Artıbilim: Adana Alparslan Türkeş Bilim ve Teknoloji Üniversitesi Fen Bilimleri Dergisi 6(2), Aralık 2023, 41-58
Adana Alparslan Turkes Science and Technology University Journal of Science

MEMS capacitive accelerometer: A review

Cihat Ediz Akbaba*[1], Mahmud Yusuf Tanrıkulu [1]

[1]Adana Alparslan Türkeş Science and Technology University, Department of Electrical-Electronics Engineering, Adana, *ORCID: 0000-0003-1078-4382, 0000-0001-7956-1289*

Geliş Tarihi:06.11.2023 **Kabul Tarihi:**21.12.2023

Abstract

Micro-electro-mechanical systems sensors are integrated systems used in many fields such as consumer electronics, the automobile industry, and biomedical, and their dimensions change between micrometers and millimeters. MEMS capacitive accelerometers are the most widely used sensor type among MEMS accelerometer sensors. As a result of the external force applied to the capacitive accelerometer sensor, the proof mass inside the sensor moves, and the capacitive change is measured as an electrical signal using reading circuits. In this review paper, general information about MEMS sensors is given, and a comprehensive review is made of MEMS capacitive accelerometers. In the study, the dynamic circuit of the MEMS capacitive accelerometer is given, and the calculation of the important values for the mechanical and electronic structure during the design of the capacitive MEMS accelerometer is explained. In addition, information about the readout circuits used to convert the capacitive change to voltage is given. Finally, the fabrication processes used to produce the final product are explained, and the studies on sample fabrication processes found in the literature are mentioned.

Keywords: Capacitive accelerometer, MEMS accelerometer, MEMS capacitive accelerometer, MEMS devices

MEMS kapasitif ivmeölçer: Bir inceleme

Özet

Mikro-elektro-mekanik sistem sensörleri tüketici elektroniği, otomobil endüstrisi, biyomedikal gibi birçok alanda kullanılan, boyutları mikrometre ile milimetre arasında değişen entegre sistemlerdir. MEMS kapasitif ivmeölçerler, MEMS ivmeölçer sensörleri arasında en yaygın kullanılan sensör türüdür. Kapasitif ivmeölçer sensörüne uygulanan dış kuvvet sonucunda sensörün içindeki kanıt kütlesi hareket eder ve kapasitif değişim, okuma devreleri kullanılarak elektrik sinyali olarak ölçülür. Bu inceleme yazısında MEMS sensörleri hakkında genel bilgiler verilmiş olup, MEMS kapasitif ivmeölçerler hakkında kapsamlı bir inceleme yapılmıştır. Çalışmada MEMS kapasitif ivmeölçerin dinamik devresi verilmiş, kapasitif MEMS ivmeölçerin tasarımı sırasında mekanik ve elektronik yapı için önemli değerlerin hesaplanması anlatılmıştır. Ayrıca kapasitif değişimi gerilime dönüştürmek için kullanılan okuma devreleri hakkında da bilgi verilmiştir. Son olarak nihai ürünü üretmek için kullanılan imalat süreçleri açıklanmış ve literatürde bulunan örnek imalat süreçlerine ilişkin çalışmalara değinilmiştir.

Keywords: Kapasitif ivmeölçer, MEMS ivmeölçer, MEMS kapasitif ivmeölçer, MEMS cihazları

*Sorumlu yazar (Corresponding author): Cihat Ediz Akbaba, edizakbaba@gmail.com.
Künye Bilgisi: Akbaba, C.E., Tanrıkulu, M.Y., (2023). MEMS Capacitive Accelerometer: A Review. Artıbilim: Adana Alparslan Türkeş Bilim ve Teknoloji Üniversitesi Fen Bilimleri Dergisi, 6(2), 41-58. **Doi: 10.55198/artibilimfen.1386846**

1. Introduction to Micro Electro-Mechanical Systems (MEMS) Sensors

MEMS structures, called microelectromechanical systems in the USA and micro-machines in Japan, are integrated systems consisting of both mechanical and electrical devices, developed using batch processing techniques and varying in size from a micrometer to millimeter [1,2]. MEMS devices, which are quite different from electronic and microelectronic circuits, consist of a combination of electronic and mechanical parts [2]. MEMS accelerometers are widely used in electronic devices such as automobiles, navigation systems, health applications, computers and mobile phones due to their features such as small size, high resolution, stability and low power consumption [3,4]. The rapidly developing MEMS technology has shown itself in many areas that can benefit humanity. For example, with smart MEMS microsurgical systems, it is possible to perform surgery without any incision on the skin, as well as to intervene in sick cells and tissues without damaging healthy cells [2]. Another example of the use of MEMS is their use in vehicle airbags. MEMS accelerometers detect the change in capacitance in sudden movement changes and create a signal ensuring the airbag works. Figure 1 shows the common usage areas of MEMS systems [5].

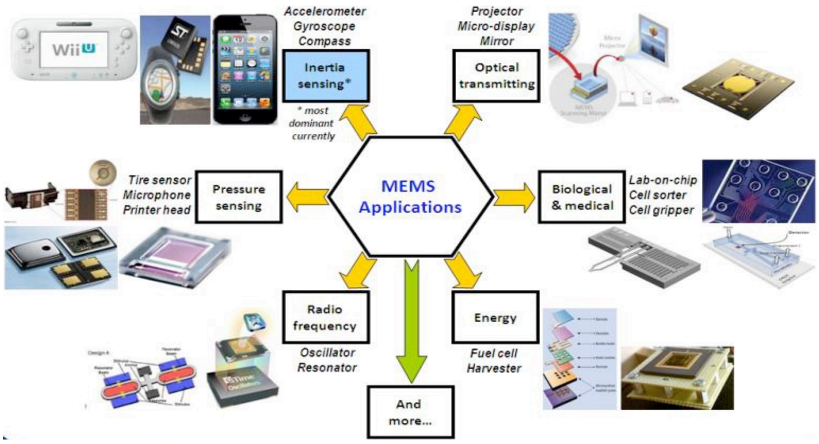

Figure 1. Common usage areas of MEMS systems [5]

MEMS technology, which consists of a combination of mechanical and electronic systems uses many of the techniques used in the integrated circuit field such as oxidation, diffusion, ion implantation, LPCVD, and sputtering [6,7]. MEMS systems have 3 characteristics: miniaturization, batch fabrication, and microelectronics [6]. Miniaturization enables the production of efficient and fast responsive components, while multiplicity enables thousands of components to be produced simultaneously. On the other hand, the microelectronics form the brain of the MEMS systems that enable sensors and actuators to work systematically.

