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# Flexible polysilicon sensor array modules using "etch-release" packaging scheme

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**Abstract**

A flexible polysilicon strain gauge array has been designed and fabricated using surface-micromachining with a $SiO_2$ sacrificial layer. The realized sensor array is mechanically flexible, which can be attached on a non-planar surface. To realize the flexible polysilicon strain gauge array, a new packaging scheme using polysilicon/oxide-based surface-micromachining was developed. The proposed packaging scheme completes the strain sensor and the circuit board on a single process, which eliminates additional assembly and alignment problems. The measured gauge factor shows that it is more sensitive than conventional metal strain gauges. Unlike a single-crystal silicon strain gauge, a crystal direction does not affect its sensitivity in a polysilicon sensor, and this isotropic property makes the realization of an omni-directional strain gauge array possible. The proposed flexible strain sensor array can be used in a measurement of stress distribution of an arbitrary and non-planar surface.


*Keywords:* Flexible; Packaging; Sensor array; Release-etching; Piezporesistivity; Strain gauge

## 1. Introduction

The piezoresistive property of silicon has been widely used in many sensor and actuator applications. Using piezoresistive properties, every material changes its electrical resistivity when deformed, many transducers were successfully used for mechanical and chemical measurement. The piezoresistive coefficient, $\pi$, is defined by the ratio of the change of the resistivity $R$ caused by the change of the length of resistor $l$.

$$\frac{\Delta R}{R} = \frac{\pi \Delta l}{l} \quad (1)$$

For many metals, the coefficient is $\pi = 2$ due to the geometrical deformation. In semiconductors, the deformation changes the band structure and therefore the effect is much higher. It ranges from $\pi = -120$ to $+120$ depending on the doping, the temperature, and the crystal orientations [1,2].

Despite the higher piezoresistive effect of silicon, metal strain gauges have wider applications. It is due to the fact that the manufacturing process of a semiconductor strain gauge is more complex than that of a metal strain gauge. While metal strain gauges are manufactured by direct sputtering onto polyimide substrate, semiconductor strain gauges are manufactured by welding of a doped silicon strip to a metal contact pad by ultrasonic methods or using conductive adhesives. This assembly process makes it expensive and difficult to realize a pre-patterned array type of semiconductor strain gauges. Direct integration of easy-to-use solder pads onto the gauge substrate is not yet available with silicon gauges. The anisotropy of single-crystal silicon also prohibits realizing a rosette type array which requires arbitrary directional strain measurement. Silicon strips are rigid and not as flexible as most metal strain gauges. This prohibits its applications to a curved surface.

It is reported that thin silicon ($<30\,\mu m$) is mechanically flexible [3]. Therefore, if a proper packaging scheme is developed, the thinned silicon and the patterned polysilicon film can be used as strain gauges that have contact pads on the substrate material with high flexibility.

There are several reports of realization of the flexible MEMS sensor array using bulk micromachining to obtain the real-time 2D profiling of certain physical parameters such as temperature, force, pressure or shear stress on a 3D object. Barth et al., in 1985, reported the first version of this idea with one-dimensional flexible Si-diode temperature sensor array in which a polyimide strip was the flexible material

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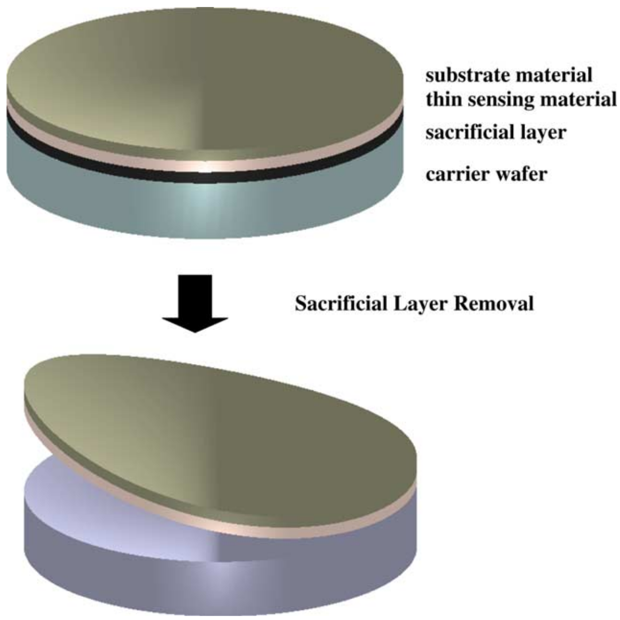


