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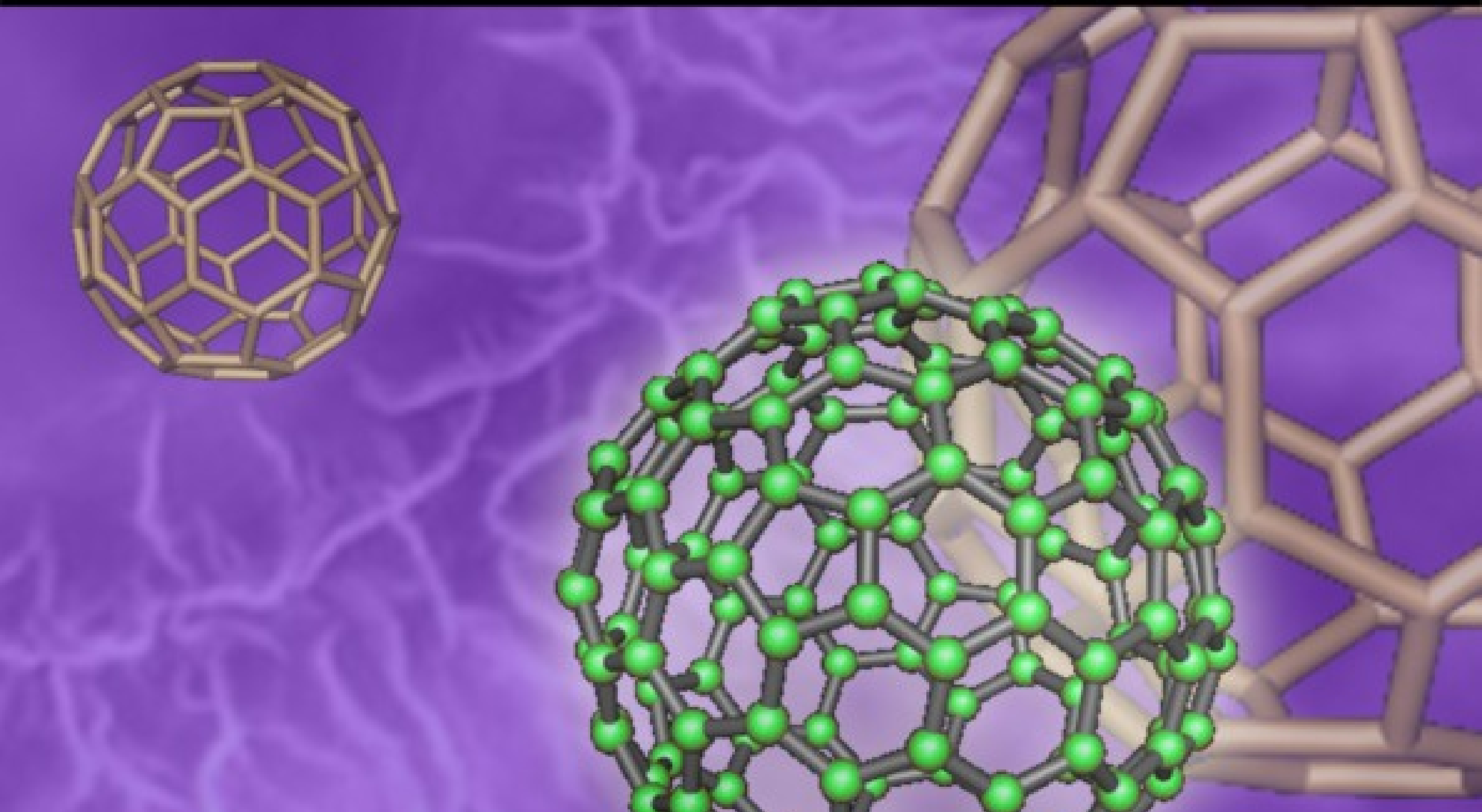

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Design Optimization of Cantilever based MEMS Micro-accelerometer for High-g Applications

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Abstract: Design optimization study of micro-cantilever based MEMS accelerometer is presented in this paper. The cantilever structure is dc biased with an ac signal to extract output voltage generated due to the change in capacitance. This signal modifies the behavior of the sensing element. The cantilever performance under a combined inertial and electrostatic force has been considered for estimating the dimensional dependence of cantilever sensitivity, non-linearity, off-set and critical acceleration and operating voltages. The cantilever performance has been verified using ANSYS™ Multiphysics software. Finally, a micro-accelerometer based on an array of 15 cantilevers has been designed and fabricated with a high sensitivity of 3 - 4 mV/g with a non-linearity of < 1 % for *high-g* (50g) applications. *Copyright © 2009 IFSA.*

Keywords: Accelerometer, Micro-cantilever, Capacitive sensing, DRIE

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1. Introduction

MEMS micro-cantilevers have been recognized as next generation electromechanical sensing and actuation elements [1]. For introducing specificity in sensing properties of cantilevers it is possible to sensitize them using a chemical or bio-molecular layer, sensitive to a specific target molecule or group of molecules. On exposure to a sample having the target molecules, such a cantilever experiences mechanical changes that are then detected. This feature makes cantilever a versatile sensor. Micro-cantilevers are poised already to have a wide variety of applications [2-5]. Therefore, design and study of micro-cantilevers as an accelerometer was chosen to facilitate the simultaneous development of a variety of micro-sensors for physical, chemical and bio-sensing applications as well [6-13]. The most significant application is in the area of biosensors [8-14]. In this work, design of a micro-cantilever system for measuring 50 g acceleration with a sensitivity of 3-4 mV/g is undertaken. Such accelerometers will be useful in automotive and industrial applications involving high acceleration requirement like airbag deployment or crash sensor in automobiles and monitoring the mechanical vibrations of machinery in an industry.

2. Micro-cantilever as an Accelerometer

A cantilever, in its simplest form, as shown in Fig. 1, is a thin rectangular plate of an elastic material clamped at one of the six faces, keeping others free [15-16]. It bends with the application of a uniform or pointed load or stress on one of its surfaces. The cantilever material may be Poly-Si, Silicon Nitride, Oxide, Metals or even polymers [17-19]. In the current study, we have chosen Poly-Si cantilevers. The cantilever fabrication is an involved process as it addresses to the problems of stress and release of the cantilevers [20]. In a novel fabrication process technology developed in house, these problems have been taken care of one by one.

