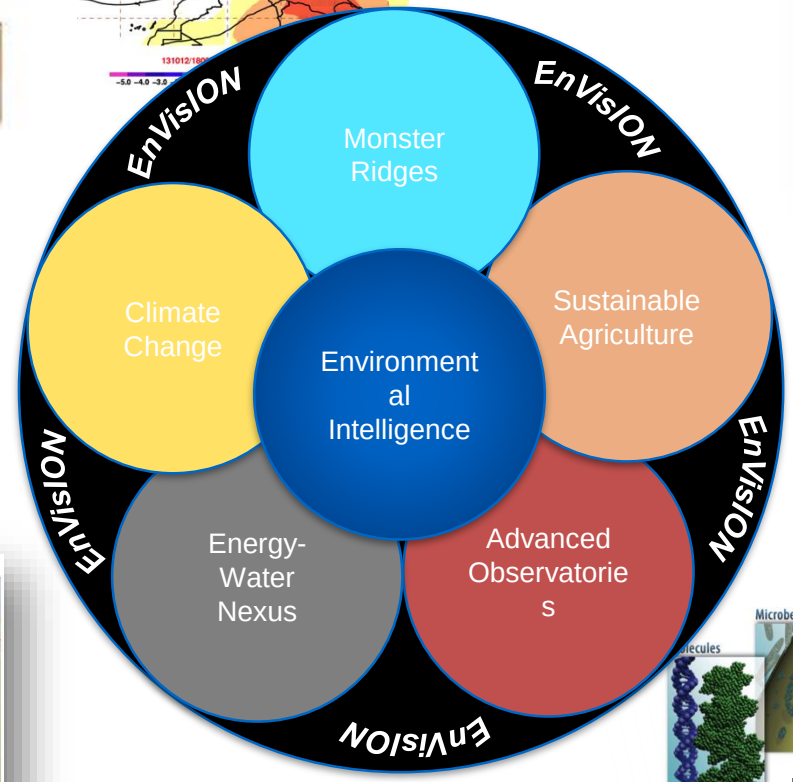


Connecting climate change to severe weather with advanced data analytics

- Signal processing
- Pattern recognition
- Prediction

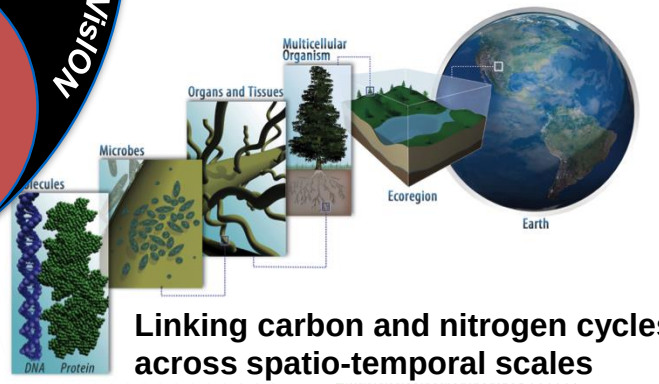
Optimizing land use, increasing crop yields, reducing water pollution

- Sensor networks
- Decision support
- Infrastructure prognostics



Water to Energy to Water

- Efficient delivery and use of resources
- Bioenergy
- Renewables



Linking carbon and nitrogen cycles across spatio-temporal scales

Advanced bio-geo-chemical measurements

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ORNL portfolio in direct digital manufacturing?

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What is our goal & what can we print?

Sensors Skunkworks

Functional Materials

Passive Wireless Technologies (PWTs)

U R Here ➔ Sensor platform designs
- Surface acoustic wave (SAW)
- Bulk acoustic wave (BAW)

➢ Remotely activated power
- Active sensors

PWT Apps.
- ➢ Leave Behind Sensors
- ➢ PWT Triggered Active Sensors
- ➢ Controlling Energy Use
- ➢ Leak/Plume/Trace Detection
- ➢ …..

Printed Electronics & Components (PECs)

➢ Integrated Systems
- Sensors, comms., energy sources, memory
- Conformal printing

➢ Discrete devices
- Ferromagnetic materials for RF electronics
- Rare earth magnets

PEC Apps.
- ➢ Flexible electronics
- ➢ Wearable sensors
- ➢ Smart skins
- ➢ Miniature RF communication systems
- ➢ RF amplifiers
- ➢ ….
- ➢ …
- ➢ ..
- ➢ .

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Goal: Ultra-low cost, Zero-power Sensors

Sensors Skunkworks

- Printable, zero-power sensors
  - Roll-to-roll processing ➔ mass producible
  - << $1/sensor ➔ disposable
  - No batteries or plugs ➔ completely passive
- Ubiquitous deployment
  - Peel-and-stick ➔ barcode labels
  - Scatter about ➔ dust in the wind
  - Wide-area coverage ➔ km^2
- Wireless ➔ without the radio
- Negligible O&M cost

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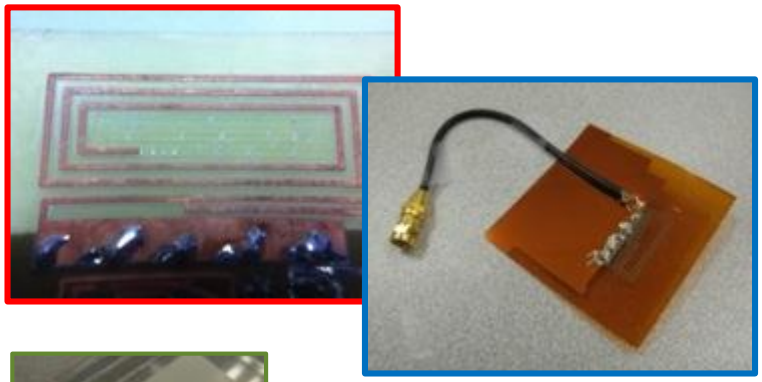
PWT Sensor Designs – SAW

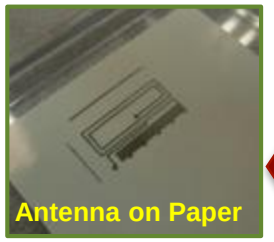
Surveillance of Wide areas with Acoustic wave Remote Monitoring Sensors (SWARMS)