Fig. 1. The concept of flexible module by removing sacrificial layer. The sacrificial layer, sensing material are deposited by conventional semiconductor processes. The thin sensing material is packaged by proper FPCB, and released from the rigid carrier wafer.

connecting Si islands formed by isotropic HNA (a mixture of hydrofluoric acid, nitric acid, and acetic acid) etching [4]. But, the thin periphery of silicon island formed by HNA wet etching becomes major failure point during folding test. Bang and Pan has developed a flexible heat-flux sensor array that is made by direct deposition of thin-film metals on commercial Kepton® (DuPont) substrates [5]. A large array of metal temperature sensors can be made in this way but its drawback is that neither ICs nor silicon MEMS can be integrated with this approach. Hence, only limited types of sensors are available and hybrid assembly of electronic circuits is unavoidable. Jiang et al. also developed flexible shear stress sensor array that compatible with IC process [6]. Jiang improved the reliability of Barth's method that is forming a silicon island but somewhat complex and expensive processes are needed such as backside deep reactive ion etching (RIE).

In this research, a surface micromachined flexible polysilicon strain gauge array was realized with a novel packaging scheme that excludes any additional assembly processes. The main idea is shown in Fig. 1. An omni-directional piezoresistive polysilicon thin film layer is deposited and patterned by a conventional lithography process on top of a silicon dioxide film. Then, a polyimide film with appropriate metallic interconnections is fabricated by $O_2$ dry etching and electroplating. Later, this polymer–metal layer will be served as a flexible printed circuit board. Since the whole procedure employs conventional semiconductor fabrication processes, it takes advantage of wide range of patterns and geometries available through photolithographic process. The overall structure including strain sensors and circuit boards will be released using a conventional surface micromachining technique resulting in an integrated flexible array of polysilicon strain gauge module.

## 2. Experiments

### 2.1. Fabrication

Fig. 2 shows a simplified fabrication diagram to realize the surface micromachined flexible polysilicon sensor array. The fabrication starts with a 4 in. silicon wafer. A 2 μm thick phosphorous silica glass (PSG) film is deposited to be used as a sacrificial layer. A silicon nitride film, 2 μm in thickness, is deposited to serve as a passivation layer. A 5000 Å-thick polysilicon film is deposited by low pressure chemical vapor deposition (LPCVD) at 650 °C. The undoped polysilicon film has no conductivity because all the free carriers are trapped at grain boundaries. The piezoresistors are formed by Boron ion implantation. The implanted dose is $1.0 \times 10^{16}\ \mathrm{cm}^{-2}$. Thermal annealing step followed after ion implantation at 950 °C for 1 h. This process causes considerable spreading of the implanted dose by diffusion and it can be assumed that the impurities are uniformly distributed in the polysilicon film. The average dose concentration is about $1.0 \times 10^{20}\ \mathrm{cm}^{-3}$. The doping concentration affects the piezoresistivity coefficients. At this concentration range, the gauge factor is expected to be 10–12 [7,8]. An RIE is used to pattern the polysilicon and the silicon nitride passivation layer. Then the polyimide (DuPont PI2611) pre-cursor is spin-coated at 1000 rpm to get 8 μm thickness. An 100% $O_2$ RIE is used to etch the polyimide to form via patterns. Cr/Cu/Cr seed layer is deposited by evaporation. Each layer has the thickness of 500 Å/5000 Å/500 Å, respectively. Vias and circuits are formed by electroplated copper. Since the adhesion between the polyimide and metal was not so good, additional polyimide has been coated, and contact pads have been opened by $O_2$ RIE. The overall thickness of polyimide is about 15 μm. Through these processes, the polyimide substrate serves as a flexible printed circuit board (FPCB) and the polysilicon strain gauge array fabricated on top of the oxide sacrificial layer can be packaged in polymer substrate without any assembly processes. Fig. 3 shows the surface micromachined polysilicon strain gauge array packaged in the polyimide substrate.