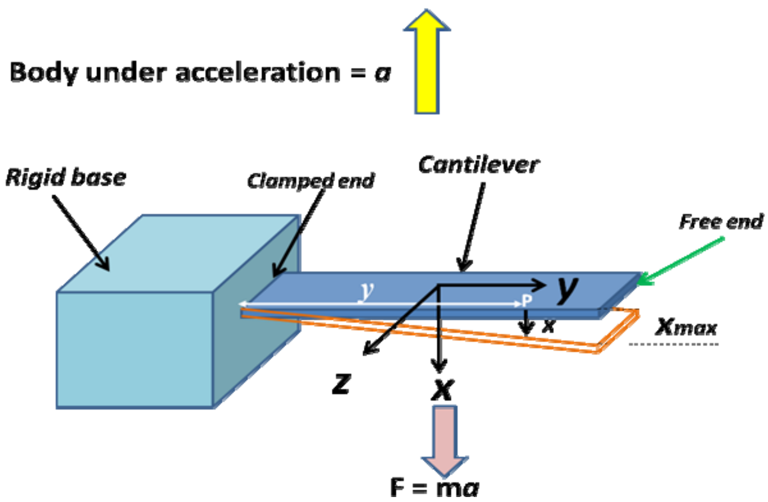

Fig. 1. A Cantilever system under uniform acceleration.

As shown in Fig. 1, when the cantilever system moves under an acceleration ***a,*** in upward direction, the cantilever experiences a force ***F=ma,*** acting at its centre of mass in opposite direction i.e. in ***x*** direction.

The deflection of the beam at any point P at a distance y from the clamped end, can be obtained by solving Euler-Bernoulli's beam equation, and is given by

$$x_y = \frac{W_o\, y^2 [y^2 + 6L^2 - 4Ly]}{24\, EI} \tag{1}$$

in ***x*** direction, where $W_o = ma/L$ load per unit length, ***m*** = mass, ***L*** = cantilever length, ***I*** = moment of inertia, ***E*** = Young's modulus of the cantilever material.

It can be seen that x_y is maximum for ***y*= *L*,** and therefore,

$$x_{max} = \frac{W_o L^4}{8EI} = \left(\frac{3\rho L^4}{2Et^2}\right) a = Ka \quad (2)$$

where K = proportionality constant. b and t are cantilever width and thickness respectively and ρ = cantilever material density.

To a first order approximation, the deflection of the cantilever is directly proportional to the external acceleration.

The resultant stress (in y direction) at a point P located at a distance ***y*** from the clamped end of the cantilever is given by:

$$\sigma_y = \frac{MC}{I} = \frac{W_o\,(L-y)^2}{2I} C, \quad (3)$$

where C is the distance from the neutral axis.

Similarly stress in x direction can be expressed as:

$$\sigma_x = -\frac{W_o\,(L-y)}{bt} \quad (4)$$

Maximum stress in x-direction is given as:

$$(\sigma_x)max = -\frac{W_o\,(L)}{bt} = -\rho L a = ka \quad (5)$$

It can be seen that the stress is also proportional to acceleration ***a*,** and thus can be used to measure acceleration.

2.1. Sensing Approach

It can be inferred from the above analysis that precise measurement of stress or strain can be used for measuring acceleration. For measuring deflection of a cantilever there are several approaches. Most popular ones are: *capacitive, thermal and tunneling* [21-23] effects. Methods based on *piezoresistive and piezoelectric* [24, 25] effects are generally used for measuring stress.

2.2. Mechanical Analysis

In the present design, capacitive sensing has been taken because of its process compatibility with mechanical structures, high sensitivity and low temperature drift [26, 27]. As illustrated in Fig. 2, the cantilever forms one electrode of the capacitor and the other electrode is fixed at the bottom.

The dead capacitance (when there is zero acceleration) of the cantilever and electrode system is given by

$$C_0 = \frac{\epsilon A}{d_o}, \tag{6}$$

where, $\epsilon = \epsilon_0\, \epsilon_r$ the permittivity of the medium, A = area and d_o = inter-electrode separation.

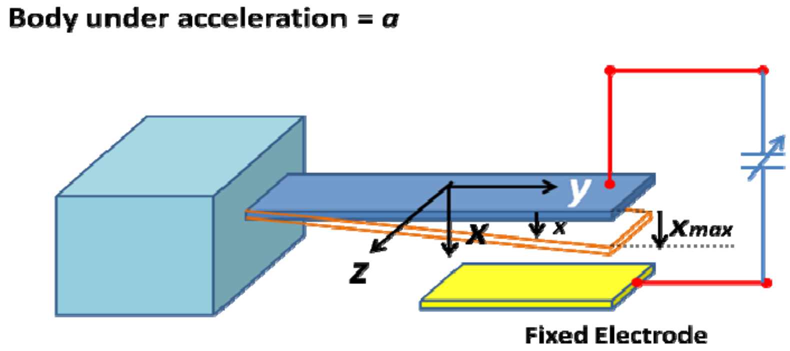

Fig. 2. Capacitive Sensing for Cantilever Deflection.

The capacitance under acceleration ***a*** of the body can be calculated from the following.

$$C_0' = \frac{\epsilon A}{(d_o - x)} \tag{7}$$

Change in capacitance

$$C_0' - C_0 = \frac{\epsilon A}{(d_o - x)} - \frac{\epsilon A}{d_o} \tag{8}$$

Taking the representative values of A = 200 × 200 micron^2, L = 600 micron and a = 50 g, one can see that the magnitude of the dead capacitance and change in capacitance due to acceleration are rather very small. It is very difficult to measure such a low value of the capacitance, as the measurement may be susceptible to the stray capacitances resulting into poor signal to noise ratio (SNR). In order to overcome this problem certain modifications were considered as described below.

The easiest way to enhance the capacitance values is to replace single cantilever by a number of them in parallel. Though this increase in number of cantilevers puts additional burden on the fabrication technology due to: (i) residual stress, (ii) simultaneous release of all the cantilevers (iii) adhesion of the cantilevers to the opposite surface and (iv) measurement of the capacitance.

It is well known that some form of voltage driving signal is usually necessary for the measurement of capacitance. But the application of a driving signal causes an electrostatic force between the bottom electrode and the cantilever that affects the cantilever performance posing limitations on the linearity and the range of the acceleration measured by the cantilever system [28]. Therefore, it is necessary to consider the influence of driving signal along with the deflection caused by acceleration together.