- Printed antennas & sensors combine RF signals with SAWs enabling passive micro-sensors
- Sensor receives power from an RF interrogator; scavenging power from RF broadcast signals
- Tuned SAW structures provide each sensor with a unique ID and allow for many-sensor arrays
- Wide variety of thin film sensor types: temperature, humidity, VOCs, hydrogen, toxins, CO/CO_2, etc. are possible

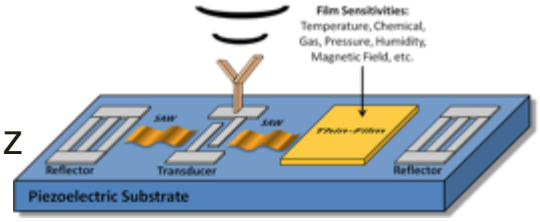
Antenna Design: 433 MHz

- "Inverted F" design
- Dimensions 16 by 27 mm
- Better than 10 dB return loss over 5 MHz





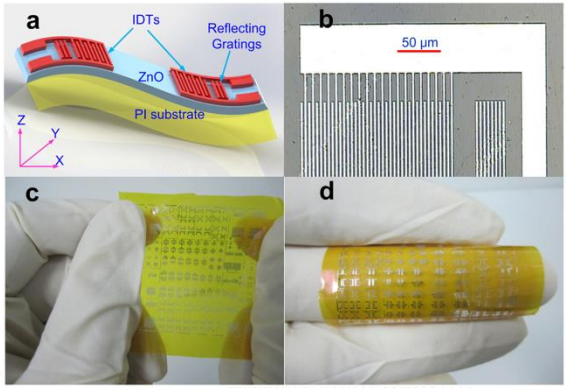
Path towards Low Cost, Ultrawideband Antenna Technology



Courtesy of Malocha et al

Surface Acoustic Wave (SAW) Sensors

What's next?
Printed fractal antennas



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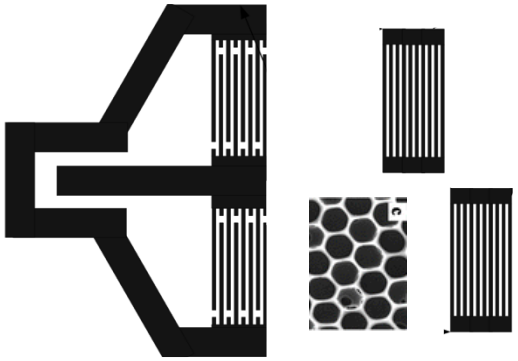
Functionalizing the RF-SAW Platform

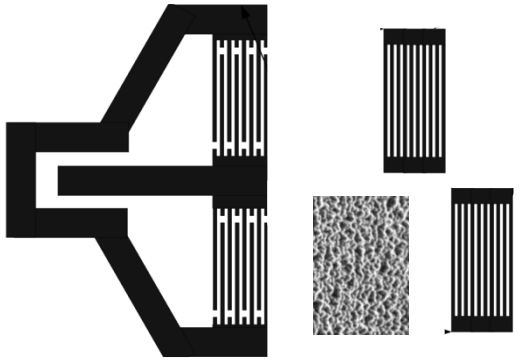
Sensors Skunkworks

Sensing Modalities

- Physical Sensing
  - Temperature
  - Pressure
  - Humidity
  - Strain/vibration
- Electronic Sensing
  - Current flow
  - Voltage
  - Charge
- Chemical Sensing
  - CO_2
  - CH_4
  - VOCs



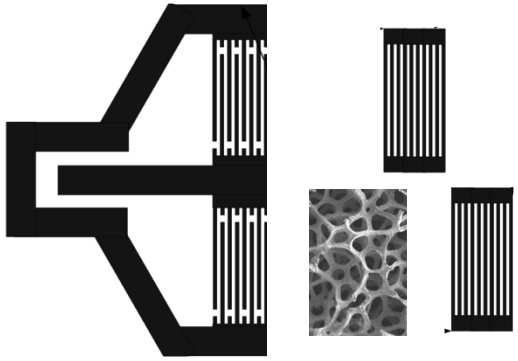
Hydrophylic PMMA film for humidity sensing

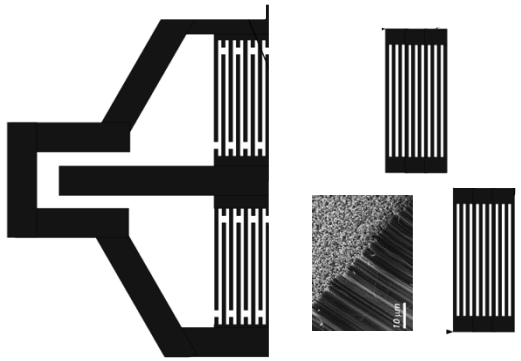


Palladium film for hydrogen sensing

Sensing Applications

- Physical Sensing
  - Energy control
  - Condition monitoring
  - Presence detection
- Electronic Sensing
  - Grid monitoring
  - Surveillance
- Chemical Sensing
  - Pipeline monitoring
  - Leak/plume detection
  - Accident response





Carbon nano-tube array for CO_2 sensing

Nano-s

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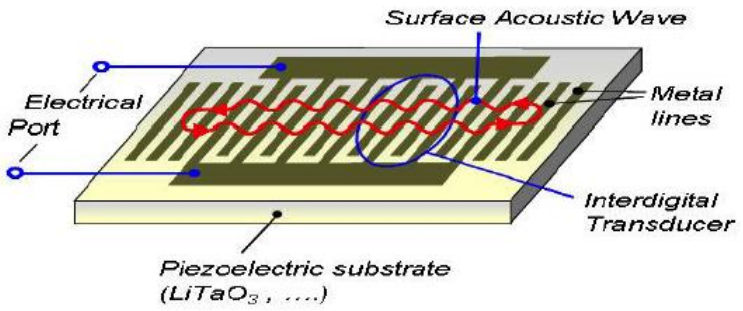
Technology Comparison – SAW vs. BAW

