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Design of a MEMS Capacitive Comb-drive Micro-accelerometer with Sag Optimization

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Abstract: The current paper presents an optimization study for the designing of a highly sensitive inertial grade capacitive accelerometer based on comb-drive actuation and sensing. The proof mass, suspension system (beams or tethers), stators and rotors have to be realized through an HAR (high aspect ratio) DRIE (deep reactive ion etching) process for which process optimization has already been done at our laboratory. As the proof mass is a bulk micro-machined structure having a mass in *milligram* range, the optimum positioning of the tethers on the proof mass is important to have minimum sag, necessary to reduce the off-axis sensitivity. The optimization for the positioning of the tethers has been carried out using a commercial software tool ANSYS^{TM} Multiphysics. The accelerometer has been modeled analytically to predict its characteristics. The dependency of sensitivity on the dimensions of the suspension beams (tethers) has also been verified using the above FEM software tool. The present device has been designed to deliver a high sensitivity of 13.6 mV/g/V for low-g applications. *Copyright © 2009 IFSA.*

Keywords: Accelerometer, Comb-drive, Capacitive sensing, High aspect ratio, DRIE

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1. Introduction

Accelerometers are used to sense the acceleration of a moving body and convert it into electrical or mechanical energy so that it could be measured [1-4]. Initially, purely mechanical accelerometers came up, which were later replaced by electromechanical devices [5, 6]. Further miniaturization of these devices could be possible only after the evolution of MEMS [7, 8]. MEMS accelerometers [9] have gained popularity, basically, because of their small size, reliability, faster response time and above all, the low cost [10-13] in comparison to conventional accelerometers, as they can be batch produced at commercial scale. They have already been deployed in several applications ranging from air bags in the automobiles to the consumer electronics, such as high-end mobiles, devices having shake control, in addition to their strategic, space, aerospace and medical applications [14-18]. Accelerometers measure acceleration of a moving body and hence can also be used to detect the position and the velocity of the body because acceleration is first and second derivative of the spatial velocity and position respectively with respect to time.

2. Accelerometer Types

MEMS accelerometers have been classified in several ways. These classifications are based on (i) number of axis (ii) fabrication technology (iii) their internal structure (iv) method of operation (v) temperature of operation (vi) type of output (digital or analog) it gives out (vii) amplitude range (viii) frequency range and band width, and (ix) sensing mechanism. Most popular classification is based on the sensing mechanism, which divides the accelerometers in mainly eight types of categories [19]. One of the important categories is based on capacitive sensing. It has distinct advantages over the other kind of sensing mechanisms. Capacitive sensing, in accelerometers, has have been implemented with different approaches and mechanical elements. These mechanical elements are micro-cantilevers, beams, membranes, bulk or surface micromachined mass structures and comb drives. Capacitive comb drive type accelerometers have earned commercial acceptance due to their high sensitivity, stable DC-characteristics, low drift, low power dissipation and low temperature sensitivity [20-21]. Comb-drive type accelerometers are further divided into surface and bulk micro-machined accelerometers depending on the technology of their fabrication. The first kind of accelerometers has a smaller proof mass whose size is limited by the process constraints [22]. This limitation can be overcome in the second type of devices, which uses wet or dry bulk micro-machining techniques. One can realize a proof mass with high aspect ratio using DRIE (Deep Reactive Ion Etching) technology and thus making the accelerometer more sensitive. This paper presents a study carried out for the design of a highly sensitive inertial grade in-plane comb-drive type micro-accelerometer to be realized by HAR (high aspect ratio) DRIE (deep reactive ion etching) process. This process has already been developed and characterized in our laboratory. In this work, we have optimized the position of the tethers which are used to support the proof mass so that it has minimum sag in the z-direction (out of plane) and hence lower off-axis sensitivity [23]. The accelerometer has been modeled analytically to predict the device characteristics. The dependency of sensitivity on various parameters of accelerometer has also been verified using FEM software tool ANSYS^{TM} Multiphysics.

2.1. Inter-digitated Comb-drive Accelerometer

In the present work we have taken up a comb-drive accelerometer, which consists of a proof mass and four tethers attached to it. These tethers are simple cantilever beams acting as suspension for the proof mass. One end of the each tether is connected to the proof mass and the other end is clamped with an anchor, as shown in Fig. 1. On both sides, fingers are attached to the proof mass which are called movable fingers or *rotors* as these can move as the proof mass moves. On both sides of the proof mass, there are two sets of fixed fingers (known as *stators*, or sometimes electrodes), protruding towards the rotors and parallel to them. These fingers together with rotors form two set of capacitors known as differential capacitors C_1 and C_2. These differential capacitors are used to measure the acceleration of the system to which the accelerometer is attached. When the system moves with an acceleration in - x direction, the proof mass will experience a force $F = ma$ in x direction, which results in displacement of the proof mass from its neutral position, and hence that of the rotors. Both the capacitances C_1 and C_2 will thus change. Therefore, the displacement can be measured by sensing the change in the capacitance as the proof mass moves due to the inertial force. The differential capacitors can be implemented either in split electrode or duel electrode mode. In the current work, we have considered split electrode mode for the sake of simplicity in the fabrication process. Fig. 1 illustrates the proof mass along with *rotors* and *stators* of a comb drive type accelerometer in a split electrode mode of operation.