Generally, the driving signal is in the form of $V_0 + V_1 \sin \omega t$, (AC component frequency is around 10^6 Hz). The average electrostatic force 'F_e' generated by this driving signal can be expressed as:

$$F_e = \frac{A\epsilon}{2(d_o - x)^2}\left(V_0^2 + \frac{1}{2}V_1^2\right) \tag{9}$$

or

$$F_e = \frac{A\epsilon}{2(d_o - x)^2} V_{eff}^2, \tag{10}$$

where A = electrode area, d_o = original distance between two electrodes, ϵ=medium permittivity and $\boldsymbol{x}$ = average of the cantilever deflection in the overlap area between the cantilever and the bottom electrode as shown in Fig. 3.

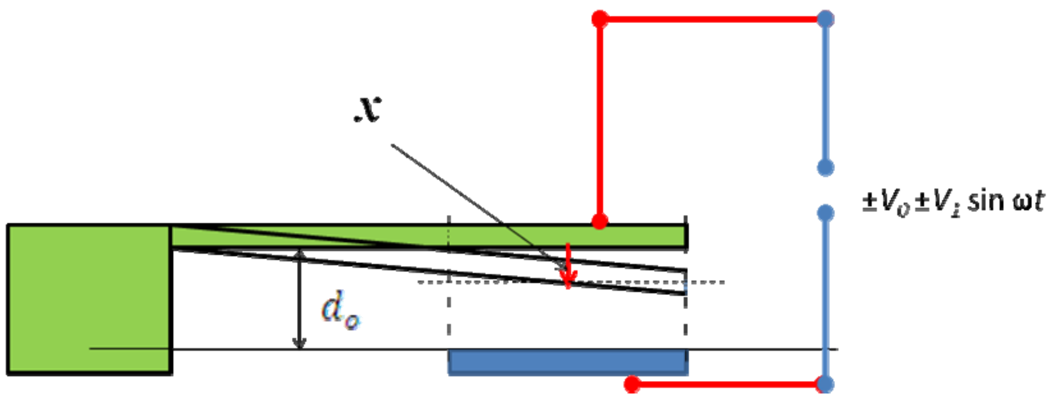

Fig. 3. Arrangement of applied driving signal for single sided driving.

2.2.1. Single-sided Drive

When the cantilever is subjected to an external acceleration as shown in Fig 3, it will experience a number of forces i.e. the force due to acceleration, the mechanical (elastic) recovery force of the structure, the environmental damping force and the electrostatic force generated by the driving signal. For the current analysis, we ignore the damping effect due to the surrounding medium to avoid the unnecessary complicacies. It will have an effect on the (i) output signal when the measurand is dynamic, (ii) mechanical quality factor Q which will be analyzed separately in a subsequent analysis. Taking a single sided driving, the cantilever equation can be written down as [29]:

$$\frac{A\epsilon}{2(d_o - x)^2} V^2 + ma - Kx = 0 \tag{11}$$

Using the normalization of displacement and the force as defined below:

$$\tilde{x} = \frac{x}{d_0} \text{ and } F_{eo} = \frac{A\epsilon}{2(d_o - x)^2} V^2 \tag{12}$$

the equation (11) can be written as:

$$\frac{F_{eo}}{Kd_o(1-\tilde{x})^2} + \frac{ma}{Kd_o} - \tilde{x} = 0 \tag{13}$$

Further defining two new variables p and q as given below:

$$p = \frac{F_{eo}}{Kd_o} \text{ and } q = \frac{ma}{Kd_o} \tag{14}$$

Eq. (13) can be written as:

$$q = \tilde{x} - \frac{p}{(1-\tilde{x})^2} \tag{15}$$

For small $\tilde{x}$ after expanding Eq. (15) in series and retaining the first term, the following expression is obtained:

$$3p\tilde{x}^2 - (1-2p)\tilde{x} + (p+q) = 0 \tag{16}$$

For small *p* and *q*, the stable solution of Eq.(15) is approximated [29] as:

$$\tilde{x} = \frac{p(1-4p+7p^2)}{(1-2p)^3} + \frac{1-4p+10p^2}{(1-2p)^3} \times q\left(1 + \frac{3p}{(1-4p+10p^2)}q\right) \tag{17}$$

Equations (15-17) describe the behavior of the cantilever under combined effect of electrostatic and external acceleration. A plot of q against $\tilde{x}$ for different values of p as shown in Fig 4 is helpful to understand the cantilever performance.

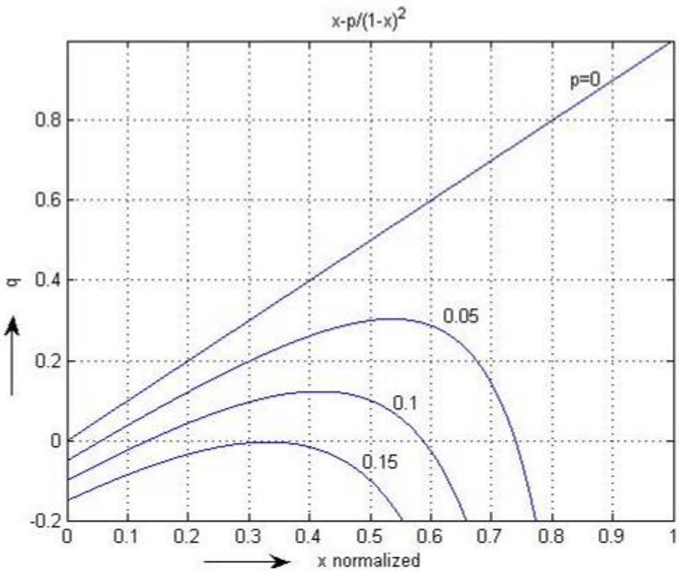

Fig. 4. Normalized acceleration verses normalized displacement.

The following parameters can be studied using the curves in Fig 4.

- Sensitivity variation with p
- Non linearity of q with $\tilde{x}$
- For a specific value of *p* the maximum value of *q (i.e.* q_{max}*)* after which pull-in takes place. Larger the p, smaller the q_{max}. the value of acceleration corresponding to q_{max} is known as critical acceleration a_c
- Pull-in voltage (value of p beyond which pull-in occurs without applying any acceleration)

The critical acceleration a_c, beyond which pull-in takes place and the accelerometer seizes to operate, can be determined from equation (14) and (15) as:

$$a_c = \frac{q_{max} K d_o}{m} \tag{18}$$

One can note that for larger p values the q_{max} values go smaller. However, the p-value decides the sensitivity of the sensing circuit. Therefore there should be a compromise for a practical application and that poses restriction on the sensor design. In fact, there would be no stable displacement at all if p is larger than 0.148 (≈ 0.15) as can be seen from the curves in Fig. 4.