Sensors Skunkworks

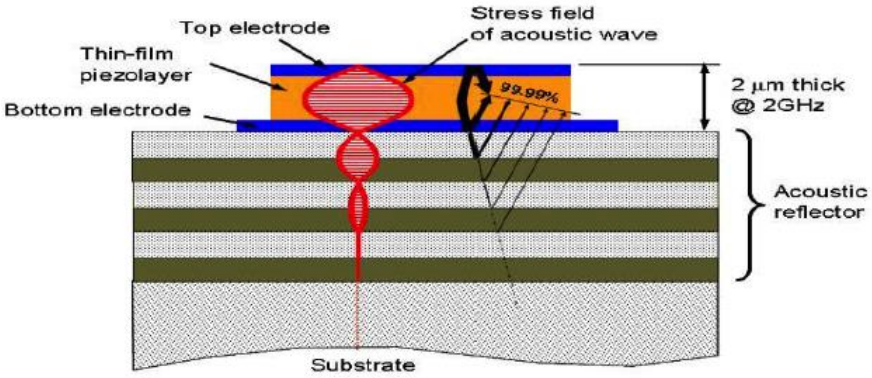
Surface Acoustic Wave
No integration with CMOS
Acoustic wave is excited in piezoelectric crystal



electrode width ≈ λ/4
$v \approx 4000$ m/s

Q-values typically ≈ 800

Bulk Acoustic Wave
Integration with CMOS possible
Acoustic wave is excited in thin-film piezo-layer



layer thickness ≈ λ/2
$v \approx 10000$ m/s

Q-values up to 2700

(Solidly Mounted Resonator)

Courtesy of Quovo Inc.

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- U R Here ➔ Remotely activated power
  - Active sensors

PWT Apps.

- Leave Behind Sensors
- PWT Triggered Active Sensors
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Printed Electronics & Components (PECs)

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PEC Apps.

- Flexible electronics
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- Miniature RF communication systems
- RF amplifiers

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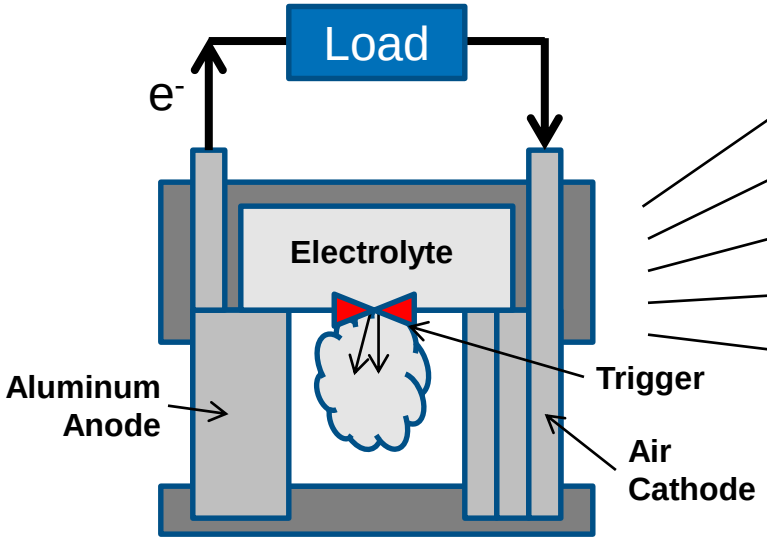
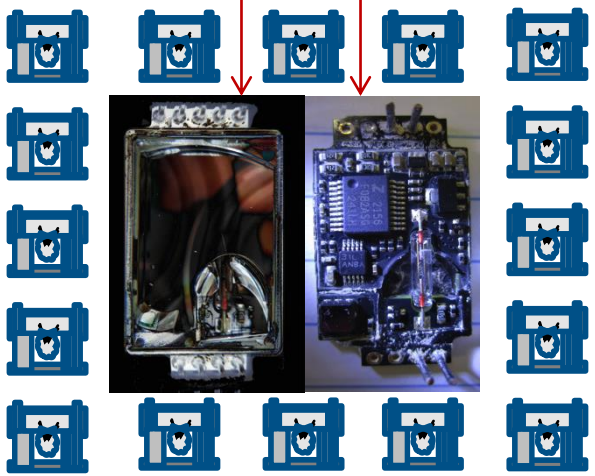
Remotely Activated Miniature Power Source for Persistent Active Sensing

Sensors Skunkworks

Proven Aluminum-Air Battery



Sensor/Instrument Payload



Shown is a 16 battery array powering a miniature NDIR spectrometer

Miniature Al-Air Battery has:

- *Electrolyte Reservoir Segregated from the Electrodes Until Triggered*
- *Triggering is Caused by a Remote Electromagnetic Pulse Exciting an RF/SAW*
- *Device Converts EM Energy into an Acoustic Impulse that Ruptures the Electrolyte Storage Membrane.*

What's new?

1. *Miniaturized*
2. *Replicated*
3. *Dormant until remotely triggered*
4. *Returns to zero-power drain, dormant condition until needed again*

