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Micromachined Electric Field Mill Employing A Vertical Moving Shutter

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Abstract

This paper presents a new type of micromachined electric field mill (MEFM) for measuring dc electric fields. This MEFM employs thermal actuators for vertical movement of an electrically grounded shutter, to mill the amplitude of a dc electric field incident on underlying sense electrodes. It addresses the main drawbacks of existing MEFMs, which are shutter displacement in large electric field, and drive signal interference from the shutter actuator. Simulation results show that for a 1kV/m dc field the output of the sensor is about 1pA.

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Keywords: Electric field measurement, electric fields, micromachining, electric field mill, thermal actuator, MEFM, MEMS

1. Introduction

Measurement of dc electric fields is employed in many areas. In industry, dc electric field measurements are used primarily to identify and control electrostatic hazard situations and for process optimization purposes [1]. In atmospheric science, electric field measurements are used to study and predict various weather phenomena like lightning [2]. Power utilities monitor electric fields around installations to develop improved insulators, ensure personal and equipment safety, and measure voltage remotely [1]. The measurement of ac electric fields is relatively easy due to the cyclic variation with respect to time. However, measurement of dc field is complicated due to collection of charge over time. Therefore, most reported dc electric field meters convert the dc field into an alternating field, by periodically shielding and un-shielding sensor electrodes from the electric field.

Shutter type field mills are the common used dc electric field measurement tool in industry. It uses the rotation of

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an earthed perforated shutter to "mill" the dc electric field, then an underlying electrode can sense the induced ac charge. However, traditional rotating field mills suffer from high power consumption (relative to battery lifetime) and frequent maintenance requirement. The maintenance of these sensors is difficult and expensive for power utilities when monitoring HVDC installations and transmission lines, due to the need for their placement in remote locations far from cities. Therefore, there is a necessity to develop a low power consumption and reliable sensor.

In recent years, various groups have worked to develop micromachined electric field mills (MEFMs). In [3-5], electrostatic actuation was used to move a perforated grounded shutter over sense electrodes. Horenstein et al. was the first to demonstrate such an MEFM [3]. Thermal actuation has been used by various groups to reduce the drive signal interference from the voltage needed to actuate the shutter in [6-7]. In 2009, Wijeweera et al. demonstrated an MEFM using a thermally actuated resonant shutter [7], and a sensitivity of 42 V/m was achieved. It addition, this device was the first MEFM to demonstrate measurement of electric field below a transmission line. In 2008, Kobayashi et al. [8] reported a field mill without a shutter, which functioned by vertical vibration of the sense electrode's position. It showed linear response in resonant frequency shift of the electrode to the electric field.

According to the shutter movement direction, the MEFMs introduced above can be divided into two categories: lateral movement [3-7] and vertical movement [8,9]. Lateral movement shutters usually suffer from the displacement of the shutter under strong electric field, which can affect and reduce the sensitivity. Vertical movement of the shutter can compensate this displacement. However, all of the reported devices employing vertical shutter movement are driven by piezoelectric actuators and require resonant operation. The high driving voltage reduces sensitivity, and the resonant frequency shifts with changing environmental conditions.

In addition to using field mills, measurement of the electrostatic force generated by the electric field is another feasible MEMS solution. In 2005, Roncin et al. [10] presented a micro-spring supported membrane, which displaced under application of an electric field. Using a laser deflection measurement system to monitor membrane motion, a resolution of 5 kV/m was shown for a dc field incident on a grounded membrane. Using ac bias on the membrane to modulate the induced dc force on the membrane, a resolution of 0.3 V/m was demonstrated. However, the laser system was power consuming and is not physically compact.

In this paper, we present a new MEFM that addresses main drawbacks of existing MEFMs. Vertical shutter movement is employed to resolve the issue with shutter displacement under high fields, and is achieved using low voltage thermal actuators to minimize drive signal interference.

