Abstract — Ongoing initiatives for energy conservation present the need for ubiquitous sensing of electrical power use in residential and commercial settings. Inexpensive and massively distributed electrical sensors installed in power distribution and transmission systems will enable collection of highly granular information regarding the operation of the power grid. Incorporated into the upcoming Smart Grid infrastructure, we envision this data-collecting capability to enhance the overall stability of the grid, as well as improve its diagnostic capabilities. In this paper, we present our ongoing work towards developing self-powered MEMS sensor modules that can be installed in both residential and commercial settings, as well as in power distribution and transmission systems. The sensor modules will measure electrical quantities such as voltage, current and instantaneous power using a suite of MEMS sensors, and will scavenge the energy needed for their operation from the current flowing in the energized conductor onto which they are attached.

Index Terms—Smart Grid, Power Systems Monitoring, MEMS, Sensors, Energy Scavenging.

I. INTRODUCTION

Ubiquitous sensors for electrical quantities such as voltage and current will allow for improved energy efficiency at the residential and commercial level. One such example is the Demand Response (DR) initiative [1], where a variable pricing structure is used to curb demand during peak hours. Distributed voltage and current sensors installed throughout the power distribution and transmission systems will provide a more granular view of the operation of the power grid, and improve our ability to maintain its stability. If these sensors collect data on a continuous basis, they can not only detect faults, but can also provide diagnostic information regarding the nature of the fault, enabling its more efficient resolution. As an example, the Pacific Gas and Electric Company (PG&E) estimated that it needed 900,000 more sensors for its power distribution circuits in order to obtain a desired level of system reliability and stability.

As the Smart Grid is envisioned, two-way communications between the loads on the demand side and the electric generating system on the supply side will allow grid operators to more precisely know how much electricity is needed at any given time and for the immediate future. Analytical techniques will assimilate this information and evaluate which electric generating stations should be used to provide the electricity and over which transmission and distribution lines the power should be transmitted. In essence, the Smart Grid will permit real-time command and control. To fulfill the promise of the smart grid, billions of dollars will be needed to replace existing utility computer systems, build new real-time communication systems, deploy smart sensors along the grid and replace existing meters with smart meters. On a global basis, the market for smart grid technologies in 2009 was about $70 billion and is estimated to grow at 19.9% annually. By 2014, the global market for smart grid technologies is projected to be about $171 billion.

In order for these sensors to be viable for ubiquitous monitoring of the power grid, as well as energy use in...
residential and commercial settings, the lifetime of the sensors has to be comparable with the lifetime of the power systems they are monitoring. Such long lifetimes necessitate that the sensor modules be self-powered; this can be achieved by the use of energy scavenging from the ambient environment.

In this paper, we present our work towards a self-powered MEMS sensor module for measuring and reporting electrical quantities, such as voltage and current. The on-board sensors are passive proximity sensors that do not require galvanic contact with the energized conductor. The module scavenges energy required for its operation by harvesting the time-varying magnetic energy produced by the current in the conductor.

II. SELF-POWERED MEMS SENSOR MODULE

Fig. 1 shows a design of the self-powered MEMS sensor module. It consists of a MEMS energy scavenging unit [2] (a), a MEMS sensor unit [3] (b), a wireless radio unit (c), as well as a printed energy storage (capacitor or battery) incorporated in the package (d). A hermetically sealed casing (e) ensures that the module can function in outdoor environments. We intend to use commercially available wireless radio chips (for example [4]), as well as a printed battery storage developed in [5]. Hence, our work is centered on developing passive proximity sensors and energy scavengers, as we describe in the sections below.

III. ENERGY SCAVENGING UNIT

A. Mesoscale AC Energy Scavenger

Energy from the magnetic field surrounding a current-carrying conductor is used to provide power to the sensor module. We developed a mesoscale AC energy scavenger, which consists of a cantilever beam covered with piezoelectric material with a permanent magnet attached to its end. The magnets are arranged such that the beam resonates at the power frequency (60 Hz in the U.S.). The magnetization vector of the magnet is such that the alternating magnetic field produced by the current in the wire, caused the cantilever to vibrate.

An image of an early version of the mesoscale AC scavenger, and a CAD layout of an improved version are both shown in Fig. 2. Fig. 3 shows the measure power output of the AC energy scavenger as a function of a resistive load near a conductor carrying 5 A_{RMS}, with a maximum power output of close to 300 µW. We have demonstrated that this energy harvester is able to generate 11 mW when placed in the proximity of a conductor carrying 50 A_{RMS} current.

![Mesoscale AC energy scavenger](image1)

Fig. 2. Mesoscale AC energy scavenger. (left) Early prototype. (right) CAD drawing of an improved version, which includes over-current protection.