In this study general information about MEMS sensors is given, and a comprehensive review is made about MEMS capacitive accelerometers. In addition, information about the readout circuits used to convert the capacitive change to voltage is given. Finally, the fabrication processes used to produce the final product are explained, and the studies on sample fabrication processes found in the literature are mentioned.

1.1. MEMS fabrication

Since the design and production of MEMS is complex, manufacturability design is very important to reduce the time and effort spent on accurate production [8]. Fabrication of MEMS structures often uses structural, sacrificial, and masking materials on a common substrate, so issues related to etching selectivity, adhesion, microstructure, and a number of other properties are very important parameters in the design process [9]. The main steps of the MEMS fabrication processes are film growth, doping, lithography, etching, dicing, and packaging [6]. In addition, the properties of the materials used as structural, sacrificial, and passivation layers in the fabrication stage of MEMS are very important and these materials play an important role in the formation of final devices not only alone but also as a result of their interaction with each other. In the MEMS fabrication process, materials such as single-crystal silicon, polysilicon, silicon dioxide, silicon nitride, metals, silicon carbide, and diamond are used [9]. Although most of the microfabrication methods used to fabricate MEMS structures are borrowed from IC technology, specialized micromachining techniques for MEMS have been developed [10]. In the production process of MEMS, techniques such as bulk micromachining, surface micromachining, and LIGA processes are very popular.

1.1.1. Bulk Micromachining

Bulk micromachining which is the oldest micromachining technology enables the selective removal of a significant amount of silicon from the substrate material to form shrunken mechanical components [2,11]. Since etching speed is an important factor affecting efficiency in the bulk micromachining technique, choosing the right methods during etching is very important [12]. By utilizing the etching properties, complex 3D shapes such as channels, pyramidal pits, and roads can be created [10]. In the wet bulk micromachining process which is the most commonly used technique, the exposed areas of the substrate are etched at certain rates [2,13]. Figure 2 shows the release of SiC material by etching silicon from the front and back of the wafer using the bulk micromachining technique [14].

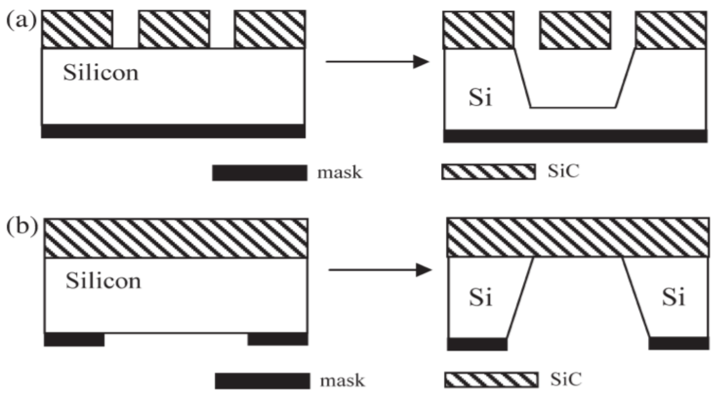

Figure 2. Bulk micromachining technique. a) Release of SiC material by etching silicon from the front side of the wafer. b) Release of SiC material by etching silicon from the back side of the wafer [14]

1.1.2. Surface micromachining

The surface micromachining technique is the process of removing the underlying film called the sacrificial layer without damaging the upper layer called the structural element. In this method, microstructures are created by depositing, growing, and etching a series of thin films onto the substrate [15]. In order for the micromachining process to be healthy, the structural material and the sacrificial material must have appropriate properties. In addition, without affecting the structural material, the etchers used to remove sacrificial materials should have very good physical and chemical etching features [16]. Figure 3 shows the steps of a typical surface micromachining technique [10].

1.1.3. LIGA (Lithographic-Galvanoformung-Abform) process

Developed in Germany in the mid-1980s, LIGA is an abbreviation of the German words lithographic, galvanoformung, abform, which translates as lithography, electroplating, and molding [17]. Combining X-ray lithography with electroplating and molding, the LIGA process is a popular technique for the fabrication of high aspect ratio microstructures [18]. Figure 4 shows an example LIGA process [19]. In the LIGA technique, a resist layer is first applied to a metal-coated substrate. This resist layer is then exposed to Ultraviolet rays by masking. In the last step, the parts of the resist layer that are not exposed to UV rays are eliminated, and the final microstructure is reached.

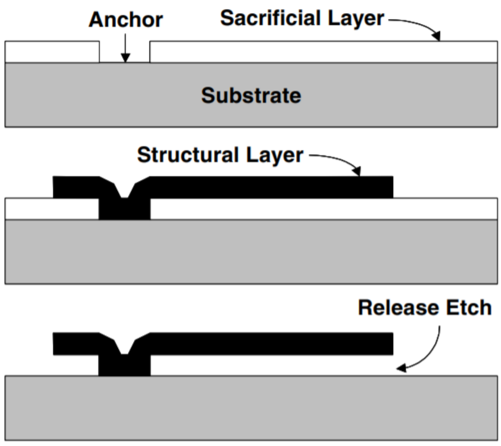

Figure 3. The steps of a typical surface micromachining technique [10]

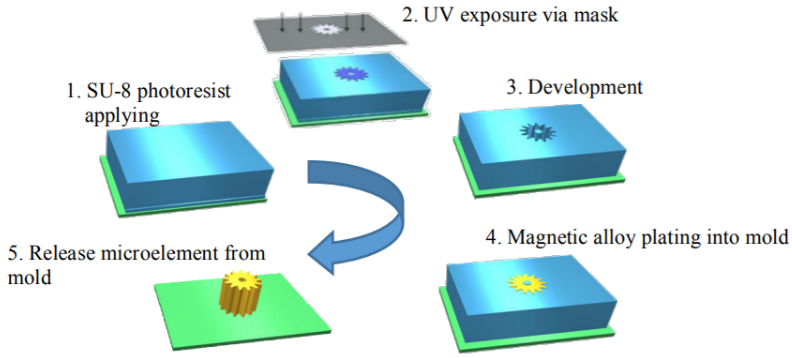

Figure 4. Example LIGA fabrication process [19]

