Electric Power Sensing for Demand Response

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Motivation for new electric power sensors

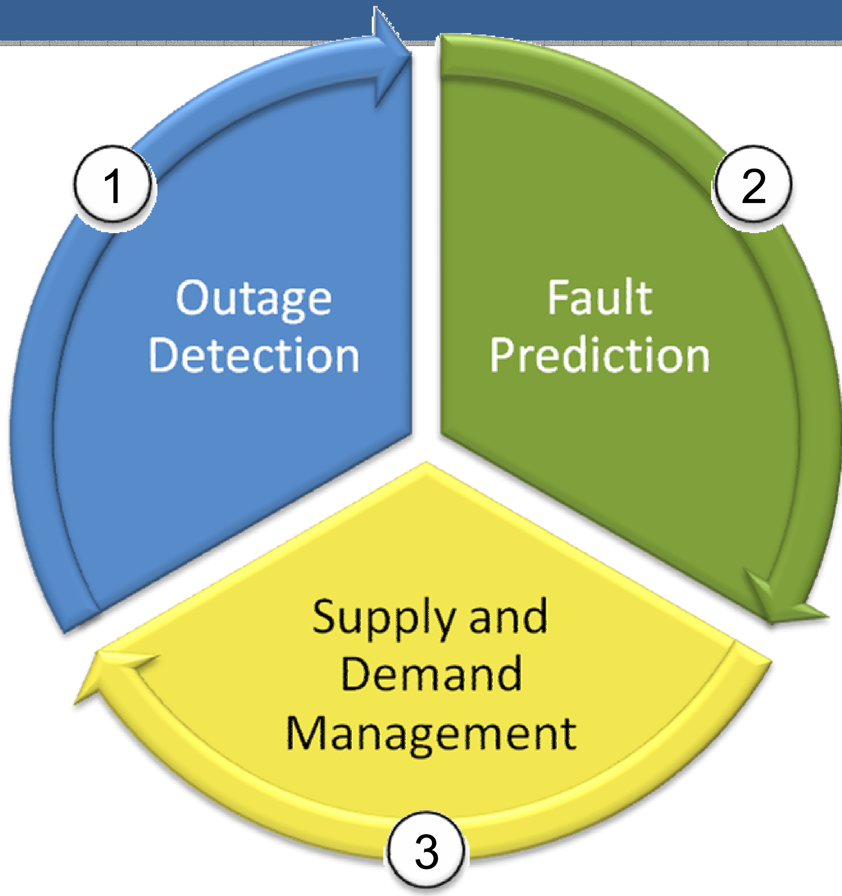
The "smart grid" will require new, inexpensive sensors to measure electric current and voltage throughout the network. Applications include:

- monitoring electricity end-use
- network fault detection and diagnosis
- condition monitoring of underground distribution cables

We have developed a new MEMS (micro-electro-mechanical systems) AC current sensor for these applications. It is passive, requiring no power source, and is thus suitable for wireless sensor node deployment. The sensor operates on proximity without needing to encircle the current carrier or break the electric circuit upon installation, resulting in an expanded set of possible deployment scenarios.

MEMS sensors can transform electric power transmission monitoring in three applications

- MEMS sensors are placed throughout the transmission and distribution grid
- **Sensors detect outages and communicate to operators** in real time
- Location of outage is pinpointed and repairs initiated more quickly



- Series of MEMS sensors are placed in transmission cable insulation
- When damage occurs to cables, **MEMS sensors detect small imbalances in transmission cable current**
- Sensors communicate that cable needs servicing or replacement

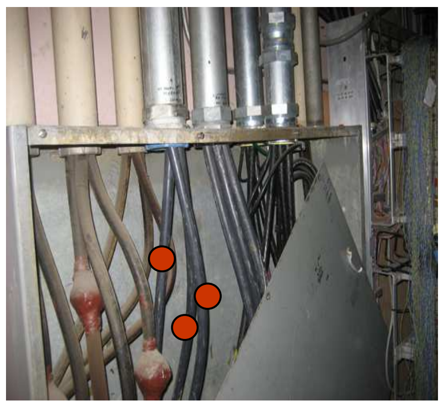
- MEMS sensors are placed at building circuit breakers and appliance cords
- Built-in transceivers **wirelessly transmit current signal to smart-meter node**
- Architecture Demand Response (ADR) or smart grid systems adjust generation or appliance consumption accordingly