2.2. Basic Working Principle

The comb-drive accelerometer can be reduced to a spring-mass damped model with an effective spring stiffness constant $\boldsymbol{k}$, mass $\boldsymbol{m}$, damping constant $\boldsymbol{b}$, and is driven by a harmonic force function $\boldsymbol{F = F_0 \sin \omega t}$, as shown in Fig. 1. It can be expressed as a second order differential equation:

$$m\ddot{x} + b\dot{x} + kx = ma = ma_0 \sin \omega t \tag{1}$$

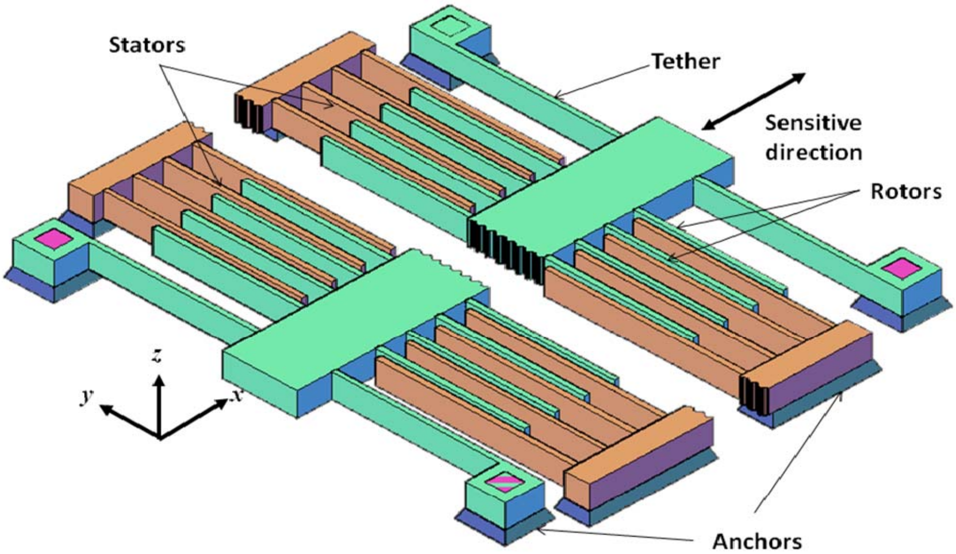


Fig. 1. 3-D schematic of the comb-drive accelerometer with split electrodes.

In Laplace transform equation (1) can be written as:

$$H(s) = \frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} = \frac{1}{s^2 + \frac{\omega_r}{Q}s + \omega_r^2}, \tag{2}$$

where $\omega_r = \sqrt{k/m}$, natural frequency of the mass-spring system,
$\boldsymbol{m}$ is the proof mass; $\boldsymbol{k}$ is the spring constant; $\boldsymbol{b}$ is the damping constant of the medium;
$\boldsymbol{Q = \omega_r m/b = (km)^{1/2}/b}$ is the quality factor.

At low frequencies $\omega << \omega_r$, static sensitivity can be given by

$$S_d = x/a = 1/\omega_r^2 = m/k \tag{3}$$

It is seen from the above that the resonance frequency ω_r of the structure can be reduced by decreasing the spring constant and increasing the proof mass, while the quality factor of the device can be improved either by reducing damping or by increasing proof mass and spring constant. The static response of the device can be improved further by reducing its resonant frequency. So, there is a compromise in designing the value of the spring constant and the proof mass. The primary mechanical noise source for the device is due to Brownian motion of the gas molecules surrounding the proof mass and the Brownian motion of the proof mass suspension or anchors. The total noise equivalent acceleration (TNEA) [$m/s^2Hz^{1/2}$] is [24] given by:

$$\text{TNEA} = \frac{\sqrt{4K_BTb}}{m} = \sqrt{\frac{4K_BT\omega_r}{Qm}} \tag{4}$$

where is K_B is the Boltzmann constant and T is the temperature in Kelvin. Equation (4) clearly shows that to reduce mechanical noise, the quality factor and proof mass should be higher.

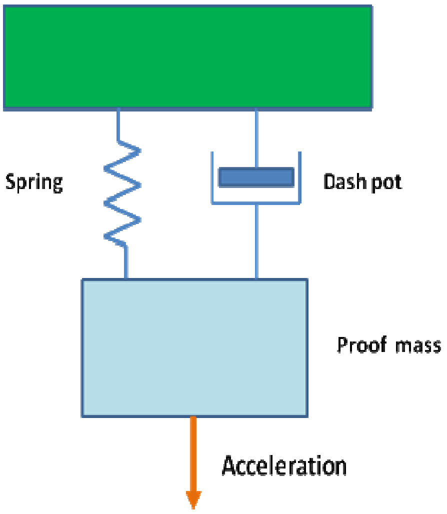


Fig. 2. Schematic of spring-mass-dashpot model of the comb drive accelerometer.

Therefore, there are three basic components in a comb drive type accelerometer which are to be appropriately chosen for achieving a target set of accelerometer specifications:

(i) Rectangular proof mass
(ii) Four number of springs
(iii) Rotor and stator pairs forming two sets of capacitors.

2.3. Design and Fabrication Approach

Following design criteria has been followed in this work:

1. Identify the application(s)

2. Finalize the device specifications meeting the targeted application(s)
3. Fix up the primary device parameters
4. Extract the secondary device parameters
5. Analytical modeling
6. Numerical simulation
7. Fine tuning of the parameters
8. Check the suitability with respect to the fabrication process
9. Identify the limitations of the chosen fabrication process
10. Finalize the design parameters based on fabrication process limitations.

In addition to the above design criteria, following fabrication approach has been taken up in the subsequent fabrication:

1. Fabrication process development and characterization
2. Device fabrication
3. Packaging and testing

Our current design is aimed at low-g (± 10 g) applications for which broad specifications are given in Table 1**.**

Table 1. Device Specifications.

S. No.	Device Specification	Unit	Value
1	Acceleration range	g	0 to ± 10
2	Sensitivity, mechanical	µm/g	>0.1
3	Frequency range	Hz	0 -1000
4	Off-axis sensitivity	%	<0.1 %
5	Non-linearity	%	<0.1 %
6	Temperature range	˚C	-40 - 80

2.4. Optimization of Tether Position on the Proof Mass

The proof mass has a sag in the z-direction due to the gravity or any other acceleration acting perpendicular to the plane of the accelerometer. This sag is a limitation to the comb drive accelerometers because as the size of the proof mass is increased for a better sensitivity, the sag of the proof mass tends to increase automatically. The sag of the proof mass tends to increase the off-axis sensitivity of the accelerometer which is undesirable. Therefore, it is necessary to minimize the sag of the proof mass to get better response from the accelerometer.

