Design and Fabrication of a MEMS AC Electric Current Sensor

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Abstract. The need for energy efficiency combined with advances in compact sensor network technologies present 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. 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. Analytical models were developed to predict the magnetic forces and piezoelectric voltage output pertaining to this design. MEMS-scale cantilevers are currently under development using a three-mask process and aluminum nitride as the active piezoelectric material. Very small (300 $\mu$m) permanent magnets have been dispenser-printed using magnetic powders in a polymer matrix. Previously presented meso-scale (2-3 cm$^3$) prototype devices exhibited sensitivities of 74 mV/A, while simulations suggest MEMS device sensitivity of 2-4 mV/A.

Introduction

Motivated by concern over global energy use and the need for better energy end-use monitoring technology, this research seeks to develop a novel design for a passive, proximity-based MEMS electric current sensor for residential and commercial AC electric loads.

The sensor design studied in this research consists of a piezoelectric cantilever with a permanent magnet mounted to its free end (see Fig. 1). When placed near a wire carrying AC current, magnetic coupling induces a sinusoidal force on the sensor magnet. This force deflects the piezoelectric cantilever, resulting in a sinusoidal voltage signal proportional to the current being measured. This sensor design is advantageous in that it requires no external power source (passive) and because it can accurately measure current while remaining electrically isolated from the current carrier (proximity-based).

Several types of integrable current sensors are in use [1] including some using magnetic materials [2]. All of these designs either require a power source or they must encircle the current...
carrier. Neither is necessary for the design presented herein. This research also relates to magnetic field sensors using magnetic materials [3,4] and magnetic microactuators [5,6].

Early work on this sensor design was presented previously [7,8]. This paper expands upon the theoretical models pertaining to the design of this type of MEMS AC current sensor. This paper also describes in detail the fabrication of the MEMS-scale piezoelectric cantilevers and permanent magnets that comprise this sensor design.

**Theoretical Background and Design Considerations**

**Force on a magnet near an AC current-carrying wire.** The force on a permanent magnet in a magnetic field is proportional to the integral of the field gradient over the magnet’s volume [5]. Considering the case of a magnet near a long current-carrying wire, the forces on the magnet in the plane normal to the wire are described by Eqs. 1.

\[
F_x = B_r \int \frac{d}{dx} (H_y) dV, \quad F_y = B_r \int \frac{d}{dy} (H_x) dV
\]

In these equations, \(x\) and \(y\) are the horizontal and vertical directions, respectively, \(F\) is the force on the magnet, \(H_x\) and \(H_y\) are horizontal and vertical components of the magnetic field in amperes per meter, \(B_r\) is the remanence of the permanent magnet in Tesla, and \(V\) is the magnet’s volume. We assume that the remanence of the permanent magnet is uniform and aligned in the positive \(y\)-direction.

An analysis of the gradient of the magnetic field surrounding an electric power cord begins by recalling the equation for the field surrounding a single current-carrying wire (Eq. 2).

\[
\frac{\hat{H}}{2\pi r} = \frac{i}{2\pi r}
\]

\(H\) is the magnetic field, \(i\) the current in the wire, and \(r\) the radial distance from the wire to the point of interest. The direction of \(H\) is determined using the “right hand rule,” aligning the thumb with the direction of the flowing current. Figure 2 plots the \(y\)-direction gradient of the \(y\)-component of the magnetic field surrounding a single wire.

![Figure 2. Plot of the magnitude of the vertical component of the \(y\)-direction magnetic field gradient around a single wire, 10 A current. Note: It is assumed that the magnet shown in the plot is magnetized parallel to the \(y\)-direction.](image)

The contour lines of this plot trace the absolute values of the gradient because the wire carries AC current and really it is the magnitude of the force generated on the magnet that is of primary concern. The darker regions of Fig. 2 indicate larger gradient magnitude, and hence large magnetic force. The plot shows that the current sensor design presented in this paper will develop maximum response when the sensor’s magnet is placed as close to the wire as is feasible, and when it is
oriented such that its magnetization vector makes a 45-degree angle with its radial vector to the center of the wire. This orientation corresponds to the diagonal line drawn on the plot, though orientation along a diagonal line cutting from top-left to bottom-right on the plot (not shown) would be equally advantageous.