Broad penetration of sensors can transform power supply & demand

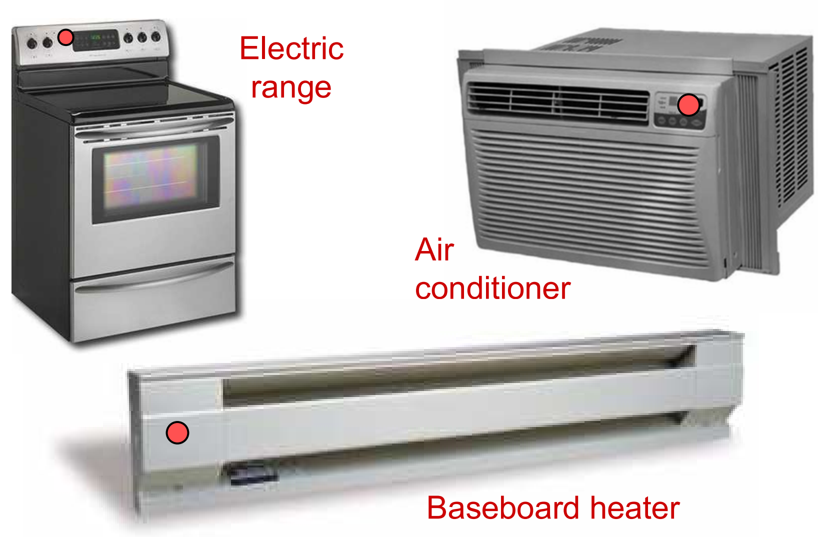
Sub-metering within buildings	Appliance end-use monitoring

- MEMS sensors can be installed onto individual circuit breakers
- Radio inside breaker box transmits data for interpretation

Cable access points



- MEMS sensors can be retrofitted or integrated into power cables within buildings

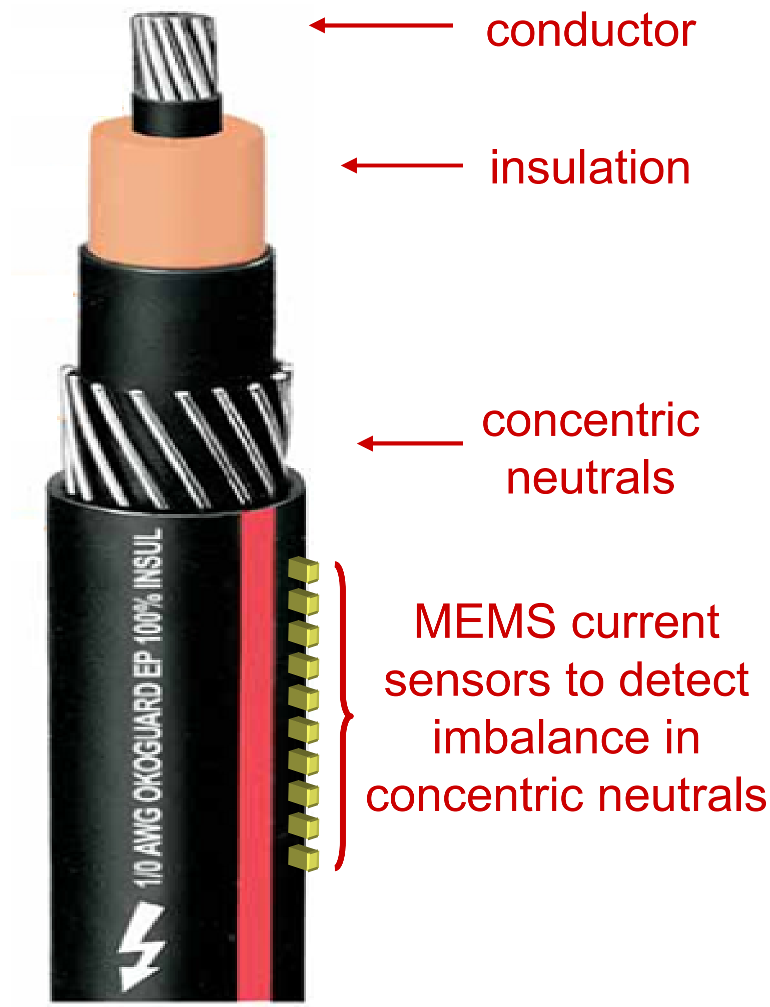


- **Incorporating MEMS sensors in appliances enables demand response and improved energy efficiency**
- MEMS sensors can be retrofit to appliance cords or built in to appliances

