MEMS-based electric field sensor with environmental adaptability consideration and its application in the near-ground atmosphere

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Abstract. The near-ground electric field (E-field) is an important parameter needed to be measured for lightning warning systems. Yet, most of the E-field sensors are based on bulky and expensive rotate-vane mills. This paper presents a novel MEMS(Micro-electro-mechanical Systems)-based sensor and its application in near-ground atmospheric E-field long-term monitoring. We solve the problem of environmental adaptability by means of a novel macromolecular polymer package and moisture-proof design. To enhance the electric field resolution, a φ36mm×17mm probe is mounted separately from the signal processing circuit. Both finite element simulation and experimental results prove that this sensor could detect the electric field as small as 5V/m. The real-time monitoring data have a good consistency with those of the commercial electric field mill.

Keywords: electric field sensor; electric field measurement; atmospheric electric field; MEMS

1. Introduction
The environmental electric fields are all around us and play a vital role in people's daily lives. E.g., lightning produces a strong atmospheric electric field (E-field), which affects the normal operation of outdoor equipment and facilities. E-field is also one of the main causes of weather-related casualties and is also one of the main threats to the launch of aerospace vehicles [1-8]. Monitoring the E-field on direct current or alternating current transmission lines can bring considerable benefits in terms of assessment of transmission status, location of damaged parts, inspection of breakdown insulators, etc., thus reducing the risk of power failure [9-11]. Some researchers have even demonstrated a special relationship between atmospheric E-fields and earthquakes [12].

In order to study the generation mechanism of atmospheric E-field and its relationship with other natural phenomena, three types of electric field sensors, namely E-field mill, optical sensor, and MEMS...
sensor, have been invented by using the charge induction principle. E-field mills based on the principle of charge induction appeared as early as the 1960s. They adjust the induced charge to alternating current mainly through rotating and stationary mechanical structures, such as the CS110, an electronic field mill made by Campbell Company, USA. Meanwhile, some optical sensors, such as electro-absorption effect \cite{14}, Kerr effect \cite{15}, Pockels effect \cite{16}, etc. have been extensively studied due to their specific optical properties \cite{13}. Since 2001, a series of MEMS E-field sensors based on the charge induction principle have been reported \cite{17}-\cite{19}. The sensor detects the E-field from the comb-shaped electrodes, where the induced charge is modulated by a vibrating shuttle. Microsensors, including MEMS E-field sensors, are expected to be widely applied in the future due to their low power consumption, low cost, small size, and ease of mass production.

However, environmental adaptability is always a difficult problem for micromachined sensors, especially for MEMS E-field sensors, whose chip size is too small and is prone to be damaged by severe environments such as dust, rain, and low air pressure. In 2008, Kobayashi reported on a PZT E-field sensor package that provided mechanical protection for the sensor with a hole on the top of the chip. This paper introduces a kind of package which can avoid the influence of humidity, water drop, and dust so as to improve the robustness of the measuring system. In addition, our method dramatically enhances the resolution due to the enhancing effect of the stand.

2. Charge induction principle

Our group reported the MEMS E-field sensor made by SOI (Silicon on Insulator) technology, as shown in Figure 1\cite{18}. It mainly consists of the Comb Drives and the Comb-shaped Electrodes, with a total size of about 5.5mm by 5.5mm. As shown in Figure 2, when the comb drives are driven by periodic vibration, the induced charge will be modulated within the same period under the action of a certain external electric field. Thus, it produces an alternating current whose amplitude is proportional to the measured E-field.

![Figure 1. 3D model of MEMS electric field sensor chip](image1)

![Figure 2. Charge induction sketch and the amplifier circuit](image2)

3. Design of the sensor

3.1. The system composition

The atmospheric electric field strength measurement system contained four necessary parts: a sensitive probe, a signal processing circuit, a stand, and a wireless transmitter/receiver. The system frame is shown in Figure 3.
The probe consists of a MEMS E-field sensor chip, a simple preamplifier circuit, and a package cap. This probe is about 3.6 cm wide, which is much smaller than traditional E-field mills. So it is beneficial in many narrow spaces and will diminish the influence on the original field. On the other hand, the probe can be taken down quickly and replaced by another one expeditiously.

