

## A MEMS AC CURRENT SENSOR FOR RESIDENTIAL AND COMMERCIAL ELECTRICITY END-USE MONITORING

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**Abstract:** This paper presents an update in the development of a MEMS sensor for alternating current designed for the application of monitoring electricity end-use in residential and commercial environments. This new current sensor design is comprised of a piezoelectric MEMS cantilever with a permanent magnet mounted to the cantilever's free end. When placed near a wire carrying AC current the magnet is forced sinusoidally, producing a voltage in the cantilever proportional to the current being measured. This paper details the fabrication process for this sensor design. Released piezoelectric MEMS cantilevers have been fabricated using a four-mask process and aluminum nitride as the active piezoelectric material. Dispenser-printed microscale composite permanent magnets have been integrated, resulting in the first MEMS-scale prototypes of this current sensor design.

**Key words:** MEMS, current sensor, permanent magnet, piezoelectric cantilever, aluminum nitride

### INTRODUCTION

The need for energy efficiency combined with advances in compact sensor network technologies presents an opportunity for a new type of sensor to monitor electricity usage in residential and commercial environments. A novel design for a self-powered, proximity-based AC electric current sensor has been developed. This sensor device is constructed of a piezoelectric cantilever with a permanent magnet mounted to the cantilever's free end (Fig. 1). When the sensor is placed in proximity to a wire carrying AC electric current, the permanent magnet couples to the wire's alternating magnetic field, deflecting the piezoelectric cantilever and thus producing a sinusoidal voltage proportional to the current being measured.

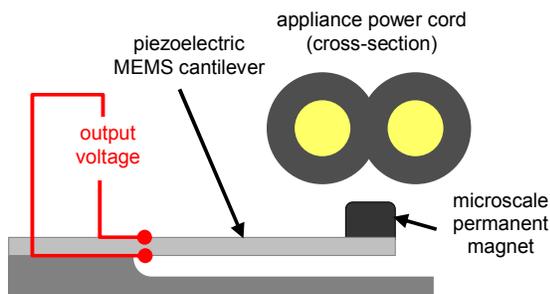


Fig. 1: Schematic of MEMS current sensor design (not to scale).

While several technologies are currently available for integratable current sensors [1, 2], this technology provides significant advantages over other available techniques. Utilizing piezoelectric materials to generate a signal voltage, this type of sensor does not require a power source and thus does not constitute a drain on a sensor node's energy budget. This sensor also functions in proximity to the current-carrying wire without needing to physically encircle the conductor, unlike other self-powered current sensing technologies such as current transformers and Rogowski coils. This feature enables an expanded set of deployment scenarios, including monitoring of current in a two-wire appliance "zip-cord" without needing to physically separate the two conductors.

Previous work presented results obtained from meso-scale hand-built current sensor prototypes using these principles [3]. These meso-scale devices showed linear behavior with sensitivities in the neighborhood of 74 mV/A, and numerical models predicted a MEMS-scale device to have a sensitivity of a 2-4 mV/A. Another recent paper [4] developed analytical relationships that govern the design of a MEMS current sensor device. As theoretical considerations have been covered extensively in previous publications, this paper focuses on the fabrication process used to produce the first MEMS-scale prototypes of this current sensor design.

## DEVICE FABRICATION

The fabrication of this MEMS current sensor entails developing processes to produce both MEMS piezoelectric cantilevers and microscale permanent magnets. These processes must also be compatible such that they can be combined to produce an integrated device.

### Fabrication of an Aluminum Nitride MEMS Cantilever

Aluminum nitride (AlN) was chosen as the active piezoelectric material because of its desirable properties for sensor applications [3, 5]. AlN can also be deposited in a CMOS-compatible process, which will eventually allow on-chip integration with additional computation and communication circuitry.

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 using 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  $\mu\text{m}$  layer of AlN was then deposited using an AMS physical vapor deposition tool (Fig 2a).

A second Ti/Pt electrode layer was deposited again using electron beam evaporation and liftoff, followed by another 1.4  $\mu\text{m}$  layer of AlN. A 2  $\mu\text{m}$  “hard mask” layer of SiO<sub>2</sub> was then deposited in an LPCVD furnace and patterned using a CF<sub>4</sub> plasma etch (Fig 2b).