### 2.2. Release-etching process

To realize the desired flexible sensor array module, the polyimide substrate and the polysilicon strain sensors should be separated from the rigid silicon carrier wafer. It can be done by removing the sacrificial oxide layer in a HF solution. Because the sacrificial layer etching can be a time-consuming process, an etching method with faster etch rate is desirable. Moreover, long exposure of polysilicon structure, which serves as sensor material, to HF has been

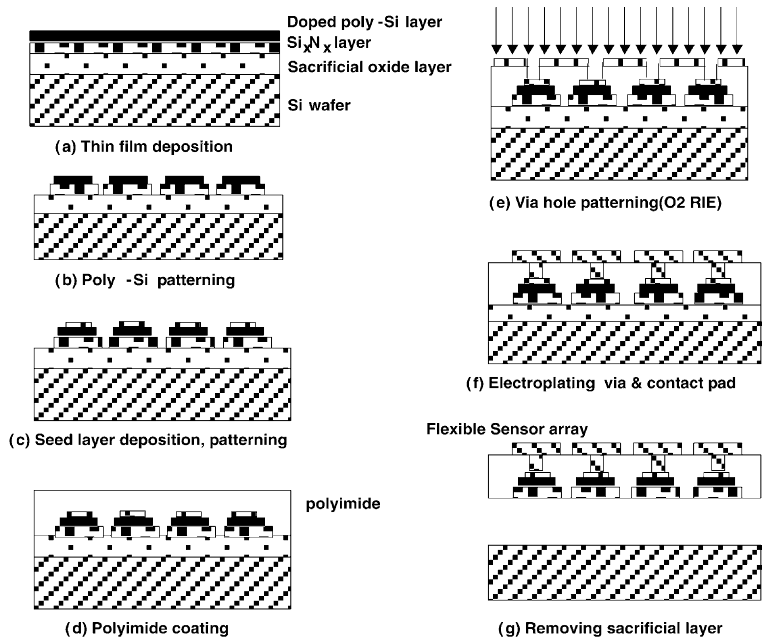


Fig. 2. Simplified fabrication process.

shown to degrade the mechanical performance of polysilicon [9]. Therefore, shorter etch time improves device integrity.

It is generally agreed that high concentration of HF etches $SiO_2$ with a reaction order higher than low concentration of HF. And silicon oxide etching has been improved by adding strong acid, like hydrochloric acid, to the HF etchant [9]. So HF:HCl (49, 36 wt.% 1:1 by volume) is chosen as etchant and PSG is selected as a sacrificial layer for shorter etching time. But high concentration HF solutions can be permeate into the interface between polysilicon and polyimide. As a result, the polysilicon piezoresistors are often detached from the polyimide substrate and failed to keep electrical connections. To prevent these problems (i.e., polysilicon piezoresistors were degraded by HF-based etchant and failed to keep electrical connection by HF–HCl solution) a passivation layer is introduced. Several dielectric layers are available in common fabrication process. Silicon nitride is chosen for this passivation layer, since it is robust, is compatible with sacrificial oxides and can withstand post-deposition high temperature procedures.

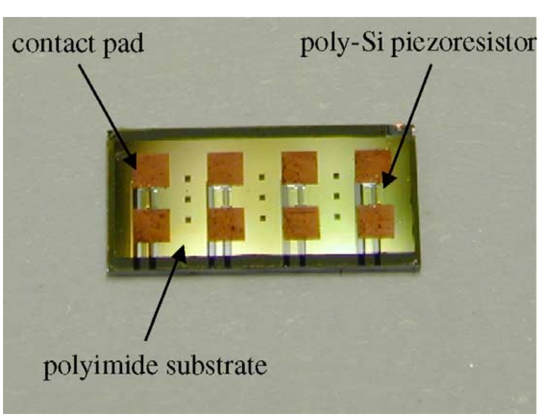


Fig. 3. Surface micromachined polysilicon strain gauge array. Four strain gauges are arranged side by side. Contact pads are formed by electroplated Cu.

Also, to increase adhesion of the polysilicon piezoresistors to the polyimide substrate, large via area was used. The adhesion between silicon and metal is better than silicon and polymer. So, the via structure performs one more function that it holds the polysilicon piezoresistors as well as electrical connections.

The nitride etching selectivity over oxide is in the order of $10^2$ [10]. According to Chang, the addition of HCl also improves the selectivity over silicon nitride by about three times [11]. However, since long time etching process can reduce the effect of etching selectivity, it is the most important to predict release-etching time and to design proper etch-holes. A precedent experiment show that etch rate of silicon nitride, which is deposited in PECVD at 300 °C (not annealed), in HF:HCl (49 wt.% HF, 36 wt.% HCl, 1:1 by volume) is about 800 Å $min^{-1}$. So, the 2 μm thick silicon nitride film will be etched in short time. So, the proper etch-holes should be designed to release sensor module from the rigid silicon carrier wafer without affecting polysilicon property and device integrity.

