# Summary of MEMS Capacitive Accelerometer

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**Abstract.** Micro-Electro-Mechanical System (MEMS) accelerometer (MEMS accelerometer), as an important MEMS device, has been widely used in the field of high-precision electronic technology and consumer electronic products. At present, the technology of MEMS accelerometer has been mature, and the sensor based on capacitance principle, piezoelectric effect, piezoresistive effect and other principles has been widely used in many aspects of national life and production and sustainable development. Combined with and according to all kinds of references, this paper briefly describes the shape composition and sensing principle of the MEMS capacitive accelerometer, enumerates the design and error optimization research of each research group for the sensor, and explains it with the relevant research data.

**Keywords:** Micro-Electro-Mechanical System (MEMS); capacitive sensor; accelerometer; design optimization.

## 1. Introduction

Since the 1980s, with the development of microelectronics and micromachining technology, Micro-Electro-Mechanical System (MEMS) have been derived, and a large number of MEMS products have emerged [1]. Micro-Electro-Mechanical System accelerometer (MEMS accelerometer) has been widely studied and applied in recent years because of its miniaturization, high performance and low cost [1]. Using Coriolis effect, the combination of MEMS accelerometer and micromachined gyroscope, especially in the fields of smart phone and UAV, has become the core technology to realize complex motion tracking and navigation system [2]. This kind of sensor plays an important role in many fields, such as automobile, aerospace, consumer electronics and medical equipment, especially in motion monitoring, navigation system and vibration analysis [3, 4, 5]. With the continuous progress of technology, the sensitivity, accuracy and stability of MEMS accelerometer have been significantly improved.

At present, compared with other similar piezoresistive accelerometers, capacitive accelerometer has higher sensitivity and resolution, so it has been widely studied and applied [6]. Different manufacturers have different requirements for MEMS accelerometers in different application industries, for example, automobile companies require MEMS accelerometers to pass the same pressure tests as mechanical accelerometers, including shock, vibration, temperature cycle, acceleration and working life tests, and semiconductor companies enhance traditional stress tests to evaluate the robustness of MEMS products [7].

Shock analysis, drop test, working life test, stress test and failure rate test of the MEMS accelerometer can optimize the design of the accelerometer to adapt to different application environments. The following is an overview of the composition principle, system analysis and optimization direction of the accelerometer based on the capacitive sensing principle.

## 2. General situation of MEMS Industry Development

### 2.1 Moore's Law and Integrated Circuit

The beginning of the history of MEMS is integrated circuit technology. As early as 1947, the transistor introduced by AT&T Bell Laboratory initiated a revolution in the field of communications and computers [8]. In the following decades, integrated circuits developed rapidly. Gordon Moore predicted that every 12 to 18 months, the integrated density of transistors on the chip would double, a law of growth known as Moore's Law [8, 9].

In the process of continuing Moore's Law, scientists continue to improve the existing process, we introduced immersion lithography, multiple exposure, Extreme Ultra-violet (EUV) lithography process, introduced FinFET, GAAFET (Gate-all-around FET), MBCFET (Multibridge-channel FET) transistor architecture (Fig. 1), to achieve the change from 2D to 3D stacking mode [10, 11, 12, 13, 14].

