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Design of A Novel Closed-loop SOI MEMS Resonant Electrostatic Field Sensor

Chunrong Peng[a], Pengfei Yang[a,b], Haiyan Zhang[a,b], Xin Guo[a,b], Shanhong Xia[a,]*

[a] *State Key Laboratory of Transducer Technology, Institute of Electronics, Chinese Academy of Sciences, Beijing 100190, P.R.China*
[b] *Graduate School of the Chinese Academy of Sciences, Beijing 100190, P.R.China*

Abstract

A novel closed-loop SOI MEMS resonant electrostatic field sensor (EFS) has been designed in this paper. The sensor architecture has three major blocks: a vibration shutter, sensing electrodes, and a closed-loop driving electrode that feeds back to the shutter. With a phase and an amplitude closed loop feedback control, the sensor can be adjusted automatically to operate at its resonant frequency. Prototyped by the SOI fabrication process, the device has a lower driving voltage and a higher quality factor (Q) over existing electrostatic comb driven EFS. An improved uncertainty of 2.1% is achieved for the SOI device operating in ambient air in a measured range of 0-50kV/m.

Keywords: Electrostatic field sensor; SOI; Closed loop; Resonator

1. Introduction

Nomenclature

ε_0	the permittivity of free space
E	the component of the electric field
A	the effective area of the sensing electrodes
i_{out}	The differential output current of the sensing electrodes of the electric field sensor

Electrostatic field measurement has been the subject of much research over the past half century [1]. Many application area such as atmospheric science, various industrial process and power system applications require precise measurement of electrostaic fields to monitor different phenomena. In atmospheric science, electric field measurements are used to study and predict various weather phenomena like lightning. Electric field affects the charging of aircraft and consequently safety launching.

Applying MEMS technology will help lower the cost, size, and power impact of taking these measurements. MEMS-based electrostatic field sensor (EFS) have been developed with different methods, such as lateral electrostatic comb-driven EFS [2, 3], and thermally driven EFS [4, 5]. However, thermally driven structure needs more power dissipation (larger than tens mW), and electrostatic comb driven EFS requires high driving voltage (larger than 20Vp-p) in air. Most of these devices are fabricated by

* Corresponding author. Tel.: +86-10-58887180; fax: +86-10-58887180.
E-mail address: shxia@mail.ie.ac.cn.

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polysilicon surface process and are prone to stiction. Considering the electrostatic driven EFS have a better stability, we designed a novel resonant electrostatic driven EFS firstly based on SOI fabrication process. In order to make the EFS operate at its resonant frequency to achieve maximum electric field response sensitivity and be immune from environment influence, such as temperature, stress, etc., we designed a new resonant EFS incorporating with a feedback driving loop to further improve signal-to-noise ratio (SNR) and stability of the sensor output.

2. Design and Working Principle

2.1. Sensing principle

The operation principle of the electrostatic field sensor is shown in Fig. 1. As the shutter oscillates back and forth, it covers the sidewalls of either positive or negative sensing electrodes, and then a differential current is generated at the sensing electrodes while an external electrostatic field E is applied. The differential output current of the electrodes is given by:

$$i_{out} = \varepsilon_0 E dA/dt \quad (1)$$

The differential output current is converted to a differential voltage by a differential transresistance amplifier, and then amplified by a gain stage.

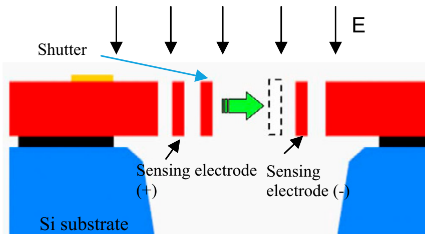

Fig. 1. principle graph of the EFS

2.2. Design of structure

The MEMS EFS structure is designed for maximum sensitivity to electric field. A schematic view of the SOI EFS is shown in Fig. 2.