![Power output of the mesoscale AC energy scavenger](image2)

Fig. 3. The power output of the mesoscale AC energy scavenger vs. a (variable) resistive load near a conductor carrying 5 A_{RMS}.

B. MEMS Energy Scavenger

Although still applicable to power the sensor module, the size of the mesoscale AC scavenger can easily dominate the module’s footprint. Thus, in parallel we are currently developing a die-sized (10 mm x 10 mm x 4 mm) MEMS AC
energy scavenger. This version uses a quad folded spring cantilever design to ensure resonance at power frequencies.

The MEMS AC energy scavenger is large enough to allow the use of a commercially available NdFeB magnet with a remanent magnetization of 13,700 Gauss, currently far superior to that of microfabricated magnets. We extended the microfabrication process from [3] to allow for reliable fabrication of thin beam structures. The new process (see Fig. 6) allows us to fabricate a folded beam structure that maximizes the area covered by the piezoelectric material. Due to ease of deposition, we chose a 1 µm thick layer of aluminum nitride (AlN) as the piezoelectric material. The process can however be easily extended to encompass PZT, which is also widely used in our lab. With a yield strength two orders of magnitude higher than PZT, AlN might be the material of choice for long duration energy scavenging applications.

Since the quad folded spring acts like a fixed-fixed cantilever beam, both stress polarities (compressive and tensile) are present in the layer of piezoelectric material (see Fig. 6.). We use photolithography to define the electrodes in a pattern to avoid charge cancelation.

Both the mesoscale and the MEMS AC energy scavenging uses a magnet to couple to the magnetic field in the current carrying conductor. This allows our scavenger to simply be in the vicinity of the current-carrying conductor, and does not require the device to encircle the wire, as is the case with inductive approaches such as Rogowski coil or clamp-on transformers.

IV. MEMS SENSOR UNIT

We are using MEMS technologies to develop sensors that can measure current, voltage (and instantaneous power) by simply being near the energized conductor (hence the term proximity sensor). We have successfully developed a MEMS current sensor, and are currently in the process of testing both a MEMS voltage and power proximity sensors.

C. Proximity MEMS Current Sensor

Similar to the energy scavenger, the current sensor is based on piezoelectric transduction of the mechanical force applied on a magnet by the magnetic field of the current in a nearby conductor. In contrast with the scavenger, the sensor is designed to have a much higher resonant frequency than 60 Hz. This ensures both high sensor bandwidth and linear operation. Our initial sensor prototype was of the same design as the energy scavenging unit shown in Fig. 2, but its resonance frequency was shifted away from 60 Hz. We have also developed a MEMS version of the passive proximity current sensor, and have successfully demonstrated its operation.

1. MEMS Current Sensor Fabrication

Aluminum nitride (AlN) was chosen as the active piezoelectric material because of its desirable properties for sensor applications [6,7] and its CMOS-compatibility. Released AlN cantilevers were fabricated using a four-mask process in the microfabrication facility at the University of California, Berkeley. Beginning with a silicon wafer, a 300 nm layer of electrically-insulating silicon-rich low-stress silicon nitride was deposited in a low-pressure chemical vapor deposition (LPCVD) furnace. Next, a 10 nm titanium seed layer and 200 nm platinum electrode layer were deposited using electron beam evaporation and patterned using a liftoff process. A 1.4 µm layer of AlN was then deposited using an AMS physical vapor deposition tool (Fig. 7a).

A second Ti/Pt electrode layer was deposited again using electron beam evaporation and liftoff, followed by another 1.4 µm layer of AlN. A 2 µm “hard mask” layer of SiO2 was then deposited in an LPCVD furnace and patterned using a CF4 plasma etch (Fig. 7b).

A Cl2 plasma etch opened vias to the buried electrode layers and defined the cantilever outline, exposing a U-shaped trench around the cantilever that would subsequently enable the release etch. Following the Cl2 plasma etch step,
The wafer was cut into individual die using a dicing saw. Using a dispenser-printing process (described subsequently), a composite permanent magnet was deposited onto the unreleased cantilever (Fig. 7c).

(a) (b)

(c) (d)

Fig. 7: Process flow for MEMS current sensor fabrication (images not to scale).

The cantilever structure was ultimately released using a gaseous xenon difluoride (XeF₂) etch (Fig. 7d). This gaseous etch was chosen for the release because it is isotropic, highly selective to silicon, and it eliminates the “stiction” problems associated with wet-etching.

Figure 8: Top and side view of MEMS AC current sensor with magnet fabricated by powder dispersion.