If we place the tethers at a distance ***'x'*,** as shown in Fig. 3, from the end corners of the proof mass, which are generally the position for placing the tethers in the available accelerometers, a sag in the proof mass is observed. The sag of the proof mass follows a pattern which shows that the sag is minimum when the tethers are attached at a certain point in the proof mass. This position of the tethers has been determined in this work using the FEM software ANSYS^{TM} Multiphysics for the dimensions of accelerometer listed in Table 2. The parameters of the proof mass and the tethers are illustrated in Fig. 4.

When the tethers are moved closer to the end of the proof mass, the sag of the inner part i.e. towards the centre of the proof mass is more; but as the position of the tethers is shifted towards centre of the proof mass, the sag goes on decreasing up to a point, Fig. 3. After reaching this critical point the sag of the outer part of proof mass is more than that of the inner part which now becomes the limiting factor.

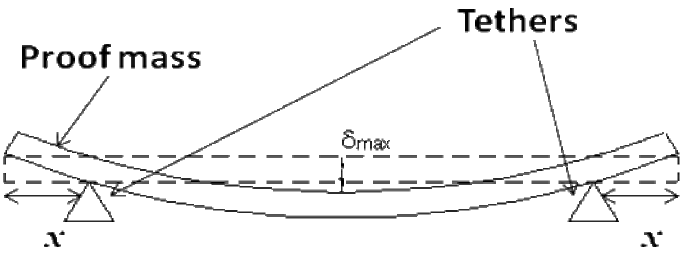


Fig. 3. Description of bending of the proof mass.

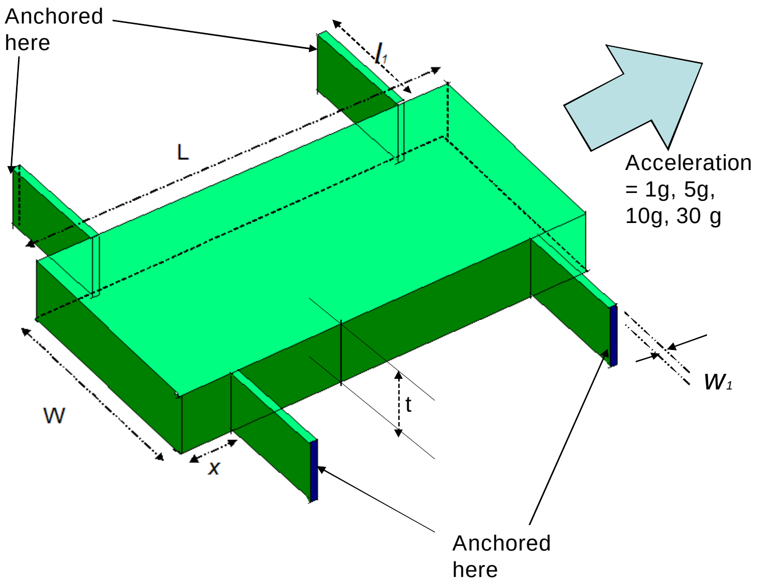


Fig. 4. Proof mass with tethers attached at a distance '*x*' from the edge.

Now, the sag of the outer part, i.e. the part of the proof mass towards the corners, has to be taken into consideration instead of the inner part. This gives an optimum position for the attachment of the tethers to the proof mass which minimizes the sag of proof mass. For the dimensions given in Table 2, for the proof mass, the optimum position comes out to be at $\boldsymbol{x}$ = 800 μm. When the distance between tethers and the ends of proof mass is varied, a curve as shown in Fig. 5, is obtained which clearly shows the optimum position of the tethers at $\boldsymbol{x}$ = 0.8 mm.

3. Analytical Modeling

The accelerometer structure suspended by four springs acting in parallel can be converted to a single DOF system whose response under an external inertial force can be predicted using the well established theory of vibration. Fig. 6 illustrates the schematic of the 1-DOF model of the accelerometer.

Table 2. Dimensions of the accelerometer structure for optimizing the position of the tethers.

Parameter	Symbol	Value of the parameter
Length of the proof mass	L_m	4 mm
Width of the proof mass	W_m	0.4 mm
Thickness of the proof mass	T_m	0.2 mm
Length of the tether (beam)	l_1 or L_b	1 mm
Width of the tether (beam)	W_1 or W_b or w	10 µm
Depth of the tether	T_b or t	0.2 mm
Gap between stator and rotor, smaller gap	d_1	10 µm
Gap between stator and rotor, Larger gap	d_2	20 µm
Number of rotors on one side of the proof mass	N_r	65