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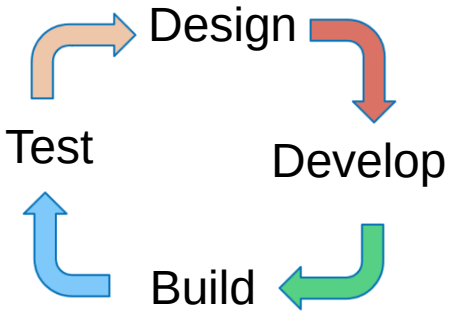
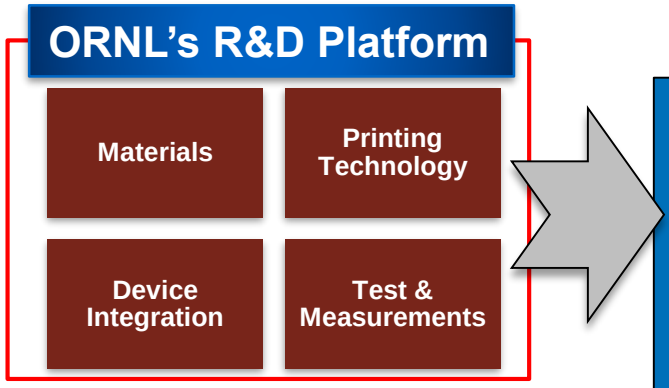
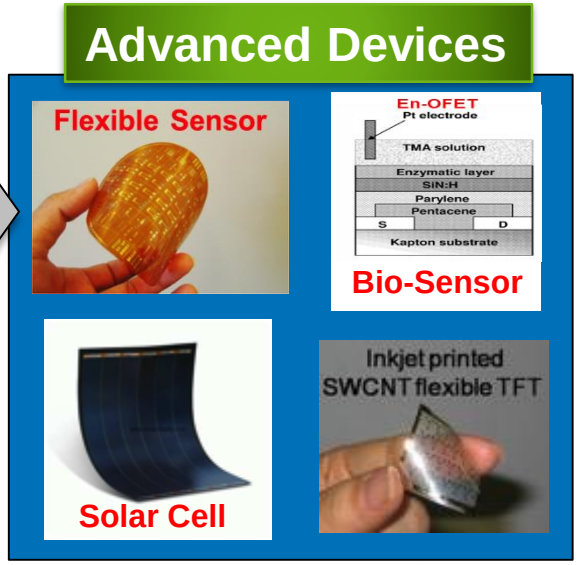
Printed Electronics and Components – Integrated Systems

Sensors Skunkworks

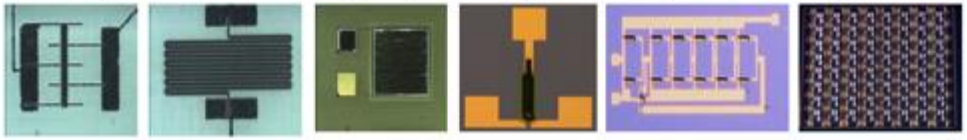




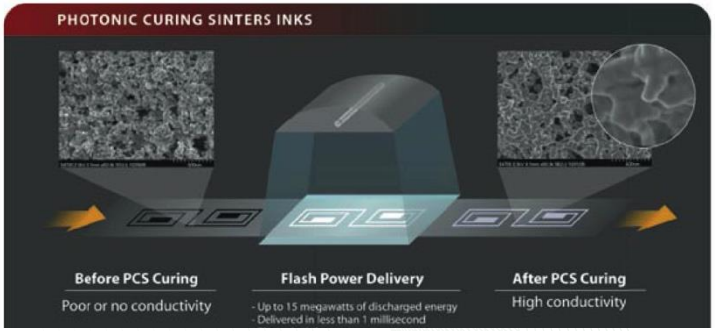


- Fine Lines, Patterns, Bumping, Films, 2D/3D Surfaces

- Building Blocks: Resistors, Capacitors, Inductors, Transistors, Memory



- 3D Micro-Structures (Developmental)



Rapid thermal processing of printed circuits on paper and polymers

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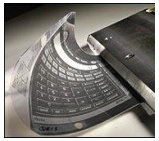
Printed Electronics and Components – Integrated Systems

Sensors Skunkworks

Flexible Displays

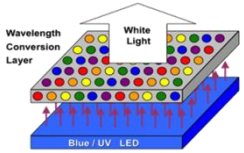


Crystallize a-Si thin film transistors for backplane

Thin Film Batteries

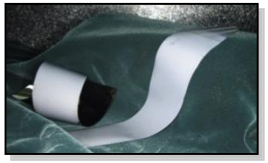
Increase storage capacity by controlling grain growth and orientation

Solid State Lighting



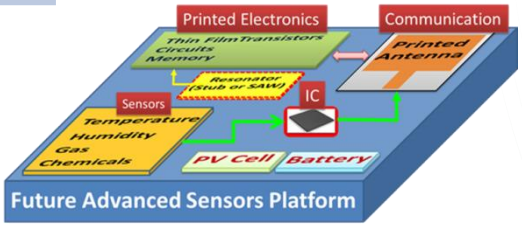
PTP anneals nanostructure to reduce defects and increase efficiency

Thin Film Photovoltaics

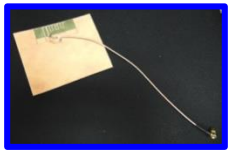


Crystallize Amorphous Silicon on Metal Foil

Texture CIGS Nanocrystals on Polymer Substrate

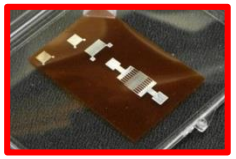


Wireless Communication



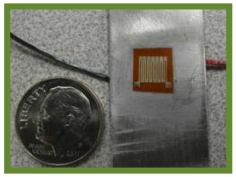
Low Cost, Flexible RF Rx/TX Components

Environmental Sensors



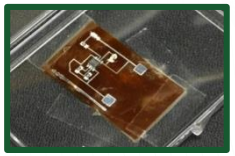
Multifunctional Printed Sensors: Additive Integration

Strain Gauges



Mechanical Sensors on Demand

Flexible Circuits



Flexible Circuits/Surface Mount Device (SMD) Technology

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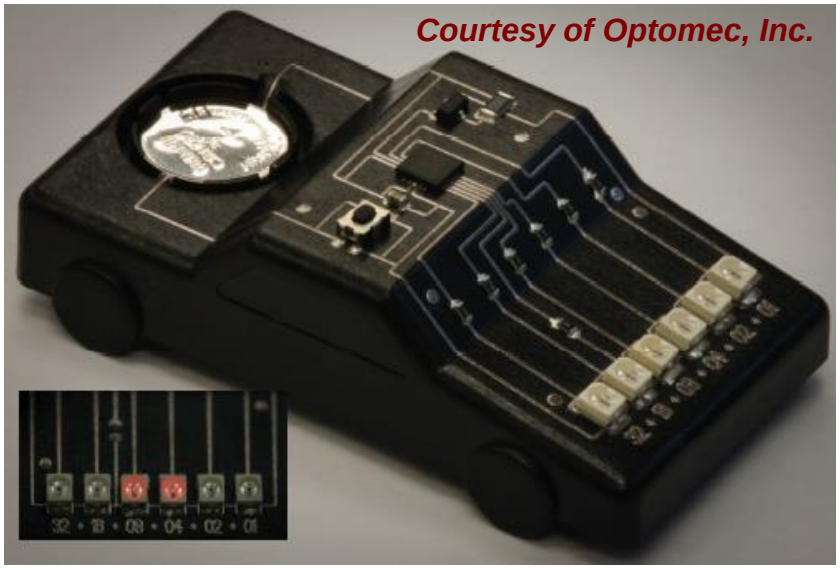
Printed Electronics and Components – Conformal Printing