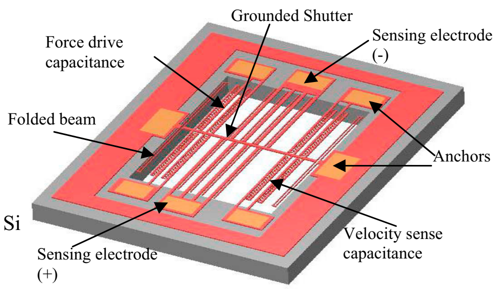

Fig. 2. schematic view of the structure of the SOI EFS

The sensor architecture has three major blocks: a vibration shutter, sensing electrode, and a closed-loop driving electrode that feeds back to the shutter. The vibration shutter is supported by two sets of thin folded beams that are connected to the grounded plane at two anchor points. The sensing electrode is a differential structure that includes the sensing electrode (+) and the sensing electrode (-). The MEMS sensor is fabricated by the SOI process. The sensing electrodes and the grounded shutter are designed at the same plane and fabricated as the top silicon layer with grounded shutters that overlap with differential sensing electrodes. These sensing electrodes are biased through high impedances to a ground reference. At each end of the SOI MEMS structure, a series of interleaved comb fingers provides velocity sensing and force excitation of the shutter. Shutter displacement is maximized by using a high-Q sensor to provide amplification of mechanical motion. However, using a high-Q system requires that the force drive is precisely at the resonant frequency of the sensor.

When the sensor works, a common DC bias voltage and AC sine waveforms are applied to the force drive capacitance structure. For minimizing the effects of feedthrough and improving the SNR, the velocity sense capacitance will produce two driving signal differing in phase by 180° which apply to upper and lower sets of force drive capacitance to differentially drive the shielding electrode of the structure at resonance. Consequently, the external electric field E is modulated due to the vibration of grounded shutter, and the sensor produces an output signal with a component at the motional frequency.

2.3. System architecture

For maximum sensitivity to electric field E, the MEMS electrostatic field sensor was designed to operation at its resonant frequency.

To modulate automatically the MEMS capacitance at its resonant frequency, a closed feedback drive loop is designed. The system level schematic of the resonant EFS is shown in Fig. 3. The differential inducing current ($i_{sen(+)}$ and $i_{sen(-)}$) is synchronously demodulated by a lock-in amplifier or a phase-sensitive demodulator referenced to the drive signal.

The drive loop consists of two sets of MEMS capacitances – the force drive capacitance C_{force} and the velocity sense capacitance C_{vib}. Both C_{force} and C_{vib} have one stationary plate which is anchored to the underlying substrate, and one dynamic plate which is mechanically coupled to the grounded shutter of C_{sen}. A time-varying force driving voltage V_{DRIVE} with a common DC bias voltage V_{DC} applied to the plates of C_{force} creates an electrostatic force that moves the dynamic plate of C_{force} and, thus, the grounded shutter. Due to a bias voltage V_{BIAS} applied to the "+" node of the sensing vibration velocity preamplifier, A dynamic current i_{vib} is generated which is proportional to the shielding electrode vibration velocity. A transresistance amplifier converts i_{vib} to a proportional voltage which serves as the input to the drive loop feedback stage, denoted as feedback network. Before applying to the EFS structure, the frequency of the driving signal is divided to half of the vibration signal output. The entire drive loop employs negative feedback to ensure that the voltage drive applied to the plates of C_{force} is at the resonant frequency of the shielding electrode. Resonant excitation is enabled, resulting in maximum shielding electrode displacement and, thus, maximum SNR at the system output node V_{out}.