The deviation of plots from the linear plot at $p=0$ gives the non-linearity of the sensing structure. It can be seen here that the non-linearity is negative, as the curves move away from the line $q=\tilde{x}$ towards the x-axis. Also, the offset can be seen in the plots (for values other than $p=0$, the plot starts below $\tilde{x}$), which represents the deflection of cantilever solely due to electrostatic force when there is no inertial force. This is known as *offset*.

With the above analysis we will now determine following important device parameters:
(i) Sensitivity,
(ii) Non-linearity,
(iii) Critical acceleration and
(iv) Offset

2.2.2. Sensitivity

Device sensitivity is defined as the amount of displacement per unit acceleration.

From Eq. (17), we have:

$$\frac{dx}{dq} = \frac{(1-4p+10p^2)}{(1-2p)^3} \tag{19}$$

and for small q

$$\therefore sensitivty = \frac{dx}{da} = \frac{m}{kd_o}\frac{dx}{dq} = \frac{m(1-4p+10p^2)}{Kd_o(1-2p)^3} \tag{20}$$

2.2.2.1. Sensitivity in Terms of Output Voltage

In order to measure the acceleration in terms of a voltage signal, a potential divider configuration of the two capacitors was considered as shown in Fig. 5. Here, in addition to the main sensing capacitor, there are two more capacitors C_r and C_t, which are fabricated along with the sense capacitor C_s. The reference capacitor C_r is placed under the clamped portion of the cantilever having fixed value. The sense capacitor C_s is placed at the free end of the cantilever so that it has the highest variation with the external acceleration. The test capacitor C_t is placed next to the sense capacitor. It provides a pull equivalent to a particular g value on application of DC voltage on the corresponding electrode. The cantilever array has been successfully realized using a combination of wet and dry bulk micromachining (ODE-orientation dependent etching and DRIE-deep reactive ion etching of Si) techniques.

For the arrangement shown in Fig. 5 it can be seen that:

$$C_r = C_0 = \frac{\epsilon A}{d_0} \tag{21}$$

and

$$C_s = C_0' = \frac{\epsilon A}{(d_0 - x)} \tag{22}$$

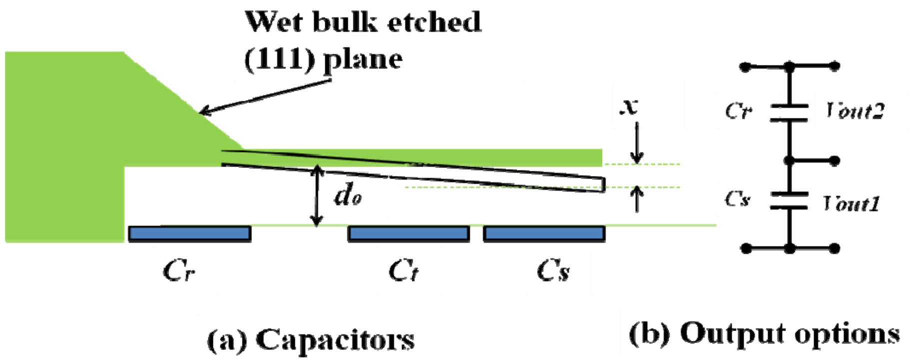

Fig. 5. Cantilever with sense (C_s), reference (C_r) and test capacitors (C_s).

Therefore, for $V_{out}1$

$$V_{out} = \frac{(d_0 - x)}{(2d_0 - x)} V \tag{23}$$

Since $x \ll 2d_o$ we can write the above equation as:

$$V_{out} = \frac{1}{2}\left(1 - \frac{x}{d_o}\right) V \tag{24}$$

Using above equations, sensitivity in terms of voltage output per unit of acceleration comes out to be:

$$sensitivity = \frac{dV_{out}}{da} = \frac{1}{2}\frac{d}{da}\left(1 - \frac{x}{d_o}\right) V = -\frac{1}{2}\frac{m(1 - 4p + 10p^2)}{k(1 - 2p)^3}\frac{V}{d_o} \tag{25}$$

Finally, ignoring the negative sign,

$$sensitivity = \frac{1}{2}\frac{m(1 - 4p + 10p^2)}{k(1 - 2p)^3}\frac{V}{d_o} \tag{26}$$

2.2.3. Non-linearity

Non-linearity is defined as the deviation of specified straight line from the calibration curve of a transducer.

For a function

$$f(x) = bx^2 + ax + c \tag{27}$$

The maximum non-linearity (NL) is given by [30]

$$NL = -\,bx_m/4a \tag{28}$$

where x_m is the point at which $f(x)$ is maximum.

Therefore, on comparing Eqs. (17) and (27) we get $b = \frac{3p}{(1-2p)^3}$ and $a = \frac{1-4p+10p^2}{(1-2p)^3}$

$$\therefore NL = -\frac{3pq_{max}}{4(1-4p+10p^2)} \tag{29}$$

2.2.4. Critical Acceleration

The cantilever is working under the driving voltage as well as the external acceleration. With increasing external acceleration, the cantilever moves closer to the bottom fixed electrode and beyond a particular value of acceleration the cantilever is pulled by the electrode and crashes. This particular value of acceleration is known as critical acceleration denoted by a_c. It has been covered in the previous section and equation (18) gives the value of critical acceleration.

2.2.5. Offset

When there is no external acceleration, the cantilever is displaced from its neutral position because of the average driving voltage applied to the sense capacitor. This displacement is known as *Offset*. It is basically the displacement of the cantilever under the electrostatic pull due to the driving voltage, without any external acceleration. From Fig. 4 we observe that offset increases with *p,* higher the p value, higher will be the offset. It can be calculated from Equation (17), that is when inertial force is zero, i.e. q=0,

$$\bar{x} = \frac{p(1-4p+7p^2)}{(1-2p)^3} \tag{30}$$

Thus there is an offset (non-zero displacement of cantilever) due to the electrostatic force as given by the above equation.

3. Design Approach

We will fix up some of the preliminary device parameters based on technology and then calculate the secondary parameters, based on the above analysis and will finally carry out an iteration to obtain the useful device design parameters.

3.1. Preliminary Design Parameters

The preliminary design parameters for the proposed accelerometer are given in Table 1.

