High-stability electrostatic field micro sensor for sounding thunderstorm applications

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Abstract: In this paper, the design and experimental results for a novel high-stability sounding electrostatic field micro sensor are presented. By means of hermetic chip sealing, digital weak signal demodulation unit, and probe sensor structure design, harsh environmental adaptation problems such as low temperature, high humidity, low air pressure, waterfall are solved. The sensor has a high resolution of 14 V/m, a wide measurement range of ±100 kV/m, and is proved to have superior stability and performance in sounding electric field experiments than traditional sensors under different kinds of weather.

Key words: electrostatic field sensor; MEMS; sounding; environmental adaptability

1 INTRODUCTION

Electric field (E-field) is one of the most important parameters in studying the electrical characteristics of the atmosphere, such as the global atmospheric electric circuit (GEC)[1], thunderstorm electrification and lightning generation mechanisms[2], discovery of transient luminous events[3] above thunderstorms and many other meteorology electrical phenomena[4-6].

Measurements of E-field have been made for over 200 years, basically by three types of instruments, including the potential probe, corona discharge probe, and the E-field mill. The potential probe amounts a pair of conductors to induce charge from external E-field, and measure the voltage difference between them by a very sensitive electrometer[7]. The probes must be mounted far enough to increase the sensitivity and decrease the distortion from the central gondola. The corona discharge probe consists of a sharp conducting point connected to an electrometer circuit, through which a corona current flows whenever the electric field exceeds a certain corona-onset threshold of more than 1 kV/m[8]. However, this kind of sensor is easily affected by environmental factors, such as air pressure, rain drops, wind speed, and so on. Another instrument, which is widely used nowadays, is the Electric Field Mill (EFM)[9]. There is a rotatable electrode driven by a motor and connected to the ground, which alternatively shields and exposes the sensing electrode, generating an induced AC current. The EFM has superior performances, such as sensitivity of 1 V/m, measurement range of ±100 kV/m, fast response time and so on. Fabrication and cost are the main shortcomings of this sensor, because it needs to be assembled by over 40 components manually.

Since the 1990s, a variety of Micro Electric Field Mills (MEFM) have been reported, having the advantage of low cost, small size, low power consumption, batch manufacturing, easy to integrate, and so on. The driven pattern as well as the performance of these MEFMs are improved gradually[10-13]. Until 2011, Pengfei Yang's design based on SOI technology reached the best sensitivity of 40V/m and quality factor of higher than 30 thousand[14, 15]. Nevertheless, those tiny electrodes of

3μm length are easily affected by environmental factors, such as wind, air pressure, rain drops, etc. This paper solves the chip's problems of packaging and weak signal detection, and introduces the application of this micro sensor in sounding thunderstorm applications.

2 CHIP WORKING PRINCIPLE

The working principle of the Electrostatic Field Micro Sensor (EFMS) is shown in Fig. 1[11]. It consists of a grounded shutter, two parts of sensing electrodes, comb drive, and so on. The SOI EFMS are not prone to stiction compared with the sensor based on polysilicon process and thus more reliable.

When the comb drive is driven by electrostatic force, the ground shutter moves forward and back on the same plane, alternatively shielding and exposing the sensing electrodes. The output current i_{out} is given by:

$$i_{out} = \varepsilon E_n \frac{dA}{dt} \qquad (1)$$

Where ε is the permittivity of air, E_n is the orthogonal component of external E-field, and A is the overall area of sensing electrodes. The voltage amplitude is proportional to the measured field.

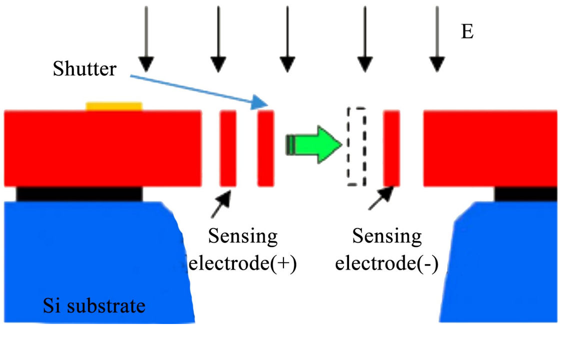


Fig. 1 Working principle of EFMS

Fig. 2[11] shows the SEM of fabricated EFMS. By means of two separate groups of differential sensing electrodes, unwanted coupling noise from the driving comb will be apparently minimized. Furthermore, comb-shaped electrode design is adopted and the electrode size is optimized in order to maximum the inducing efficiency.

