Optimized design of a micromachined G-switch based on contactless configuration for health care applications

Andojo Ongkodjojo and Francis E. H. Tay
MEMS Laboratory, Department of Mechanical Engineering, National University of Singapore
mpeooa@nus.edu.sg and mpetayeh@nus.edu.sg

Abstract. This paper proposes design concept and fundamentals of a novel acceleration micro-switch (G-switch), which is an integration of bimorph actuator and field effect transistor (FET). This micro-switch can be used to actuate the alarm system for calls for help – minimizing injuries after the fall among elderly; or trigger the air-inflatable hip protector for the fall prevention. The device can be attached to the developed MEMS-Wear smart shirt. Its structural design and switching FET are optimized using the global optimization method so that the bimorph as a movable gate can collapse on the gate insulating layer, when there is an impact force, which is greater than a threshold value (experimentally found to be 4.8 g based on the previously published report). This contactless mechanism optimizes the field effect between the bimorph and the substrate causing an electrical current flow profusely with a sensitivity of 0.1 mA/V^2 with a FET’s ratio of ~19. The device will consume less power as the gate to source voltage (V_{GS}) can be applied up to 4 V. All design parameters must satisfy the specified design constraints. In future, the optimized design will be fabricated and incorporated into the smart shirt for testing upon the fall events.

1. Introduction
In this paper a novel fall sensor such as an acceleration micro-switch (G-switch) is designed for geriatric health care applications. The sensor can be one of the physiological sensing or intelligent monitoring devices providing miniature, lightweight, and ultra-low power as required for health monitoring applications [1]. The proposed device is designed to detect falls among elderly as fall activities are very common among them; and provide some interventions such as wireless alerting upon falls for reducing risk of falls. The other commercialized sensors are the gyroscopes and accelerometers, which can detect lateral, vertical, and antero-posterior accelerations in the lateral and sagittal planes of the body. They were attached to the comfortable shirt as wearable sensors [2], [3].

There are some challenging aspects for micro-switches for health care applications. They must provide low actuation voltage and consume less power so that the power’s life-time can be significantly increased. Besides, they also provide reliability and flexibility for detecting impact forces. In this paper, we optimize the field effect transistor (FET)’s flowing current towards the applied voltage while satisfying the specified design constraints. In addition, this paper facilitates the relationship between the threshold acceleration (g) and the design parameters such as the beam length, width, and thickness of each layer for the bimorph configurations.

Some developments of acceleration micro-switches include the bimorph structure based on electrostatic actuation [4], the array of cantilever beams for detecting different accelerations [5], the
lateral contact-based cantilevers with two sensing directions [6], the lateral crableg-type structure using the electroplating MEMS process for high degree of integration [7], [8], the acceleration switch-array structure based on the cantilever beams and double clamp beam-mass units [9], the acceleration switch consisting of the contact parts, the inside and outside beams, and the seismic mass with holding time using the squeeze film effect for airbag application [10], the hybrid switch showing the suspensions, capacitor banks and lateral contacts with different shapes and sizes using Lorentz force (actuation) and electrostatic force (holding) [11], the vertically driven micro-switch such as a beam clamped on both two ends with the proof mass concentrated at the centre, and the laterally driven micro-switch such as the deformable loop spring beam [12], and the contactless acceleration switch with the double clamp beam as the movable gate of the FET [13]. When compared with the contactless switch as reported in [13], our device is designed in a form of bimorph configuration with the optimized design parameters while satisfying the design constraints; and it will be fabricated and incorporated into the smart shirt for testing upon the fall events. Besides, the bimorph structure provides high sensitivity, big generative force, high switching response, and better validation to experimental data [14]. Besides, the fringing field effects are considered for the electrostatic force.