2. Accelerometers

Accelerometers which measure the acceleration applied to a mass have high sensitivity and it is used in many fields from industry to scientific studies [20]. The acceleration sensor measures the acceleration with the change of the test mass in it against the gravitational force (g=9.8 m/s^2). These sensors convert the mechanical movement created by the movement of the test mass into electrical signal. It is possible to model accelerometers with a spring-mass-damper system. Figure 5 gives the dynamic model and the free body diagram of an accelerometer [21]. Here, *m* is the proof mass, *b* is the damping coefficient, and *k* is the spring constant. When the system is carefully examined, it can be seen that the proof mass is attached to the base with a spring and damper. When a force is applied to the accelerometer, while the proof mass moves, the spring and damper resist this movement. According to Newton's second law, the sum of the forces acting on the object is equal to the product of the mass of the object and its acceleration, and the equation of motion of the mass m is given in Equations 1. In Equation 2, the differential equation of the system is given.

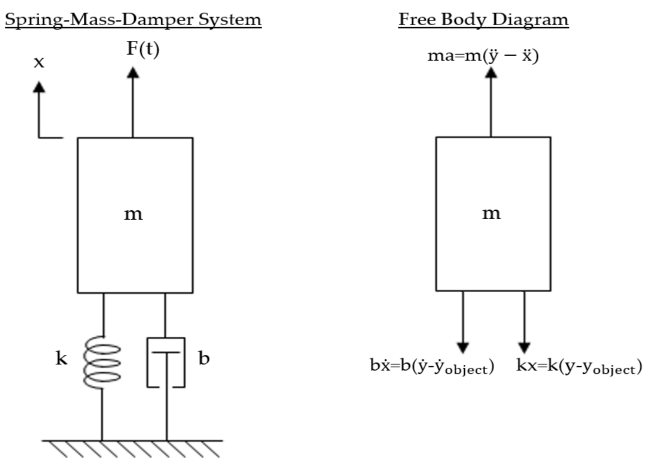

Figure 5. Spring-mass-damper system and free body diagram for an accelerometer [21]

$$m\ddot{x}_d + c\dot{x}_d + kx_d = F(t) \quad (1)$$

$$m\frac{d^2x(t)}{dt^2} + c\frac{dx(t)}{dt} + kx(t) = ma_{ext}(t) \quad (2)$$

When Laplace transform is applied to the system expressed by a quadratic equation, the transfer function of the system can be found as in Equation 3. In the equation, w_r is the resonant frequency and the Q value is the quality factor. To obtain high mechanical sensitivity, the resonant frequency should be chosen as low as possible. In addition, if the quality factor of the system is less than 0.5, the system is over damped, if it is equal to 0.5, it is critically damped, and if it is greater than 0.5, it is under damped. Under damped systems are preferred due to low mechanical noise and quick response time [21].

$$\frac{X(s)}{A_{ext}(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} = \frac{1}{s^2 + \frac{w_r}{Q} + {w_r}^2} \quad (3)$$

The most commonly used accelerometers are piezoelectric, piezoresistive, optical, and capacitive accelerometers [5,22]. Piezoelectric accelerometers, which are frequently used in the civil and aerospace industries and generally measure mechanical changes such as vibration and shock, use the piezoelectric effect of certain materials to detect the change in acceleration [23]. Optical accelerometers, working with the principle of moving the proof mass with the change in wavelength caused by the change in light intensity have advantages such as high sensitivity and low noise compared to conventional electrical accelerometers [24,25]. The capacitive accelerometers, one of the most used accelerometers, senses the change in electrical capacitance to determine the acceleration of an object. In capacitive accelerometers, the distance between the plates changes in proportion to the applied acceleration. Thus, an electrical signal is produced in proportion to this change [26].

3. MEMS accelerometers

MEMS-based accelerometers are the fastest developing devices using MEMS technology, and these devices have wide applications in many fields such as automotive, consumer electronics, aerospace, biomedical, and robotics [3,27,28]. Figure 6 shows the usage areas of MEMS accelerometers according to their bandwidth and acceleration range [29]. MEMS accelerometers used in most of these applications have many advantages such as mass manufacturability, low cost production, small size, low power, and easy system integration [30]. While one of the main advantages of a MEMS accelerometer is its linear frequency response, it has disadvantages such as charging shortage and gravitational acceleration being calibrated [31]. A typical MEMS accelerometer detects an external acceleration by the displacement of a suspended mass attached to an anchor. Displacement sensing can be achieved using techniques such as capacitive, thermal, piezoresistive, piezoelectric, and optical [32,33]. Among these techniques, capacitive sensing technology is the most popular among MEMS accelerometer techniques because of its ease of fabrication [31,32].

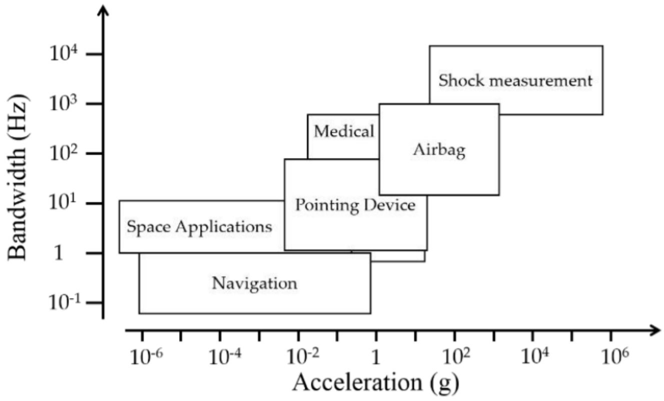

Figure 6. Usage areas of MEMS accelerometers according to bandwidth and acceleration range [29]

4. Capacitive MEMS accelerometers

Capacitive accelerometers are extensively employed in the MEMS markets due to their simple structure, low production costs, low power consumption, and low thermal dependence [28,34]. A capacitive accelerometer using MEMS is typically a structure that uses a capacitor with a moving plate placed between two fixed plate. When the total force is zero, the value of both capacitors is zero, when there is a change in force, the moving plate will approach the fixed plate, which will increase the capacitance value [35]. In Figure 7, the dynamic circuit of the capacitive accelerometer consisting of spring, damping, and proof mass in the main structure is given [3]. Looking at the dynamic model, there is the proof mass which is suspended in the central part and acts as a sensing element. The mass is attached to the substrate by a spring with constant k_x and damping with a damping coefficient B_x. There are capacitances between fixed fingers and movable fingers attached to the proof mass. When the proof mass is subjected to acceleration, the movable fingers attached to the mass move, and this movement produces an output as capacitive displacement. To measure the capacitance change, an electronic circuit can be designed to convert this change into voltage [29].