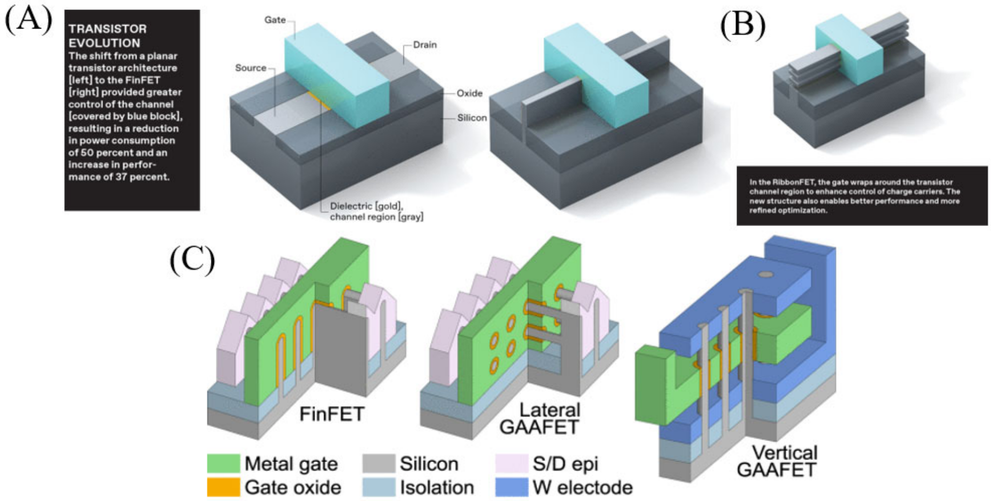



Fig. 1 (A) Planar MOSFET structure (left) and FinFET fin structure (right) [11], (B) Gate surround structure RibbonFET which constitutes GAAFET [11], (C) FinFET, Lateral GAAFET, Vertical GAAFET structure [12]

However, at present, the micro-nano processing size of integrated circuits has been reduced to nearly nanometer limit, the leakage current and short channel effect caused by quantum tunneling effect make Moore's law begin to slow down gradually [15], and the increase in the number of transistors falls into a bottleneck period. it is difficult for the performance of various processors to grow by leaps and bounds. The "failure" of Moore's Law has now been widely accepted, and researchers believe that the failure of Moore's Law provides a new creative era for computer scientists, advocating the study of emerging architecture and packaging [16, 17, 18].

### 2.2 Micro-machining technology

At the American Physics Conference in December 1959, Richard P. Feynman, a Nobel laureate and famous physicist, made a far-sighted and pioneering report: "There Is Plenty of Room at the Bottom", which first raised the problem of science and technology on the nanometer scale [19]. In his report, Dr. Feynman describes the extensive development space and progress of micromanufacturing technology, and discusses the great potential of using micro-structures composed of atoms, molecules, to store information. Since then, human beings began to study the micro-nano manufacturing technology and related laws under the micro-size.

In the past few decades, microelectronic device manufacturing technology has made great progress, creating an eye-catching, accurate and high-performance device system. These technological breakthroughs have reduced the size of the equipment to such an extent that it is imperceptible to the human eye. Micro-Electro-Mechanical system (MEMS), as an innovative field of micro devices, is devoted to the development of micro sensors and actuators. The continuous development in the field of MEMS brings great hope for the optimization and cost-saving of small electrical devices. MEMS technology integrates sensors, actuators and control circuits on microchips to form MEMS sensors, providing smaller, more accurate and higher performance solutions for a variety of applications, including medical, automotive, consumer electronics, and so on. These developments have created a more advanced and convenient world of science and technology for us [3, 4, 5, 20, 21].

In order to identify the parameter changes in the environment, the MEMS sensor senses and transmits the relevant parameter change information by measuring its mechanical, magnetic, chemical, optical, acoustic, thermal or electromagnetic. Researchers began to study the MEMS technology of transistors as early as the mid-1950s. Subsequently, commercial devices based on MEMS sensors were produced, such as inkjet printers, MEMS microphones, MEMS accelerometers, MEMS gyroscopes, MEMS pressure sensors, display sensors, MEMS switches and MEMS biosensors [22].

