Piezoresistive Cantilever for Mechanical Force Sensors

T. Chu Duc, J. F. Creemer, P.J.F. Swart, P. M. Sarro

Delft University of Technology, DIMES
Laboratory of Components, Technology and Materials, PO Box 5053, 2600 GB Delft,
The Netherlands
e-mail: t.chuduc@dimes.tudelft.nl

***Abstract*— This paper describes piezoresistive cantilever force sensors that are used to evaluate the impact force between micro-handling tools and microparticles in the nano-Newton range. The 500 nm-thick piezoresistive sensors are made from epitaxial silicon on single crystal silicon. This cantilever is based on conventional silicon wafers and fabricated using bulk micromachining. The cantilevers are 300-500 µm long, 10-20 µm high, and 10-18 µm wide. The applied force on this sensor is parallel to wafer surface. This structure can eliminate the effect of the vertical force, increasing the sensitivity and accuracy of the system. The force sensitivity of implemented sensors ranges from 150 to 300 V/N. The force resolution estimated at 6 nN.**

***Index Terms*— force sensor, nano-Newton force sensor, piezoresistive cantilever, piezoresistor.**

I. INTRODUCTION

THE development of nano-Newton force sensors for manipulating microparticles or living cells has become a great technological challenge for advanced microassembly and future living cells surgery. There are several force sensing methods: piezoresistive, capacitive and optical laser detection. In general, the piezoresistive method is used for nano mechanical sensors [1], binding force measurement [2], and bio-chemical mass sensing [3], as capacitive and optical methods are difficult to miniaturize sufficiently. Piezoresistive transducers are widely employed as sensing element in pressure sensors, accelerometers, and atomic force microscope (AFM) cantilevers. Recently, developments in piezoresistive cantilever fabrication lead to submicron cantilevers with pN [4] and even fN [5] resolution. However, most of the previously developed high sensitivity force sensors employ SOI (silicon on insulator) wafers and vertical structures [1,2,4,6]. The high cost of SOI wafers and the use of vertical structures, i.e. the applied force is perpendicular to the wafer surface, are the main limiting factors for the envisioned applications.

This paper presents a novel piezoresistive cantilever force sensor that overcomes these limitations by using regular silicon wafers and providing high enough sensitivity and the possibility to easily be combined with handling tools. The applied forces are parallel to the wafer surface. Nano-Newton resolution sensitivity is expected to be achieved.

II. FABRICATION

The force sensor consists of a p-type silicon cantilever on which p-type epitaxial silicon piezoresistors are integrated. Cantilevers with a thickness between 10-20 µm, a length of 300-500 µm and a width between 10 and 18 µm are realized. The fabrication process is based on the DIMES-03 bipolar process [7] and can be divided in three major parts, as schematically shown in Fig. 1. The first one, Fig. 1a comprises the definition of the piezoresistors. The starting material is p-type (100) wafers with a 1 µm thick n-type epitaxial layer, with a resistivity of 0.5 Ωcm. The piezoresistors are formed using a second epitaxial layer, 500 nm thick, p-doped with a resistivity of 3.75×10^{-2} Ωcm. By using the epitaxial growth a very uniformly doped layer with a very accurate thickness can be obtained. The 1-2 µm wide, 35-75 µm long piezoresistors are defined using reactive ion etching (RIE).

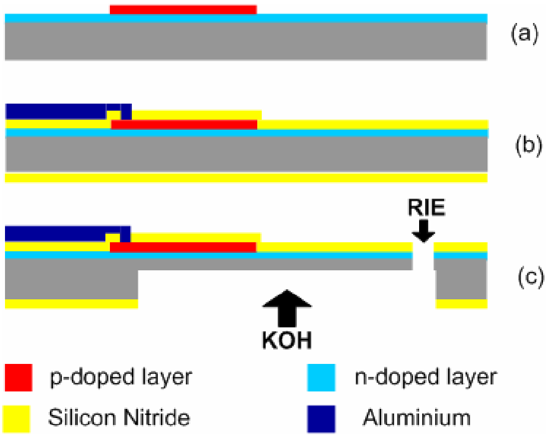

Figure 1. Schematic view of the fabrication processes: a) piezoresistors definition; b) insulation and metallization; c) micromachining for the cantilever release.