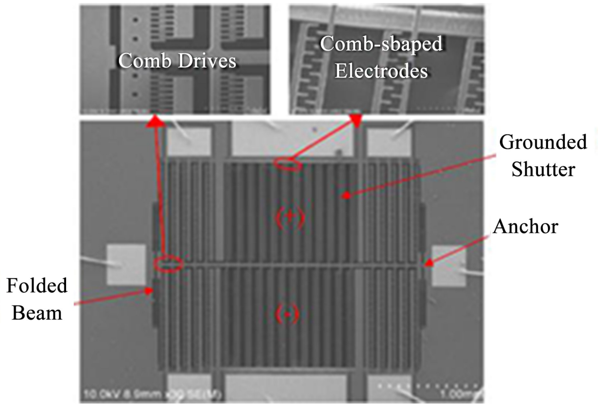


Fig. 2 SEM of EFMS

3 SENSOR DESIGN

This paper presents a new design of sounding electric field micro sensor, including the chip package, the chip output detection, and the sensor structure for environmental adaptation.

3.1 Chip Package

Chip package is vital to the application of EFMS, as it maintains the microchip into a highly reliable and stable circumstance. A photo of the chip package is shown in Fig. 3. There are two parts of high polymer material, which are bonded by reflow soldering. The top of the cap is metalized in order to accelerate the equilibrium of induced charge. The microchip is situated in the middle of the 1-mm-deep cavity underneath the metal cover and is positioned close enough to the bottom of cap such that when the package is exposed into the E-field, the sensing efficiency is maximized.

Fig. 3 Sketch of Chip Package

It is shown in Fig. 4 that the frequency response of micro sensor maintains even when the air pressure reduced to 1% of normal pressure and kept for about 2 hours, indicating that this sealing is air-tight enough for higher than 30 km.

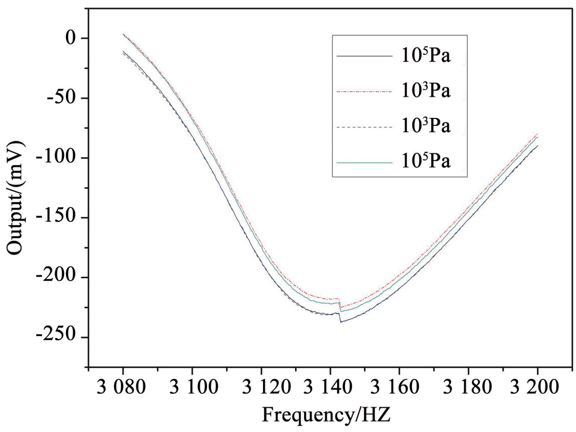


Fig. 4 Experiments of chip package under low air pressure

3.2 Drive and Weak Signal Detection System

Fig. 5 shows a block diagram of the drive signal and signal detection system. Actuation voltages for the sensor chip were 20V DC added to antisymmetric 2 Vp-p waveforms at 3.1 kHz. The actuation amplitude was about 8μm, slightly less than the anchor restricting gap of 10μm. Two differential output currents of the sensor chip were processed first in the preamplifier circuit, then in the sampling AD converter, and last in the CPU for digital demodulation. Sensor response to the external E - field was finally converted into a digital output.

We made pA-magnitude weak current magnification using two transresistance amplifiers for I-V converting, shown in Fig. 6. The output voltage of the I-V convertor can be found from

$$V_{out} = I_{chip} \cdot R_f \quad (2)$$

Where V_{out} is the output voltage, I_{chip} is the sensor chip output current, and R_f is the value of the feedback resistor. The amplifier's input current I_{chip}, contributes an output voltage error proportional to the value of the feedback resistor. Therefore, 4.7MΩ resistor with the precision of 0.1% is an ideal option.

After I-V converting, there is an instrumentation amplifier for two voltage differentiating, where the unwanted coupling noise is dramatically reduced, and the final single output voltage is proportional to the applied E-field. The gain equation is given by

$$G = \frac{49.4k\Omega}{R_G} + 1 \quad (3)$$

Where R_G is the value of external gain setting resistor.

3.3 Environmental Adaptation Design

To measure E-field inside thunderstorms, hash environment conditions such as waterfall, low temperature, low air pressure, electrification by friction should be considered. In this paper, we design a detachable probe sensor structure, as well as a downward metal probe package and foam heat preservation circuit package.