A general one-dimensional HF–$SiO_2$ etch model is reported by Eaton et al. [12]. The modeling of the release-etching in Eaton's work is based upon finding relationships among flux, concentration, and etch rate. The oxide etch rate, $\delta$, is presumed to be directly proportional to the flux of HF to the etch front, $J_{HF}$. The proportionality constant is inferred from the net reaction of HF with $SiO_2$. The flux is determined from Fick's law and an empirical rate law, $k_1C + k_2C$. Details can be found in [9,12–14]. The etch

Table 1
List of variables

| Variables | Unit | Value | Description |
|---|---|---|---|
| $k_1$ | cm mol$^{-1}$ s$^{-1}$ | $1.2 \times 10^{-4}$ | First order etch rate constant |
| $k_2$ | cm$^4$ mol$^{-1}$ s$^{-1}$ | 0.065 | Second order etch rate constant |
| $D$ | cm$^2$ s$^{-1}$ | $1.6 \times 10^{-5}$ | Diffusivity of HF in water |
| $\alpha$ | cm$^3$ s$^{-1}$ | 4.8 | Proportionality constant |
| $C_b$ | mol l$^{-1}$ | 24 | Bulk etchant concentration |

time with respect to etch distance is described by Eq. (2), where the $D$, $k$, $C_b$, $\delta$, $t$ are diffusivity of HF in water, etch rate coefficient, bulk etchant concentration, etch distance, and time, respectively. The related variable and the used values are listed in Table 1 [12]. Using Eq. (2), the graph of etching time versus etch distance is plotted in Fig. 4. It takes about 20 min to etch 250 μm of PSG channel. Therefore, it is reasonable for etch-holes to be arranged every 240 μm.

$$t(\delta) = \frac{k_2[(D/k_1^2 - \delta^2/D - \beta/k_1^2)\eta - 2\delta - \beta(\delta/D)]}{\alpha(k_1^2 - \eta^2)} - \frac{k_2 D \ln[(k_1\beta + k_1^2\delta + \eta D)/D(k_1 + \eta)]}{\alpha k_1^3} \quad (2)$$

$$\eta = k_1 + 2C_b k_2 \qquad \beta = \sqrt{2\eta\delta D + k_1^2\delta^2 + D^2}$$

By dipping the fabricated dies (shown in Fig. 3) into HF:HCl 1:1 solution, the flexible sensor array module was successfully released from the carrier wafer. The realized sensor array is shown in Fig. 5. The overall device dimension is 15.7 mm × 6 mm and the thickness is about 15 μm. It shows high flexibility. Contrary to the concern that the polyimide substrate would curl out of shape, no curling has been observed.

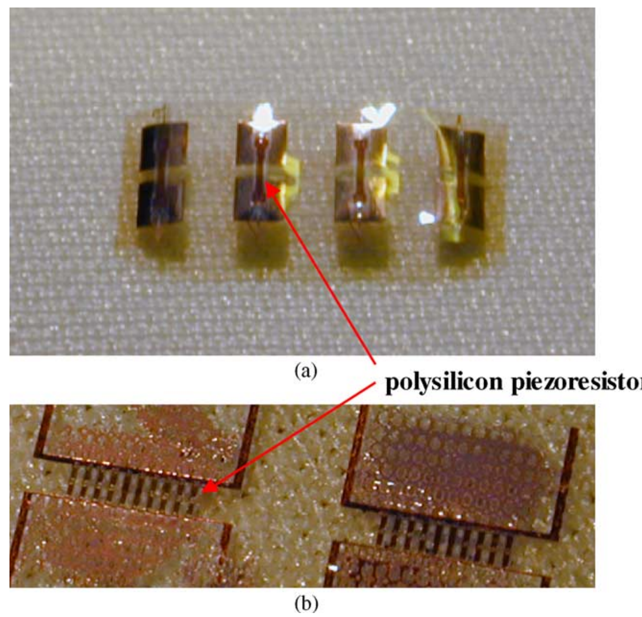


Fig. 5. The realized flexible polysilicon strain gauge array is on the plat surface. (a) Four thin polysilicon piezoresistors are arranged in polyimide substrate. (b) A number of polysilicon piezoresistors are arranged side by side.