Piezoresistors are aligned along [110] dimension in the (001) plane. The piezoresistors are isolated from the substrate and each other by the n-type epilayer and implanted regions using boron at 180 keV with a dose of 5×10^{15} cm^{-2}. The contact windows are implanted using arsenic (180 keV, 5×10^{15} cm^{-2}) and boron (15 keV, 3×10^{15} cm^{-2}) for the substrate and the resistor, respectively.

A 300 nm thick LPCVD silicon nitride layer is deposited as electrical isolation layer on front-side and also as backside masking layer during silicon etching in KOH. After opening the contact windows, a 600 nm aluminum layer is sputtered and patterned for resistor interconnects, Fig. 1b.

The final part of the process, Fig. 1c, consists of the cantilever definition and release. First, the bulk silicon is etched from the backside in a 33 wt% KOH solution at 85 °C to create a 10-20 μm thick silicon membrane. The front-side of wafer is protected by using a vacuum holder. Then the releasing of the cantilever is done by using RIE to etch the 10-20 μm remaining silicon from the front side.

Fig. 2 shows the layout of the piezoresistors. The resistor pair located on the cantilever is the sensing resistors (resistance changes when stress is applied onto the cantilever). Two other resistors are outside of the cantilevers, thus their resistance is not depending on the stress and are used for compensation in a Wheatstone bridge. The fabricated cantilever is showed on the Fig. 3. The cantilevers are 300-500 μm long, 10-18 μm wide, and 10-20 μm high.

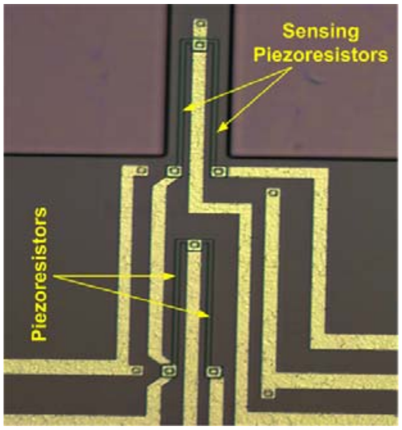

Figure 2. Optical image of the implemented piezoresistors

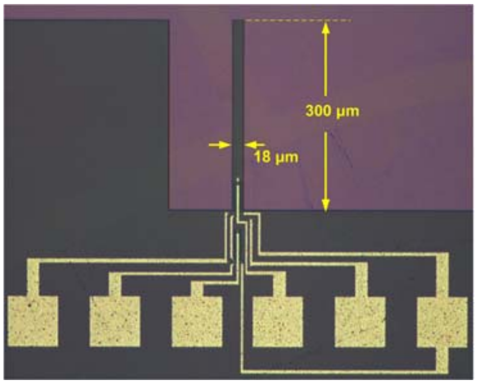

Figure 3. Optical image of a lateral force-sensing piezoresistive cantilever

III. MEASUREMENTS AND RESULTS

The detection of force by piezoresistive cantilever sensor depends on the relative change in the resistance. This change is best measured by a Wheatstone bridge. There are two piezoresistors located on two sides of the cantilever. The resistances of those resistors change in an opposite direction if a lateral force is applied.

The resistance change for piezoresistors used in a mechanical sensor can be calculated as the function of the surface stress in the cantilever. The resistance change due to the mechanical stress is given by [8]

$$\left.\frac{\Delta R}{R}\right|_{x_0} = \left.\left(\pi_l \sigma_l + \pi_t \sigma_t\right)\right|_{x_0} \qquad (1)$$

where x_0 is the distance from fixed end of cantilever to the investigated point, π_l and π_t are the longitudinal and the transverse piezoresistance coefficients, σ_l and σ_t are the longitudinal and the transverse stresses, respectively. The σ_t can be neglected in the bending cantilever so the equation (1) can be reduced to:

$$\left.\frac{\Delta R}{R}\right|_{x_0} = \left.\pi_l \sigma_l\right|_{x_0} \qquad (2)$$

The bridge configuration of the resistors compensates for the signals caused by a vertical deflection. It reduces the cross sensitivity and the offset.