### 2.3 MEMS capacitive accelerometer

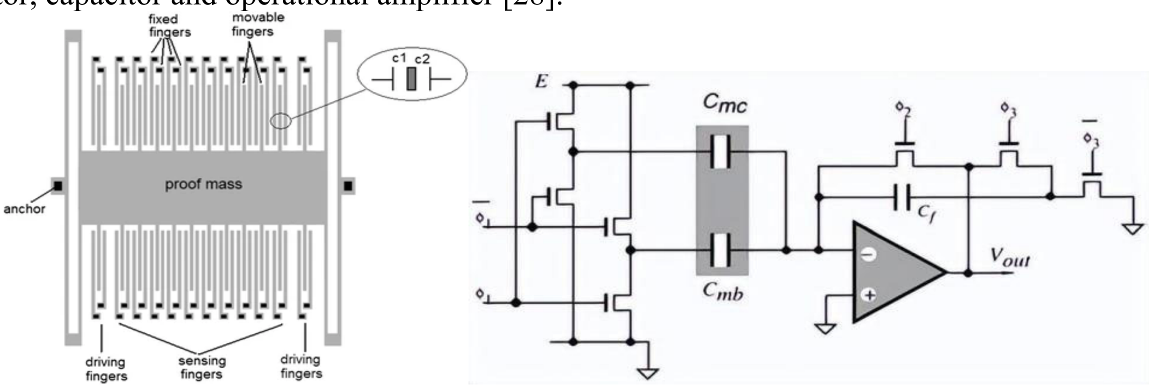
In the past few decades, characterizing acceleration change by capacitance change is one of the most commonly used techniques for high-performance MEMS accelerometers. It has attracted much attention because of its advantages such as high accuracy, simple structure and easy integration, low noise, low power consumption, high performance-to-price ratio and reliability [23, 24, 25]. The accelerometer has been used in high-end industrial and biomedical sensors, such as consumer electronics, automotive, structural health monitoring, inertial navigation, medical and other fields [24, 26, 27].

## 3. Sensing principle

### 3.1 Physical structure

The following author will introduce the sensing principle of MEMS capacitive accelerometer.

The composition of the MEMS capacitive accelerometer is analyzed below. Through the elastic strain connecting beam structure as the sensitive unit, the acceleration is converted into the relative displacement, and the capacitance is used as the input of the displacement sensed by the conversion element. Through the output of the capacitance-voltage conversion circuit integrated on the silicon chip, the output voltage can be used to represent the acceleration. In the design and manufacture, the internally developed accelerometer consists of a comb drive structure based on silicon on insulator (SOI) (Fig. 2 (A)) and integrated on a PCB with capacitive signal conditioning ASIC (Fig. 2 (B)). The external integration of the sensor adopts PI controller designed by basic components such as resistor, capacitor and operational amplifier [28].




(a) (b)

Fig. 2 (A) Comb-shaped capacitive plate structure of MEMS accelerometer [29], (B) A Capacitor-to-Voltage Converter Circuit Diagram suitable for Integration on Silicon Wafer

The common uniaxial comb accelerometer can characterize the acceleration by measuring the change of overlap area between comb rulers or the change of gap spacing between comb rulers. The former type is called variable area accelerometer, while the latter type is called variable polar accelerometer (Fig. 3 (A) (B)) [25]. Uniaxial accelerometers in different directions can be combined to form XYZ three-axis accelerometers and gyroscopes (Fig. 3 (C)) [24, 30, 31].