● Represents MEMS sensor

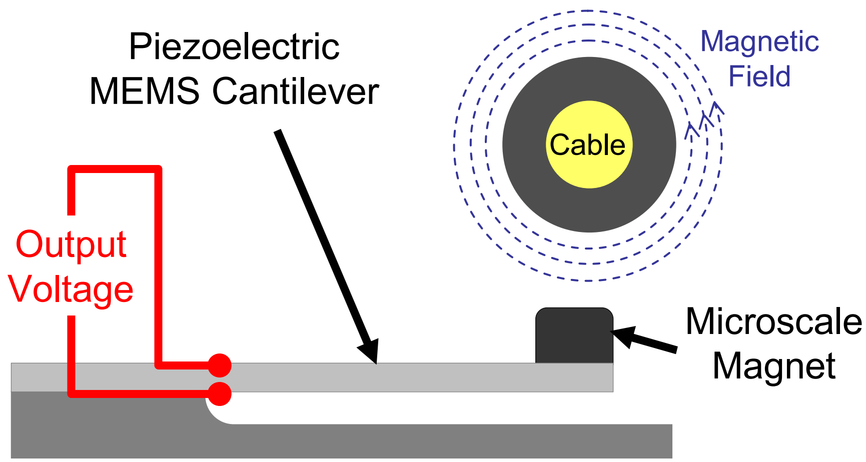
Application: Electric power distribution cable condition monitoring

- Electric power distribution cables carry power at intermediate voltages in the range of 4 - 35 kV, connecting high-voltage transmission with low-voltage local networks
- Insulation breakdown due to water infiltration is a common cause of sudden and costly outages
- An array of MEMS current sensors placed on the cable's exterior can detect imbalances in current among the concentric neutrals, indicating cable needs servicing or replacement