2. Design concept, theory, and fundamental of the impact force sensing-based G-switch

In this section a novel acceleration micro-switch (Fig. 1) is proposed with a minimum acceleration of 4.8g, which was experimentally found for the falls [15]. The cantilever bimorph is used as a movable gate to form the FET. When the cantilever senses an impact force after the person hits the ground, which is higher than the threshold acceleration, it deflects towards the insulating layer (SiO2 with a thickness of 0.2 μm), and then touches the layer. The threshold adjustment channel will invert so that the current can flow between the source (S) and the drain (D), which turns ON the FET for actuating the alarm (Fig. 2). Therefore, the switch can be used as a fall sensor too. It will be incorporated on the MEMSWear smart shirt, which was developed for the geriatric healthcare [2], [3], and [15] as shown in Fig. 3. The smart shirt used the Bluetooth™ transmitter for sending the acceleration signals to the personal computer for data processing. The text messages and electronic-mails were sent through the global network communication system upon the detection of the fall activities. When compared with the accelerometers or the gyroscopes, some of the advantages using the G-switch are less power consumption, more simple, and cheaper in manufacturing cost. The power will be electrically connected to the alarm, when the switch is an ON state. Thus, the device will reduce the power consumption significantly.

Figure 1. Schematic diagram of the G-switch (bimorph structure) with the electrode attached below forming the field effect transistor (FET) for switching applications.
When there is no input acceleration, the restoring spring force must be greater than the electrostatic force; and thus, there is no deflection of the bimorph. To consider the curvature problem for the bimorph, an initial deflection of the tip of the bimorph is included in our design. When the bimorph experiences an impact force in the same direction as shown in Fig. 4, the force will act upon the structure, and move it towards the base. The mechanical force increases linearly, while the electrostatic force increases exponentially relative to the gap. When the electrostatic force increases at a lower rate than the spring force, the effective spring force will be positive. If the acceleration force is less than the effective spring force, the bimorph will be pulled back to the stable position, once the acceleration force is removed. If the impact force is large enough to move the bimorph further into a position, where the electrostatic force overcomes the mechanical force (pull-in phenomenon happening), the optimum electrical field is then generated between the gate and the substrate. Furthermore, the electrostatic force attracts further and latches it until the reset switch ($S_R$) is open for removing the electrostatic force.

As the applied voltage ($V_{gs}$) is smaller than the pull-in voltage, the bimorph’s length, width, and thickness of each layer can be easily determined such a way that the bimorph is pulled abruptly to the insulating layer from the pull-in gap position, once the threshold acceleration (4.8 $g$) is detected as expressed by equation (1). In the pull-in phenomena, the structure usually collapses at a pull-in gap of $2z_0/3$. The cantilever initially bends in a displacement of $\delta$ downward towards the substrate because
the Silicon has a compressive residual stress while the metal film has a tensile residual stress (the residual stress in the polysilicon ($\sigma_{Si}$) is assumed to be $-450$ MPa, and the relative residual stress value for the metal film ($\sigma_{Au}$) is assumed to be $73$ MPa [17]). These values substantially depend on our fabrication process in the future. The equation has been derived from the balanced forces: $F_g \geq F_s - F_e$ at the critical gap position as shown in Fig.4, where the acceleration and electrostatic forces are opposed by the restoring force $F_r$.

$F_{def} = F_g + F_e - F_s$ at the critical gap position as shown in Fig.4, where the acceleration and electrostatic forces are opposed by the restoring force $F_r$.

![Figure 4](image-url)

**Figure 4.** Spring – capacitor model involving the fringe field effect-based electrostatic force ($F_{def}$), the restoring spring force ($F_s$), the impact force ($F_g$), and the residual stress-induced curved cantilever.

$$g \leq \frac{8\pi k_{eq}z_0^3 - 9k\varepsilon_0l(3\pi
+ 2z_0)\delta^2}{\pi_{2.115}}$$

where $z_0$ is the initial gap between the bimorph and the insulating layer (m), $g$ is the standard acceleration of gravity (= $9.8$ m/s$^2$), $k_{eq}$ is the equivalent spring constant of the bimorph (N/m) as given by equation (2), $k$ is the dielectric constant of the insulating gate/SiO$_2$ layer (= 3.9), $\varepsilon_0$ is the permittivity of free space (= $8.854 \times 10^{-12}$ F/m), $\rho_{Au}$ is the density of the electrode layer (= $1.93 \times 10^4$ Kg/m$^3$), $\rho_{Si}$ is the density of the structural layer (= $2.329 \times 10^3$ Kg/m$^3$), $l$ is the length of the bimorph (m), $h_e$ is the thickness of the electrode layer (m), $h_s$ is the thickness of the Silicon layer (m), $w$ is the width of the bimorph (m), and $V_{dc}$ is the applied voltage (V), which is equal to the gate to source voltage. Based on equation (1), we will be able to design micro-switches for sensing any externally applied acceleration by replacing the threshold value.