Fig. 4 shows the schematic views of lateral force-sensing piezoresistive cantilever, and the arrangement of the Wheatstone bridge. The bridge has four contacts, two of which provide the DC or AC supply voltage, the others are the outputs. When a lateral load is applied to the tip of cantilever, the differential change of resistance occurs on two resistors Rs1 and Rs2. Others piezoresistors R1, R2 are the compensation resistors. The resistance change on the sensing piezoresistors due to the applied force is given by [8]:

$$\frac{\Delta R}{R} = \frac{-zF}{I}\pi_l L_S\left(L - \frac{L_S}{2}\right) \qquad (3)$$

where z, in the range of 2 to 5 μm, is the distance from cantilever neutral axis to the piezoresistor, L_s is the length of the piezoresistor, F is the applied force to the tip of the cantilever, $I = 1/12 \cdot W^3 \cdot H$ is the lateral moment of inertial of the cantilever with respect to the [110] axis.

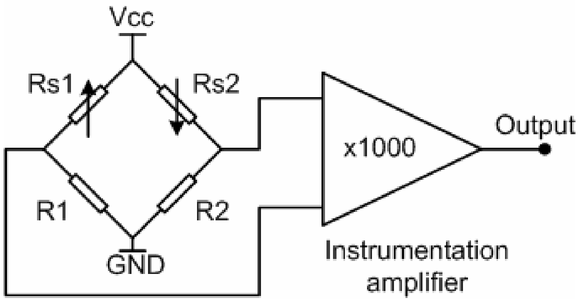

Figure 4. Schematic circuit of the lateral force-sensing piezoresistive cantilever

When the piezoresistor is changed by ΔR the output signal is given by:

$$V_{out} \approx \frac{V_{cc}\Delta R}{2R} \qquad (4)$$

where V_{cc} is the supply voltage and R is the resistance of the non-stress piezoresistor.The output is expected to change with 0.15-0.3 μV when the applied force changes 1 nN, which yields a sensitivity of 150 - 300 V/N depending on the geometry of the cantilevers and the characteristics of the piezoresistive layer with the longitudinal piezoresistance coefficients given by [8]:

$$\begin{aligned}\pi_{l,110} &= \frac{1}{2}\left(\pi_{11}+\pi_{12}+\pi_{44}\right) \\ &= \frac{1}{2}\left(6.6+(-1.1)+138.1\right)=71.8\end{aligned} \qquad (5)$$

where π_{11}, π_{12}, π_{44} are three independent coefficients of the first order piezoresistive tensor.

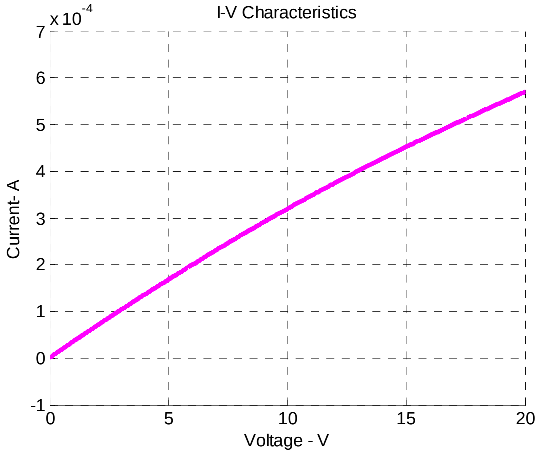

Figure 5. I-V characteristics of the piezoresistors

The stiffness of the cantilever at its end is given by $K=EWH^3/4L^3$ [8], where H, W, L, E are the thickness, width, length, and the modulus of elasticity of the cantilever, respectively. K can be calculated from the resonance frequency, which can be measured. The relation is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{\left(\frac{33}{104}+\frac{25M}{256\bar{m}}\right)\bar{m}L}} \qquad (6)$$

where $\bar{m}$ is the mass per unit length *of* the cantilever and M is the added mass (if any) at the end of the cantilever. The value of $\bar{m}$ is known from the cross-sectional geometry of the cantilever and the mass density of silicon [9]. Experimentally, the resonant frequency is obtained by mounting this cantilever on a piezoelectric actuator. From sweeping the frequency and monitoring the amplitude of the output the resonance frequency of the cantilever is detected. For the 300 μm long, 18 μm wide, and 10 μm thick cantilever the theoretical value of the lateral resonance frequency is 240 kHz. The corresponding spring constant of the cantilever, K = 90 N/m.