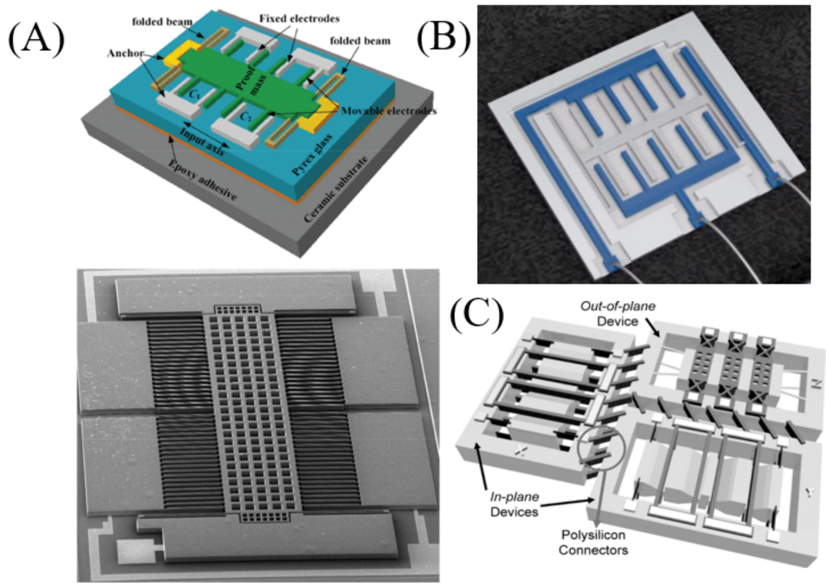



Fig. 3 (A) Concept of accelerometer and microscopic image of physical object [32], (B) Structure simplified diagram, (C) XYZ three-axis gyroscope [30]

### 3.2 Dynamics model

It is known that the capacitance of the solitary conductor is $C=\frac{Q}{U}$, and the capacitance of the parallel plate capacitor is $C=\frac{q}{u_A-u_B}=\varepsilon_0\frac{S}{d}$. Taking the variable pole distance capacitive uniaxial accelerometer as an example, the capacitive accelerometer can be regarded as a typical mass-spring-damping system from the point of view of dynamics. According to the available mechanical model of Newton's second law, the control theory is used to analyze:

$$M\cdot\frac{d^2x}{dt^2}+D\cdot\frac{dx}{dt}+K\cdot x=M\cdot a$$

Convert the above formula into the differential equation of a second-order system:

$$\frac{d^2x}{dt^2}+2\zeta\omega_n\cdot\frac{dx}{dt}+\omega_n^2\cdot x=a$$

Among them, the natural frequency $\omega_n=\sqrt{\frac{K}{M}}$, damping ratio $\zeta=\frac{D}{2\sqrt{MK}}$, quality factor $Q=\frac{1}{2\zeta}=\frac{\sqrt{MK}}{D}$ ($M$ means Mass block mass, $K$ means equivalent spring coefficient, $D$ means equivalent damping coefficient, and $a$ means external input acceleration).
Through the Laplace transform under zero initial condition, the transfer function is obtained as follows:

$$G_{(s)}=\frac{C_{(s)}}{R_{(s)}}=\frac{1}{s^2+2\zeta\omega_n s+\omega_n^2}=\frac{1}{s^2+\frac{D}{M}\cdot s+\frac{K}{M}}$$

In the case of low frequency, that is when $\omega\ll\omega_n$, the transfer function $G_{(s)}\approx\frac{1}{\omega_n^2}$. That is, under ideal conditions, the sensitivity of the sensing system is inversely proportional to the square of the resonant frequency. When the frequency increases gradually, the sensitivity of the system will be affected by the damping coefficient and vibration frequency [33, 34].

### 3.3 Electrical model

The equivalent circuit of the MEMS capacitive accelerometer is shown (Fig. 4) :

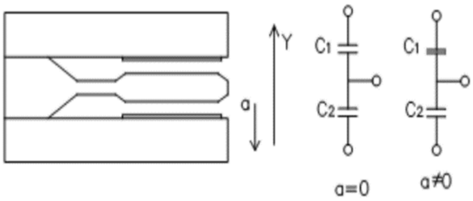



Fig. 4 Equivalent circuit diagram of accelerometer

Let the polar distance between the upper and lower plates be $d$, the initial positive area of the metal mass and the plate is equal to $S$, and the opposite dielectric constant is $\varepsilon$, when the external input acceleration leads to the displacement of the plate along the longitudinal direction, there is the following expression:

$$C_0 = \varepsilon\frac{S}{d_0} = \varepsilon\frac{S}{d}, C_1 = \varepsilon\frac{S}{d_1} = \varepsilon\frac{S}{d+\Delta d}, C_2 = \varepsilon\frac{S}{d_2} = \varepsilon\frac{S}{d-\Delta d}$$