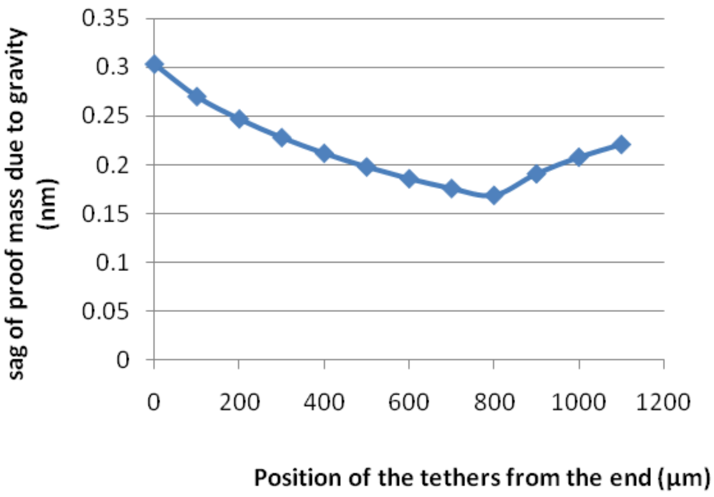


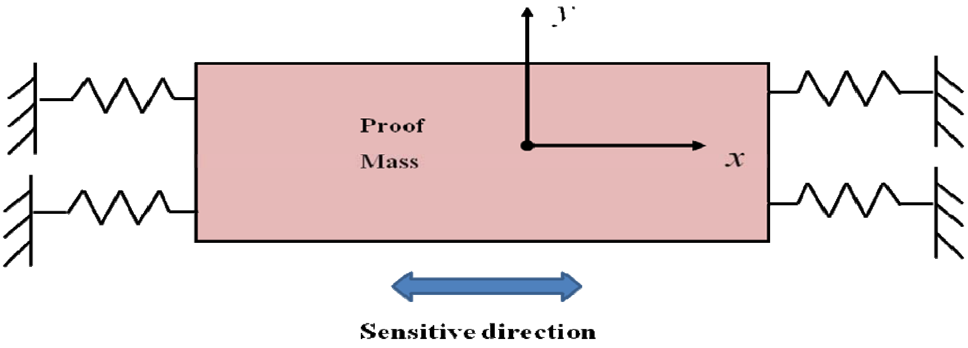
Fig. 5. Variation of sag as a function of the tether position on the proof mass.

3.1. Modeling of Stiffness

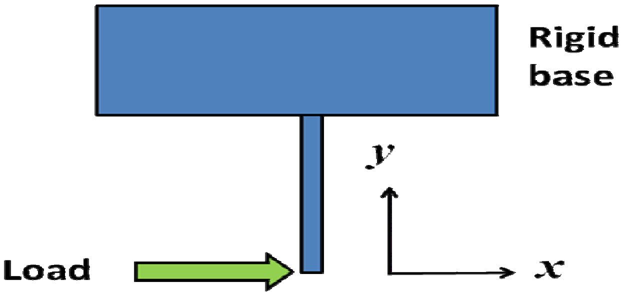
As already stated above the proof mass supported by four tethers at four points, Fig. 6(a) is modeled in a single DOF system in the x-direction, as shown in Fig. 6 (b). The spring constant in the x-direction of a cantilever beam loaded at the end is given by the equation:

$$k_x = \frac{3EI}{l^3} = \frac{3E}{l^3} \times \frac{tw^3}{12} \tag{5}$$

where E = Young’s modulus of elasticity;
I = area moment of the tether;
t and w = Tether thickness and width respectively.



(a) Proof mass suspended with four springs.



(b) One DOF equivalent model.

Fig. 6. Modeling of the accelerometer.

All the springs modeled in Fig. 5 are acting in parallel. So the effective spring constant is

$$K_{eff} = 4k_x = 35.8\ N/m \tag{6}$$

Here, the electrostatic softening of the springs has not been taken into account. This issue will be dealt later in the section 3.5.

3.2. Modeling of Damping

The damping of the system has been calculated using the two parallel plate model which uses the Hagen–Poiseulle flow equation [25]. This model considers a pair of movable fingers and fixed fingers as the two parallel plates and the fluid between the two parallel plates to be the air at atmospheric pressure due to which damping occurs. The damping coefficient [26] between a pair of stator and rotor is given by the equation:

$$b = 7.2\mu l \left(\frac{t}{d}\right)^3 \tag{7}$$

where μ = effective viscosity for air (@ 1 atmosphere and 20°C, μ =1.56 x 10^{-5} Kg/ms);
t = finger thickness, l = finger length;
d = distance between two fingers.

So, the damping constant for one pair of parallel rotor and stator can be easily calculated using the above equation. For an inter-finger gap of 10 and 20 µm, the estimated b values are 8.827×10^{-4} kg/s and 1.0108×10^{-4} kg/s respectively.

All the dampers modeled above are acting in parallel and the hence the effective damping constant can be calculated by equation (4) as:

$$b_{eff} = N * b1 + N * b2 \tag{8}$$

where N is the total number of fingers on the proof mass

For an assumed number of 65 fingers on either side of the proof mass the value of b_{eff} comes out to be 0.11827 kg/s.

3.4. Quality Factor

The quality factor describes how damped an oscillator is. Higher *Q* indicates a lower rate of energy loss relative to the stored energy of the oscillator which means the oscillations die out more slowly. The mechanical quality factor of an accelerometer is given as:

$$Q = \frac{\sqrt{K_{eff}\, m}}{b_{eff}} \tag{9}$$

The condition of the damping is generally defines as:
Q > 0.5 => under damped;
Q = 0.5 => critically damped;
Q < 0.5 => over damped.

For the assumed dimension of the accelerometer in the present work for Q = 0.0627, the system is over damped which is desirable because the system oscillations will die out fast exponentially. The damping factor of a system ξ is estimated by using the following equation:

$$\xi = \frac{b_{eff}}{2 * \sqrt{k_{eff} * m}} \tag{10}$$

The damping factor for the considered accelerometer is estimated to be 7.96. This suggests that the system is over damped. The solution of equation (1) for the given accelerometer energized by a sinusoidal force can be written down as:

$$\frac{X}{X_{st}} = \frac{1}{[\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + (2\xi \frac{\omega}{\omega_n})^2]^{1/2}} \tag{11}$$

where:
X= Amplitude of the displacement of the accelerometer;
X_{st}=Static displacement of the accelerometer i.e. F_0/k;
ω = frequency of the excitation;
ω_n= natural frequency of the accelerometer.

The term $\frac{X}{X_{st}}$, known as the magnification factor is plotted against the frequency to show frequency response of the accelerometer. The estimated natural frequency of the system for the above mentioned dimensions is 768 Hz. The frequency response and Bode plot were obtained using MATLAB^{TM} 7.0 as shown in Fig. 7 and 8.