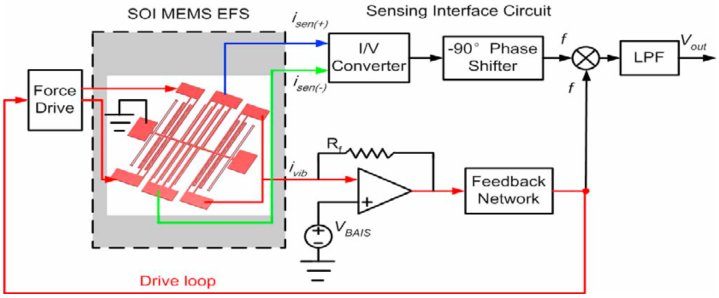

Fig. 3. system level schematic of the SOI EFS with feedback driving loop

3. Device Fabrication

The device was prototyped by the Silicon-On-Insulator Multi User MEMS Process, or SOIMUMPs, as shown in Fig. 4. The SOIMUMPs is a commercial program that provides cost-effective MEMS fabrication. For reducing the risk of the EFS structures sticking to the substrate, the substrate layer is etched completely through by a DRIE silicon etch process step.

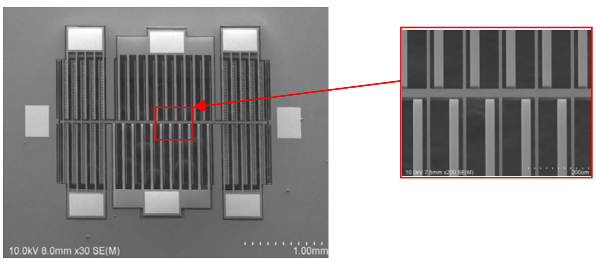

Fig. 4. photograph of the SOI EFS

4. Experiments

With a digital lock-in amplifier based system, we firstly achieve the output frequency response of the SOI MEMS EFS, as shown in Fig. 5 (a). This gives quality factor (Q) of approximately 31034 at a vacuum degree of ~1mTorr with lower actuation voltages (i.e., 250mV DC and 20mVp-p) than other reported electrostatic driven EFS, and the measured resonant frequency at which the sensor has a maximum sensitivity is 1862.1Hz. An improved uncertainty of 2.1% is achieved for the SOI device in a measured range of 0-50kV/m in ambient air at room temperature (~25˚C) wit h current sensor designs, as shown in Fig. 5 (b). The minimum detectable electric field with this sensor is better than 50V/m in ambient air. In addition, the power dissipation of the device is less than 1 mW.

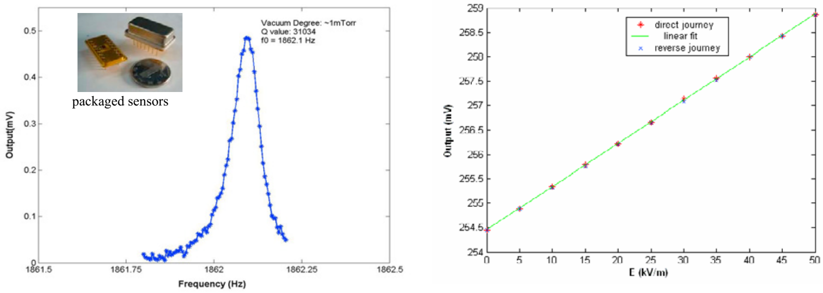

Fig. 5. (a) frequency response; (b) electric field response of the SOI EFS

5. Conclusions

The design, fabrication, and experimental results for a micromachined electric field sensor were presented. The prototyped device is realized with the SOI MEMS process. Due to the substrate layer being etched completely through, the SOI electrostatic field sensor is not prone to sticking to substrate and has a lower damp coefficient. Consequently the device has a higher quality factor (Q) than other reported electrostatic driven EFS, and improve the accuracy of the measurements. The minimum detectable electric field with current sensor designs is better than 50V/m. the SNR of the device is improved owning to its differential driving and differential detection. The closed-loop resonant structure will be achieved a higher performance through modulates automatically the MEMS capacitance structure at its resonant frequency in despite of temperature or humidity influence.

Acknowledgements

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