The differential capacitance is:

$$\Delta C = C_2 - C_1 = \varepsilon\frac{S}{d-\Delta d} - \varepsilon\frac{S}{d+\Delta d} = \varepsilon\frac{2S\Delta d}{d^2-(\Delta d)^2}$$

$$C_1 = C_0\frac{1}{1+\frac{\Delta d}{d}}, C_2 = C_0\frac{1}{1-\frac{\Delta d}{d}}$$

To expand according to a power series:

$$C_1 = C_0[1-(\frac{\Delta d}{d})+(\frac{\Delta d}{d})^2+\cdots], C_2 = C_0[1+(\frac{\Delta d}{d})+(\frac{\Delta d}{d})^2+\cdots]$$

$$\frac{\Delta C}{C} \approx 2\frac{\Delta d}{d}$$

Sensitivity: $S = 2\frac{\Delta d}{d}$, Nonlinear error: $\delta = (\frac{\Delta d}{d})^2 \times 100\%$.

As analyzed above, the variable pole distance capacitive accelerometer with differential structure has high sensitivity, linearity in a certain range, and reduces the nonlinear error. However, when the acceleration is too large and the condition $d >> \Delta d$ fails, the sensor will have nonlinear characteristics, so the displacement of the comb-shaped plate can be reduced by increasing the elastic modulus of the elastic strain beam.

## 4. Performance evaluation of MEMS capacitive accelerometer

### 4.1 Main performance parameters

We usually evaluate the performance of the MEMS accelerometer from the following parameters [6].

i. Sensitivity: the degree to which the accelerometer responds to changes in acceleration.

ii. Linearity: check the linear relationship between the sensor output and the actual acceleration, and evaluate its consistency at different acceleration levels.

iii. Range (Maximum range): the range of acceleration that can be measured by the sensor.

iv. Frequency response: the response force of the sensor to acceleration signals of different frequencies.

v. Bandwidth: the sensor can accurately measure the frequency range of the acceleration signal.

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### 4.2 Performance parameter evaluation and design

In the researchIn the research of MEMS capacitive accelerometer, the relevant research group analyzes and evaluates the performance of related sensors. Through a series of tests on the inertial sensor, Kourepenis et al verified its robustness and reliability in extreme conditions such as air gun impact of 60,000g and the temperature range from-40 °C to + 85 °C, showing the high performance and applicability of the sensor [35]. In the paper "Evaluation of MEMS capacitive accelerometers", Beliveau et al evaluated the performance and energy of three kinds of MEMS capacitive accelerometers and found that their responses and fault modes above and below the maximum induction level provide key data for sensor design [6]. Albarbar, A. The researchers measured the vibration of three different MEMS accelerometers, obtained the frequency response curves of the sensor under sinusoidal, pulse and random excitation respectively, and compared the response of the sensor through images [36].

According to the above analysis, the sensitivity is inversely proportional to the square of the natural resonant frequency, so the increase of sensitivity usually leads to the decrease of dynamic range and measurement bandwidth [37]. Accurate modeling of effective parameters and corresponding adjustment of design parameters is an important part of the design. Relevant research groups coordinate the relationship between sensitivity and bandwidth in order to optimize the design of sensors to adapt to a variety of measurement environments.

Edalatfar et al first explored the capacitance sensitivity and gap ratio, and gave the optimal design of the ratio of 3.2. Then, by designing a mutual capacitive MEMS accelerometer with high sensitivity and wide bandwidth, the sensor with sensitivity of 11.801mV/g and resonant frequency of 2.3kHz is successfully realized, which effectively solves the tradeoff between sensitivity and bandwidth (Fig. 5 (A)) [38]. Ru Li et al. also analyzed the gap ratio and obtained the optimal gap ratio of 3.44 (wide gap of 3.1 μm and narrow gap of 0.9 μm), and higher resonant frequency 4.27kHZ and higher voltage sensitivity 35.93 mV/g (Fig. 7 (B)) [25]. In addition to the structural design of the sensor to change the parameter performance, some research groups have also carried out research on other aspects. For example, Pournia and others focus on the influence factors of substrate resistivity by increasing the substrate doping to the minimum detectable concentration (MDC), which successfully improve the performance and resolution of the accelerometer [39].