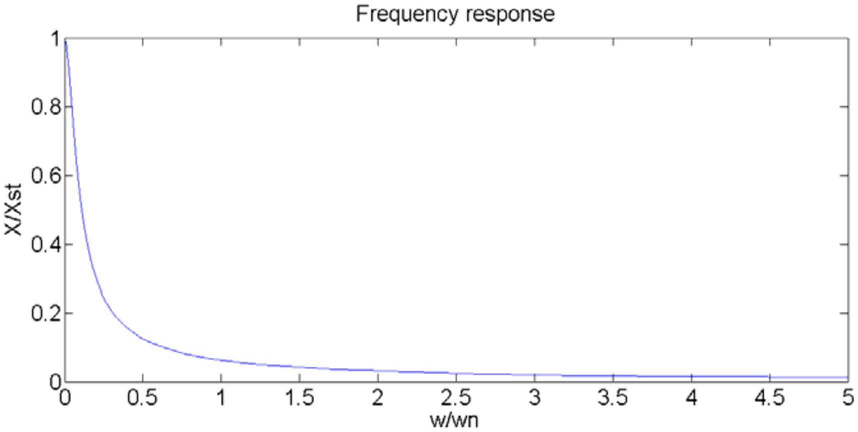


Fig. 7. Frequency response of the accelerometer for the given parameters.

From Fig. 8 it can be seen that the magnitude does not vary much in 0-200 rad/s range of the frequency. This leads to the conclusion that in the above said frequency range, the magnitude is frequency independent, but at higher frequencies the magnitude changes considerably. So, the operating frequency of the accelerometer should lie in this range where the magnitude does not vary with the frequency.

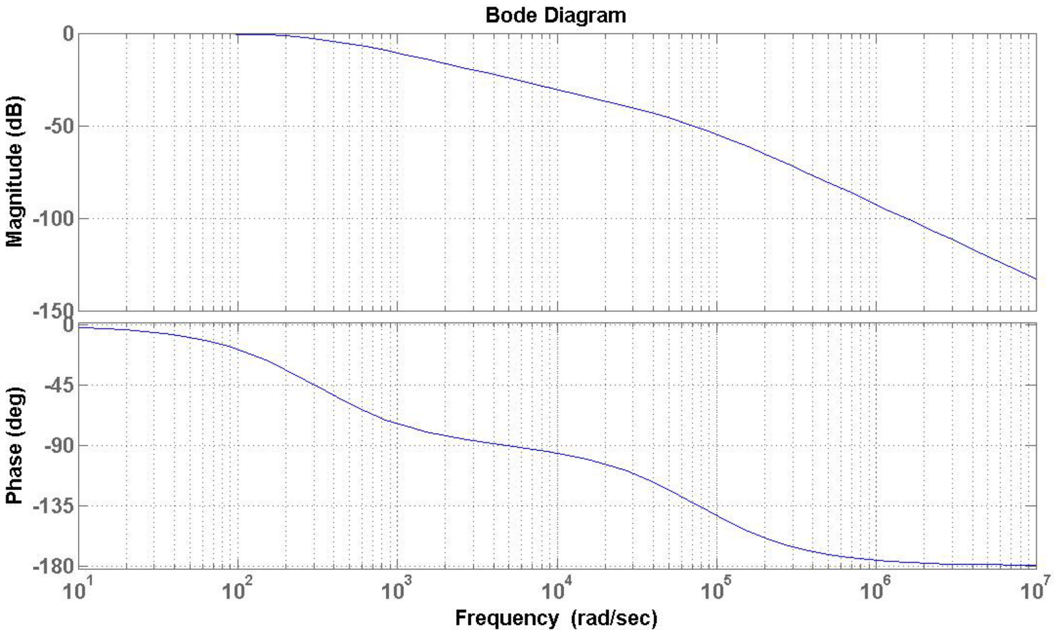


Fig. 8. Dynamic response of the device.

3.5. Electrostatic Softening of the Spring

In order to measure the change in capacitance due to the external acceleration, modulation signals are applied on the differential capacitors which generate an electrostatic force on the fingers, Fig. 9. This force is given by:

$$F = \frac{-N\varepsilon ltV_m^2}{2(d_1 + x)^2} + \frac{-N\varepsilon ltV_m^2}{2(d_2 - x)^2} \tag{13}$$

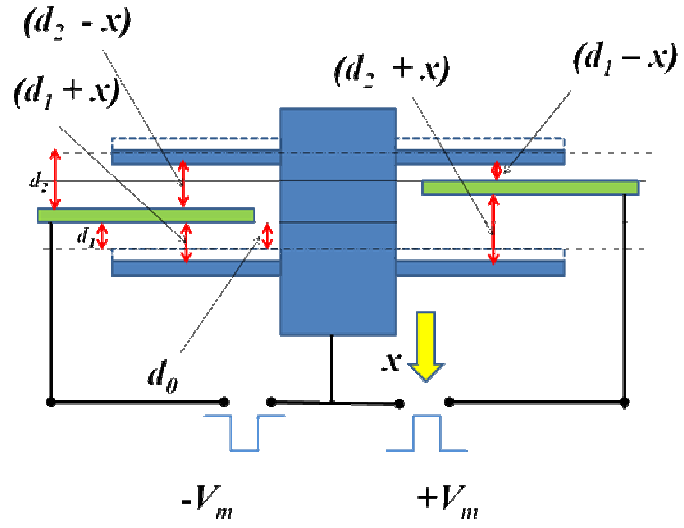


Fig. 9. Applied modulation signal.

where:
N = number of fingers;
ε = permittivity of the air;
l = length of the fingers;
V_m = Amplitude of the modulation signals.