$$k_{eq} = \frac{w\left[E_{Au}^2 h_e^4 + E_{Si}^2 h_s^4 + 2E_{Au} E_{Si} h_e h_s \left(2h_e^2 + 3h_s h_e + 2h_s^2\right)\right]}{4l^3\left(E_{Au} h_e + E_{Si} h_s\right)}$$

where $E_{Au}$ and $E_{Si}$ are Young’s modulus for the Silicon layer (= $1.62 \times 10^{11}$ Pa) and for the electrode layer (= $7.9 \times 10^{10}$ Pa), respectively [$E = E/(1 - \nu)$, Pa, where $\nu$ is the Poisson’s ratio (= 0.27 for Silicon and 0.42 for Au), if the bimorph is relatively wide such that it behaves like a plate].

Another design constraint is the pull-in voltage considering the fringing field effects as given by equation (3). The applied voltage must be smaller than this constraint for any displacement below the critical balanced position. Otherwise, the structure will initially collapse before detecting the acceleration. However, the electrostatic force will be able to attract the structure towards the substrate more strongly, when the gap between the electrode layer and the substrate is smaller.

$$V_{pull-in} = \sqrt{\frac{8\pi k_{eq}z_0^3}{9k\varepsilon_0l(3\pi
+ 2z_0)}}$$
For considering the initially downward deflection of the tip of the bimorph caused by the residual stresses of the two different materials as shown in Fig. 4, the maximum deflection is given by [17]:

$$\delta = R \left( 1 - \cos \left( \frac{L}{2R} \right) \right)$$  \hspace{1cm} (4)

where \( R \) is the radius of curvature caused by the residual stress (m); and the relationship between the radius of curvature and the residual stress is expressed by:

$$R = \frac{E_{Si} (h_s + h_g) [3m + p (\mu (1 + n)^2)]}{6(m \sigma_{Si} - \sigma_{Au})}$$  \hspace{1cm} (5)

where \( p = 1 + 4mn + 6mn^2 + 4mn^3 + m^2n^2 \), \( m = E_{Au}/E_{Si} \), and \( n = h/\mu \). Thus, the working forces across the bimorph structure starts at a gap of \( (z_0 - \delta) \). This working operation is actually different from the other reports [17], which was initially upward in the deflection caused by the residual stress.

3. The Field Effect Transistor (FET) for a contactless mechanism

When the externally applied acceleration is equal to or higher than a predetermined value, the movable part of the system (the bimorph) comes into contact with the gate insulating layer attached to the substrate for forming a Field Effect Transistor (FET) utilizing an insulator (SiO\(_2\)) as shown in Fig. 1. The DC voltage is applied between the gate and source terminals for generating the current between the source and drain terminals. When the electrode layer is positively charged, the electrical charge is coming through the gate insulating layer. This positive-charge layer will then attract many electrons from the substrate such that the base becomes a conducting channel through which the current is flowing. When the strength of the electric field is at a maximum level, the threshold adjustment channel inverts for allowing current to flow between the source (S) and the drain (D) terminals, which turn ON the FET. Thus, the source and the drain terminals act as electrodes providing electrical signal, which is sent for triggering the alarm or the hip protector. Thus, this contactless switch has provided ON-OFF switching without the metal contacts.