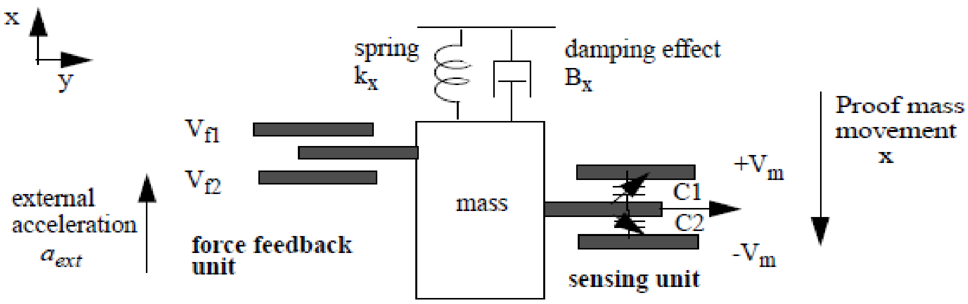

Figure 7. The dynamic circuit of the capacitive accelerometer [3]

When the system accelerates, the proof mass moves and as a result of the displacement of the moving fingers, the value of one of the capacitances increases while the other decreases. The magnitude of the acceleration is calculated by measuring the capacitance values. As a result of the acceleration, the values of the capacitances C1 and C2 are measured as in Equation 4 [36].

$$C1 = \varepsilon n S\left(\frac{1}{d-x}\right), \qquad C2 = \varepsilon n S\left(\frac{1}{d+x}\right) \tag{4}$$

where, n is the number of movable fingers, epsilon value is the electrical conductivity between the fingers, d is the distance between the fingers, x is the displacement due to acceleration, and S is the surface area of a single finger.

In Equation 5, it is seen that the total force acting on the system is directly proportional to the product of the mass of the object and its acceleration [37].

$$F_a = ma = F_m + F_K + F_B \tag{5}$$

where, F_a is the applied force, F_m is the inertial force of the proof mass, F_K is the force of the spring constant, and F_B is the damping effect. The expression of the displacement of the proof mass subjected to the force in terms of a differential equation is given in Equation 6.

$$F_a = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + kx \tag{6}$$

Applying the Laplace transform to Equation 6, we can obtain Equation 7 and Equation 8, and the transfer function of the system is as in Equation 9.

$$F_a = MS^2X(S) + BSX(S) + KX(S) \tag{7}$$

$$F_a = (MS^2 + BS + K)X(S) \tag{8}$$

$$\frac{X(S)}{F_a} = \frac{1}{MS^2 + BS + K} \tag{9}$$

The final mathematical model of the capacitive accelerometer can be expressed as in Equation 10.

$$\frac{X(S)}{F_a} = \frac{1}{s^2 + s\frac{B}{M} + \frac{K}{M}} = \frac{1}{s^2 + s\frac{\omega_r}{Q} + {\omega_r}^2} \tag{10}$$

where, ω_r is the resonant frequency and Q is the quality factor. At low frequencies, when $\omega \ll \omega_r$, we can write Equation 11 [38].

$$\frac{X(S)}{F_a} = \frac{1}{{\omega_r}^2} \tag{11}$$

As can be seen from Equation 11, the sensitivity is inversely proportional to the resonance frequency. Therefore, we can say that the sensitivity increases as the resonance frequency decreases. A decrease in resonance frequency requires an increase in proof mass and a decrease in spring constant, and with a decrease in this value, the sensor bandwidth also decreases [39]. In addition, parameters such as resonance frequency, quality factor are related to sensor size.

The proof mass value is calculated as follows [37].

$$m = \rho(W_p L_p T_p + N W_F L_F t) \tag{12}$$

where, ρ is the density of the material from which the proof mass is made, W_p is the width of the proof mass, L_p is the length of the proof mass and T_p is the thickness of the proof mass. N is the number of movable fingers. W_F, L_F, and t are the width, length, and thickness of the movable sensing fingers, respectively.

In Equation 13, the expression of the spring constant of the system is given. Here, l_b is the length of the beam, ω_b is the width of the beam, h is the thickness of the beam, and E is the Young's modulus of the structural material. In order to get a good performance and sensitivity from the capacitive accelerometer, it is very important to choose the parameters at the right value such as beam width and beam length [38]. In addition, parameters such as the width and length of the movable fingers play an important role in the accuracy of acceleration measurement [38].

$$K_s = \frac{1}{2} Eh(\frac{\omega_b}{l_b})^3 \tag{13}$$

The formula used to find the damping coefficient is shown in Equation 14 [40]. Here, N_f is the total number of sensing fingers, n_{eff} is the effective viscosity of the air, and d_0 is the capacitance gap.

$$B = N_f \; n_{eff} \; l_b \; (\frac{h}{d_0})^3 \tag{14}$$

In a system with capacitive accelerometer, some readout circuits are needed to measure the capacitive change after capacitive sensing takes place. There are some important parameters such as signal to noise ratio (SNR), power consumption, and readout method in sensor reading circuits. SNR value is very important for accurate measurement of physical quantity, and to obtain a higher SNR we need to increase the signal power while reducing the noise power [41]. In addition, power consumption and low supply voltage is very important as capacitive accelerometers are widely used in small devices [42]. Since sensitivity is important when detecting, the values of the circuit elements should be chosen correctly for readout circuits. Figure 8 shows the simplified readout circuit diagram of a MEMS capacitive accelerometer realized by [43].