2. Sensor Design

A schematic of the sensing principle is shown in Fig. 1 (a) for the vertical movement of the shielding shutter. When the shutter is elevated above the sense electrodes, the induced charge from the incident field is reduced on the electrodes. Obviously, a higher shutter position has a better shielding effect. The shutter design is shown in Fig. 1(b). It possesses a double-sided comb shape supported by U-shaped thermal actuators for vertical shutter motion. Thermal actuators are positioned at either side and are formed from aluminum coated with SiO_2. At the center of the actuator is a thin film titanium heater. Flexible aluminum ground lines on either side of the actuators connect the shutter to the substrate, and also provide heat sinking.

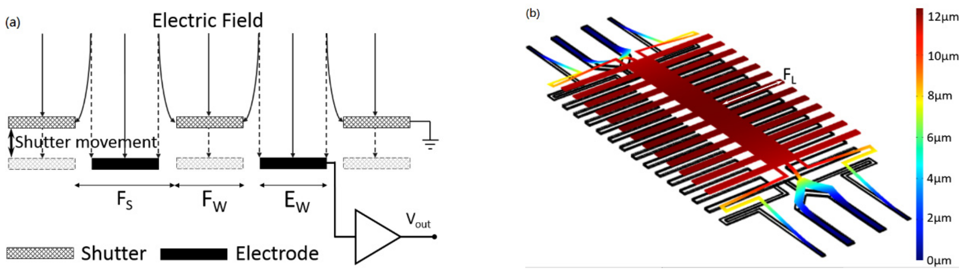

Fig. 1. (a) Schematic of vertically moving shutter resulting in variable electric field shielding on underlying sense electrodes. (b) Schematic of sensor design, showing shutter displacement.

The shutter's periodic vertical movement can generate an ac current on the sense electrodes. Initially, when the shutter is lowered to the electrode height, the amount of charge induced on the electrodes can be calculated using Gauss's Law. For an electrode area of A the magnitude of charge Q induced by an electric field E is given by:

$$Q = \varepsilon_0 A E \quad (1)$$

If each vertical movement of the shutter results in charge change of ΔQ, and the vibration frequency is f, then the induced ac current can be written as:

$$i = f \Delta Q \quad (2)$$

Equations 1 and 2 shows that electric field E can be measured by monitoring the current i on the sense electrodes. We can also see that the sensitivity of the sensor can be increased by increasing the sensing area and/or increasing the speed of shutter movement over the electrodes.

3. Vertical movement shutter design

Of importance are the dimensions of the comb fingers, in comparison to the underlying sense electrodes. Performance was investigated using COMSOL Multiphysics 4.4 software. Fig. 2. (a) plots the change in charge (ΔQ%) on the sense electrodes as a function of shutter height, for: electrode width E_W=10μm, electrode length E_L=100μm, comb finger width F_W=10μm, comb finger length F_L=100μm, and for finger spacings F_S=16-30μm. We can see that narrower finger spacing results in superior electrode shielding. Fig. 2. (b) explores ΔQ as a function of F_L, showing that beyond F_L=100μm minimal improvement occurs. Fig. 3 shows the thermal cool down time constant of the actuator to be ~ 140μs (7kHz).

For device fabrication, a 12 finger per side comb-shutter with F_S=16μm and F_L=100μm will be selected, providing a resonance frequency of ~10kHz, slightly higher than the 7kHz time constant. A peak shutter vertical operation height of 12μm will be used, requiring heating of the thermal actuator by ~350°C. Table 1 compares the sensor output at different operation frequencies. We can see that at 7kHz operation and with shutter movement of 9.5μm (from 2.5μm to 12μm), we obtain the highest output current of $\Delta Q = 1.4\times10^{-16}$ C per oscillation for a 1kV/m dc electric field. Since the sensor output current is proportional to working frequency, at 7kHz operation sensor output is ~1pA. This is similar in performance to the device of [7], when scaled with electrode area. It should be mentioned that higher output current can be easily obtained by connecting multiple actuators in parallel, thus, effectively increasing the collection area for the entire sensor array.