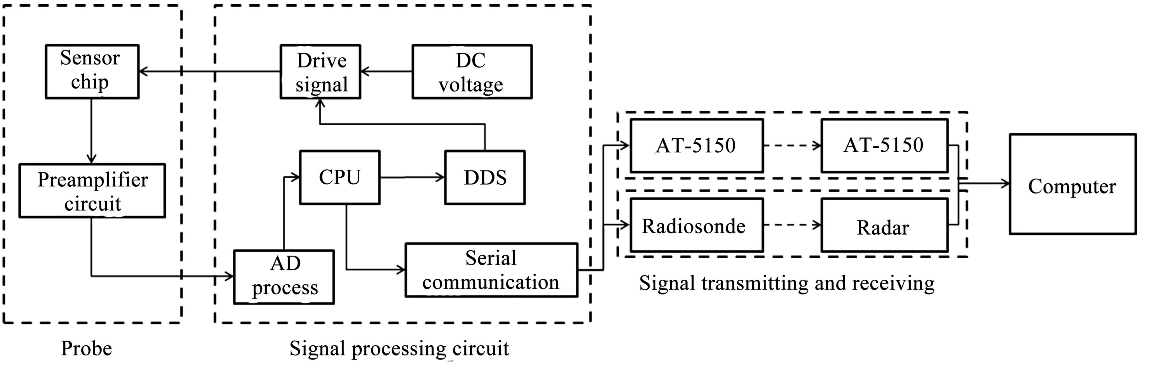


Fig. 5 Drive and signal detection system diagram

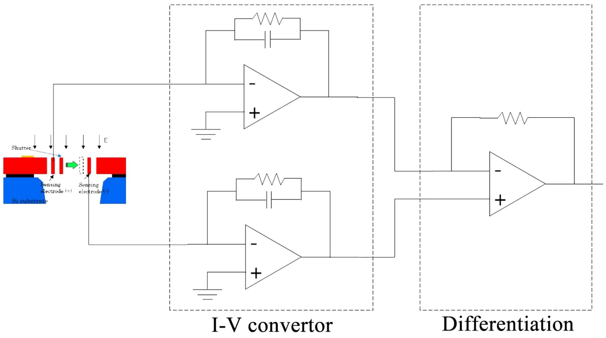


Fig. 6 Scheme of preamplifier

In order to avoid the E-field from the friction charge of foam material, the sensor probe is separated 1.5m away from the signal processing unit in Fig. 7.

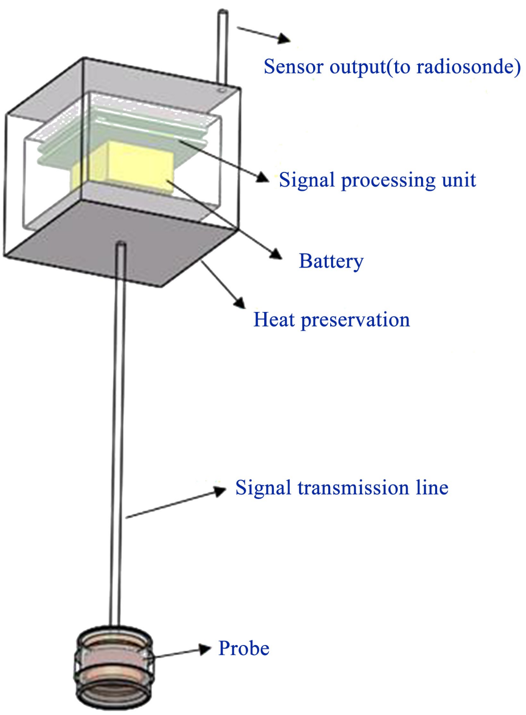
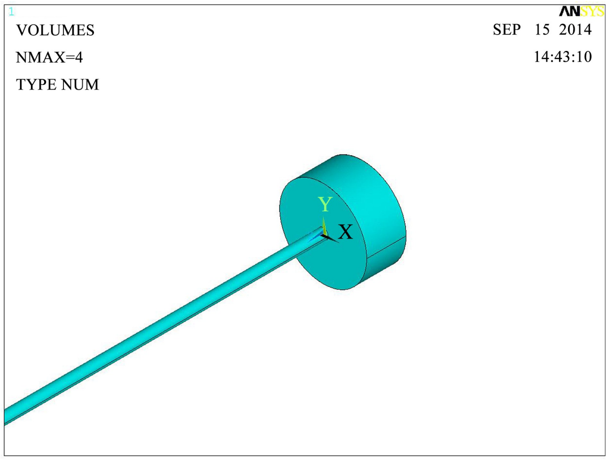
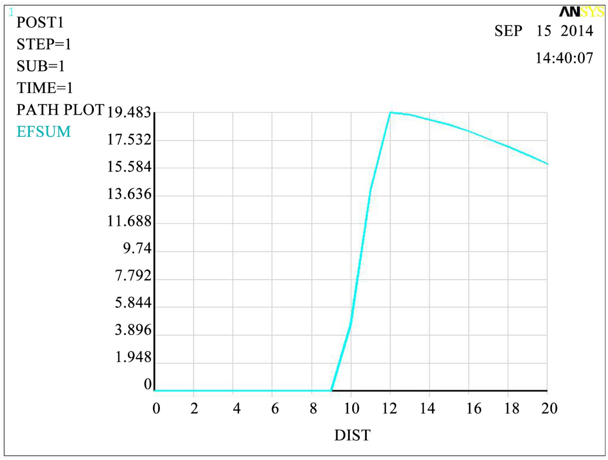