Based on the above preliminary design parameters we have carried out an iterative analysis using the derivations in the previous section, to determine the secondary structural parameters, such as the length of the cantilever L, gap distance d_o, and the driving voltage V. These results were further optimized with software tool MATLAB™. The results are tabulated in Table 2. Three designs have been proposed as given in Table 2.

Table 1. Design and performance parameters.

S. No.	Parameter	Notation	Value
1.	Range	a_{des}	0-50 g
2.	Critical Acceleration	a_c	≥75 g
3.	Sensitivity	$S=V/a_{in}$	3-5 mV/g single sided driving
4.	Non Linearity	NL	<1 %
5.	Offset	$\bar{x}$ at $q = 0$	≤0.1µm
6.	Width of the cantilever	b	200 micron
7.	Thickness of the cantilever	h	1.0 micron
8.	Dimension of sense, reference and test capacitors	C_s, C_r and C_t	200 × 200 micron
9.	Driving Voltage (Av.)	V	1-2 V

Table 2. Proposed design variables and optimization parameters.

S. No.	Design Variables			Optimization Parameters		
	Length (L)	Gap Distance (d_o)	Driving Voltage (V)	Sensitivity (S)	Non Linearity (NL)	Critical Acceleration (a_c)
	µm	µm	V	mV/g	%	g
1	600	6	1.5	3.4	-0.31	115
2	700	8	1.5	4.7	-0.28	94
3	800	10	1.0	4.5	-0.13	84

It is noted from Table 2 that the critical acceleration *(a_c)* is significantly higher for 600 µm cantilever as compared to others. It is because of the larger stiffness of the beam for smaller length. The sensitivity of all the above structures is fairly high (approximately in the range of 3-5 mV/g) and non-linearity much less than the limit set at 1 %. The amount of bending of the cantilevers, percentage change in capacitance, the voltage output under an acceleration of 50 g and the offset due to electrostatic force are tabulated in Table 3.

The following conclusions can be drawn from the Table 3:

- With the increasing voltage *p* increases and the offset increases. Even with a slight voltage increase, the offset increases approximately by almost an order of magnitude. Hence, it is better that the driving voltage does not exceed 1.5V.
- The change in capacitance is fairly large, i.e. 19-30 %, which will give a significant voltage output (approx 0.3-0.6 V) as shown in the table 3, which can be easily picked up by the front-end circuit.

Table 3. Performance parameters.

S. No.	L	d_0	V	p	Mass m	Spring Constant k	Offset	Displacement *x* for 50g	Capacitance C_0	Cap. of Array of 15	ΔC	V_{out} for 50g
	µm	µm	V		10^{-10} Kg	N/m	µm	µm	fF	pF	%	V
1	600	06	1.5	0.0177	2.80	0.0988	0.106	1.42	59	0.86	19.12	0.28
2	700	08	1.5	0.0118	3.26	0.0622	0.094	2.62	44	0.66	24.69	0.50
3	800	10	1.0	0.0040	3.73	0.0417	0.040	4.47	35	0.52	30.86	0.57

The results of Table 2 have been rounded off for the purpose of device fabrication ease. However, this rounding off of the dimensions and voltage has negligible effect on the desired performance. One point to be noted here is that the above critical acceleration is valid once the cantilever is operated in single sided driving mode, whereas in double-sided driving critical accelerations will be higher. Fig. 6 is a plot of normalized acceleration verses normalized displacement. It shows the behaviour of the proposed cantilevers under a combined effect of electrostatic and inertial forces.

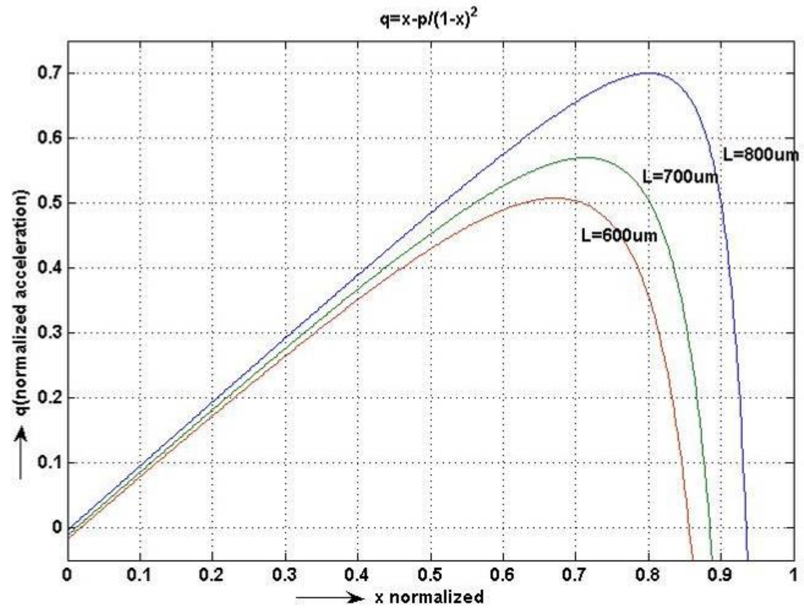

Fig. 6. Plots for normalized acceleration Vs. normalized displacement.

3.2. Simulation

The maximum stress developed in the cantilever, the deflection due to 50 g and the natural frequencies were verified through software tool ANSYS™ as shown in Table 4 and the ANSYS plots, Fig. 7 - 9. There is a slight variation in the values obtained from the two sources. It is probably because our analysis is based on simple one dimensional consideration with approximations.

Table 4. Comparison of cantilever parameters with ANSYS™ results.