The spring constant due to the electrostatic forces is obtained by differentiating the force given by the equation (13) with respect to the displacement x.

$$k_e = \frac{-\partial F}{\partial x} = \frac{-N\varepsilon ltV_m^2}{(d_1 + x)^3} + \frac{-N\varepsilon ltV_m^2}{(d_2 - x)^3} \tag{14}$$

The effective spring constants, calculated using the equation (14) are tabulated in the Table 3, and are plotted in Fig. 10. The damping factors are also calculated when the electrostatic softening is taken into account simultaneously.

For the modulating voltage of 1 to 5 V, there is very little change in the damping factor, Table 3, which suggests that the frequency response remains almost the same as before. This can be attributed to the high aspect ratio of the structure which can be attained by using HAR DRIE technology. With the increasing depth of the structure the spring constant of the tethers increase and the change due to the electrostatic softening becomes relatively insignificant, particularly at low driving voltages.

Table 3. Effective spring constant and damping factor for different voltage.

Voltage(V)	K_{eff} (N/m)	Damping factor(ξ)
1	35.57	7.99
2	34.87	8.07
3	33.70	8.21
4	32.07	8.42
5	29.98	8.71

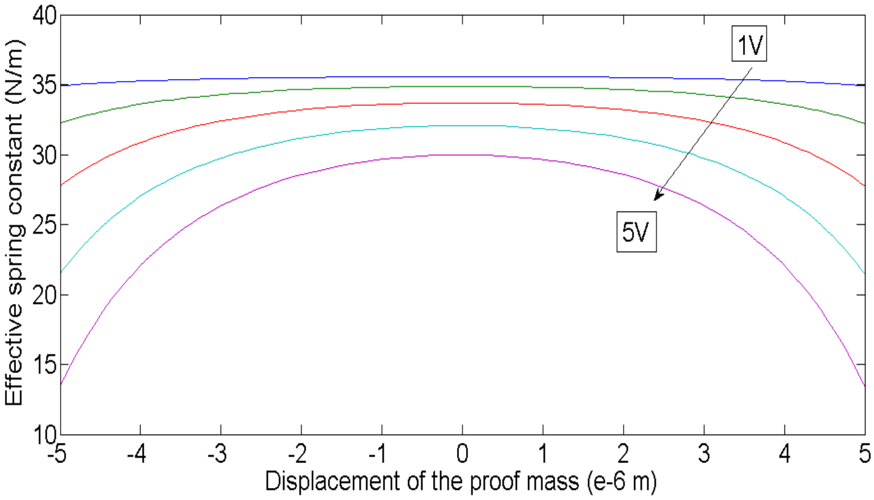


Fig. 10. Variation in the effective spring constant with the displacement of the proof mass for different voltages.

4. FEM Modeling

The accelerometer was modeled analytically as described in the section 3 by simplifying the structure to a single DOF structure. Although the model is a simplified one, it provides the theoretical basis for the prediction of the properties of the accelerometer. In the present section, the structure is modeled using the FEM software ANSYS^{TM} and the mechanical sensitivity is determined by altering various parameters of the accelerometers. This information can be used for deciding the dimensions of the accelerometer because by changing the parameters, the sensitivity of the accelerometer can be increased which is an important consideration.

Here, the dimensions of the proof mass were kept constant and the dimensions of the tethers were varied which, in turn, change the effective spring constant of the system which is an important factor in determining the system characteristics. While varying the parameters, the electrostatic forces were neglected. As inferred above that the effect of electrostatic forces is quite insignificant as compared to the mechanical forces for the considered dimensions of the accelerometer, so the assumption seems to hold reasonably.

4.1. Variation of Tether Length

Here the length of the tether was varied while the width of the tether was taken as 10 μm and the depth of the tether was fixed at 200 μm. As the length of the tether was increased, the mechanical sensitivity of the accelerometer went on increasing. This can be verified by the equation (5) which suggests that the spring constant is inversely proportional to the cube of length of the tether. So, when the length of the tether is increased the spring becomes less stiff and the mechanical sensitivity of the accelerometer increases. The variation is shown in the Fig. 11.

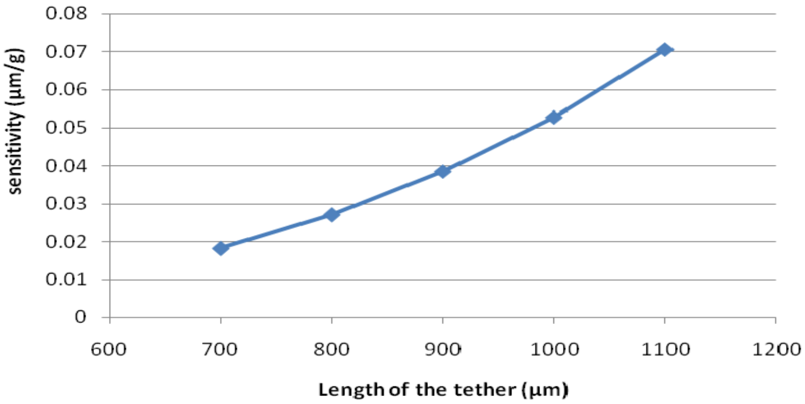


Fig. 11. Variation in sensitivity with respect to length of the tether.

4.2. Variation in Tether Width

The width of the tether was varied keeping the length and the depth constant at 1100 µm and 200 µm respectively. As the width of the tether was increased, the mechanical sensitivity of the accelerometer also decreased which is in support with the equation (5) that establishes that the stiffness is directly proportional to the third power of the width the tether. So as the stiffness of the tether increases the mechanical sensitivity of the accelerometer decreases, which is clearly shown in the Fig. 12.