Based on the working principle of the FET, the flowing current \( (I_{DS}) \) in saturation as given by equation (6) [18] will be generated by applying \( V_{GS} > V \) and \( V_{DS} > V_{GS} - V \), where \( V \) is the threshold voltage of the gate (normally, \( V = 0.2V_{DD} \)). When the gate-source voltage is higher, the generating current \( (I_{DS}) \) will be higher (for our case, \( V_{GS} = 0.8V_{DD} \) and \( V_{DD} = 5 \) V).

$$\frac{I_{DS}}{(V_{GS} - V)^2} = \frac{k\varepsilon_0 \mu_n W_{fet}}{2z L_{fet}}$$  \hspace{1cm} (6)

where \( \mu_n \) is the surface electron mobility (= 650 cm\(^2\)/V sec), \( W_{fet} \) is the width of the transistor channel/gate (\( \mu \)m), \( L_{fet} \) is the length of the transistor channel/gate (\( \mu \)m), and \( z \) is the gap between the gate and the substrate, which is equal to the thickness of the insulating layer \( (h_{SiO2} = 0.2 \mu m) \). The insulating layer can be used to reduce the stiction problems. For optimization and design, equation (6) is used as our single objective function.
4. Results of the optimized design for the G-switch

In this section, we would like to optimize the design of the acceleration switch so that the bimorph is very sensitive to the externally applied acceleration (a threshold acceleration of 4.8 g) and consumes less power. There are main design parameters such as the beam length (l), the beam width (w), the height of the electrode layer (h_e), and the height of the Silicon layer (h_s). They are optimized so that the sensitivity of the contactless switch \( \frac{I_{DS}(V_{GS} - V_t)}{V_{GS} - V_t^2} \) will be maximum, while satisfying the specified design constraints such as the collapse from the pull-in gap caused by the impact force \( g_{pull-in} \), the pull-in voltage \( V_{pull-in} \) considering the fringing field effects, and the initial deflection \( \delta \) caused by the residual stresses of the materials. Table 1 presents the constrained global optimization results generated by the Simulated Annealing algorithm [16]. This table also shows that the optimization results have satisfied the specified design constraints. In the algorithm we need to adjust the design variables, the design constraints, the single objective function, the constants, the specified design values, the derived equations, and some algorithm settings. In Fig. 5 the optimum solution has been shown to be converged to the global maximum. As the simulated temperature decreases, the optimization algorithm increases the sensitivity value and goes to the global optimum solution. The sensitivity value is strongly influenced by the FET’s ratio.

Table 1. The optimized design parameters of the micro-switch based on the global optimization.

| Variable | Unit  | Description                                                                 | Results |
|----------|-------|-----------------------------------------------------------------------------|---------|
| l        | μm    | Length of the bimorph (reasonable range: 500 μm – 1 mm)                    | 689.2   |
| w        | μm    | Width of the bimorph (reasonable range: 50 – 200 μm)                       | 200     |
| h_e      | μm    | Height of the electrode layer (reasonable range: 0.1 – 1 μm)               | 1       |
| h_s      | μm    | Height of the Silicon layer (reasonable range: 2 – 7.5 μm)                 | 2.9     |

**Design Variables**

| Variable | Unit  | Description                                                                 | Results |
|----------|-------|-----------------------------------------------------------------------------|---------|
| W_fet\(^1\) | μm    | Width of the transistor channel or gate                                      | 200     |
| L_fet\(^2\) | μm    | Length of the transistor channel or gate                                      | 10.6    |
| Ratio    |       | W_fet/L_fet                                                                | 18.9    |
| w_n      | rad/s | Natural frequency of the bimorph                                             | 6.5189 x 10\(^4\) |
| R        | μm    | Radius of the curvature caused by the residual stress                        | 3.4344 x 10\(^3\) |
| δ        | μm    | The initial deflection caused by the residual stresses                       | 68.9    |
| (z_0 − δ)\(^3\) | μm  | The initial gap (δ < 0.1)                                                    | 6.08    |
| C_f      | F    | Gate capacitance (capacitance between the gate and substrate)               | 3.6613 x 10\(^2\) |
| V_{pull-in} | V    | Pull-in voltage (V_{GS} < V_{pull-in})                                      | 4.1     |
| g_{pull-in} | m/s\(^2\) | The acceleration force causes the bimorph deflect at a pull-in gap of 2z_0/3 for ensuring the bimorph collapse (g_{pull-in} ≥ 9.8) | 9.8     |

**Single Objective Function**

\[ I_{DS}(V_{GS} - V_t)^2 \] mA/V^2  Maximum sensitivity for the contactless switch 0.1

\(^1\) The width of the transistor channel (W_fet) is the same with the width of the bimorph (w).
\(^2\) The length of the transistor channel (L_fet) is determined by a ratio of 65 (L/L_fet = 65).
\(^3\) The gap between the neutral position and the gate insulating layer (z_0) = 75 μm.