Length	Deflection(for 50 g)		Maximum Stress (MPa)		Natural Frequency (1st Mode)	
(µm)	Theoretical (µm)	ANSYS (µm)	Theoretical	ANSYS	Theoretical (kHz)	ANSYS (kHz)
600	1.42	1.31	1.235	1.23	3.82	3.84
700	2.62	2.42	1.677	1.67	2.81	3.82
800	4.47	4.14	2.198	2.19	2.15	2.16

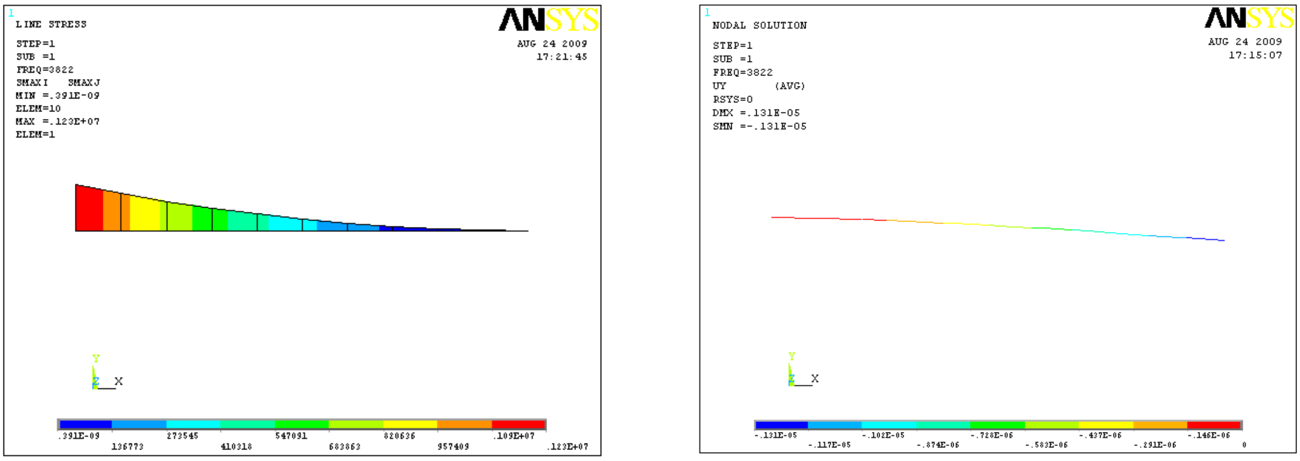

Fig. 7. ANSYS plots for 600 micron cantilever.

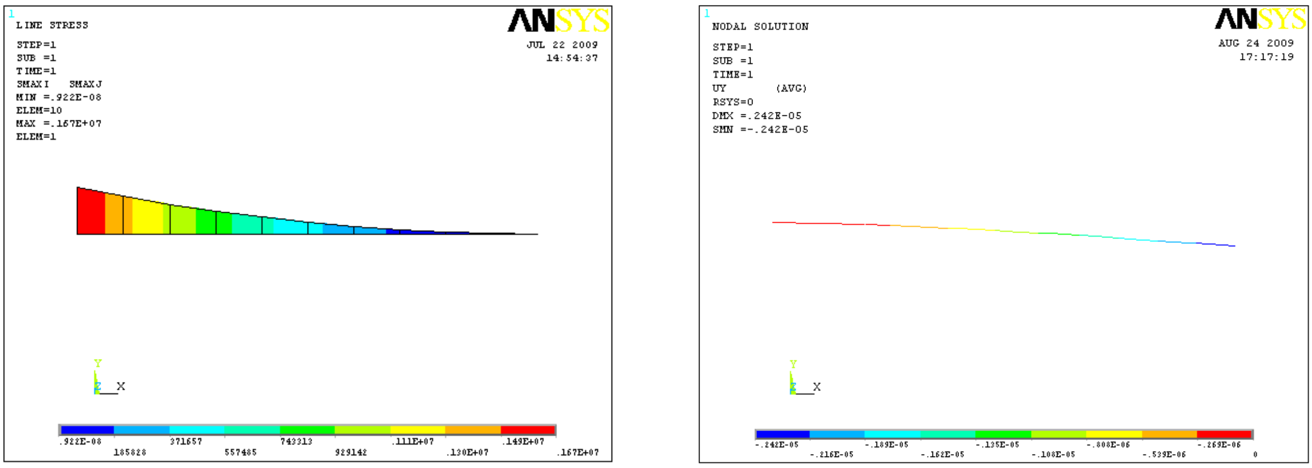

Fig. 8. ANSYS plots for 700 micron cantilever.

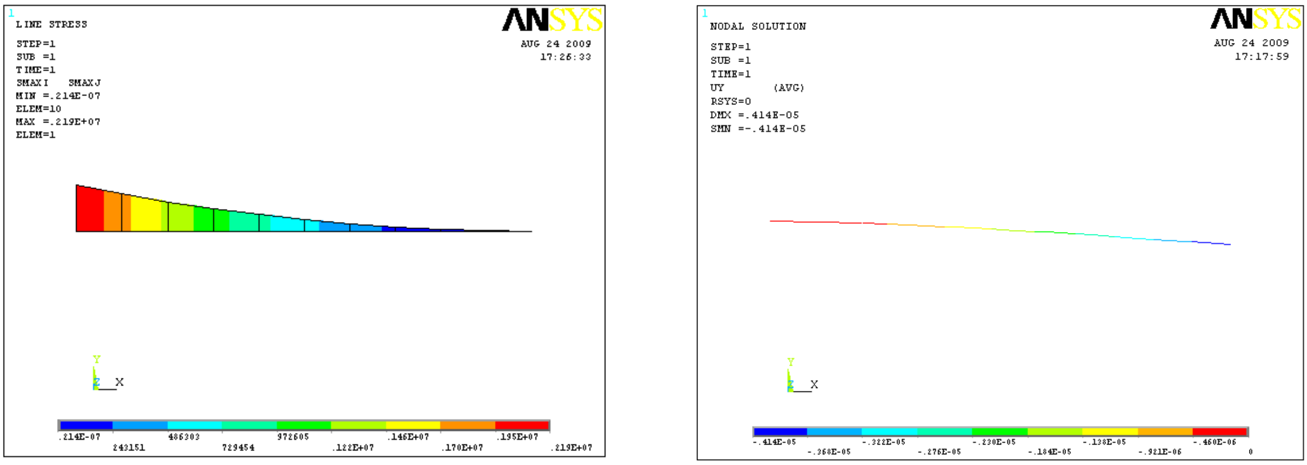

Fig. 9. ANSYS plots for 800 micron cantilever.

3.3. Damping, Brownian Noise and Minimum Detectable Acceleration

The equation of motion for the displacement x of a damped harmonic oscillator with mass m, spring constant k, and mechanical resistance *c*, is given as [31]:

$$m\ddot{x} + c\dot{x} + kx = ma - f_n(c,T), \tag{31}$$

where $f_n(c,T)$ = the fluctuating force. According to Fluctuation-Dissipation Theorem [32], the damper provides a path for energy to leave the mass-spring system and the random thermal agitation from environment in-turn affects the oscillator's motion. Thus the inclusion of the fluctuating force $f_n(c,T)$ prevents the system temperature from dropping below that of the system's surroundings.