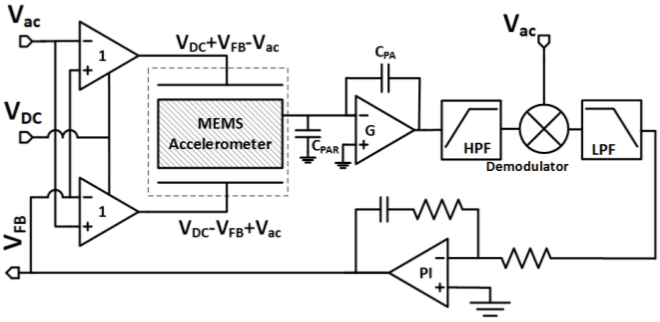

Figure 8. Simplified readout circuit diagram of a MEMS capacitive accelerometer [43]

In the given circuit, differential V_{ac} and $-V_{ac}$ signals are applied to the electrodes. In case of a capacitance mismatch between the two electrodes due to external acceleration, an electric current signal is generated in the preamplifier stage and this signal is then converted to voltage. This voltage is then filtered and demodulated by the passive RC high pass filter and then it is filtered again by the low pass filter and the signal is applied as input to the PI controller. The output of the PI controller is superimposed on the modulation signals and it is given as a feedback to the sensor to keep the proof mass stable. This results in a high linearity performance for the accelerometer. In addition, the range and noise values can be adjusted for different applications by adjusting the V_{dc} voltage applied equally to both electrodes [43]. Capacitive displacement is converted to an analog signal thanks to the reading circuit inside the accelerometer package, and this analog signal can be converted to a digital signal with an ADC converter, if necessary.

5. Example fabrication and design studies for capacitive MEMS accelerometers

In the study by [44], a single axis MEMS differential capacitive accelerometer design was carried out. The design process was performed using MEMS+, and the MATLAB Simulink environment was used for simulation processes. A readout circuit was created to measure the capacitance change caused by the displacement of the proof mass structure due to the applied acceleration. The reading circuit consists of a capacitance-voltage converter, a demodulator, and a low-pass filter. In addition, it is stated in the study that the designed accelerometer can be produced using the DRIE-based process. The accelerometer designed according to the obtained simulation results showed high sensitivity and good linearity. The 3D solid model and the reading circuit of the designed accelerometer are given in Figure 9 [44].

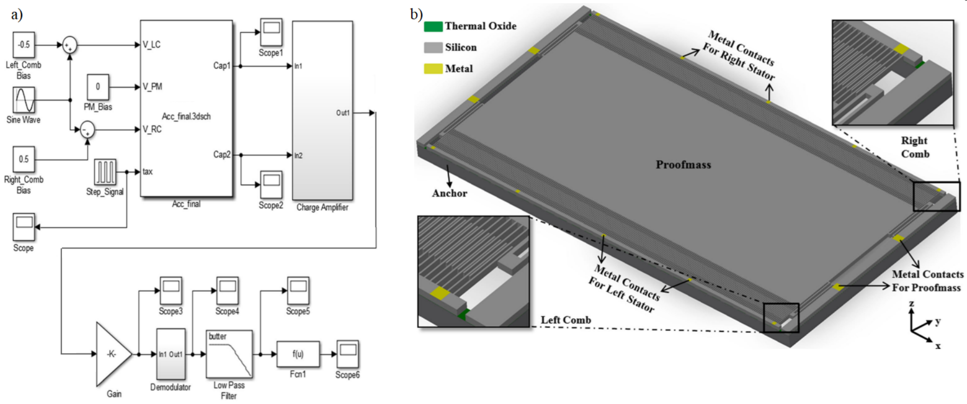

Figure 9. a) The reading circuit of the designed accelerometer b) The 3D solid model of the designed accelerometer [44]

In study [39], a single-axis capacitive full differential accelerometer design with two proof masses was carried out with the surface micro-machining technique. In the study, the proof mass structure was electrically isolated and divided into two parts to show a fully differential feature. Figure 10 (a) shows the general structure of the proposed accelerometer [39]. The designed sensor was optimized and simulated using the COMSOL Multiphysics tool. In addition, some sensor capacitors are embedded in the proof mass structure to increase sensitivity. In the fabrication stage, chemical vapor deposition (CVD), electroplating, lift-off, and photolithography methods were used together with the surface micromachining technique. Figure 10 (b) gives the fabrication process of the accelerometer [39].

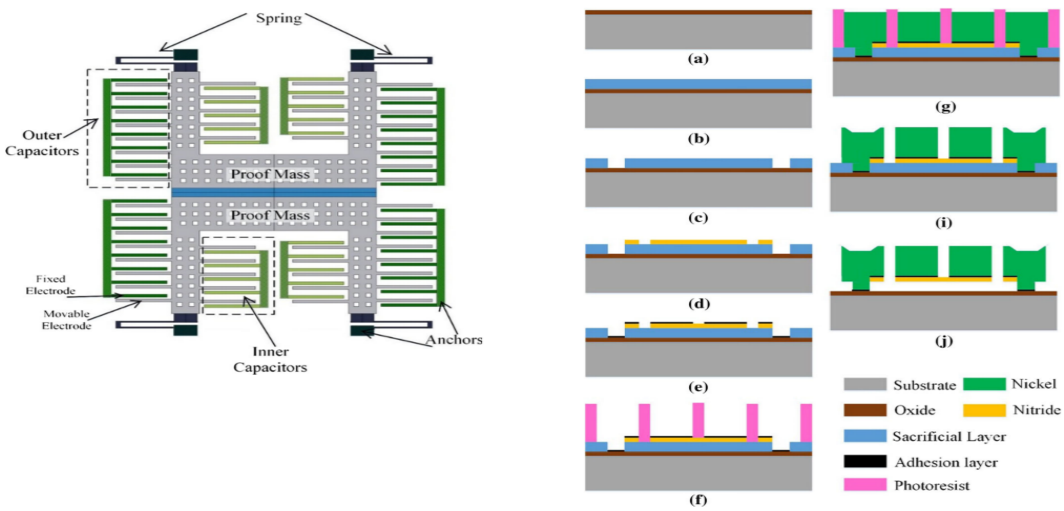

Figure 10. Accelerometer general structure and fabrication process [35]

In study [45], a MEMS capacitive accelerometer specially designed for Structural Health Monitoring (SHM) applications is presented. The IntelliSuite MEMS design tool was used for simulations in the design performed using the surface micro-machining technique. The design and simulation of the readout circuit used to convert the differential capacitance to voltage were carried out with the SPICE circuit design program. Figure 11 gives the detailed fabrication process for the designed accelerometer. When the fabrication process was examined, first of all, 1 µm thick Si_3N_4 material and 2 µm thick sacrificial material was deposited on the silicon substrate, respectively. Then, a 4 µm thick polysilicon layer was formed with the LPCVD technique, and finally, the surface micromachined folded beam-type accelerometer structure was obtained by removing the sacrificial layer.