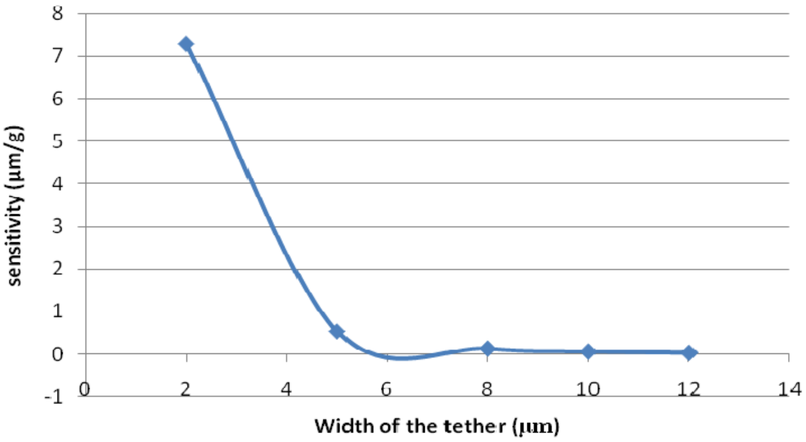


Fig. 12. Variation in sensitivity with respect to the width of the tether.

4.3. Variation of Tether Thickness

The depth of the tether was varied keeping the width of the tether at 10µm and the length of the tether as 1000µm. As illustrated by the Fig. 13, the sensitivity of the accelerometer decreases as the depth of the tether is increased and puts a limit to the thickness of the structure. This variation follows the trend given in the equation (5) that shows that the stiffness of the tether is directly proportional to the width of the tether. The variation in sensitivity against thickness of the tether is plotted in Fig. 13.

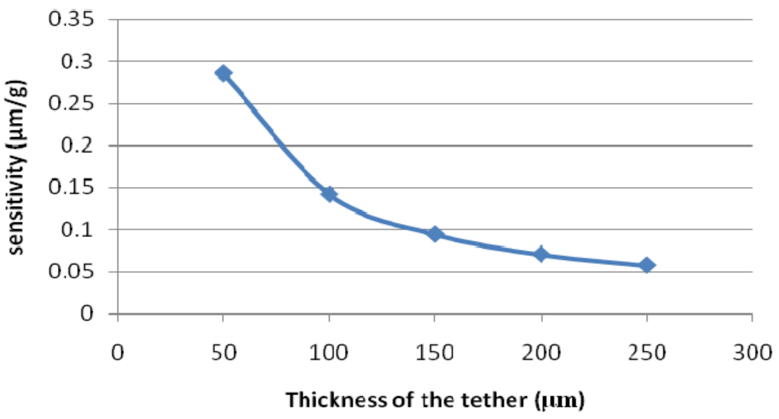


Fig. 13. Variation in sensitivity with respect to the thickness of the tether.

4.4. Capacitance Variation with Proof mass Displacement

For the assumed arrangement of the fingers attached to the proof mass, the capacitance of the left side of the proof mass increases with the displacement of the proof mass in + x direction, whereas, the capacitance of the right hand side of the proof mass decreases. This scheme is useful in sensing the change in capacitance of the system that corresponds to the acceleration of the system because as the system experiences acceleration, the proof mass and the fingers move and the capacitance changes. And hence the overall sensitivity of the accelerometer is increased as the change in the capacitance of the system can be measured in a better way for the same magnitude of the acceleration.

Fig. 14 illustrates the variation of the capacitance with the displacement of the proof mass. Here C1 and C2 represent the capacitance of the left and right hand side of the proof mass respectively. It is clear from the Fig. 10, that as the proof mass moves in the positive direction, the capacitance of the left hand side increases while the capacitance of the right hand side decreases.

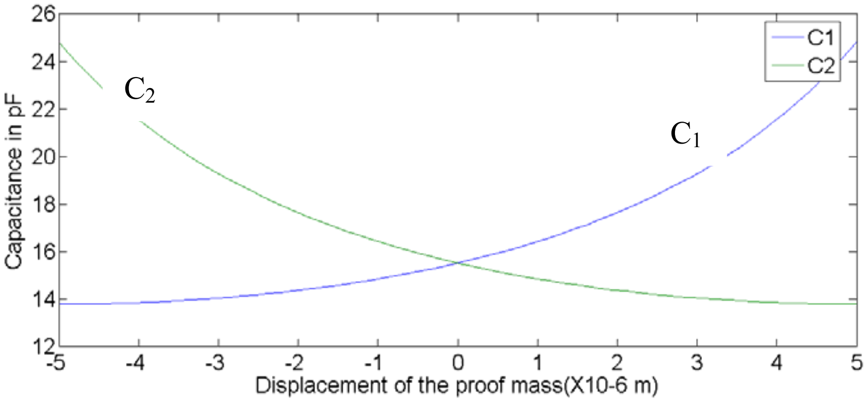


Fig. 14. Plot of the capacitance Vs displacement of the proof mass.

5. Optimized Device Parameters

From the simulation results presented above, we observe that the sensitivity, which is the most important parameter of the device, can be achieved through the optimization of the dimensions of the tethers, such as the width, length and thickness of the beam. The proof mass m can also be very precisely set and fabricated using the current technology, for the desired device parameters. Among these parameters, the beam depth is one of the effective parameters to adjust the device sensitivity without increasing the overall device area. However, the minimum beam depth is limited by the aspect ratio in HAR DRIE process. Therefore, we may combine other parameters (such as beam length, mass width and length) to further improve the device sensitivity. Generally, we would prefer larger device sensitivity in order to have a better SNR (signal to noise ratio). However, the simplified spring-mass model for the beam-mass system is valid only for very small deflection approximation. Further, the device linearity between acceleration input and differential capacitance change will be degraded if the maximum displacement of the movable fingers exceeds 10 % of the capacitance gap. Therefore, it is necessary to have a good trade-off between the device sensitivity, linearity, off-axis sensitivity and quality factor for the design optimization. One of the biggest advantages of the current design is that it has low parasitics.