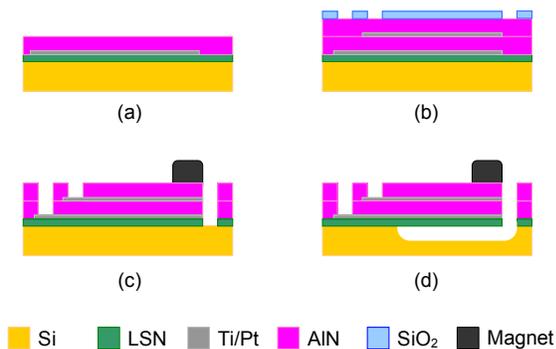


Fig. 2: Process flow for MEMS current sensor fabrication (images not to scale).

A Cl<sub>2</sub> 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. It was

initially anticipated that the Pt electrodes would serve as etch stops during the Cl<sub>2</sub> plasma etch, but it was determined that the exposed portion of the uppermost buried electrode deteriorated excessively before the etch exposed the bottom electrode layer. Thus another masking step was added. Once the upper electrode was exposed, 6  $\mu\text{m}$  of hard-baked photoresist was patterned to protect this electrode layer before proceeding with the etch. Following the Cl<sub>2</sub> 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 on to the unreleased cantilever (Fig. 2c).

The cantilever structure was ultimately released using gaseous xenon difluoride (XeF<sub>2</sub>) etch (Fig 2d). 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.

It can be observed that this design incorporates two separate layers of aluminum nitride: The bottom “active” piezoelectric layer and the upper “passive” elastic layer. The latter is necessary to displace the cantilever’s neutral axis out of the active layer in order to maximize the strain in the active layer under deflection and ultimately enhance the sensor’s voltage signal. While this elastic layer does not need to be piezoelectric, AlN was chosen both because it is compatible with the rest of the fabrication process and because it matches the material stiffness of the AlN piezoelectric layer (Young’s modulus 300-350 GPa). It can thus form an elastic layer of similar thickness to the piezoelectric layer, whereas a much thicker layer of a less-stiff material would be required to perform this function. Moreover, with this design a third top-level electrode could be added, resulting in piezoelectric aluminum nitride bimorphs (with two active piezoelectric layers) with minimal modification to the fabrication process.

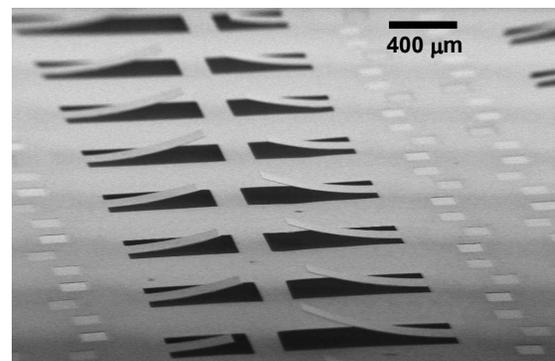


Fig. 3: SEM image of released aluminum nitride cantilevers

Released AlN cantilevers were fabricated with lengths of 400, 600, 800, and 1000  $\mu\text{m}$ , and widths of 100, 150, and 200  $\mu\text{m}$  (Fig. 3). Three different electrode configurations were fabricated for each length-width combination. Electrodes were configured to extend from the base of the cantilever either fully to the tip of the cantilever, or to one-half or one-quarter of its length. Voltage developed in the piezoelectric layer is related to the average strain in its electroded portion [6] and strain in a deflected cantilever will be concentrated near its base. It is thus possible that a cantilever electroded near its base will be more sensitive to deflection (and thus will make a better sensor) than one electroded over its entire length. Each of these length-width-electrode combinations will be tested going forward to determine which provides the best current sensing behavior.

Piezoelectric behavior of all released cantilever configurations was verified by exciting the cantilevers with a sine-wave voltage signal and observing their vibration under an optical microscope.

#### Fabrication of a Microscale Permanent Magnet

While a variety of options exist for fabricating MEMS-scale permanent magnets [7, 8], the magnets for this current sensor prototype were fabricated using a dispenser printing process developed at the University of California, Berkeley [9]. This dispenser printer is comprised of a pneumatic pressure controller connected to a syringe which can dispense finely-controlled droplets of functional “ink” onto a substrate. The substrate is mounted on a 3-axis stage with a resolution of approximately 1  $\mu\text{m}$  (Fig. 4).

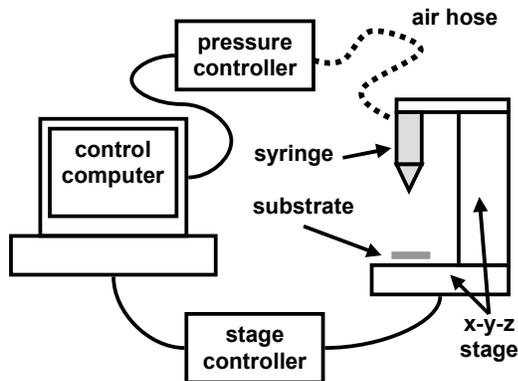


Fig. 4: Schematic of dispenser printer set-up.