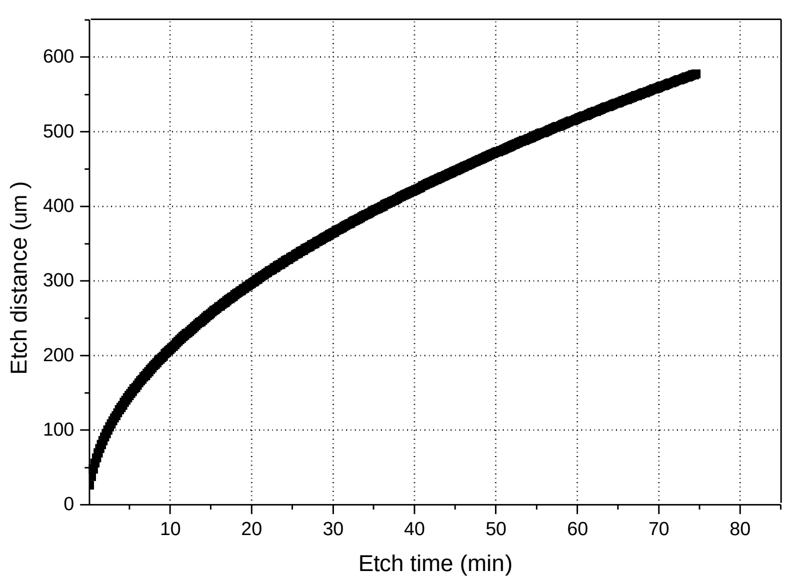


Fig. 4. Etch distance vs. etch time for 1D channel. The slope of this curve is instantaneous etch rate.

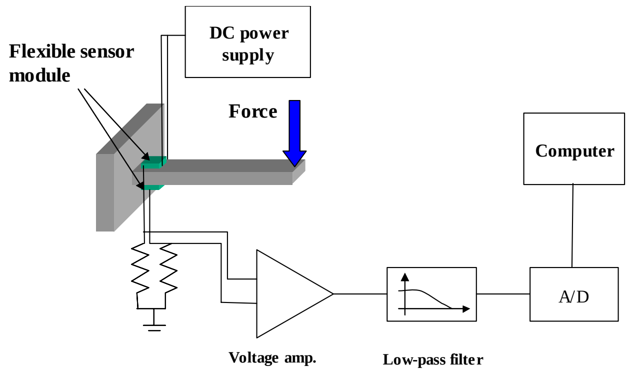


Fig. 6. Test apparatus used for gauge factor measurement. The curvature of the cantilever can be determined from moment–curvature equation. And the resistance change rate can be calculated from voltage signals.

### 2.3. Gauge factor measurement

A gauge factor (GF) is defined by the resistance change rate with respect to the applied strain. The GF of the flexible polysilicon strain gauge has been measured using the measurement setup as shown in Fig. 6. The strain gauge array is attached in the one end of cantilever. A known force is applied at the other end of cantilever by a scale weight. The strain can be calculated from Eq. (3) known as moment–curvature equations that the curvature of cantilever is directly proportional to the bending moment $M$ and inversely proportional to the quantity $EI$, which is the flexural rigidity of beam.

$$\kappa = \frac{M}{EI} \qquad \varepsilon = \kappa y \tag{3}$$

where $\kappa$, $M$, $E$, $I$, $y$ are curvature of deflected cantilever, applied bending moment, Young's modulus, moment of inertial of the cross-sectional area, distance from neutral surface, respectively. The change rate of resistance can be calculated from the voltage signals that are attained by an ac–dc converter. Fig. 7 shows the graph of the strain versus

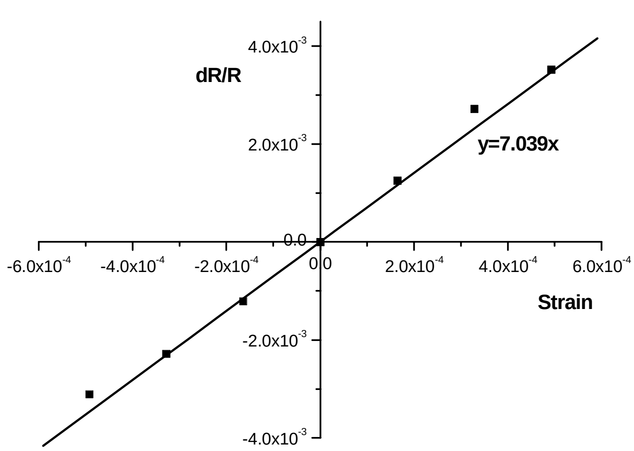


Fig. 7. A graph of strain vs. resistance change rate. The gradient of the liner graph indicates the gauge factor of the flexible polysilicon strain gauge.