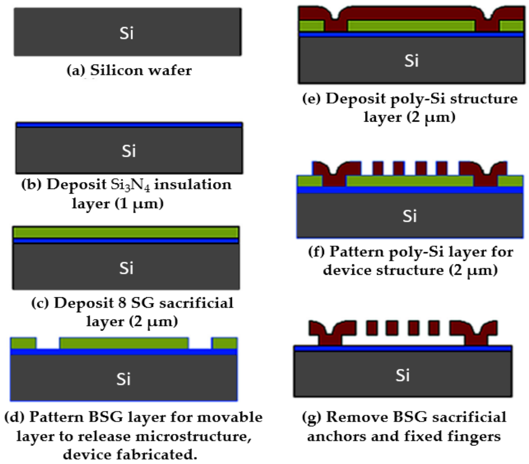

Figure 11. Fabrication process for designed capacitive accelerometer [45]

In study [29], a MEMS differential capacitive accelerometer was designed and simulated using 8 µm UV-LIGA technology. Device simulation was performed using CoventorWare® and MEMS+ tools, and the simulation results are similar to the calculated results. According to the simulation results obtained, the device showed good linearity at DC-400 Hz bandwidth. The designed accelerometer was put into the fabrication process using UV-LIGA technology [46]. Figure 12 shows the fabrication flow chart. When the figure is examined, copper was used as the sacrificial layer, nickel was used as the structural layer, and the seed layer was sputtered to obtain the anchoring sites and the pattern was created. Finally, the structural layer, Nickel, was grown using electroplating, and the Cu layer was released after etching.

Study [47] presents a MEMS capacitive accelerometer with a symmetrical, double-sided, and H-shaped beam structure. The fully symmetrical structure is produced using a double-layer SOI wafer structure. Figure 13 shows the fabrication steps. When the figure is examined, after the H-shaped beam-mass structure is defined as a mask, the wafer is oxidized and then photoresist coating is applied. Then, after some scraping on both sides of the wafer, the photoresist is removed. With the onset of thermal oxidation at high temperatures, a capacitive gap is defined on one side of the wafer. As a result of the processes, MEMS capacitive accelerometer with a fully symmetrical double-sided H-shaped beam-mass structure was produced.

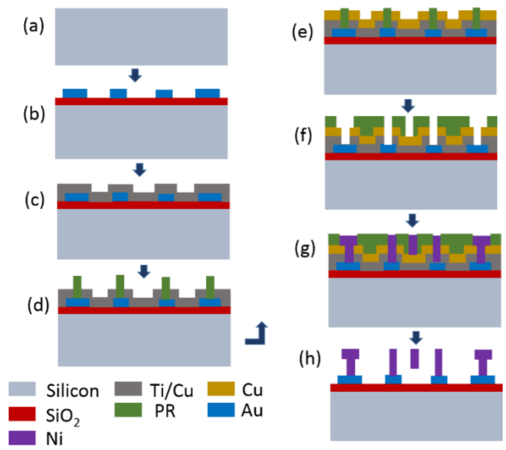

Figure 12. The fabrication process of the accelerometer designed using UV-LIGA technology [29]

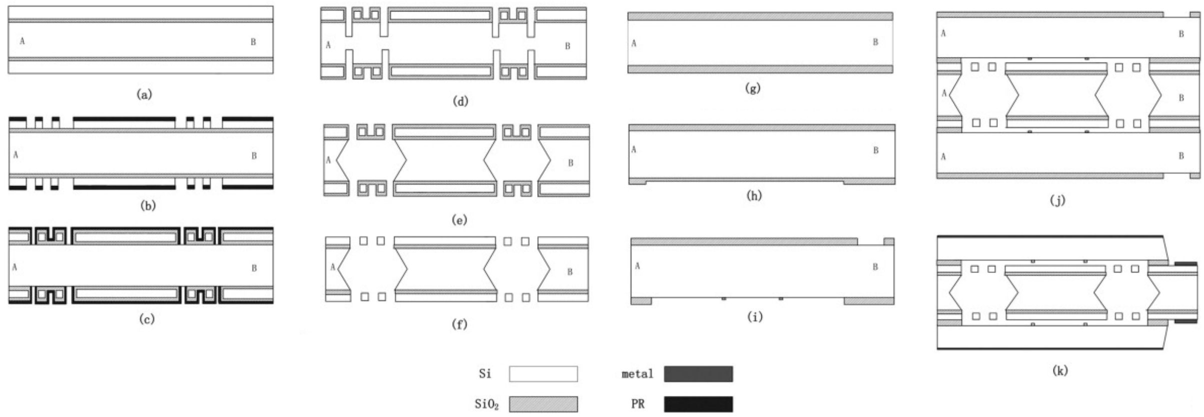

Figure 13. Fabrication process for the presented accelerometer [47]

When the studies are examined, it has been observed that many parameters are important in order to provide high performance when designing capacitive MEMS accelerometer structures. Table 1 gives the parameters obtained for the examined studies.