The dispenser printer was used to deposit composite magnets using strontium ferrite (SrFe) magnetic powder from Hoosier Magnetics, Inc. at an 80% volume loading. Polyvinylidene fluoride (PVDF) was used as the polymer matrix for the magnets. The

solvent n-methylpyrrolidone (NMP) was used to dissolve the PVDF and adjust the viscosity of the magnetic ink for optimal printability. Once printed, the magnets were dried on a 100  $^{\circ}\text{C}$  hot plate to drive off the solvent, and were then magnetized using a custom-built bench-top electromagnet capable of generating a maximum magnetic flux density of approximately 1 T.

An important feature of this magnet fabrication process is that it is compatible with the AlN cantilever process previously described. The 3-axis stage allows for precise positioning of the magnet at the tip of the cantilever. Also, because both the SrFe powder and PVDF matrix are unaffected by the  $\text{XeF}_2$  release etch, the magnets can be printed on to the piezoelectric cantilevers and magnetized before the release step. Printing on to unreleased structures was preferred, as released structures would have been considerably more delicate.

Figure 5 shows a prototype MEMS current sensor, with a dispenser-printed composite magnet at the tip of a released piezoelectric cantilever. The printed magnets are approximately 200  $\mu\text{m}$  across by 75  $\mu\text{m}$  tall. A technique has also been developed to print taller magnets by using multiple “shots” of ink from the printer in a single location, with a brief pause of 2-3 minutes between each shot to allow the previous one to dry partially.

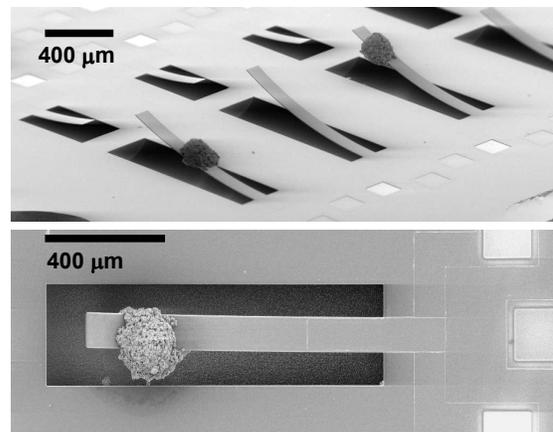


Fig. 5: SEM images of aluminum nitride cantilevers with dispenser-printed composite magnets.

Remanent magnetization of these composite magnets was initially verified by their attraction to ferromagnetic metals. MEMS SrFe magnets were also characterized in a vibrating sample magnetometer (VSM) in order to characterize their magnetic hysteresis behavior (Fig. 6).

Future work on magnet fabrication will focus on incorporating higher-energy samarium cobalt (SmCo) and neodymium iron boron (NdFeB) powders to enhance device sensitivity.

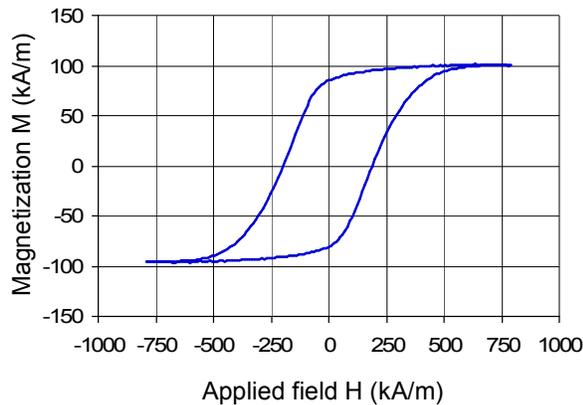


Fig. 6: *M-H hysteresis curve for dispenser-printed strontium ferrite magnet.*

### CONCLUSIONS AND FUTURE WORK

This novel design for a MEMS AC electric current sensor offers advantages over existing technologies because it operates while remaining electrically isolated from the conductor and because it does not need to physically encircle the conductor. It also requires no supply power for operation, and thus does not constitute a drain on the energy budget of an integrated device. Integrated into a compact sensor network node, this technology could enable “smart” homes and buildings which monitor end-use of electricity to a high degree of detail.

Piezoelectric aluminum nitride MEMS cantilevers have been successfully fabricated and integrated with dispenser-printed composite microscale permanent magnets. Future work will involve optimizing device geometry to increase sensitivity, and the development of stronger MEMS magnets using higher-energy samarium cobalt (SmCo) and neodymium iron boron (NdFeB) magnetic powders.

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