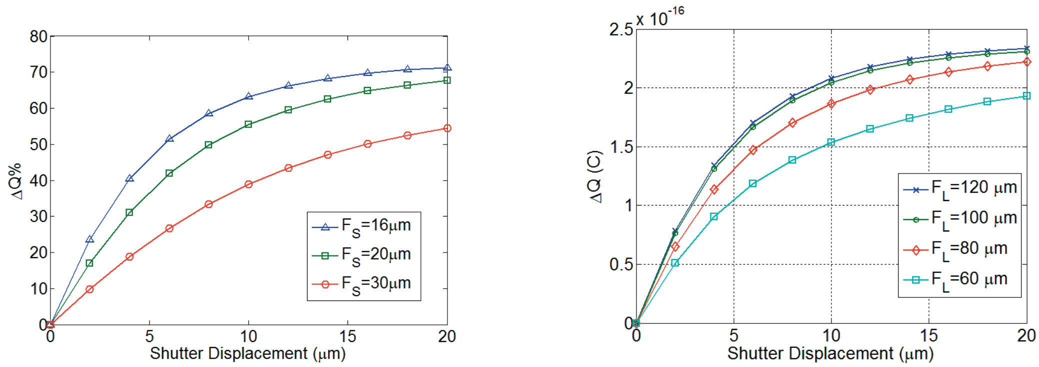

Fig. 2. (a) Percent shielding of underlying electrodes as a function of shutter height, for finger spacings ranging from 16μm to 30μm. Narrower finger spacing results in superior shielding of underlying electrodes. (b) Differential charge on sense electrodes as a function of shutter height, for finger lengths ranging from 60μm to 120μm. Incident dc field is 1kV/m, and sensor simulated has 24 electrodes/shutter fingers (12 per side). We can see that longer shutter fingers provide superior shielding of underlying electrodes.

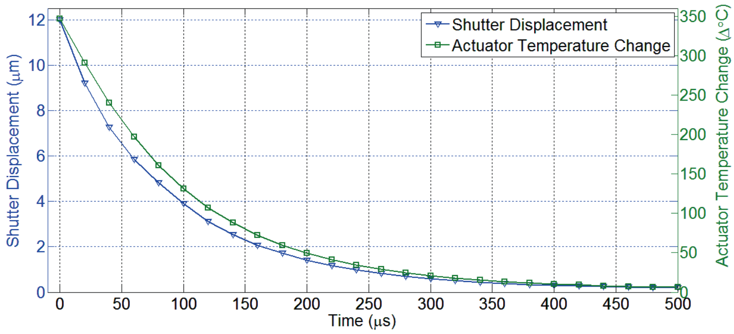

Fig. 3. Cooling transient simulation, showing time constant to be approximately 140μs (7kHz).

Table 1. Sensor output current as a function of shutter height and frequency for a 1kV/m dc electric field.

Shutter height range (μm)	ΔQ (C)	Time Constant (ms)	Frequency (Hz)	Output current (pA)
2 - 12	1.5×10^{-16}	0.17	6000	0.9
2.5 - 12	1.4×10^{-16}	0.14	7000	0.98
3 - 12	1.1×10^{-16}	0.125	8000	0.88

Conclusions

This paper introduces a new MEFM design that employs a vertical moving electrically grounded shutter that is driven by low voltage thermal actuators. It addresses the main drawbacks of existing MEFM designs, which are interference by high voltage shutter actuators and the displacement of the shutter under strong electric field. This later effect can be compensated for in this new design by adjusting the vertical motion of the shutter. For the design modeled, simulation results show that an output current of ~1pA can be obtained for shutter operation at 7kHz, for a 1kV/m dc field. This is similar in performance to existing MEFM designs, as a function of electrode area.

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