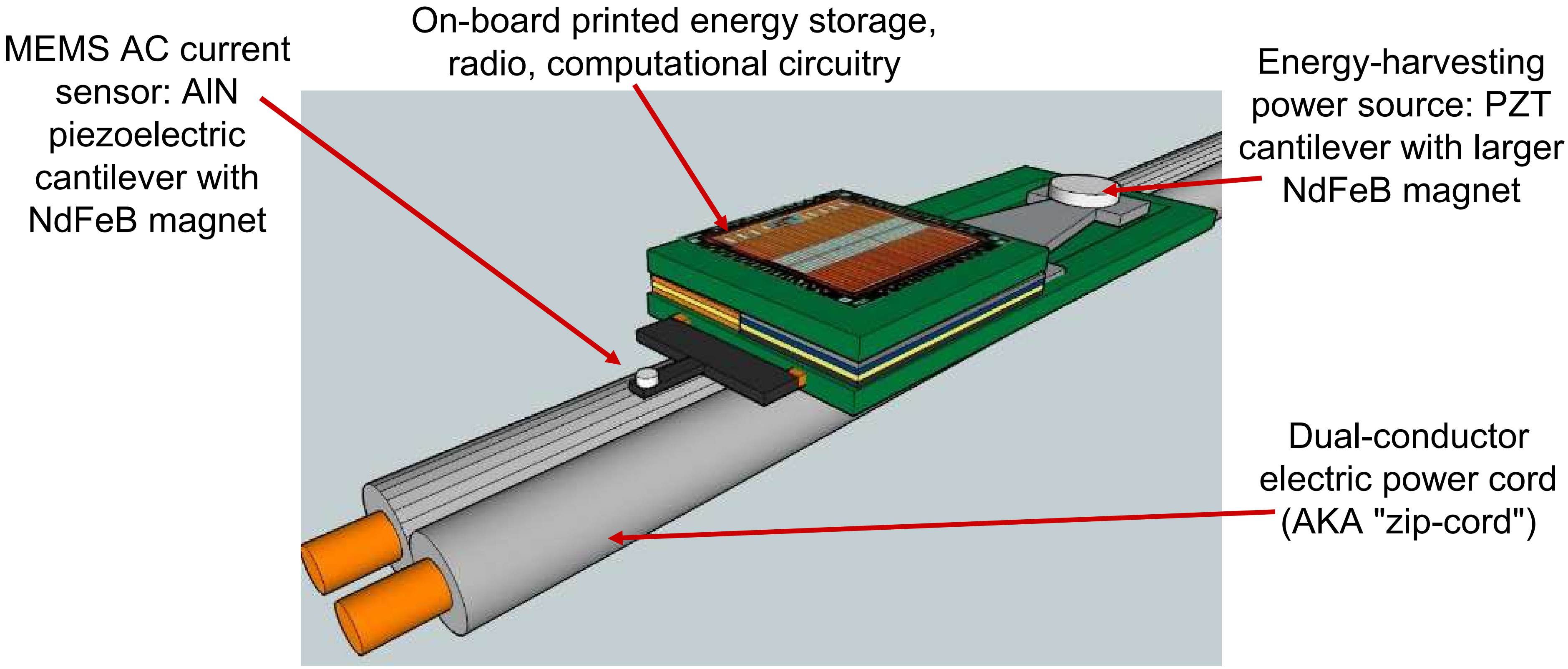


Design concept: Piezoelectric cantilever and permanent magnet

- **AC current** results in an oscillating magnetic field around a wire.
- **Cantilever oscillates** due to the magnet on the end of the cantilever interacting with the magnetic field of the wire.
- **Piezoelectric coating** on cantilever outputs an oscillating voltage.
- **Oscillation amplitude** and output voltage are proportional to the amplitude of the current traveling through the wire.