Based on the above analysis and simulation exercise, an optimized design of MEMS comb accelerometer for a balanced device sensitivity and linearity was arrived at. These design parameters are shown in Table 4. ANSYS^{TM} simulation shows the proposed accelerometer design has displacement sensitivity of 0.136 μm/g which is equivalent to 40.8 mV/g for V_{in} =3 V.

Table 4. Optimized Device Parameters.

S. No.	Device Element	Symbol	Value in micron
1.	Length of proof mass	L_m	4000
2.	Width of proof mass	W_m	400
3.	Length of the tether (beam)	L_b	1100
4.	Width of the tether(beam)	W_b	8
5.	Tether depth	T_b	200
6.	Distance of the tether from the edge of the proof mass	x	800
7.	Length of the rotor	L_r	1020
8.	Width of the rotor	T_r	10
9.	Depth of the rotor	W_r	200
10.	Length of stator	L_s	1100
11.	Width of the stator	W_s	10
12.	Depth of the stator	T_s	200
13.	Electrode overlap area	l_e	1000
14.	Electrode gap 1	d_1	10
15.	Electrode gap 2	d_2	20

6. Conclusions

Design optimization of a single crystal silicon micro-machined MEMS comb-drive micro-accelerometer with straight beam structure has been carried out using a simplified spring-mass model. ANSYS^{TM} simulation was used to extract the relationship between the device sensitivity and various design parameters, such as beam width, beam length and mass dimensions. Simulation results demonstrate that the device sensitivity increases rapidly with beam width. Thus the beam width is an efficient design parameter to adjust the device sensitivity. Further, increasing beam length or mass width can also improve the device sensitivity, but at the expense of increasing the overall device area. In other words, by adjusting design parameters a device configuration having desired sensitivity can be arrived at. Based upon this analysis, an optimized straight-beam comb-drive accelerometer has been designed with a sensitivity of 13.6 mV/g/V. The proposed accelerometer device can be implemented for ±10g applications in consumer electronics, navigation, space and industry.

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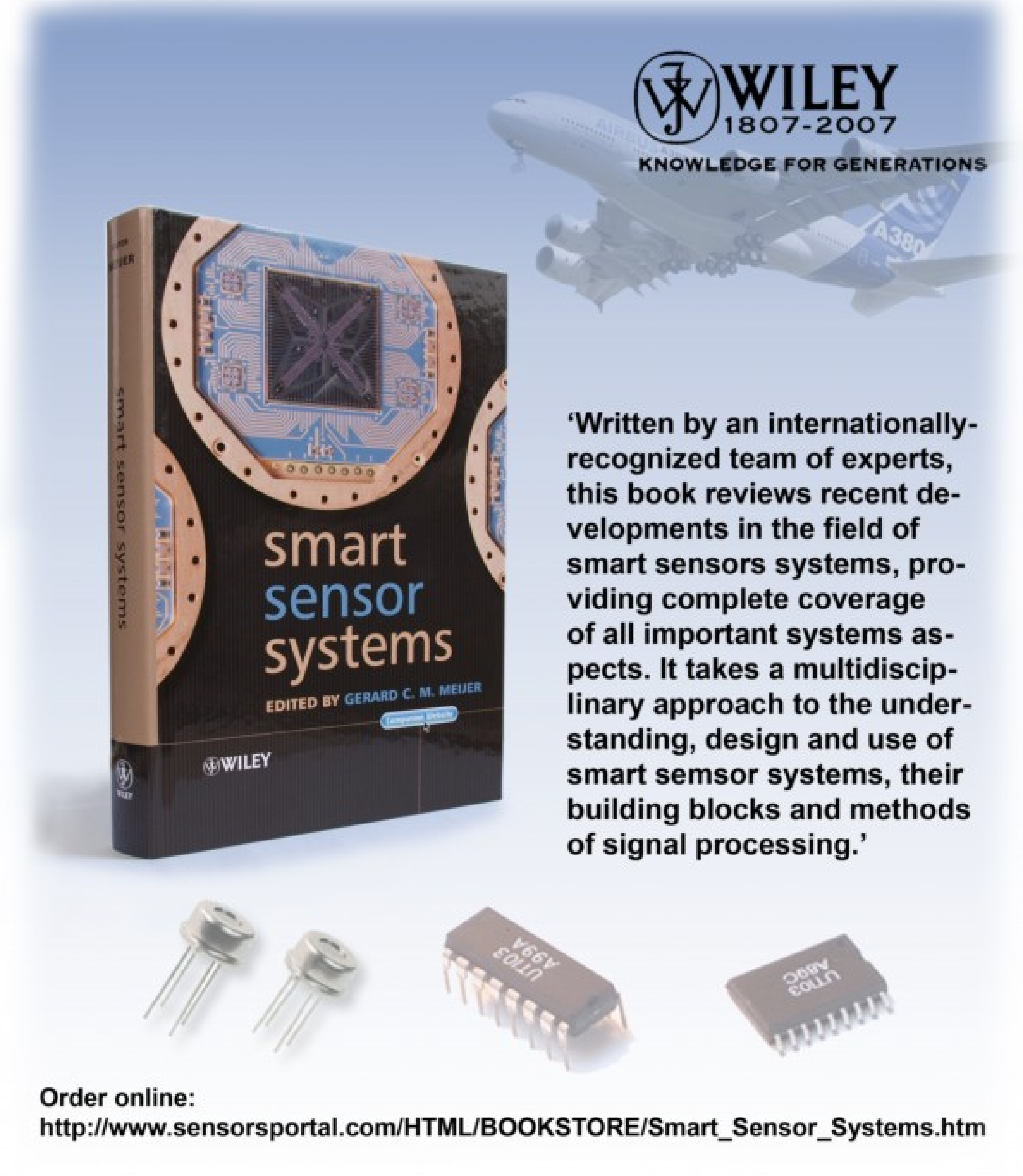

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