Table 1. Design parameters of capacitive accelerometers presented in examined studies

	Ref [26]	Ref [35]	Ref [40]	Ref [41]	Ref [43]
Bandwidth	400 Hz	not given	100 Hz	0-250 Hz	not given
Frequency range	not given	not given	not given	0-40 Hz	1.5 kHz-3 kHz
Displacement sensitivity	0.19 µm/g	not given	0.121 µm/g	21.39 µm/g	not given
Capacitive sensitivity	3.83 fF/g	15.8 fF/g	225 fF/g	1.22 pF/g	not given
Mechanical sensitivity	not given	29.8 µm/g	0.12 µm/g	not given	not given
Voltage sensitivity	not given	not given	not given	1,783 V/g	0.24 V/g
Natural frequency	not given	not given	1.5 kHz	100Hz-500Hz	not given
Resonance frequency	1448 Hz	2870 Hz	not given	not given	2240 Hz
Electrical noise	not given	not given	5 aF/$\sqrt{Hz}$	5.612 µg/$\sqrt{Hz}$	not given
Quality factor	4	not given	not given	not given	106

5. Conclusion

In this study, it is aimed to give a comprehensive perspective on MEMS capacitive accelerometers. In addition, the structure, working principle, design parameters, and fabrication process of capacitive accelerometers have been observed in detail. Design parameters such as bandwidth, frequency range, sensitivity, electrical noise, quality factor for MEMS capacitive accelerometer sensors are compared within the studies in the literature. When the studies are examined extensively, it is understood that MEMS capacitive accelerometer sensors are used widely MEMS market because they have a simple structure, low production cost, low power consumption, and low thermal dependence. Although there are various studies on capacitive accelerometers, it appears that the ultimate limit for performance has not been reached. There is also a potential gap in the materials used for Accelerometers. Studies on new materials and new process flows should be continued to increase the performance and process efficiency of MEMS capacitive accelerometers.

Conflict of interest statement: There is no conflict of interest.

Research and publication ethic statement: The study does not require Ethics Approval.

References

[1] Fujita, H. (1997). A decade of MEMS and its future. In Proceedings of the Proceedings IEEE The Tenth Annual International Workshop on Micro Electro Mechanical Systems. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots, 1-7.
[2] Mishra, M.K., Dubey, V., Mishra, P., Khan, I. (2019). MEMS technology: a review. Journal of Engineering Research Reports, 1-24, doi:10.9734/JERR/2019/v4i116891.
[3] Hristov, M.H., Ruskov, S.I., Denishev, K.H., Uzunov, I.S., Grozdanov, V.E., Gaydazhiev, D.G. (2009). Design and simulation of horizontal accelerometers. Annual Journal of Electronıcs.
[4] Vajargah, M.K., Shamsi, H. (2023). An accurate Verilog-A based model for MEMS capacitive accelerometer. AEU-International Journal of Electronics Communications, 164, 154625, doi:10.1016/j.aeue.2023.154625.
[5] Liu, C.-H., Chang, H.-D., Li, K.-H., Lin, C.-H., Hsu, C.-J., Lin, T.-Y., Chou, H.-H., Huang, H.-C., Liao, H.Y.(2013). Adaptable and integrated packaging platform for MEMS-based combo sensors utilizing innovative wafer-level packaging technologies. In Proceedings of the 2013 IEEE 63rd Electronic Components and Technology Conference,1675-1681.
[6] Pannaga, N., Rai.P, R.(2013). Review: MEMS fabrication technology. International Journal of Engineering Research & Technology (IJERT) 02.
[7] Partnership, P.F. (2002). An introduction to MEMS (micro-electromechanical systems). Prime Faraday Partnership.
[8] Niekiel, M.F., Meyer, J.M., Lewitz, H., Kittmann, A., Nowak, M.A., Lofink, F., Meyners, D., Zollondz, J.H.(2023). What MEMS research and development can learn from a production environment. Sensors, 23, 5549, doi:10.3390/s23125549.
[9] Gad-el-Hak, M.(2005). MEMS: design and fabrication; CRC press.
[10] Judy, J.W.(2001). Microelectromechanical systems (MEMS): fabrication, design and applications. Smart Materials Structures,10, 1115, doi:10.1088/0964-1726/10/6/301.
[11] Kovacs, G.T., Maluf, N.I., Petersen, K.E.(1998). Bulk micromachining of silicon. Proceedings of the IEEE, 86, 1536-1551.
[12] Pal, P., Swarnalatha, V., Rao, A.V.N., Pandey, A.K., Tanaka, H., Sato, K. (2021). High speed silicon wet anisotropic etching for applications in bulk micromachining: A review. Micro Nano Systems Letters, 9, 1-59, doi:10.1186/s40486-021-00129-0.

[13] Ghodssi, R., Lin, P. (2011). MEMS materials and processes handbook; Springer Science & Business Media: Volume 1.
[14] Cheung, R., Argyrakis, P. (2008). Microscale sensors based on silicon carbide and silicon. Proceedings of the Institution of Mechanical Engineers, 222, 19-26, doi:10.1243/09544062JMES663.
[15] Antonello, R., Oboe, R. (2011). MEMS gyroscopes for consumer and industrial applications. Microsensors, Intech, 253-280, doi:10.5772/17689.
[16] Mamilla, V.R., Chakradhar, K.S. (2014). Micro machining for micro electro mechanical systems (MEMS). Procedia Materials Science, 6, 1170-1177, doi:10.1016/j.mspro.2014.07.190.
[17] Almuramady, N. (2017). Dry friction between rough surfaces of silicon and functionalized gear microelectromechanical systems. Cardiff University.
[18] Meyer, P., Schulz, J., Hahn, L. (2003). DoseSim: Microsoft-Windows graphical user interface for using synchrotron x-ray exposure and subsequent development in the LIGA process. Review of Scientific Instruments, 74, 1113-1119, doi:10.1063/1.1532542.
[19] Timoshkov, I.V., Khanko, A.V., Kurmashev, V.I., Grapov, D.V., Kastevich, A., Govor, G.A., Vetcher, A.K. (2019). Applications of uv-liga and grayscale lithography for display technologies. Доклады Белорусского государственного университета информатики и радиоэлектроники, doi:10.35596/1729-7648-2019-125-7-81-87.
[20] Victorino, M., Jiang, X., Menon, C. (2018). Wearable technologies and force myography for healthcare. In Wearable Technology in Medicine and Health Care; Academic Press,135-152.
[21] Erdener, Ö. (2005). MEMS Accelerometer Design. MS Thesis, İstanbul Teknik Üniversitesi,İstanbul.
[22] Suh, M. (2015). Wearable sensors for athletes. In Electronic Textiles; Elsevier: 257-273.
[23] Yoder, N., Adams, D. (2014). Commonly used sensors for civil infrastructures and their associated algorithms. In Sensor Technologies for Civil Infrastructures; Elsevier: 57-85.
[24] Casas-Ramos, M.A., Castillo-Barrera, L.G., Sandoval-Romero, G. (2018). Optical accelerometer for seismic measurement. Vibroengineering PROCEDIA, 21, 38-41, doi:10.21595/vp.2018.20379.
[25] Plaza, J.A., Llobera, A., Dominguez, C., Esteve, J., Salinas, I., Garcia, J., Berganzo, J. (2004). BESOI-based integrated optical silicon accelerometer. Journal of Microelectromechanical Systems, 13, 355-364, doi:10.1109/JMEMS.2004.824884.
[26] Venkatanarayanan, A., Spain, E. (2014). Review of recent developments in sensing materials. Comprehensive Materials Processing, 13, 47-101, doi:10.1016/B978-0-08-096532-1.01303-0.
[27] Gomathi, T., Shaby, S.M.(2016). Capacitive accelerometers for microelectromechanical applications: a review. In Proceedings of the 2016 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT), 486-490.
[28] Kesilmiş, Z., Mutlu, A., Aksoy, M. (2008). Yapay sinir ağı ile kapasitif MEMS ivme ölçerin rezonans frekansı kestirimi. Elektrik-Elektronik Bilgisayar Mühendisliği Sempozyumu ELECO'2008, Türkiye, 26 - 29 Kasım, 87-90
[29] Sinha, S., Shakya, S., Mukhiya, R., Gopal, R., Pant, B. (2014). Design and simulation of MEMS differential capacitive accelerometer. In Proceedings of the Proceeding of ISSS international conference on smart materials, structures and systems.
[30] Zou, X., Seshia, A.A. (2015). A high-resolution resonant MEMS accelerometer. In Proceedings of the 2015 Transducers-2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), 1247-1250.