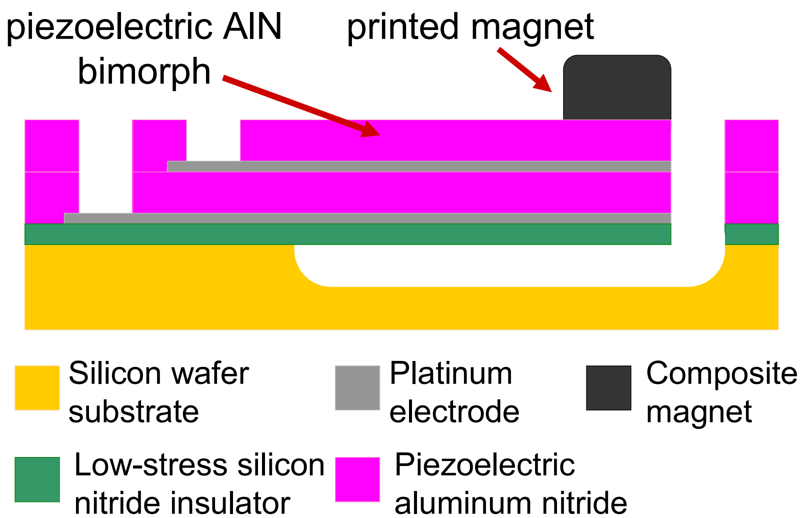
Concept sketch: Integrated current sensor node



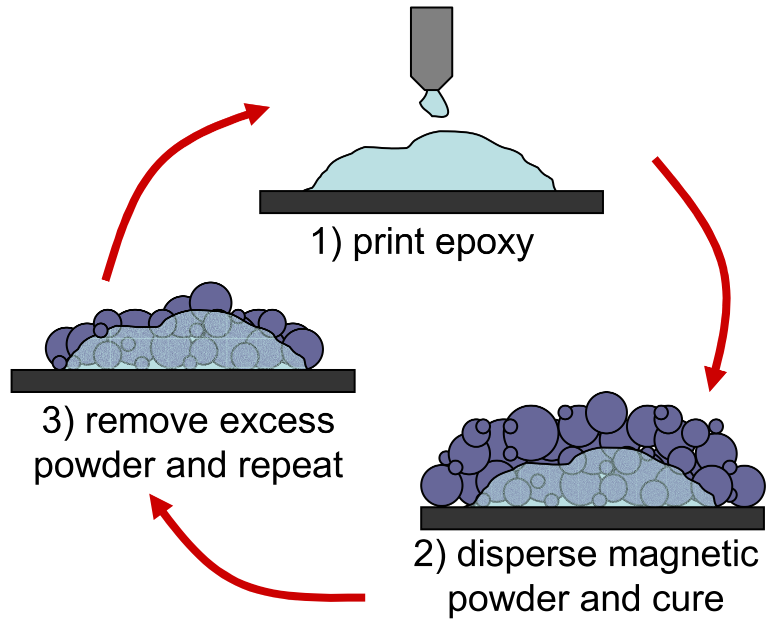
A self-contained, self-powered current sensor node can be constructed using two similar piezoelectric cantilever devices, one optimized for current measurement and the other for energy harvesting power generation. These devices combined with printed storage (battery/capacitor) and low-power computation and radio circuitry would comprise a complete sensor node.