resistance change rate. The gradient of the liner graph indicates a gauge factor of the flexible surface micromachined polysilicon strain gauge. The measured gauge factor, 7, shows that the strain sensor array has higher GF than metal strain gauges, but considerably lower than single-crystal strain gauge. French et al. investigated into the theoretical and experimental piezoresistive effect in polysilicon with including the effect of grain boundaries. A peak longitudinal gauge factor of about 43 for p-type material was achieved experimentally [15].

When considering the processing steps for strain sensor it is not sufficient to simply choose the largest gauge factor. A further consideration about stability, hysterisis, and temperature coefficient of resistance (TCR), temperature coefficient of gauge factor (TCGF) matching must be made if strain gauge bridge is used. It is reported that heavily doped samples (above $3 \times 10^{19}\,\mathrm{cm}^{-3}$) show good stability and TCR, TCGF matching requires heavy doping concentration [16], but the GF falls down due to same reason of single crystalline silicon. That is, there are trade-offs between high GF and stability. In this work, TCGF, TCR matching, and stability are chosen for array type sensor module.

Unlike a single crystal silicon strain gauge, the polysilicon has random crystal orientations. So, a sensor array for detecting arbitrary directional strain can be fabricated as a matrix form with photolithographic process. Moreover, because of the thin device thickness (about 15 μm), it is a lot flexible compared to the conventional silicon strain gauge.

### 2.4. Strain loss in polymeric film

The flexible polysilicon strain gauge is mounted onto a specimen using an adhesive film. This adhesive serves a very vital function in the strain measuring system in that it must transmit the strain from the specimen to the guage-sensing element without distortion of strain. But it seems that some strain gradient may exist in the polymeric film (adhesives and polyimide substrate) and a partial strain loss seems to be inevitable. Therefore, in order to determine the strain loss in adhesive and carrier material, a simple rule of mixture was employed. In polyimide, polysilicon, and adhesive system, the effective Young's modulus and effective Poisson ratio can be inferred from the properties of each material as shown in Fig. 8. Fig. 9a shows the strain gauge attached to specimen that is subjected to uni-axial tensile stress. One can suppose that the boundary conditions at the strain gauge substrate would be like Fig. 9b. The bottom side of strain gauge will be subjected to constant strain, the left and right side of it are free loading, and at topside of it some strain may exist, but the strain is somewhat smaller than the strain at bottom side. In this condition, the analytic stress distribution can be founded using Airy's stress function [17].

$$\nabla^4\phi = 0, \quad \sigma_{xx} = \frac{\partial^2\phi}{\partial y^2}, \quad \sigma_{yy} = \frac{\partial^2\phi}{\partial x^2}, \quad \tau_{xy} = -\frac{\partial^2\phi}{\partial x \partial y} \tag{4}$$

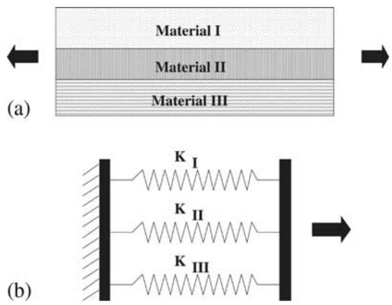


Fig. 8. Rule of mixture. The spring constant of mixture like (a) can be modeled as parallel springs shown in (b).

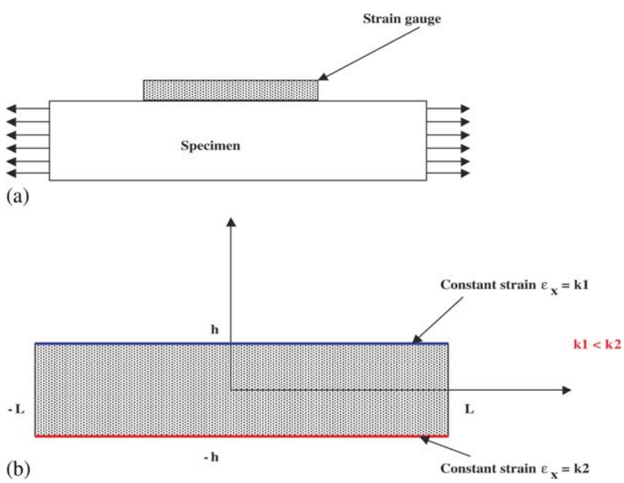


Fig. 9. Model and boundary conditions used in FE simulation. (a) Simple model: strain gauge attached to a specimen subjected to a constant tensile stress. (b) Boundary conditions of strain gauge: the bottom and top sides are subjected to constant strain.