Sensors Skunkworks

- Material performance should be maintained irrespective of the integration scheme
- Resolution and Cost/performance ratio will dictate manufacturing technology integration
- Multifunctionality and Multi-technology co-integration possibilities: Promising for novel products and new markets that have not yet been envisioned



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What is our goal & what can we print?

Sensors Skunkworks

Functional Materials

Passive Wireless Technologies (PWTs)

- Sensor platform designs
  - Surface acoustic wave (SAW)
  - Bulk acoustic wave (BAW)
- Remotely activated power
  - Active sensors

PWT Apps.

- Leave Behind Sensors
- PWT Triggered Active Sensors
- Controlling Energy Use
- Leak/Plume/Trace Detection

Printed Electronics & Components (PECs)

- Integrated Systems
  - Sensors, comms., energy sources, memory
- Conformal printing

U R Here ➔

- Discrete devices
  - Ferromagnetic materials for RF electronics
  - Rare earth magnets

PEC Apps.

- Flexible electronics
- Wearable sensors
- Smart skins
- Miniature RF communication systems
- RF amplifiers

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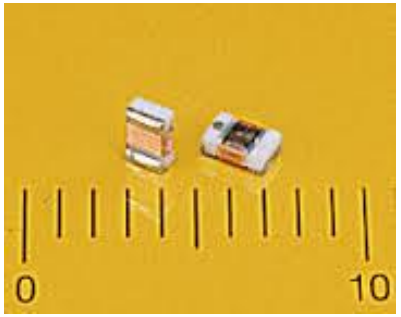
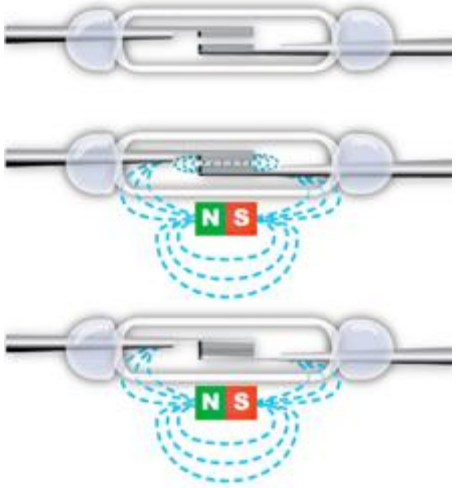
Printed Electronics and Components – Discrete Devices

Printing conductors, dielectrics, insulators, and exotic functional materials enable many types of miniature devices.

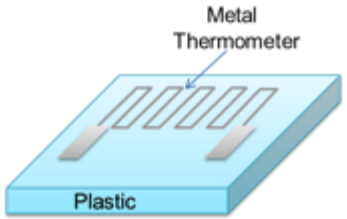
Ultra-miniature inductors



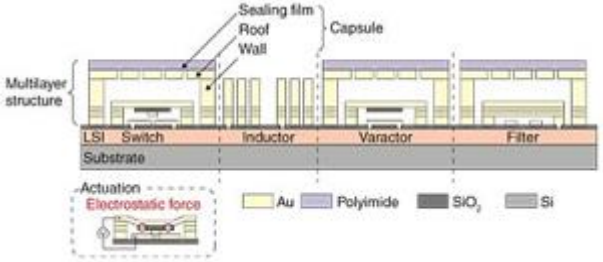
Magnet switches



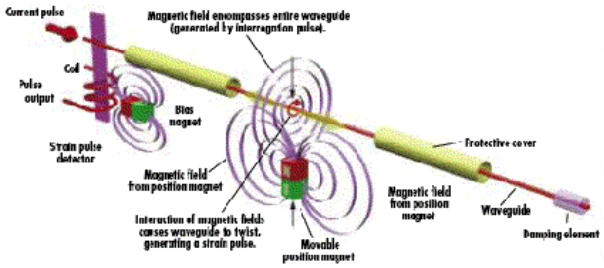
Thin film temperature sensors



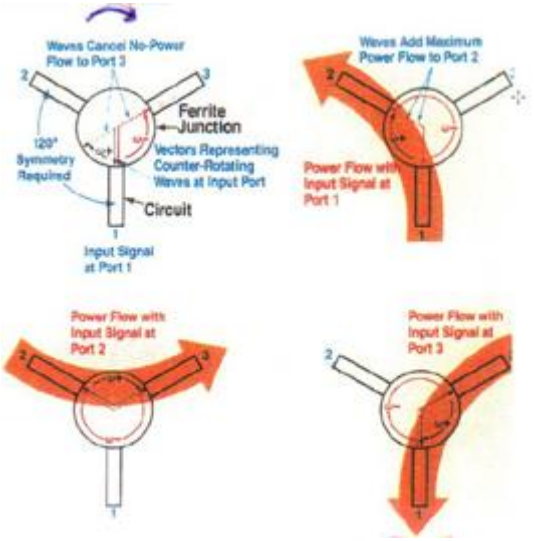
Integrated RF MEMS

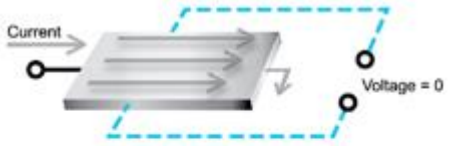


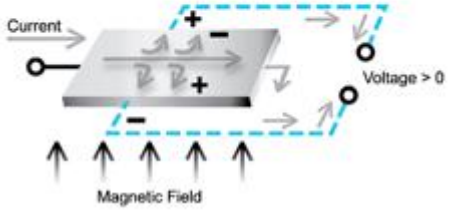
Magneto-strictiion position sensor



RF circulators







Hall Effect sensors

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Printed Electronics and Components – Discrete Devices