[31] Aizawa, T., Kimura, T., Matsuoka, T., Takeda, T., Asano, Y. (2009). Application of MEMS accelerometer to geophysics. International Journal of the JCRM, 4, 33-36, doi:10.11187/ijjcrm.4.33.

[32] Nie, Y., Huang, K., Yang, J., Cao, L., Cheng, L., Wang, Q., Tian, H., Peihua, W., Heng, L. (2020). A proposal to enhance high-frequency optical MEMS accelerometer sensitivity based on a one-dimensional photonic crystal wavelength modulation system. IEEE Sensors Journal, 20, 14639-14645, doi:10.1109/JSEN.2020.3006220.

[33] Yazıcıoğlu, R.F. (2003). Surface micromachined capacitive accelerometers using mems technology. Middle East Technical University.

[34] Delfan Hemmati, K., Azizollah Ganji, B. (2022). Increase of three-axis accelerometer sensitivity using capacitor in spring. Journal of Electrical Engineering, 54, 97-106, doi:10.22060/eej.2021.20123.5420.

[35] Tan, S.-S., Liu, C.-Y., Yeh, L.-K., Chiu, Y.-H., Lu, M.S.-C., Hsu, K.Y. (2010). Design of low-noise CMOS MEMS accelerometer with techniques for thermal stability and stable DC biasing. In Proceedings of the IEEE Custom Integrated Circuits Conference 2010,1-4.

[36] Szermer, M., Zając, P., Amrozik, P., Maj, C., Jankowski, M., Jabłoński, G., Kiełbik, R., Nazdrowicz, J., Napieralska, M., Sakowicz, B. (2021). A Capacitive 3-Axis MEMS accelerometer for medipost: A portable system dedicated to monitoring ımbalance disorders. Sensors, 21, 3564, doi:10.3390/s21103564.

[37] Gomathi, K., Balaji, A., Mrunalini, T. (2021). Design and optimization of differential capacitive micro accelerometer for vibration measurement. Journal of the Mechanical Behavior of Materials, 30, 19-27, doi:10.1515/jmbm-2021-0003.

[38] Benmessaoud, M., Nasreddine, M.M. (2013). Optimization of MEMS capacitive accelerometer. Microsystem Technologies, 19, 713-720, doi:10.1007/s00542-013-1741-z.

[39] Keshavarzi, M., Hasani, J.Y. (2019). Design and optimization of fully differential capacitive MEMS accelerometer based on surface micromachining. Microsystem Technologies, 25, 1369-1377, doi:10.1007/s00542-018-4187-5.

[40] Amini, B.V. (2006). A mixed-signal low-noise sigma-delta interface IC for integrated sub-micro-gravity capacitive SOI accelerometers. Georgia Institute of Technology.

[41] Yoo, Y., Choi, B.-D. (2021). Readout circuits for capacitive sensors. Micromachines, 12, 960, doi:10.3390/mi12080960.

[42] Zhong, L., Lai, X., Song, H., Xu, D. (2018). Differential capacitive readout circuit using oversampling successive approximation technique. IEEE Transactions on Circuits Systems I: Regular Papers, 65, 4072-4085, doi:10.1109/TCSI.2018.2849992.

[43] Terzioglu, Y., Alper, S.E., Azgin, K., Akin, T. (2014). A capacitive MEMS accelerometer readout with concurrent detection and feedback using discrete components. In Proceedings of the 2014 IEEE/ION Position, Location and Navigation Symposium-PLANS 2014, 12-15.

[44] Mukhiya, R., Agarwal, P., Badjatya, S., Garg, M., Gaikwad, P., Sinha, S., Singh, A., Gopal, R. (2019). Design, modelling and system level simulations of DRIE-based MEMS differential capacitive accelerometer. Microsystem Technologies, 25, 3521-3532, doi:10.1007/s00542-018-04292-0.

[45] Kavitha, S., Daniel, R.J., Sumangala, K. (2016). Design and analysis of MEMS comb drive capacitive accelerometer for SHM and seismic applications. Measurement, 93, 327-339, doi:10.1016/j.measurement.2016.07.029.

[46] Qu, W., Wenzel, C., Gerlach, G. (1999). Fabrication of a 3D differential-capacitive acceleration sensor by UV-LIGA. Sensors Actuators A: Physical , 77, 14-20, doi:10.1016/S0924-4247(98)00377-X.
[47] Zhou, X., Che, L., Liang, S., Lin, Y., Li, X., Wang, Y. (2015). Design and fabrication of a MEMS capacitive accelerometer with fully symmetrical double-sided H-shaped beam structure. Microelectronic Engineering, 131, 51-57, doi:doi.org/10.1016/j.mee.2014.10.005.