Nyquist's relation [33, 34] gives the spectral density of the fluctuating force related to any mechanical resistance, given by the following equation:

$$f_n(c,T) = \sqrt{4k_b cT)} \qquad [\frac{N}{\sqrt{Hz}}] \tag{32}$$

Out of the two types of noise experienced by the oscillating system - mechanical and the transistor noise in the front-end circuit, only mechanical noise is considered in the present work. In atmospheric air, the movement of proof mass is subjected to the mechanical noise due to molecular agitation i.e. the random movements of air molecules around the sensor. One of the more well-known mechanisms for mechanical-thermal noise is Brownian motion where the agitation of the object is caused by molecular collisions from a surrounding air and the agitation is directly related to the air viscosity. If the sensor is intended for low-level signals, this mechanical-thermal noise could be the limiting noise component, thus the minimum detectable acceleration will be the acceleration due to Brownian noise. For a damped suspended proof mass, the Brownian noise acceleration, derived from Eq. (35) is given by [35]:

$$\sqrt{\frac{a^2}{\Delta f}} = \frac{\sqrt{4K_b Tc}}{mg} \qquad g/\sqrt{Hz} \tag{33}$$

Therefore,

$$a_{min} = \frac{\sqrt{4K_bTfc}}{mg}\ g \tag{33}$$

Damping factor

$$\zeta = \frac{c}{2m\omega_n} = \frac{1}{2Q} \tag{35}$$

Quality Factor

$$Q = \frac{m\omega_n}{c} \tag{36}$$

Signal to noise ratio

$$SNR = \left(\frac{\text{input signal}}{\text{noise}}\right)^2 = \left(\frac{ma}{f_n}\right)^2 = \frac{a^2 mQ}{4k_b T\omega_n} \tag{37}$$

From the above it is clear that the quality factor should be as high as possible for high SNR, where as increasing the quality factor decreases the damping factor which makes the system under damped. Hence, a compromise has to be drawn between the amount of Brownian noise and the dynamic characteristics of the system.

At atmospheric pressure air has high viscosity (μ=1.85 × 10^{-5}) which plays a significant role in damping of a microstructures. The mean free path of the air molecules is of the order of 0.1 μm, the typical dimension of the microstructure which is the electrode distance 'd_0' in this case is much larger than the mean free path, thus the collisions between the molecules are significant in number and the atmospheric air is considered as a viscous fluid. Hence it is better to consider the viscous flow model in determining the performance of the cantilever structure in atmospheric pressure.

As the cantilever moves towards the electrode (due to application of inertial force), the air film between the cantilever and the electrode is squeezed so that some of the air flows out of the gap. Therefore, an additional pressure Δp develops in the gap due to the viscous flow of the air. On the contrary, when the cantilever moves away, the pressure in the gap is reduced to keep the air flowing into the gap. In both the cases, the forces on the plate caused by the built up pressure are always against the movement of the cantilever. The work done by the cantilever is consumed by the viscous flow of air and transformed into heat. This kind of air damping is called squeeze film damping.

For a long rectangular plate, damping coefficient for squeeze film damping is given by [36]

$$c = \frac{\mu b^3 l}{d_o^3} \tag{38}$$

where μ = the kinematic viscosity of the medium.

For cantilever based accelerometer,
Air as the surrounding medium $\mu = 1.8 \times 10^{-5} Pa - s$ at $T = 27°C$

It can be seen from the above table that the damping factors are of the order of few 10 s due the large damping force offered by atmospheric air. Also the minimum acceleration is much greater than 0.1 mg/√Hz, which means that Brownian noise will have a significant effect on the performance of the sensor in low g applications, though the system will perform well in *high-g* mode because of high SNR. The step response of the sensor to 50 g acceleration is shown as in Fig. 10. It is observed that in approximately 10 ms the cantilevers attain their desired displacement, i.e. their response is fast enough for them to be used as static sensors.

When the system is set to continuous oscillation by a periodic acceleration $a = a_o sin(\omega t)$ the steady state deflection of the cantilever is of the form $x = x_0 \cos(\omega t + \phi)$. The steady state vibration amplitude can be written down as:

$$x_0(\omega) = \frac{a_0}{\omega_n^2} \cdot \frac{1}{\sqrt{[(\omega/\omega_n)^2 - 1]^2 + 4\zeta^2(\omega/\omega_n)^2}} \tag{39}$$

As indicated by the notation, x_0 depends on the driving frequency ω. In particular, x_0 becomes diminishingly small when ω is sufficiently large, and the accelerometer will cease to be useful for accelerations at such a frequency. In practice, the bandwidth within which the accelerometer is useful is given by the *cutoff frequency* ω_c. This frequency is defined by the equation [37, 38]

$$x_0(\omega_c)/x_0(0) = 1/\sqrt{2}, \tag{40}$$

and is given by

$$\omega_c = \gamma\omega_n, \tag{41}$$

where

$$\gamma = \sqrt{1 - 2\zeta^2 + \sqrt{(1 - 2\zeta^2)^2 + 1}} \tag{42}$$

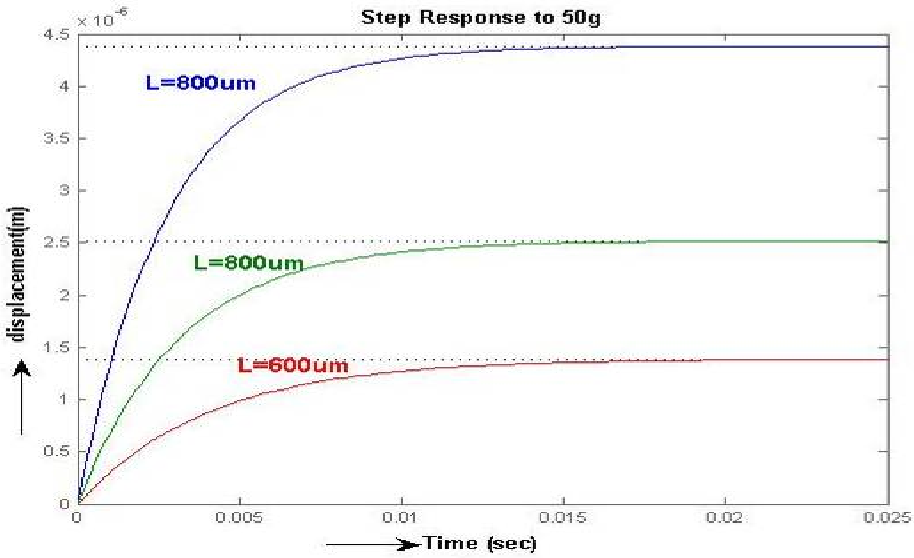

Fig. 10. Step response for 50 g acceleration.