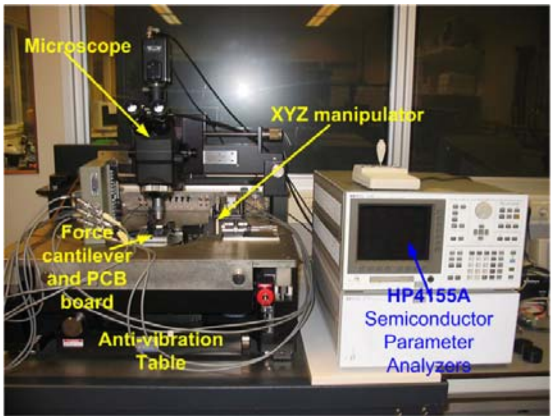

Figure 6. Picture of the measurement setup. The XYZ manipulator is used to bend the cantilever in the lateral and vertical dimensions.

Figure 5 shows the I-V characteristic of the piezoresistors at room temperature. The I-V characterization has a linear relation, meaning that the contacts and resistors behave as expected. The zero-stress value of the resistors is 31 kΩ. In order to characterize the force cantilever, the cantilever is bonded on a stable table, a micro-needle is fastened on a XYZ manipulator is used to bend the tip of the cantilever, Fig. 6. The cantilever is bent over a small angle. Monitoring the deflections we received the response of the piezoresistor. The applied force and stress are given by, respectively,

$$F = Ku \qquad (7)$$

$$\sigma_l\Big|_{x_0} = \frac{-zF}{I}\left(L-x\right)\Big|_{x_0} \qquad (8)$$

where u is the deflections of the cantilever.

Figure 7 show the resistance change of the piezoresitors due to the applied stress, the change in piezoresistor value is up to 30 % when applied stress is about 800 MPa.

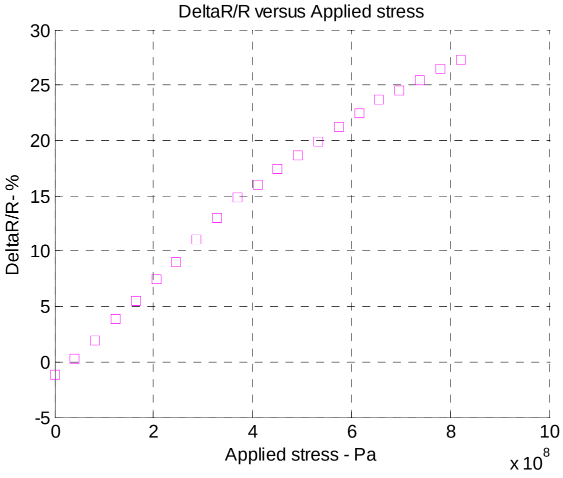

Figure 7. The resistance change of the piezoresistors due to the applied stress

Figure 8 shows the output signal when a lateral force is applied. The supply voltage is 1V DC. The voltage-applied force curve shows a linear relation. The sensitivity derived from this curves is 160 V/N. This experimental result meets the above theoretical value meaning that the epitaxial and etching processes behave as expected. The bridge configuration of resistors not only compensates the common-mode signals but also for the signal caused by the vertical applied forces. In fact, the lateral signal is 19 dB higher than the vertical signal for the cantilevers with the stiffness of 90 N/m.

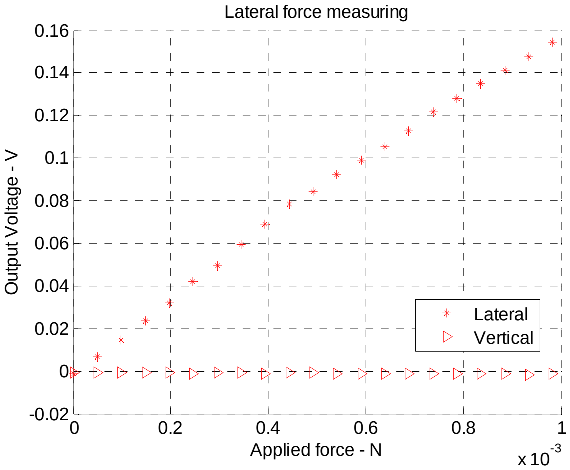

Figure 8. Output voltage due to the applied force, for lateral and vertical deflection

Johnson and flicker (1/f) noise are the two dominant noise sources of the piezoresistive cantilever [10]. The Johnson power noise spectral density for the resistance *R* at the temperature *T* is given by:

$$S_J = 4k_B TR \qquad (9)$$

where k_B is the Boltzmann constant. The flicker power noise spectral density is given by:

$$S_f = \frac{\alpha V^2}{fN} = \frac{\alpha V^2}{\rho_0 lwtf} \qquad (10)$$

where *V* is the biased voltage across a resistor with the total number of carriers *N*, *f* is the frequency, and α is a dimension-independent device parameter which is between $3.2\text{x}10^{-6}$ and $5.7\text{x}10^{-6}$ in single crystal silicon [10], ρ_0 is the charge carrier concentration, *l*, *w*, *t* is the piezoresistor length, width, and thickness, respectively. In single crystal silicon, the flicker noise dominates in the band below 100 Hz. Above this frequency it can be neglected in comparison with the Johnson noise.