Fig. 7 Scheme of probe type sensor structure

Additionally, by lengthening the metal signal transmission line, the magnification effect of E-field is enhanced. FEM result is shown in Fig. 8. When E-field of 1 V/m is applied around, the strength of E-field on the sensing probe is 19.483 V/m. As thermal drift is decided only by the sensor chip, the drift proportion is apparently reduced.



(a) probe model



(b) E\|field along the model, the curve peak located on the sensing part of probe

Fig. 8 FEM result

In the sensing part, the chip package is further packaged by electrically grounded metal, so that it won´t get polluted by waterfall and dust.

Most of the electronics components are designed working above -40℃. In real circumstance, however, the lowest temperature in high attitude up to 30km is about -70℃. We use a foam package to make heat preservation of signal processing unit and battery. By means of optimizing the size and thickness of material, as shown in Fig. 9, the circuit's heat itself could maintain the air temperature inside the cavity at 0℃ above.

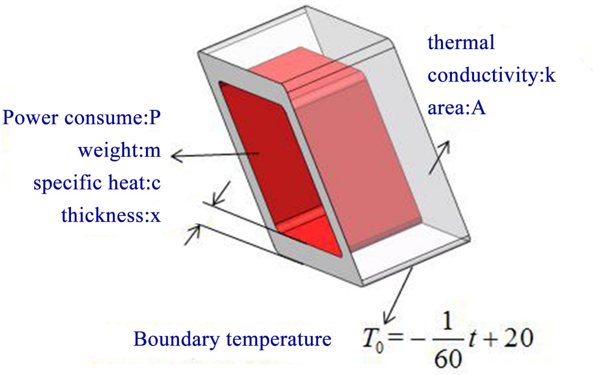


Fig. 9 Heat preservation model

Under the boundary temperature in Fig. 9, the temperature inside the cavity is

$$T=\frac{-\frac{Ak}{120x}t^2+\frac{20Ak}{x}t+pt+20mc}{\frac{Akt}{x}+mc} \tag{4}$$

A full view of EFMS is shown in Fig. 10. The sensor was assembled from only 9 tiny components, which is much more convenient to assemble and use than a traditional electric field mill. The weight is 87g, significantly compared to the EFM's weight of 4000g, or the two-sphere electric field mill of 1000g (all without battery). Under these advantages, it is promised to use this sensor in daily sounding meteorological services, for people to understand more about atmosphere electricity.

Fig. 10 Full view of EFMS

4 EXPERIMENTS

To test the EFMS, we first calibrated the sensor, and settle it into a temperature & humidity box to examine the environmental adaptability. As shown in Fig. 11(a), the uncertainty of the sensor response inside a 100 kV/m field is 1%. However, this does not include the full measurement range, because the input voltage of sampling ADC employed in sensor system is ±5V while the sensor response is 350mV under 100 kV/m.