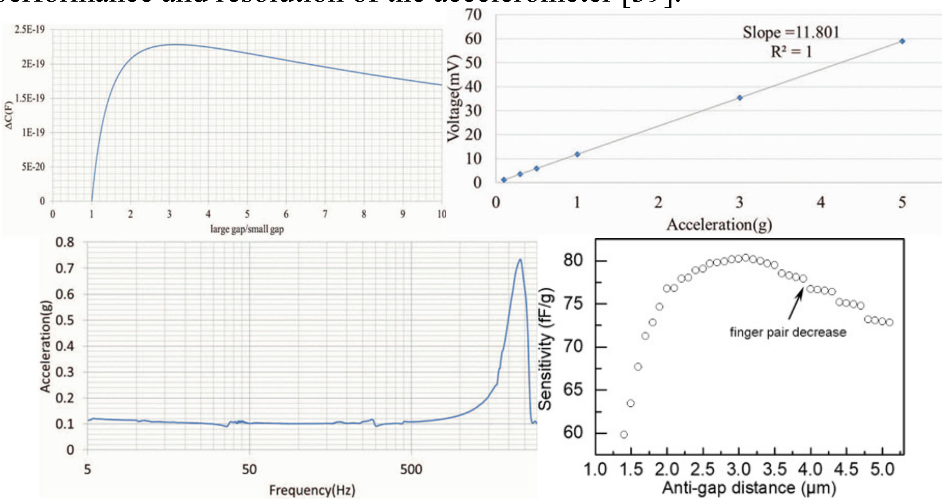


Fig. 5 (A) Relevant experimental data obtained by Edalatfar et al [38], (B) the capacitance sensitivity-gap ratio scatter diagram obtained by Ru Li et al [25].

## 5. Error Optimization of Sensor

### 5.1 Suppression of temperature drift and temperature compensation

Temperature drift affects the electrical characteristics of MEMS capacitive accelerometer, so in practical application, in order to achieve high-precision sensing, it is necessary to compensate or restrain the temperature drift.

Each research group made research on improving sensor structure, manufacturing process and introducing compensation. The research group obtained the mismatch of parasitic capacitance at different temperatures through theoretical derivation and experiments to verify the relationship between electrostatic output and preload voltage [40, 41]. The temperature characteristics of the sensor are improved by analyzing the influence of the width-narrow gap ratio (WNGR) of the sensor compared with the temperature coefficient of the scale factor (TCSF) and linear error of the sensor (Fig. 6 (A)) [42, 43, 44]. Other research groups use finite element simulations to analyze temperature sensitivity and residual stress caused by thermal expansion [45], or use closed-loop systems, phase-locked loop (PLL) controllers and other control principles to compensate for temperature-induced sensor output drift (Fig. 6 (B)) to further improve performance [46, 47, 48].

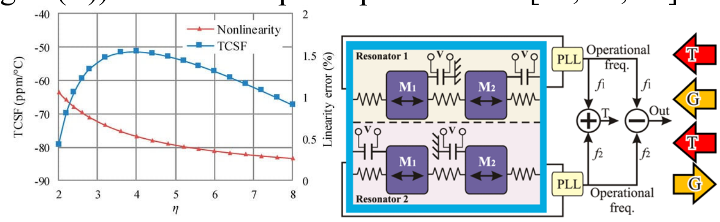

Fig. 6 (A) TCSF-WNGR linear degree diagram [44], (B) Concept diagram of accelerometer with thermal compensation function [47]

In addition, from the point of view of mathematical modeling, some research groups provide a new method for temperature compensation by using algorithm models such as genetic algorithm and BP neural network [49, 50]. For example, Qing Lu et al developed a temperature compensation fusion algorithm combining empirical mode decomposition, wavelet threshold and genetic algorithm-back propagation (GA-BP) neural network. The performance of high-g MEMS accelerometer at different temperatures is significantly improved [49].