Sensors Skunkworks

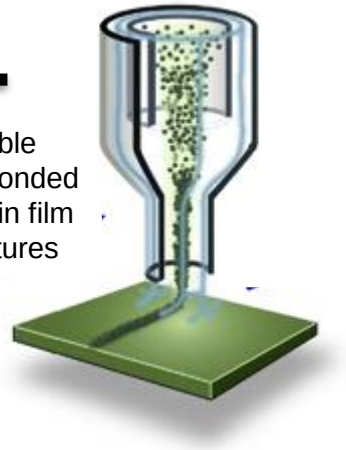
>5Million REM/yr
>60 tonnes/yr

REMs ground into fine particles

Particles may be pre-coated before deposition

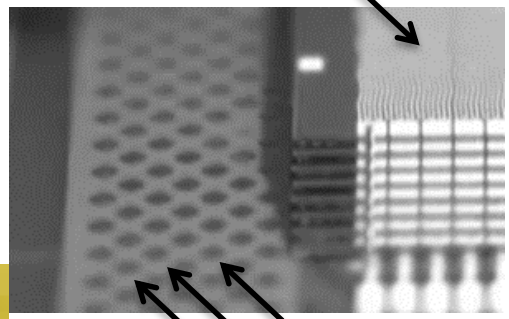
Particle size <1μm

High definition deposition methodology



Printed variable magnetization bonded magnets and thin film laminate structures

Bonded magnet laminates



RE particle loading sites

Bonded magnet parts used in power tools, hair dryers, toys, blenders, and many other consumer products

- The market for bonded magnets is >$10B/yr.
- Many products employ over-specified magnets.
- Bonded magnets from recycling frees up Nd supplies for high performance applications requiring premium RE magnets.

Direct printing bonded magnets creates customized properties, micron feature size/shape, 100nm thickness control, tailored particle loading (precise flux patterning, and versatile material composition).

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Summary

Direct digital printing technology is rapidly advancing the state-of-the-art in sensors and electronics.

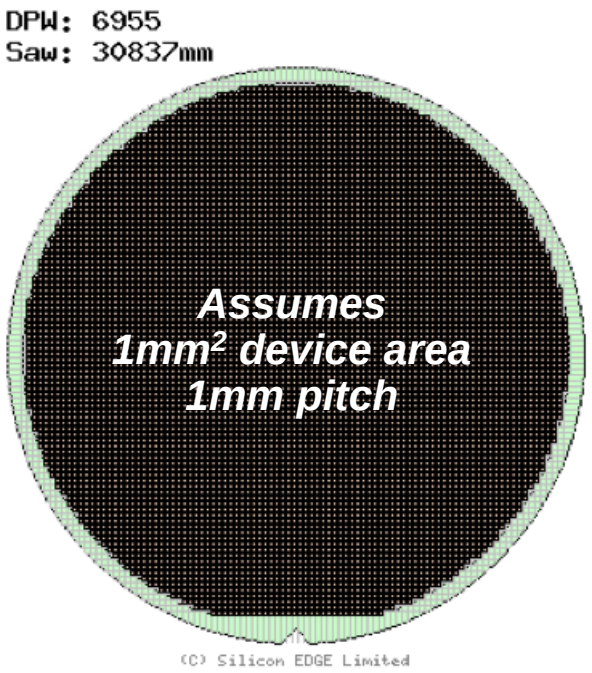
Passive Wireless Technologies (PWTs)

- Sensor platform designs
  - Surface acoustic wave (SAW)
  - Bulk acoustic wave (BAW)
- Remotely activated power
  - Active sensors

Printed Electronics & Components (PECs)

- Integrated Systems
  - Sensors, comms., energy sources, memory
- Conformal printing
- Discrete devices
  - Ferromagnetic materials for RF electronics
  - Rare earth magnets

PWT SAW sensors



Bill of Materials ~ $100
Devices per Wafer ~ 7,000
Cost per Sensor < 2¢

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Example Application

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Leaks of Concern

> 6 SCFH → 1 Ton/Year

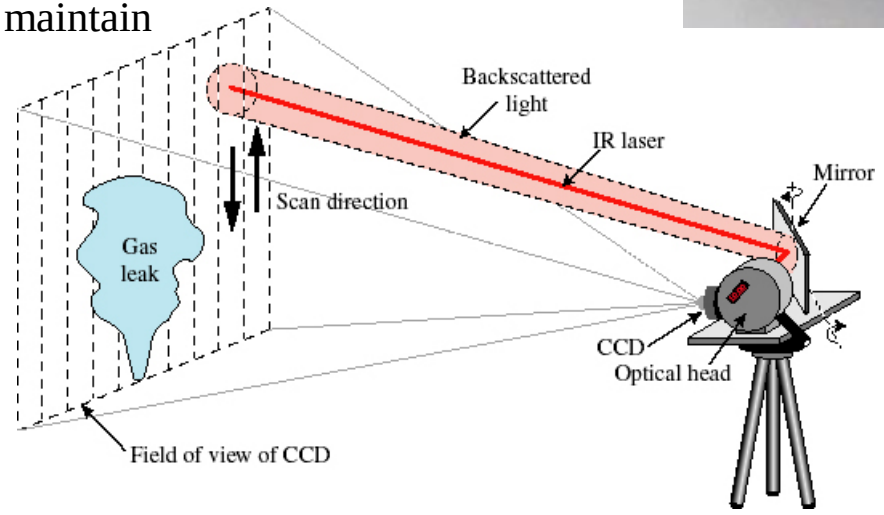
(0.17 Standard m^3/sec)