Two other sensors shielded from extra E-field showed good stability in Fig. 11(b)(c) when the temperature changed from room temperature to -70℃ and the relative humidity changed from 30% to

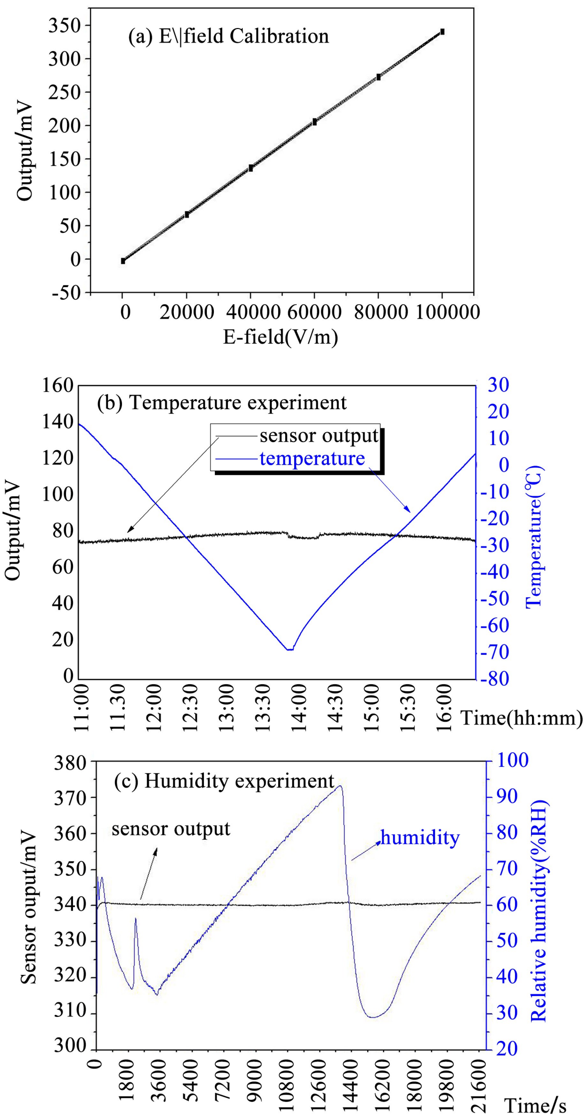


Fig. 11 Calibration and environmental test result

95%. The output drift is less than 5% of full scale output. In contract, those without package or other environmental considerations are 75% to 300%.

Outdoor balloon-borne sounding experiments were run by bonding to radiosondes for data transmission and using a radar for data receiving. As shown in Fig. 12, the E-field probe was freely hanged downwards, so that it would be as far away from the balloon electrification as possible. Because the balloon flight system was light in weight, we may use the 300-gram size hydrogen balloon instead of 1500-gram size hydrogen balloon for traditional two-sphere EFM sonde. In this measurement system, E-field sound transmitted the space E-field into the radiosonde. And the radiosonde measured temperature, humidity and attitude, then encoded all the meteorological information to transmit downward. The signal transmission is stable under harsh weather conditions.