Therefore, from the Table 5 one can see that high amount of damping has decreased the cut off frequency by an order of magnitude. This indicates that the sensor needs to be packaged in vacuum for low damping factor and hence larger bandwidth. The frequency response is shown in Fig. 11.

Table 5. Cantilever parameters with air damping.

L	d_o	m	k	c	Q	ζ	SNR for 50g	a_{min}	ω_n	ω_c
(μm)	*(μm)*	*(10^{-10} kg)*	*(N/m)*	*(10^{-4})*				*(mg/√Hz)*	*(KHz)*	*(Hz)*
600	6	2.80	0.0988	4.00	0.015	37	2.94×10^{12}	0.889	2.93	40
700	8	3.26	0.0622	1.97	0.025	22	7.9×10^{12}	0.547	2.16	49
800	10	3.73	0.0417	1.15	0.035	14	1.79×10^{13}	0.366	1.68	60

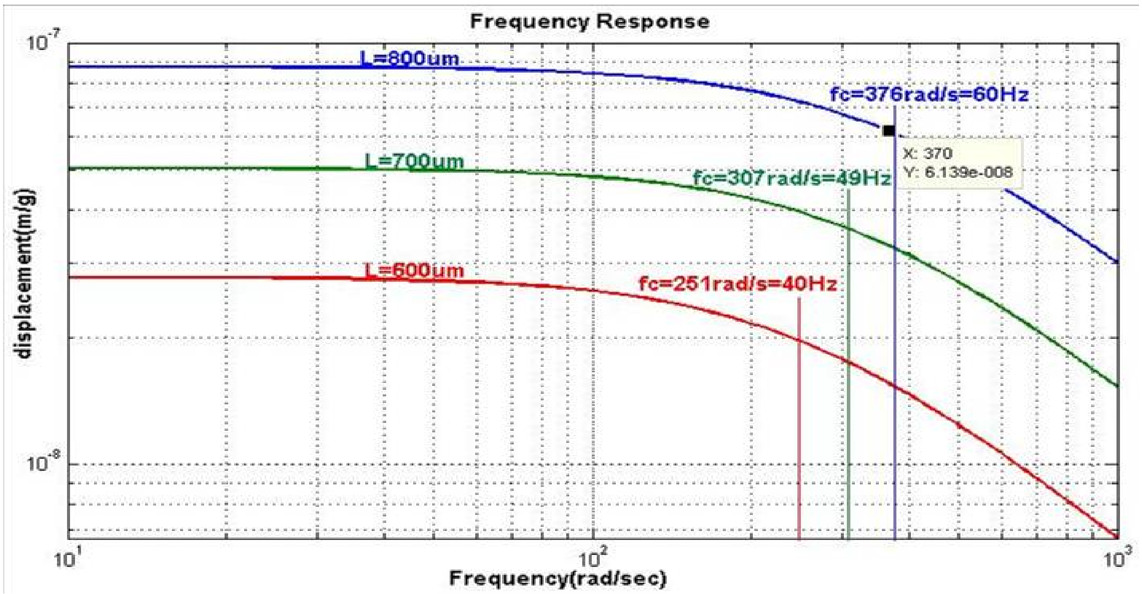

Fig. 11. Frequency response of the cantilevers.

4. Conclusions

In the present work, behavior of a polysilicon cantilever beam has been analyzed under a combined effect of electrostatic and external inertial force for the development of a high-g accelerometer. Driving voltage has a direct effect on the performance of the cantilever. Device dimensions have been extracted for a particular set of preliminary design parameters. Subsequently, the static and dynamic frequency responses of the cantilevers were simulated using MATLAB™. The static response of the accelerometer is fast enough to be used as a crash sensor, whereas as the frequency response indicates that the cantilever needs to be vacuum bonded to improve its performance. In order to avoid parasitic, cantilever arrays have been incorporated in the design.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
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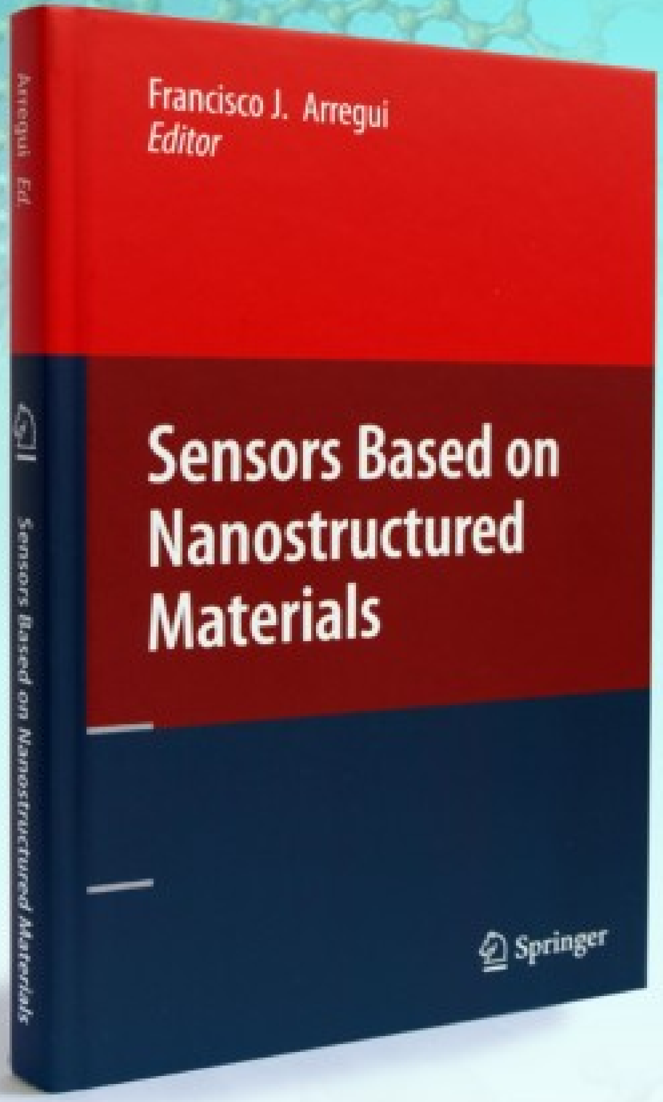

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