As the intended application of this research is to monitor residential and commercial electricity use, we examine the case of a two-wire “zip-cord” common to many appliances (Fig. 3). The gradient of the magnetic field surrounding a two-wire appliance cord is calculated by superimposing the magnetic fields from each of two parallel wires and calculating the gradient. Figure 4 shows the $y$-direction gradient of the $y$-component of the magnetic field surrounding an appliance cord, as well as the potential placement of the current sensor’s magnet. Again, the contour lines of this plot trace the absolute values of the gradient.

Magnet placement along the vertical dashed line that bisects the appliance cord’s cross section in Fig. 4 is particularly advantageous. It corresponds to a region where significant force is developed and it has the added benefit that any horizontal forces are balanced due to symmetry.

This centerline merits further examination, as the gradient values along this line give some insight as to the optimal height at which to locate the current sensor’s magnet. Equation 3 describes the value of the $y$-direction gradient of $H_y$ along this centerline at some displacement $y$ above the plane of the appliance cord.

$$\frac{d}{dy} (H_y)_{\text{centerline}} = -\frac{i}{\pi} \frac{2yd}{(y^2 + d^2)^{3/2}} \quad (3)$$

In this equation, $d$ is a dimension of the appliance cord and is equal to half the distance between the centers of the two wires. As an example, for the appliance cord shown in Fig. 3, $d = 1.8$ mm.

Taking the derivative of Eq. 3 and setting it equal to zero finds the locations of maximum gradient absolute value along the centerline as described in Eq. 4.

$$y_{\text{optimal}} = \pm \frac{d}{\sqrt{3}} \quad (4)$$

However, for the appliance cord in Fig. 3, this $y_{\text{optimal}} = 1.04$ mm which is inside the cord’s insulation. Given this limitation, it is best to locate the current sensor’s magnet as close to the appliance cord’s insulation as possible. At some point in the future it may be possible to embed a MEMS version of this current sensor inside the appliance cord’s insulation in order to maximize force on the magnet and thus the sensor’s sensitivity.
Voltage developed in a piezoelectric cantilever as a result of tip deflection. Roundy and Wright developed an analytical model for the power output of a piezoelectric cantilever when used for vibration energy scavenging [9]. Using their method of analysis produces Eqs. 5, which describe the relationship between strain, voltage, and input force on a piezoelectric cantilever.

\[
\ddot{S} + 2\zeta_m \omega_n \dot{S} + \omega_n^2 S = \frac{k_{mp} a_3 d_{31}}{m t_p} V + \frac{F_{in}}{k_2 m} \\
V = \frac{a_2 c_p d_{31} t_p}{a_3 \varepsilon} \dot{S}
\] (5)

In these state equations \( S \) is the strain developed in the cantilever’s piezoelectric layer(s) due to tip deflection, \( V \) is the voltage developed across the piezoelectric layer’s electrodes and \( F_{in} \) is the force on the tip-mounted sensor magnet. Continuing, \( m \) is the mass of the sensor magnet, \( k_{sp} \) is the equivalent spring constant of the cantilever’s tip deflection, \( k_2 \) is a geometric term relating tip displacement to average strain in the piezoelectric layer, \( \omega_n \) is the natural frequency of the equivalent spring-mass system and \( \zeta_m \) is the dimensionless mechanical damping coefficient of the cantilever. The thickness of the piezoelectric layer appears as \( t_p \), \( c_p \) is the elastic modulus of the piezoelectric material, \( d_{31} \) is the piezoelectric coupling coefficient, and \( \varepsilon \) is the dielectric permittivity of the piezoelectric material. Finally, \( a_1, a_2 \) and \( a_3 \) are constants determined by whether the piezoelectric cantilever is a unimorph, a series-poled bimorph, or a parallel-poled bimorph.