MEMS device fabrication process

MEMS device schematic

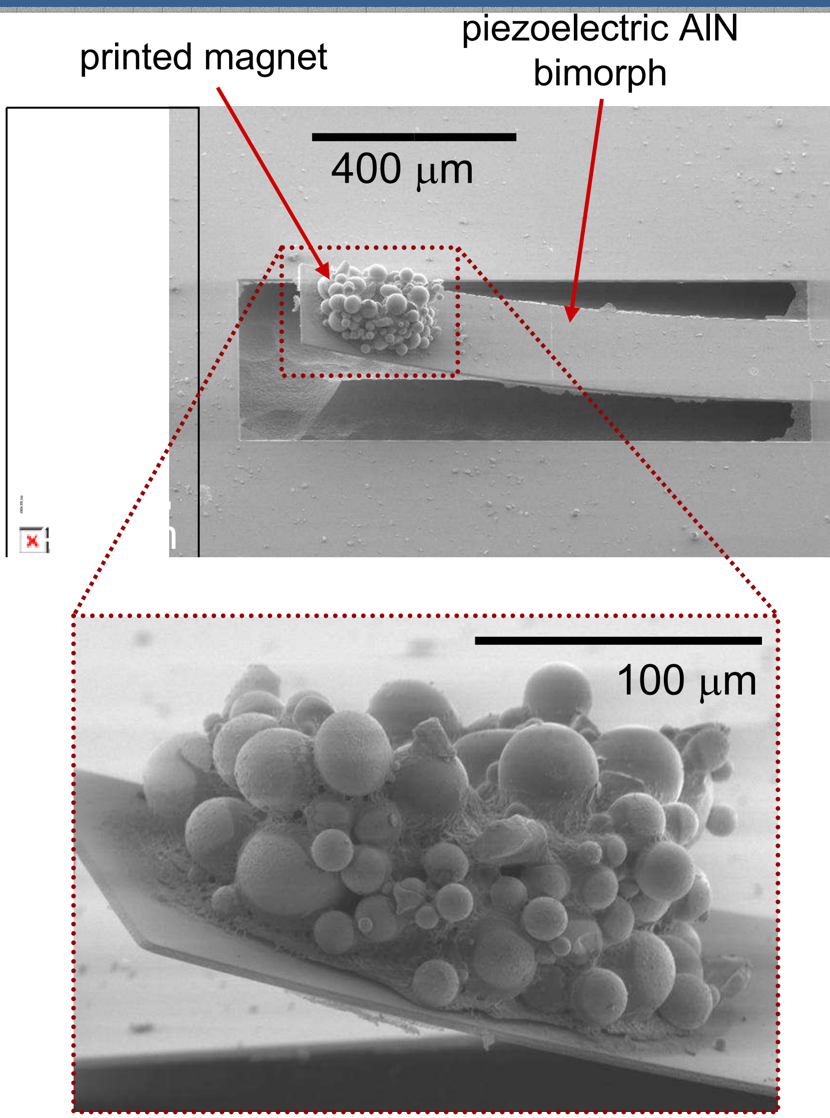


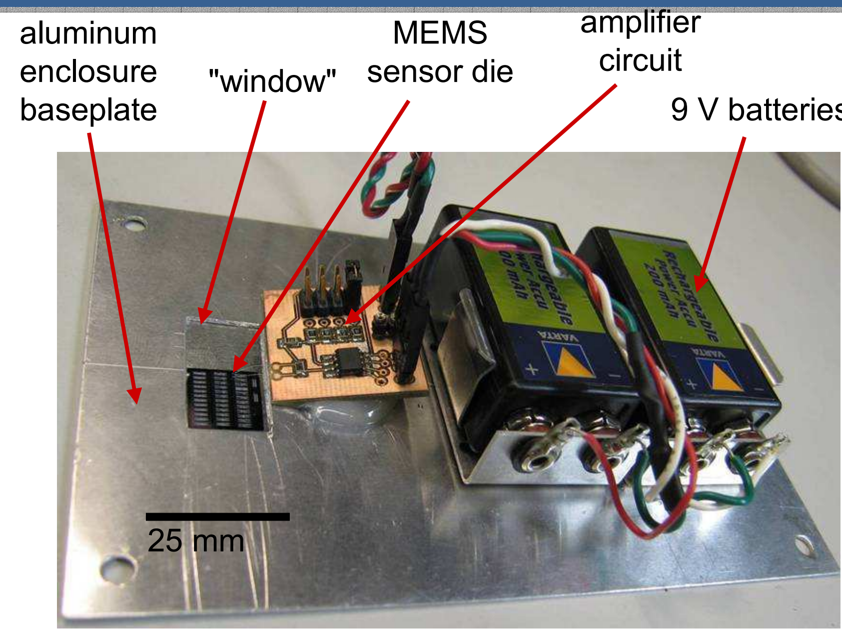
Microscale magnet fabrication

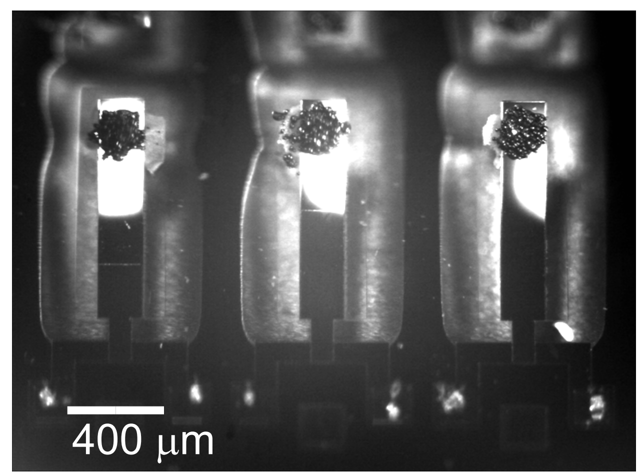


- MEMS piezoelectric aluminum nitride bimorph cantilevers were fabricated using a four-mask process in the UC Berkeley Microlab
- Microscale composite permanent magnets were dispenser printed using NdFeB-alloy magnetic powder in an epoxy matrix