Sensors Skunkworks

Typical 10m x 10m well pad

Pressurized leaks are directional
Weather conditions increase dispersion

Optical remote sensors can image leaks, but they're expensive to deploy and maintain



Modest leakage forms a cloud around the leak

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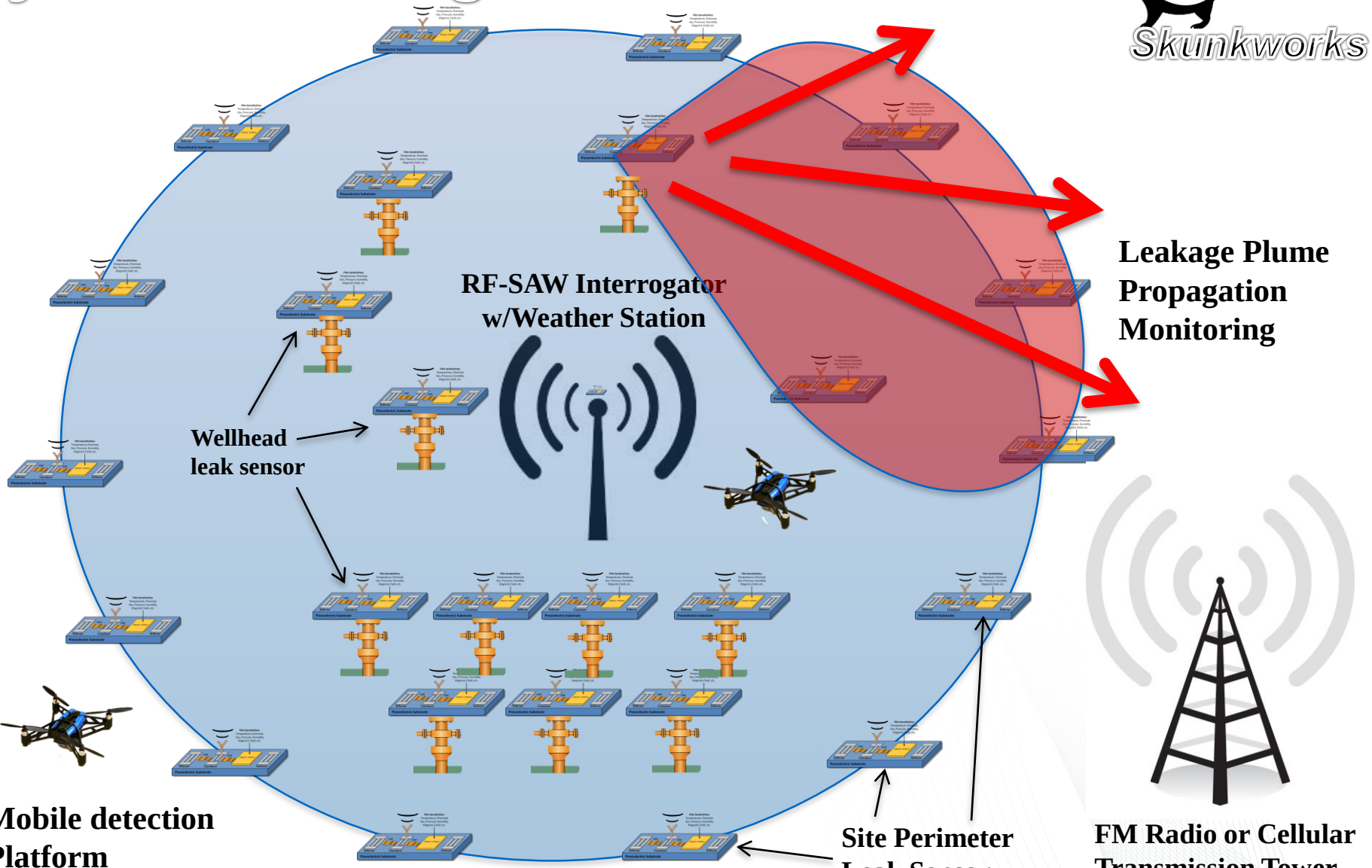
Hydro- fracturing Site

Sensors Skunkworks



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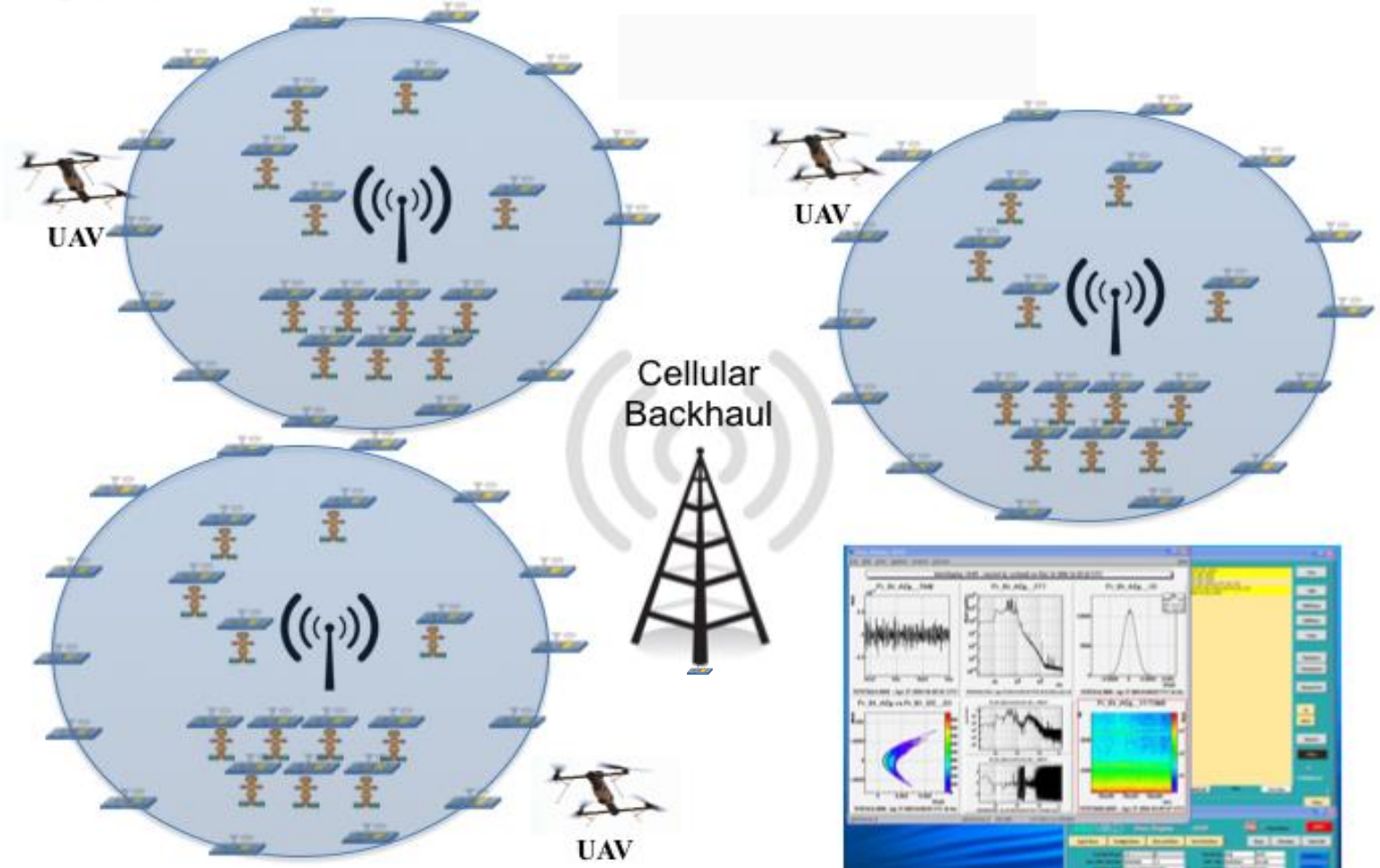
SWARMS Multiple Hydro-fracturing Network