The function of the signal processing circuit is to supply power for the amplifier circuit, provide a drive signal to the sensor chip and demodulate the output of the probe. It is put into a metal box, sealed, and fixed to the stand. Then the demodulated digital output is transferred to the host computer from a commercial wireless transmitter and receiver.

![Figure 3](image)

**Figure 3** The system frame of the outdoor E-field measuring system

### 3.2. Design of the package for the sensing chip

The micro resonant shutters and electrodes on the microchip are only 3 microns wide. They are very vulnerable to severe outdoor atmospheric conditions, such as high humidity, dust, wind, sleet, etc. Hence, when the chip is applied to the actual situation, the packaging is indispensable. However, MEMS encapsulation is still a hot topic because MEMS encapsulation not only protects the chip from external interference but also provides a physical channel for sensing parameters. For MEMS E-field sensors, there are no reports of actual encapsulation before.

In this work, we propose an innovative package based on a unique shaped polymer to protect the sensor chip, as shown in Figure 4. The polymer has the useful properties of stable molecular structure, high resistivity, and high stain resistance, making it an excellent material for packaging electric field sensors. It takes three steps to make this package. First, locate the sensor chip in the middle of the preamplifier circuit, and bond the gold wire to the circuit. The sensor chip faces the package cap. Second, remove the oil and dust contaminations on the polymer package cap with alcohol in the ultrasonic cleaner, Dry the cap in the drying oven at 80 degrees centigrade. Third, stick the package cap onto the preamplifier circuit with the epoxy glue. A copper circular ring is designed on the circuit board to enhance the adhesion strength. When this probe is used outdoor, the package cap faces down toward the ground; thus, the MEMS chip is hardly impacted by humidity and dust, and the cap could neither be wet in the rain, forming some kind of water films to shield the outside electric field.

The calibration result of the packaged chip was shown in Figure 5 as the uncertainty is 2.43%, approximately linear to the external E-field. It shows that the package is sufficient for the sensor chip.

![Figure 4](image)

**Figure 4** Picture of the sensor package cap
3.3. The design of the protection for the preamplifier circuit

Besides the sensor chip, the preamplifier circuit is another crucial part that needs environmental consideration. As the sensing electrodes’ area is tiny small, the output of the induced current is about 10-12A. Unlike traditional E-field mills, inside which there is the only desiccant for humidity maintaining, if the MEMS preamplifier circuit is out of protection, the amplifier circuit, especially the I-V conversion part, will undoubtedly be disturbed by electromagnetic interference, high humidity, and contamination.

In this design, we proposed one circuit protection to protect the preamplifier circuit, as shown in Figure 6. The circuit protection contains a ring step and a cover, both made by the PCB technique. Accordingly, we could use soldering tin to make the amplifier circuit, the ring step, and the cover to join up quickly and firmly. Furthermore, in the design of PCB, making the charge signal path short and far away from the drive signal would help to lower the feedthrough signal, therefore reducing the zero of output.

3.4. Finite element simulation

To prevent the E-field from being shielded by the vertical part of the stand, a kind of stand with a long horizontal pole was proposed. The total height of the stand and the length of the horizontal rod are both 1 meter. The edge of both the round probe and the cylindrical stand was gentle in order to prevent corona discharge in use.

ANSYS Electrostatic Module was used to simulate the enhancement of the atmospheric E-field cased by the whole system, including the metal stand. The applied boundary conditions were initialized as follows: The E-filed strength is 100V/m; direction is from top to bottom. Because the probe was mostly made of PCB, and on the surface of PCB, there was copper, which affects E-field much more vital than other materials, we considered the probe a whole metal volume. As the permittivity of metal is infinity high in math calculation, we set the permittivity of the probe, and the metal stand to be 9999. Furthermore, their voltage was set to be zero because they both connect to the ground in the outdoor monitoring. The other medium in space is air, whose permittivity is 1. Read the E-field on the surface of the probe after a steady-state solution. The way we read E-field beneath the probe is to define a line path vertical to the sensing surface of the probe, as shown in Figure 7(a), then draw out the E-field on this line, as shown in Figure 7(b). The two peaks of the curve appear on the top face and the bottom face of the probe and this kind of metal stand made the E-field on the bottom face magnify about 6.9 times.
That is to say because the resolution of our used MEMS E-field sensor is better than 40V/m [19], the minimum resolvable field of our equipment would be better than 5.8V/m.