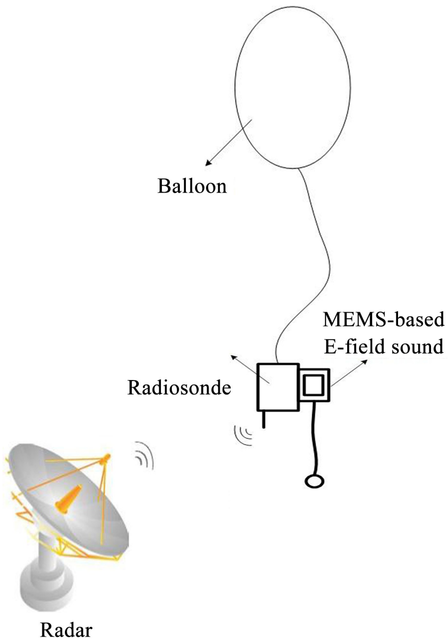
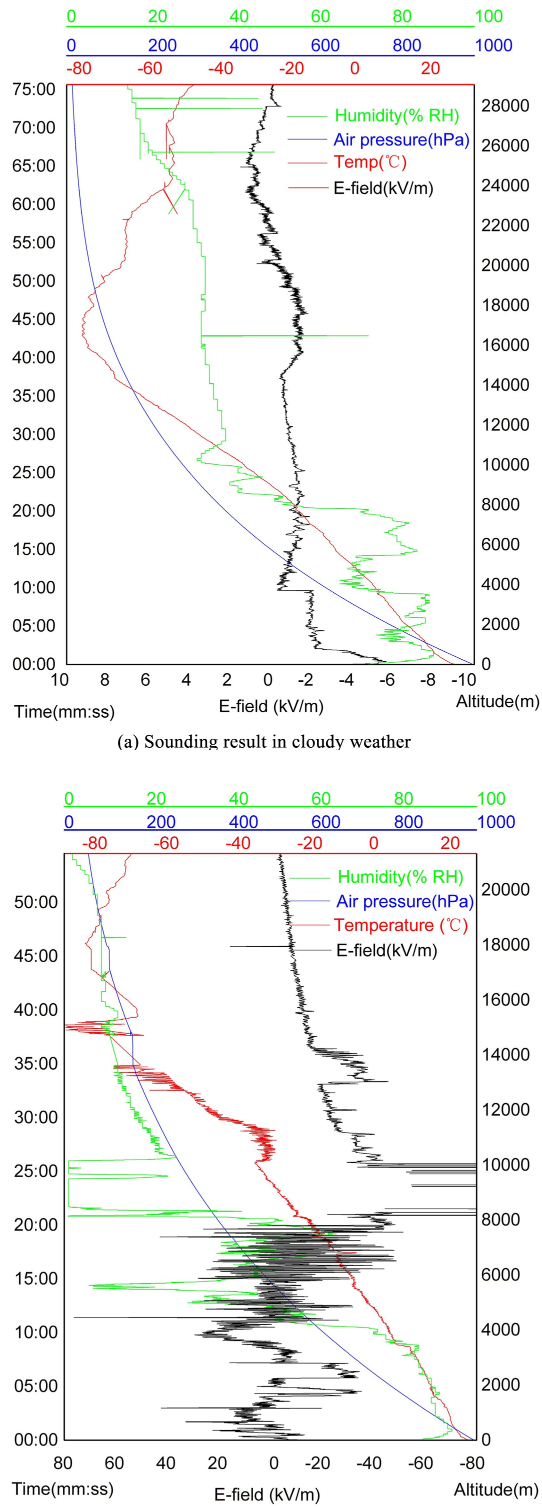


Fig. 12 Sounding E-field system setup

Fig. 13 illustrate two measured results of cloudy weather and thunderstorm weather. When the humidity (green line) increased at several kilometers attitude, E-field varied in three main peaks, which was in coordinate with the tripole charged regions model of charged cloud. And E-field changed rapidly when flied through a thunderstorm, indicating that there were severe thunder strokes inside. The max E-field measured inside this thunderstorm was -80 kV/m.



(a) Sounding result in cloudy weather

(b) Sounding result in thunderstorm weather

Fig. 13 Sounding result in two kinds of weather

This balloon-borne sounding E-field experiments have been done for tens of times in China since 2012. It has been proved to be a more convenient and better performed sensor than traditional ones. Finally, we made a comparison between EFMS and several reported sounding E-field sensors in Tab. 1. The resolution 14V/m is the lowest E-field strength that the sensor can differentiate under certain applied E-field. The uncertainty, short for relative overall uncertainty, is calculated by Eq.(1) according to GB/T 18459-2001[16].

$$U=\frac{\max|B_i+t_{0.95}S_i|}{Y_{FS}} \tag{5}$$

U is the relative overall uncertainty. B_i and S_i are the systematic error and stochastic error at E-field i respectively. Because there are six measuring point in uncertainty measurement, the coverage factor $t_{0.95}$ equals 2.571. Y_{FS} is the full scale output of sensor.

Table 1 Performance comparison between several E-field sounds

Performance	EFMS	Rotate-vane E-field sound	Two-sphere E-field meter	Two-sphere E-field meter	Rocket-borne E-field meter
Probe dimensions (mm)	Φ3.5 * 4	80×80×120	Length: 1000 Diameter: 143	Length: 800 Diameter: 120	Φ55 cm * 760
Weight (g)	87	180	-	500	320
Measurement range (kV/m)	−100~+100	±(0.2~30)	0.5~50	−0.01~10	1~100
Resolution (V/m)	14	20	500	-	1000
Uncertainty	3%	1%	10%	-	15%

6 CONCLUSIONS

In this paper, we introduce a new Electrostatic Field Sensor based on MEMS technology for sounding thunderstorm applications. Chip package, weak signal detection and environmental adaptation techniques are employed during the design, and this sensor has been applied through balloon flights for many times. It is proved that this sensor has the advantages of light weight, small size, low cost, low power consumption, batch manufacturing, easy to integrate, etc.

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