MEMS current sensors and test assembly

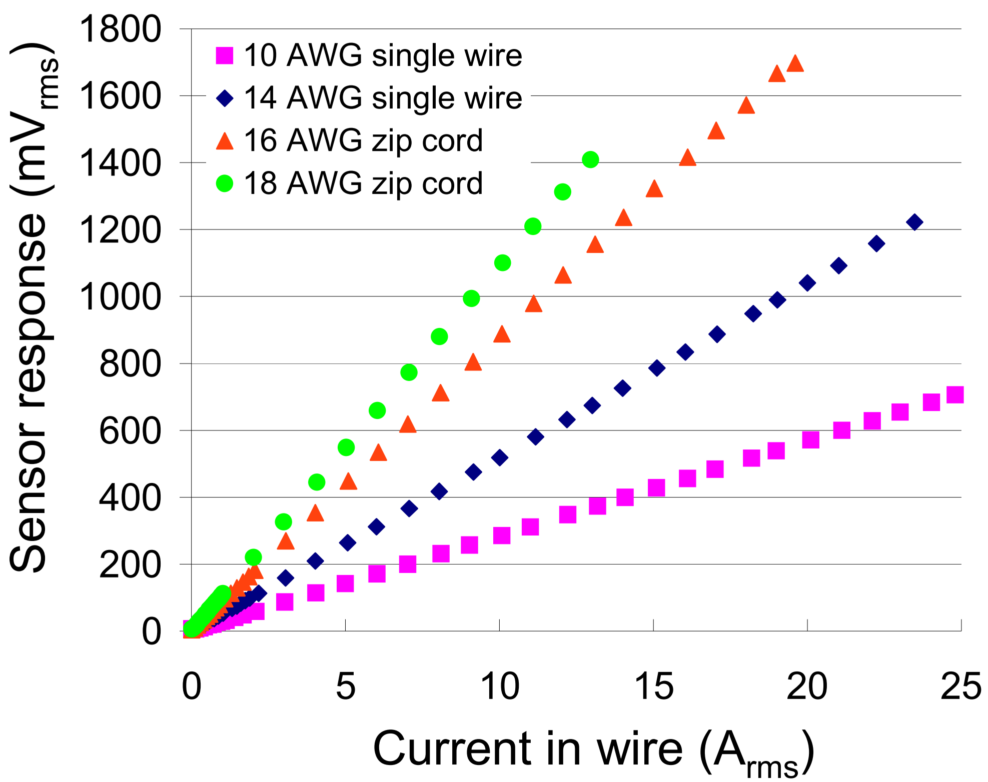






MEMS current sensor exhibits linear response

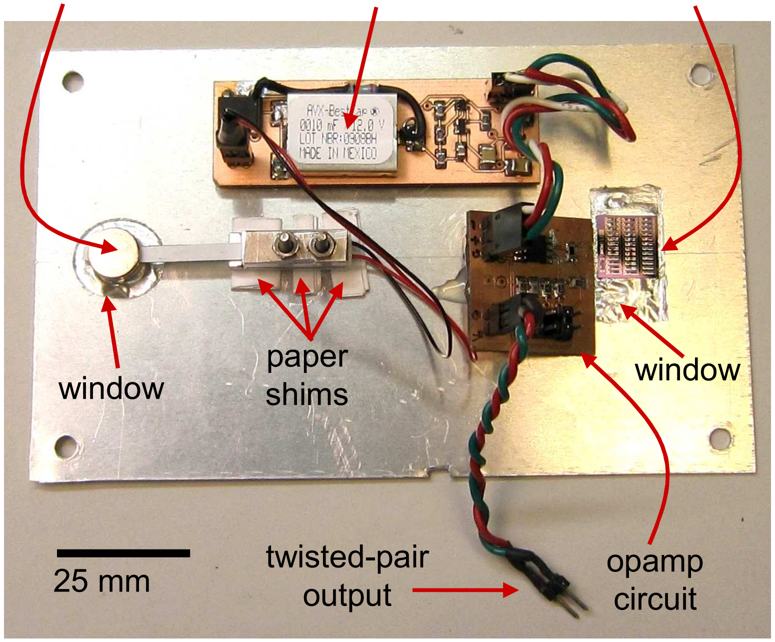
Amplified sensor response (101x gain)



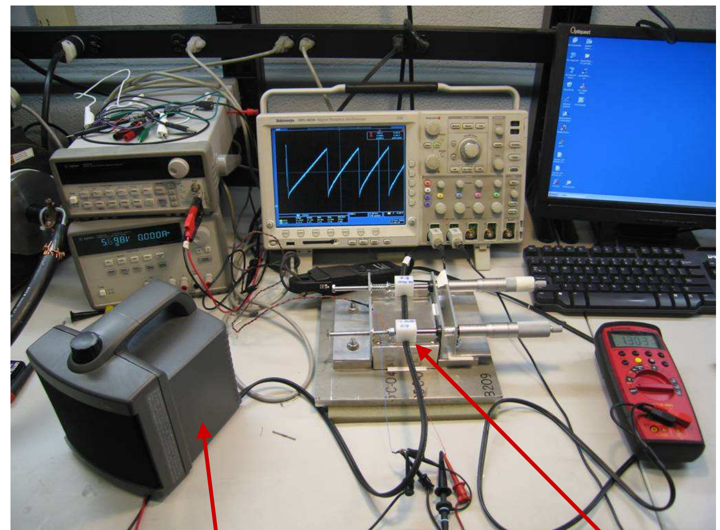
- Sensor response is linearly proportional to the current being measured ($R^2 > 0.999$)
- "Raw" (unamplified) sensitivity ranges from 0.3-1.1 mV/A
- Greater sensitivity measuring zip cords than single wires because two conductors contribute to magnetic force
- Greater sensitivity measuring smaller wires because sensor is closer to center of conductor
- Linear sensing behavior down to roughly 200 mA