For maximizing the design objective function while satisfying the specified design constraints, the bimorph length tends to go to the minimum reasonable range. However, it achieves the certain design value because of the threshold acceleration applied to the bimorph. When the beam length is shorter, the bimorph can detect a bigger threshold value. Thus, a very long beam is more sensitive to small magnitudes of the applied accelerations as it provides a softer spring. This behaviour is accompanied by the less thickness of the bimorph, and the bimorph width tends to go to the maximum reasonable range as shown in Table 1. Besides, the micro-actuator as the movable gate can operate at higher frequencies (fast switching response) for smaller widths. However, they exhibit higher pull-in voltages. In our design, the pull-in voltage is relatively small because of the maximum width of the
reasonable range. Therefore, design compromises for achieving a design objective must be taken into account for specific application.

When compared with the radius of curvature based on the theoretical analysis and the experimental observation as reported in [19], the radius of curvature as expressed by equation (5) generates the same results (∼100 μm and ∼300 μm in radius of curvature), which are independent of the bimorph lengths. Based on these facts, equation (5), which has been used for our optimization and design, is valid. Besides, the natural frequency based on our model agrees well with the natural frequency obtained using the Polytec laser Doppler vibrometer with an error of 9%. Furthermore, the initial deflection was experimentally measured to be 14 μm and the maximum operating frequency was 21 kHz with a lifetime of over 10⁹ cycles based on the previous report in [20]. When we use equation (4), the initial deflection is approximately 14.5 μm with our assumption that the value of [6(mσ_b - σ_w)] is 200 MPa, which substantially depend on the fabrication process. Besides, the operating frequency is 10.2 kHz, which is within the maximum operating frequency.

![Figure 5. Sensitivity value of the micro-switch \( I_{DS}/(V_{GS} - V_t) \) converged to the best solution.](image)

5. Conclusion
A novel contactless G-switch, which is an integration of the bimorph actuator and the field effect transistor (FET), has been proposed and designed based on the single constrained optimization method using the Simulated Annealing algorithm. Based on the optimized design, the bimorph can collapse on the gate insulating layer, when there is an impact force with a threshold acceleration of 4.8g. The sensitivity of the switching transistor is 0.1 mA/V² with a FET’s ratio of ∼19 and a V_{GS} of up to 4 V, which will consume less power.

For further implementation and application, the contactless switch will solve the metal-to-metal contact problems, which are susceptible to arcing, micro-welding, deformable, oxidation, and contact bouncing. Besides, this configuration facilitates the advantages of using the FET for the switching applications. Thus, the micromachined switch will increase the device’s life-time significantly.

In the future, the design will be fabricated and incorporated into the MEMS-Wear smart shirt for testing upon the fall activities. Because the design parameters of the bimorph can be adjusted to detect other impact forces, the contactless micromachined switch can be developed as a micro-sensor in wide range of health care applications.
Acknowledgements

The authors are grateful to the Agency for Science, Technology and Research (A*STAR), Singapore for the funding under the research projects: “MEMS-Wear – Incorporating MEMS Technology into Smart Shirt for Geriatric Healthcare” [R-265-000-149-305], and “MEMS-Wear II – Mission Critical Wearable Embedded Systems for Elderly Care” [SERC Grant No. 052 118 0051].