![Figure 7](image_url) (a) Model of measuring E-field system and (b) simulation results of E-field

4. Experiments

4.1. High humidity experiments

Among those factors, humidity is the main environmental factor that affects the stability of the sensors. Meanwhile, the influence of temperature compared with humidity is not that significant. The main problem to be solved in this paper is the humidity drift.

Before the external probe was placed, two humidity experiments were designed and finished. The experiments are to test the performance of the package and the protective effect of the circuit. As shown in Figure 8(a), when the humidity increases, the output of the unprotected mems sensor immediately increases from -400 mV to -325 mV and does not descend with the decrease of humidity for half an hour. With the packaging and preamplifier protection later, as shown in Figure 8(b), the output is kept stable between 400 mV and 401 mV under the condition of high humidity for several consecutive cycles.

![Figure 8](image_url) High humidity experiment results. (a) Probe without package and circuit protection, (b) Probe with package and circuit protection

In addition to the experiments above, we also conducted several high humidity experiments on different sensors to ensure the feasibility and repeatability of this method. It is a new scheme for the MEMS electric field sensor and one of the key points in practical application.

4.2. Outdoor E-field monitoring experiments

Figure 9 shows the test system introduced in a relatively open and flat space in Beijing, alongside the commercial Campbell CS110 E-field mill (EFM) for comparison. The total power of the sensor chip and the signal processing circuit we use is 0.6W. All the data were transmitted and recorded by a pair of commercial wireless modules. Figure 10 (a, b, c) shows the atmospheric electric field measured by our system on a sunny day, foggy day, and rainy day, which is in contrast to Campbell CS110 EFM. The output voltage is converted to electric field strength by site calibration. As can be seen from the curves, the measured results were consistent with those of Campbell CS110 EFM.

On a sunny day, the output of the MEMS sensor was consistent with the data output direction and quantity in the 5V/m range monitored by Campbell in real-time. Therefore, the minimum resolvable field of our system is better than 5V/m, which is approximately consistent with the simulation results. Because of its high resolution and good stability performance on sunny days, the MEMS sensor has a
broad application prospect in the study of E-field on sunny days and its relationship with climate and aerosol.

It is well known that the relative humidity is still very high on foggy days. Figure 10(b) shows the consistency of the two sensors and demonstrates once again the usefulness of the package and circuit in preventing high humidity.

Figure 10(c) shows the curve in sleet and cloudy weather at noon, with rain began in the afternoon. These high field values reflect the discharge of thunderclouds, which are detected by both sensors. Therefore, weather forecasting and lightning warning are promised to be another application of MEMS E-field sensors.

![Figure 9: Picture of the outdoor atmospheric E-field monitoring](image)

![Figure 10: Measured results of outdoor atmospheric E-field, (a) a sunny day on Nov. 11, 2012; (b) a foggy day on Nov. 22, 2012; (c) a sleety day on Nov. 3, 2012, in Haidian District, Beijing, China.](image)
Table 1 shows the detailed performances of this MEMS E-field sensor compared with the Campbell CS110. By means of the miniature probe and the metal stand designs, the E-field resolution is enhanced remarkably. Through all the environmental adaptability considerations, our sensor shows good stability; therefore, it is promised to be used for atmospheric E-field measurement in the future.

Table 1 Performances of MEMS E-field sensor compared with the Campbell CS110

|                      | MEMS E-field sensor | Campbell CS110       |
|----------------------|---------------------|-----------------------|
| Probe size (mm)      | Φ32×20              | 152×152×432           |
| Measurement range (kV/m) | -30~30              | -22.3~22.3            |
| E-field resolution (V/m) | 5                   | 3                     |
| Operating Temperature Range (°C) | -40~55             | -55~85                |
| RH range (%RH)       | 0~100               | 0~100                 |
| Power @ 1Hz (W)      | 0.6                 | 0.7                   |

5. Conclusion

We firstly report a practical MEMS E-field sensor for measuring the atmospheric electric field with high stability in various environmental factors. The measuring system was constituted by a sensitive probe based on a micro-fabricated sensor chip, a signal processing circuit, and a metal stand. Both finite element simulation results and E-field experiments proved that this E-field measuring system could detect the electric field as small as 5V/m. The monitored results were in fair consistent with those of commercial Campbell CS110 EFM.

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