The expression $\phi$ is known as Airy's stress function. If Eq. (4) is solved for $\phi$, an expression containing $x$, $y$, and a number of constants will be obtained. The constants are evaluated from the boundary conditions, and the stress for the plane-stress case can be obtained. Solving Eq. (4), the linear function of $\sigma_{xx}$ was attained. However, the exact constants cannot be determined because the topside strain wasn't known. Hence, finite element (FE) simulation was performed. The boundary condition of topside was substituted by free loading in simulation. Fig. 10 shows the result of the FE simulation. The result shows a linear distribution of strain ($\sigma_{xx}$). But the strain loss is negligible (<1%). Therefore, we can conclude that the measured gauge factor is a reasonable value and negligible loss is induced by the polyimide and adhesive.

## 3. Conclusions

A novel flexible polysilicon strain sensor and a flexible packaging scheme have been proposed. A polysilicon strain gauge array has been realized using surface micromachining with a $SiO_2$ sacrificial layer. The piezoresistor array is formed by conventional semiconductor processes and coated by a polymer substrate material. Using the release-etching process, a surface-micromachined strain sensor array can be obtained without any additional assembly processes.

The measured gauge factor shows that the polysilicon strain gauge is more sensitive than the conventional metal strain gauge. The strain loss in an adhesive film and a polyimide film is negligible. Unlike a single crystal strain gauge, it has no directional limitation, and can be arbitrarily patterned for variety of applications by photolithographic process. It is due to the fact that the piezoresistive coefficient of polysilicon has no crystal-oriented dependency.

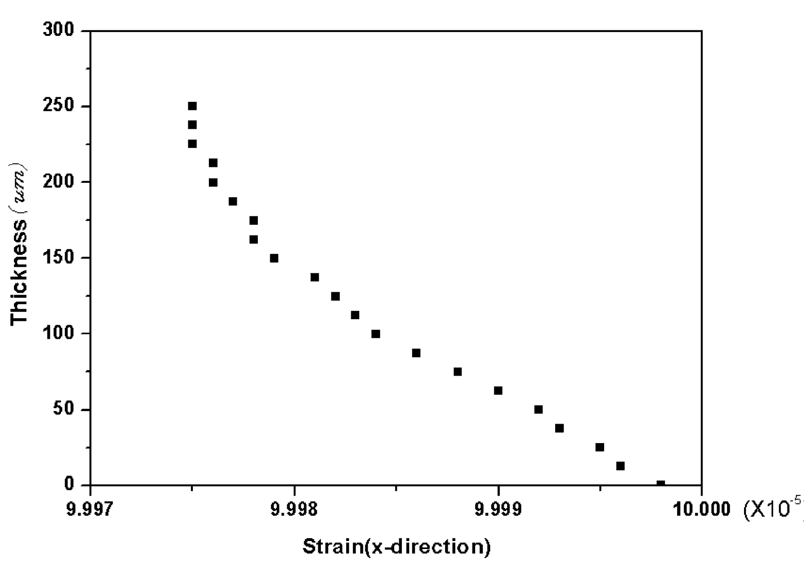


Fig. 10. FE simulation result of strain gradient in polymer substrate.

Furthermore, the thin device thickness makes it more flexible than most strain gauges, which will have wider choice of applications such as measurement of strain distribution in an arbitrary and non-planar surface.

The proposed packaging scheme realized the polysilicon sensor and the polyimide circuit board in a single step, which will eliminate any additional assembly process and increase its accuracy in placement of sensors in an array. Therefore, the scheme can improve measurement accuracy and reduce the overall cost of sensor modules. Even though only strain sensor array has been demonstrated in this report, the same fabrication and packaging scheme can be applied in wider range of applications such as flexible thermal or pressure sensor array.

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