References

[1] E. Jovanov, A. Milenkovic, C. Otto, and P. C. de Groen 2005 “A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation”, *Journal of NeuroEngineering and Rehabilitation*, 2:6.
[2] M. N. Nyan, F. E. H. Tay, A. W. Y. Tan and K. H. W. Seah 2006 “Distinguishing fall activities from normal activities by angular rate characteristics and high-speed camera characterization”, *Medical Engineering & Physics*, in press.
[3] M. N. Nyan, F. E. H. Tay, K. H. W. Seah, and Y. Y. Sitoh 2006 “Classification of gait patterns in the time-frequency domain”, *Journal of Biomechanics*, in press.
[4] J. S. Go, Y.-H. Cho, B. M. Kwak and K. H. Park. 1996 “Snapping microswitches with adjustable acceleration threshold”, *Sensors and Actuators A* 54 579–583.
[5] A. Selvakumar, N. Yazdi and K. Najafi. 1996 “Low power, wide range threshold acceleration sensing system”, *IEEE Proceedings of the 9th Annual International Workshop on Micro Electro Mechanical Systems: An Investigation of Micro Structures, Sensors, Actuators, Machines, and Systems* 186–191.
[6] T. Tonnesen, O. Ludtke, J. Noetzel, J. Binder, and G. Mader. 1997 “Simulation, design and fabrication of electroplated acceleration switches”, *J. Micromech. Microeng.* 7 237–239.
[7] M. Wycisk, T. Tonnesen, J. Binder, S. Michaelis and H.-J. Timme. 2000 “Low-cost post-CMOS integration of electroplated microstructures for inertial sensing”, *Sensors and Actuators A* 83 93–100.
[8] S. Michaelis, H.-J. Timme, M. Wycisk, and J. Binder. 2000 “Acceleration threshold switches from an additive electroplating MEMS process”, *Sensors and Actuators A* 85 418–423.
[9] X. Li and M. Bao. 2001 “Micromachining of multi-thickness sensor-array structures with dual-stage etching technology”, *J. Micromech. Microeng.* 11 239–244.
[10] T. Matsunaga and M. Esashi. 2002 “Acceleration switch with extended holding time using squeeze film effect for side airbag systems”, *Sensors and Actuators A* 100 10–17.
[11] R. L. Borwick III, P. A. Stupar, and J. DeNatale. 2003 “A hybrid approach to low-voltage MEMS switches”, *IEEE Proceedings of the 12th International Conference on Solid State Sensors, Actuators and Microsystems (Transducers’03)* 859–862.
[12] W. Ma, G. Li, Y. Zohar, and M. Wong. 2004 “Fabrication and packaging of inertia micro-switch using low-temperature photo-resist molded metal-electroplating technolology”, *Sensors and Actuators A* 111 63–70.
[13] Joon-Won Kang. 2004 “Contactless accelerometer switch”, US Patent 2004/0161869 A1.
[14] A. Ongkodjojo, F. E. H. Tay, and R. Akkipeddi. 2005 “Micromachined III-V multimorph actuators for MOEMS applications – concept, design, and model”, *Journal of Microelectromechanical Systems* 14-3 610–618.
[15] F. E. H. Tay, M. N. Nyan, T. H. Koh, and K. H. Seah. 2005 “Smart shirt that can call for help after a fall”, *International Journal of Software Engineering and Knowledge Engineering* 15-2 183–188.
[16] A. Ongkodjojo and F. E. H. Tay. 2002 “Global optimization and design for microelectromechanical systems devices based on simulated annealing”, *Journal of Micromechanics and Microengineering* 12 878–897.
[17] R. T. Chen, H. Nguyen, and M. C. Wu. 1999 “A low voltage micromachined optical switch by stress-induced bending”, The Technical Proceedings of the 12th IEEE International Conference on Micro Electro Mechanical Systems (MEMS’99) 424–428.

[18] D. A. Pucknell and K. Eshraghian 1994 “Basic VLSI Design”, Third Edition, Prentice Hall.

[19] C. Chang, C.-F. Chiang, C.-H. Liu, and C.-H. Liu. 2005 “A lobster-sniffing-inspired method for micro-objects manipulation using electrostatic micro-actuators”, Journal of Micromechanics and Microengineering 15 812–821.

[20] X.-Q. Sun, K. R. Farmer, and W. N. Carr. 1998 “A bistable microrelay based on two-segment multimorph cantilever actuators”, The Technical Proceedings of 11th IEEE International Workshop on Micro Electro Mechanical Systems (MEMS’98) 154–159.