### 5.2 Suppression of noise

In MEMS, noise types include thermal noise (Johnson or Nyquist noise), generation-recombination noise, flicker noise (1/f noise) and mechanical noise [37, 51, 52]. The main noise sources in the MEMS accelerometer are the mechanical vibration of the spring, the electrical noise of the signal conditioning circuit, and the noise of the system itself. it is proved that the low frequency noise of the sensor is 1/f noise and the high frequency noise is white Gaussian noise [51]. Improper noise processing will degrade the signal quality, cause the output signal fluctuation and affect the reliability and life of the equipment [37].

For noise suppression, we can usually choose the following methods: reduce the equivalent spring coefficient, improve the mass of the proof mass, reduce the interface circuit noise, choose active noise reduction and algorithm optimization [52, 53, 54, 55, 56, 57].

In addition to the above noise reduction methods, new types of structural design can also be selected. An effective method is to adopt geometric anti-springs (GAS). The core principle of GAS is to use a special structure to reduce the spring coefficient of the system, thus reducing the natural frequency of the system, which is mainly used to reduce the resonance frequency of large seismic isolation filters (Fig. 7 (A)) [58]. In a MEMS device, if a part of the spring connected to the block is in a pre-loaded compression state, the noise can be reduced by reducing the spring coefficient to close to zero [53, 58, 59]. The relevant research team miniaturized and integrated GAS technology into the structural design of MEMS for the first time, and successfully reduced the coefficient of elasticity by 26 times, reducing the mechanical background noise to $2\mathrm{ng}/\sqrt{\mathrm{Hz}}$ (Fig. 7 (B)) [58].

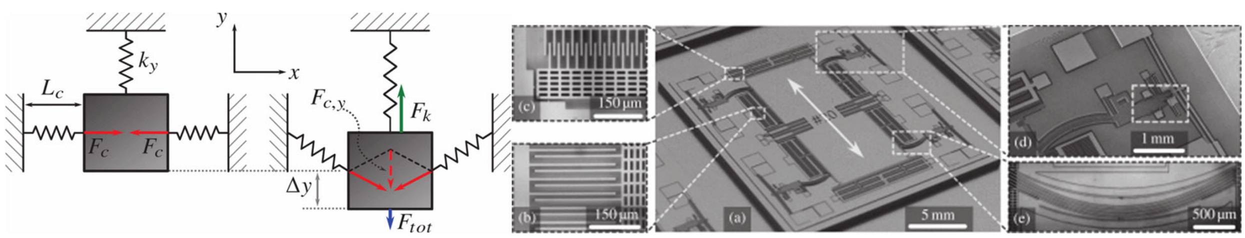

Fig. 7 (A) Schematic diagram of GAS structure (consisting of two pretightened compression springs and one tension spring) [58], (B) Structural microscopic image of the sensor [58]

## 6. Summary and prospect

This paper comprehensively explores the design and optimization of MEMS capacitive accelerometer, covering basic theory, physical structure analysis, and application scenarios. The article elaborates on the working principle, structural characteristics, performance and optimization strategies of sensors in practical applications. The study has improved the stability and accuracy of sensors in extreme environments by analyzing and optimizing key technical parameters such as temperature compensation, suppression of temperature drift, and noise control. Currently, despite the emergence of acceleration sensors based on various principles, capacitive acceleration sensors continue to receive attention due to their widespread applications in scientific research, military, and daily life. Looking ahead to the future, it is expected that in the era of intelligent Internet of Things, high-performance, low-power, high-precision, and multifunctional MEMS accelerometers will become more popular.

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