The equivalent voltage noise in a band f_{max} - f_{min} is given by:

$$V_n = \sqrt{4k_B TR\left(f_{\max} - f_{\min}\right) + \frac{\alpha V^2}{\rho_0 lwt}\log\left(\frac{f_{\max}}{f_{\min}}\right)} \qquad (11)$$

By using Equation 11 with a band between 2 Hz and 1 kHz and the output signal from Fig. 8, the minimum detectable force of the piezoresistive force cantilevers can be estimated as 6 nN.

IV. CONCLUSIONS

This paper presents the design, fabrication and characterization of lateral nano-Newton force pizeroresistive cantilevers. These cantilevers are based on single crystal silicon instead of SOI wafers. The proposed structure and its electronic circuit suppress the effect of the vertical force with 19 dB in practice. A sensitivity of 160 V/N is measured. The force resolution of cantilevers is estimated at 6 nN. Our force sensor can potentially be used in micro- assemblies and biological assays where force feedback is needed.

ACKNOWLEDGMENT

The authors would like to acknowledge the whole DIMES-ICP group for technical support. This work is partly sponsored by the Vietnamese Ministry of Education and Training..

REFERENCES

[1] Toshiyuki Toriyama, Yasutada Tanimoto, Susumu Sugiyama, “Single crystal silicon nano-wire piezoresistors for mechanical sensors,” J. Microelectromechanical systems, vol. 11, no. 5, pp 605-611, October 2002.

[2] H. Onoe, M. Gel, K. Hoshino, K. Matsumoto, and I. Shimoyama, “Binding force measurement between micro-scale flat surfaces in aqueous environment by force-sensing piezoresistive micro-cantilevers” Proc. 18th IEEE Conference on MEMS, Miami, Florida, USA, Jan 30-Feb 05, pp 16-19, 2005.

[3] D.R. Baselt, G. U. Lee, K.M. Hansen, L.A. Chrisey, R.J. Colton, “A High-Sensitivity Micromachined Biosensor,” Proceeding of IEEE, vol. 58. no 4, pp 672-680, April 1997.

[4] M. Gel, Shimoyama, “Force sensing submicrometer thick cantilevers with ultra-thin piezoresistors by rapid thermal diffusion,” J. Micromech. Microeng. vol 14, no 3, pp 423-428, 2004.

[5] J. A. Harley, T. W. Kenny, “Piezoresistive cantilevers with femtonewton force resolution,” Proceedings 10th conference on Solid-state sensors and actuators, Tranducers, pp 1628-1631, 1999.

[6] Y. Su, A. G. R. Evans, A. Brunnschweiler, “Micromachined silicon cantilever paddles with piezoresistive readout for flow sensing,” J. Micromech. Microeng, vol. 6, no. 1, pp 69-72, March 1996.

[7] L.K. Nanver, E.J.G. Goudena, and H.W. van Zeijl, “Optimization of fully implanted NPNs for high frequency operation”, IEEE-TED, Vol. 43, pp.1038-1040, 1996.

[8] Stephen D. Senturia, Chapter 18 in Microsystem design, Kluwer Acedamic Publishers, pp 469-495, 2001.

[9] M. Taher A. Saif, Chad Randall Sager, and Sean Coyer, “Funcionalized Biomicroelectromechanical Systems Sensors for Force Respose Study at Local Adhesion Sites of Single Living Celss on Substates” , Annals of Biomedical Engineering, Vol. 31, pp. 950-961, 2003.

[10] Xiaomei Yu, J Thaysen, O. Hansen, A. Boisen, “Optimization of sensitivity and noise in piezoresistive cantilever”, J. Applied Physics, Vol. 92, No. 10, pp 6296-6301, Nov 2002.