MEMS current sensor prototype powered by energy harvesting

Self-powered sensor assembly



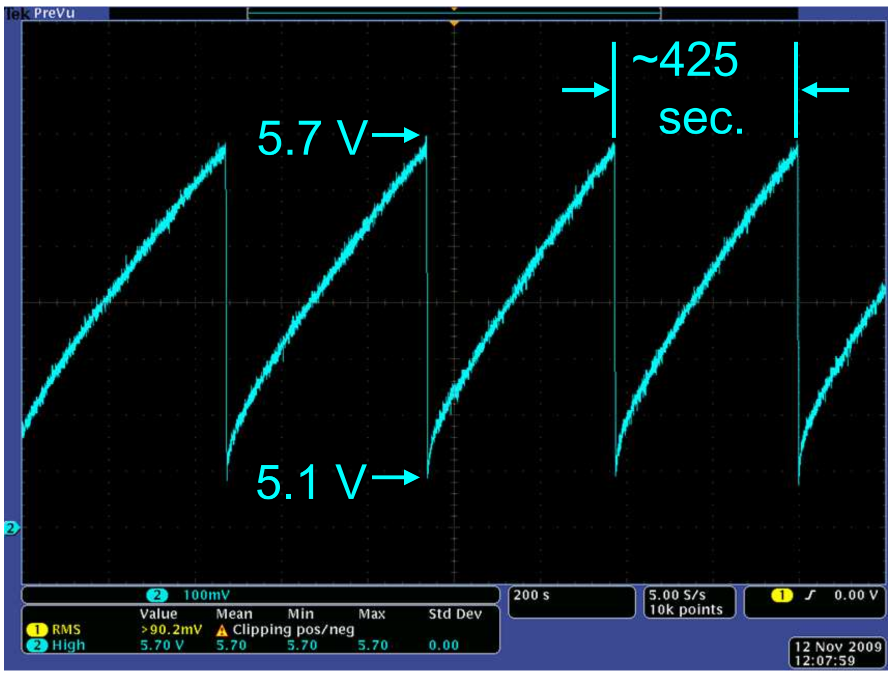
Test apparatus



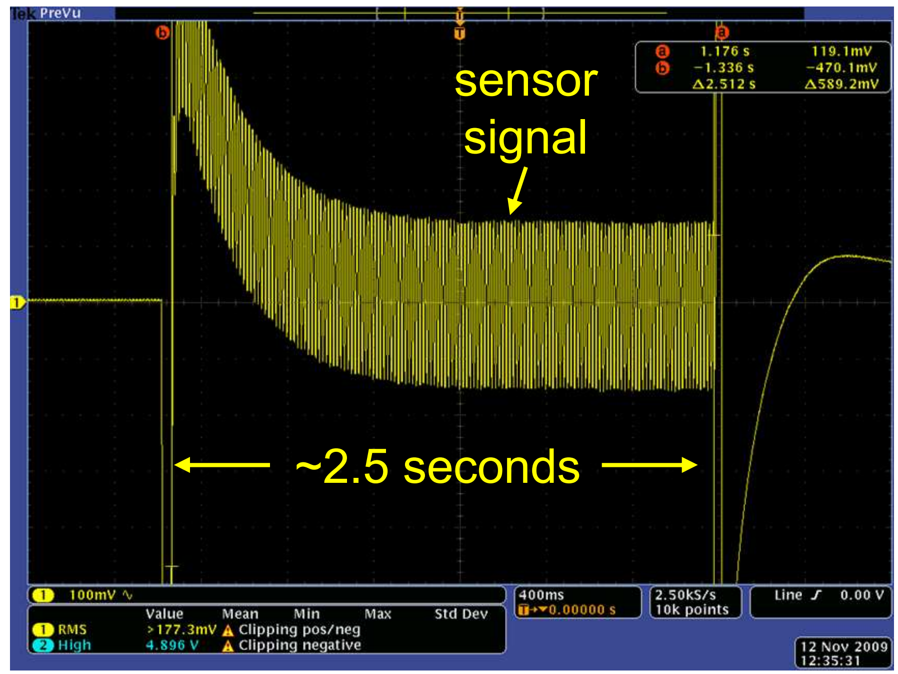
- MEMS current sensor integrated with an energy scavenger coupled to the same wire to create a fully self-powered sensor
- Included power conditioning and storage to run the opamp circuit periodically, providing duty-cycled sensor output

Self-powered current sensor successfully demonstrated

Storage capacitor charge-discharge cycle



Periodic current sensor operation



- Sensor ran at an 0.6% duty cycle when coupled to a 1500 W space heater cord drawing a 13 A current
- Average power transfer to storage capacitor was 70 μW

MEMS AC current sensor: Takeaways

- This sensor makes a non-intrusive current measurement, and works very well on both single wires and two-wire appliance "zip-cords"
- The sensor is a passive element, and is thus suitable for wireless sensor node applications
- The sensor can be powered by a power line energy harvester to create an integrated self-powered device

Thanks!

Questions?

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