A direct-write dispenser printer [8] was used to fabricate microscale permanent magnets using magnetic powder and a polymer binder. A neodymium alloy magnetic powder (MQP S-11-9 from Magnequench, Inc.) was chosen because of its strong magnetic properties and corrosion-resistance. An epoxy resin (Hexion EPON 828 resin with EPICURE 3370 curing agent) was used because of its inherent mechanical strength and good adhesion to the MEMS cantilever surface.

A “powder dispersion” fabrication method was developed to achieve the desired magnet size. A “dot” of uncured epoxy mixture approximately 150 μm in diameter was first printed on the cantilever tip. The magnetic powder was then manually dispersed over the MEMS die with a small spatula, adhering the particles to the substrate only where epoxy had been printed. The epoxy was allowed to cure, whereupon the excess magnetic powder was removed and recycled for later use. The result was a small cluster of magnetic particles firmly adhered to the cantilever tip. This process was repeated three times for each magnet, increasing the magnet’s height with each iteration. A final layer of epoxy was printed on top of the magnet structure in order to provide additional mechanical stability. The neodymium powder is magnetically isotropic, and thus the composite micromagnets have no net magnetic moment as fabricated. The micromagnets were magnetized in a 4 T field using a Quantum Design Physical Property Measurement System.

The powder dispersion method produced micromagnets approximately 150 μm in diameter and 100 μm tall. An SEM of a released AlN cantilever with a printed composite micromagnet is shown in Fig. 8. Magnetic behavior of the micromagnets was confirmed by their attraction to ferromagnetic metals and was also characterized using a Quantum Design MPMSXL-7 vibrating sample magnetometer. Magnetic remanence ($B_r$) of the sensor magnets was found to be approximately 0.4 T, comparing well to values for micromagnets found in the literature [9].

2. MEMS Current Sensor Testing

A MEMS current sensor measuring 1000 μm x 200 μm was selected for testing. The sensor’s signal was amplified through a non-inverting op-amp circuit by a factor of 100.6. Using an oscilloscope and an impulse stimulus, the sensor’s resonance frequency was found to be 960 Hz. This sensor was tested against both a 16 AWG and 18 AWG two-wire “zip-cord.” In each case the optimal position for the sensor was found by holding the current in the zip-cord constant and using the micrometer positioning system to adjust the wire’s position relative to the sensor until a maximum signal was observed. The current in the cord was then adjusted incrementally up to the maximum possible current as limited by the zip-cord’s resistance, roughly 13 A for the 18 AWG cord and 20 A for the 16 AWG cord.

Response in both cases (Fig. 9) was highly linear ($R^2 > 0.99$). Measured sensitivities were 0.87 mV/A for the 16 AWG cord and 1.08 mV/A for the 18 AWG cord (recall that the data presented in Fig. 9 are amplified by a factor of 100.6). Greater sensitivity was observed against the 18 AWG power cord because its smaller conductor cross-section and thinner insulation allow the closer positioning of the sensor magnet than in the 16 AWG case. Continuing research focuses on further characterizing the response of the MEMS sensor with a view towards future design optimization.
D. Proximity MEMS Voltage Sensor

We are currently developing both a solid-state and a MEMS version of a passive proximity voltage sensor. These sensors are specifically targeting overhead distribution and transmission line systems, and will be able to sense both line-to-line, as well as line-to-ground voltages by measuring the gradient of the surrounding electric field.

V. RADIOMOTE

The on-board radio mote will transmit the data from the sensors via a wireless local area mesh network, consisting of other radio motes, to a local server repository. We will take advantage of existing low-powered wireless motes from Texas Instruments, as well as other researchers from CITRIS, BSAC, and BWRC at U.C. Berkeley, and evaluate which of these is the most suitable hardware platform for our sensors; the criteria for evaluation will be energy efficiency, reliability and security. The ability to scavenge power allows us to place repeater nodes to ensure that the data reach the server repository. The security concerns are addressed based on the evolving NIST recommendations [10]. The local area network will be based upon the IEEE 802.15.4 standard, which includes a sound mechanism for cybersecurity implementation [11].

VI. CONCLUSION

We present the ongoing development of self-powered MEMS sensor modules that can be installed ubiquitously in residential, commercial, distribution and transmission electrical circuits for measuring electrical quantities such as current, voltage, and instantaneous power. The module scavenges energy needed for its operation from the electrical circuit it is monitoring. The module does not require any galvanic contact to be made as it is sufficient for the module to be placed in close vicinity to the conductor to both scavenge energy and perform the measurements. The module contains a radio chip, which allows it to wirelessly communicate the measured results. The use of MEMS technologies allows us to both keep the cost of the module low and to limit its size to that of a memory stick. We believe such a module can be the enabling technology for ubiquitous instrumentation of the future Smart Grid.

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VIII. REFERENCES