Sensors Skunkworks



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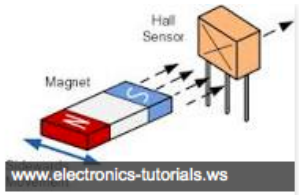
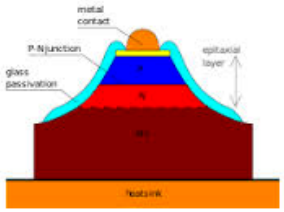
A **Hall effect sensor** is a transducer that varies its output voltage in response to a magnetic field. **Hall effect sensors** are used for proximity switching, positioning, speed detection, and current **sensing** applications. In its simplest form, the **sensor** operates as an analog transducer, directly returning a voltage.



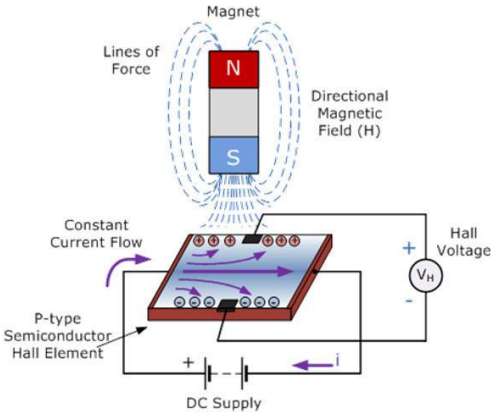
Hall effect sensor - Wikipedia, the free encyclopedia
https://en.wikipedia.org/wiki/**Hall_effect_sensor** Wikipedia

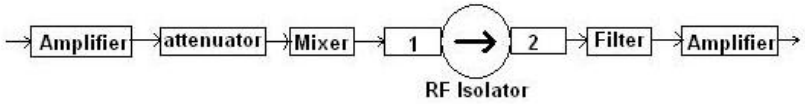
More about Hall effect sensor

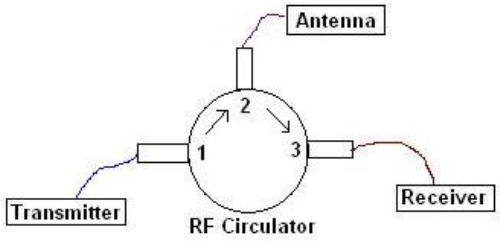
In electronics, a varicap diode, **varactor** diode, variable capacitance diode, variable reactance diode or tuning diode is a type of diode designed to exploit the voltage-dependent capacitance of a reversed-biased p–n junction.



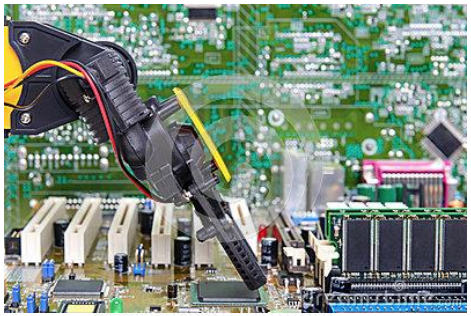
Varicap - Wikipedia, the free encyclopedia
https://en.wikipedia.org/wiki/Varicap Wikipedia



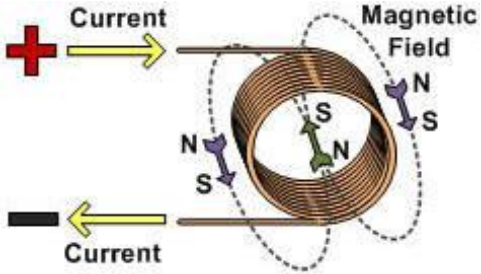




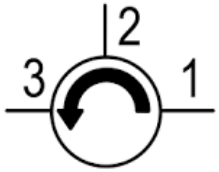
Automated robotic electronic circuit board repair



Printing electrodes that enable magnetic domain alignment of printed magnets



A **circulator** is a passive non-reciprocal three- or four-port device, in which a microwave or **radio frequency** signal entering any port is transmitted to the next port in rotation (only).



Circulator - Wikipedia, the free encyclopedia
https://en.wikipedia.org/wiki/**Circulator** Wikipedia

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