Eqs. 5 can be manipulated using Laplace analysis to produce the frequency response function shown in Eq. 6. This equation describes the frequency and magnitude of the piezoelectric cantilever’s open-circuit voltage signal in response to the sinusoidal force on the tip magnet when placed near an AC current carrier.

\[
V_{oc} = F_{in} \frac{c_p d_{31} t_p a_3}{\varepsilon k_2 m a_2} \frac{1}{\omega_n^2 \left(1 - \frac{c_p d_{31}}{\varepsilon} \right) - \omega^2 - j(2\zeta_m \omega_n \omega)}
\] (6)

In this equation \( F_{in} \) becomes the amplitude of the sinusoidal force on the tip-mounted sensor magnet, \( \omega \) is its frequency (\( \omega = 2 \times \pi \times \text{frequency--mains current is generally 60 Hz in North America and 50 Hz in Europe} \)), and \( j \) is the imaginary number (\( \sqrt{-1} \)).

These analytical models for magnet force and piezoelectric cantilever output voltage were validated experimentally using a meso-scale current sensor prototype. The results of these experiments, as well as simulations of MEMS-scale devices, were presented in [8].

Sensor Device Fabrication

Development of a MEMS-scale prototype current sensor entails two primary tasks: fabrication of a microscale piezoelectric cantilever, and fabrication of a similarly-sized permanent magnet.

MEMS Piezoelectric Cantilever. The first task in approaching the fabrication of a MEMS piezoelectric cantilever is selection of an appropriate active material. In this case aluminum nitride (AlN) was chosen as the active piezoelectric material. While lead zirconate titanate (PZT) generally exhibits greater piezoelectric coupling, AlN’s material properties make it better suited to sensor applications where development of a voltage signal is desirable [8,10]. AlN devices can also be fabricated in a CMOS compatible process, potentially enabling integration with signal processing and communications circuitry on a single silicon die.

Fabrication of AlN MEMS cantilevers using a three-mask process is under development in the UC Berkeley Microfabrication Facility. This design uses a piezoelectric “active” lower layer
sandwiched between platinum electrodes, and a passive AlN upper elastic layer, which serves to move the cantilever’s neutral axis out of the active layer and thus increase its voltage response.

The fabrication process flow is outlined in Fig. 5. In this process, (a) a 300 nm layer of low-stress nitride is first deposited on a silicon substrate using low-pressure chemical vapor deposition (LPCVD), followed by patterning of the platinum bottom electrode via electron beam evaporation and liftoff, and sputter deposition of the AlN active layer using an AMS physical vapor deposition (PVD) tool; (b) a second Pt electrode layer is patterned by liftoff, followed by a second AlN layer, and an SiO$_2$ “hard mask” which is deposited by LPCVD and patterned with a CF$_4$ plasma etch; (c) a Cl$_2$ plasma etch defines the cantilever outline and opens vias to the lower electrode layers using the Pt electrodes as etch stop layers, and the permanent magnet is printed and magnetized pre-release (described in the following section); (d) the cantilever is released using a XeF$_2$ dry release etch.

**Dispenser-Printed Micromagnet.** Composite permanent magnets were dispenser printed using a process developed at UC Berkeley [11]. The magnets were printed using a PVDF polymer binder with 80% by volume strontium ferrite (SrFe) powder from Hoosier Magnetics, Inc.. The magnets were magnetized by drying them in the presence of a strong magnetic field. These composite magnets demonstrated remanent magnetization by their attraction to ferromagnetic metals. Thus far magnets have been printed with largest transverse dimension of approximately 300 µm, but it is anticipated that dimensions of 100 x 100 x 100 µm$^3$ should be achievable with the use of finer printing tips. Figure 7 shows images of SrFe dispenser-printed magnets.
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. Efforts continue to integrate the piezoelectric cantilever fabrication process with that of the dispenser-printed 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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References