

# A Sensor Skin Using Wire-Free Tactile Sensing Elements Based on Optical Connection

Kouichi Yamada<sup>1</sup>, Kenji Goto<sup>2</sup>, Yoshiki Nakajima<sup>1</sup>, Nobuyoshi Koshida<sup>1</sup>,  
and Hiroyuki Shinoda<sup>2</sup>

<sup>1</sup> Tokyo University of Agriculture & Technology 2-24-16 Koganei, Tokyo 184-8588 Japan

<sup>2</sup> The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 Japan

ykou@cc.tuat.ac.jp, shino@alab.t.u-tokyo.ac.jp

**Abstract:** A key to realize an elastic sensor skin that covers the entire body of machines is removing metal wires to tactile sensing elements. Using wireless tactile sensing chips based on RF connection is a hopeful method, which was proposed recently. However, it is difficult to make the RF tactile sensing element smaller than several millimeters because the energy transmission efficiency decreases as the chip size decreases. In this paper we propose a wireless tactile sensing element based on optical connection. The sensing chip with 1 mm cubic shape operates with optical power, and sends optical codes of 6 stress components measured by an optical sensing method. We describe the chip design and the 6 stress sensing principle, and show experimental results of the stress sensing using a prototype of a 4 mm cubic chip. Then we estimated the required optical power for the sensing chip, and checked the operation of the digital circuit on the chip.

**Keywords:** Tactile sensor, Artificial skin, Sensitive skin, Wireless measurement, Optical connection

## 1 Introduction

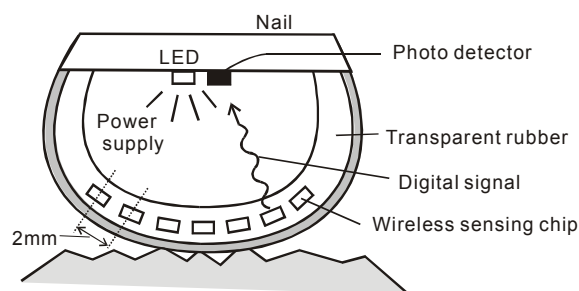
A key idea for realizing an elastic tactile sensing device that can sense as a human does, is removing metal wires. A former paper presented a wireless tactile sensing chip using inductive connection for receiving and transmitting power and signals [1]. However, it is difficult to make a tactile sensing element smaller than several millimeters because the energy transmission efficiency decreases as the coil size on the sensing chip decreases [2].

In this paper we propose a wireless tactile sensing element based on optical signal transmission. The sensing chip in 1 mm cubic shape operates with optical power, and sends optical codes of 6 stress components measured by an optical sensing method. We describe the chip design and the principle of stress detection, and show experimental results using a 4 mm prototype sensor chip. We estimated the required optical power, and examined the chip operation.

## 2 Tactile Sensing Based on Optical Connection

A schematic diagram of an artificial skin we propose here is shown in Fig. 1. Each tactile sensing chip is embedded with 2 millimeter interval in a soft artificial robot finger. The transparent robot skin allows optical connection between the sensor chip and the optical transmitter/receiver located inside the finger. Each sensor chip operates with the optical power from the transmitter (LED). Meanwhile this light also

becomes optical signals from a computer. In addition, the stress on a sensor chip is measured from the intensity change of the LED light detected inside the sensor chip. The sensor chip emits light digital signals with porous silicon formed on it [3]. The signal is detected by an external optical detector.



**Fig. 1:** Schematic diagram of a sensor skin using optical tactile sensing elements.

## 3 Wire-Free Optical Tactile Sensing Element

The structure of the sensing chip is shown in Fig. 2. The sensor chip consists of two parts. One is a VLSI chip for receiving optical power with PN Junction, measuring optical intensity on it, and signal processing. The other is a flexible cube with apertures attached onto the VLSI chip for measuring 6 components of stress around the chip.

The layout of the VLSI chip is shown in Fig. 3. The surface is shared with a solar cell of PN junction for

receiving optical power, a porous silicon luminescer formed on the VLSI chip, a signal processing part, and photo diodes.

This VLSI chip was made in ROHM 0.35mm process that is supported by VDEC (VLSI Design and Education Center) at the University of Tokyo.

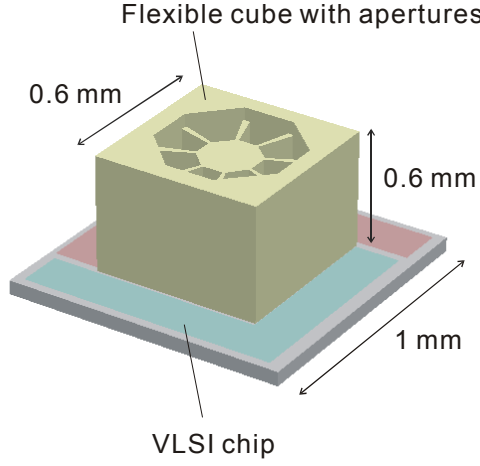


Fig. 2: Structure of the optical tactile sensing element.

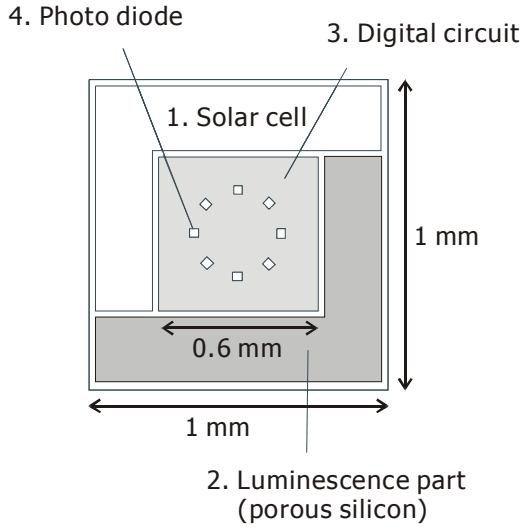


Fig. 3: Layout of the VLSI chip

#### 4. Method of Stress Measurement

Since what is the essential stress component in tactile sensing is still unclear, it is desirable our device can sense all components of stress tensor. Because the sensor chip with VLSI circuit can measure light intensity at multiple points, it is possible to detect 6 components of stress tensor theoretically.

Structure of a flexible cube attached to the LSI chip is shown in Fig. 4. It is a 0.6 mm cube that has 8 holes to the photo diodes. The holes 1, 3, 5, and 7 have the same

structure that has symmetrical projections on the facing walls inside the hole as is shown in Fig. 4. Meanwhile the holes 2, 4, 6, and 8 have projections attached at different heights on the walls. The sensor detects the deformation of the flexible cube from the light-intensity-change at the photodiodes. The photodiodes 1, 3, 5, and 7 detect shearing/normal stress  $\sigma_{xz}$ ,  $\sigma_{yz}$ ,  $\sigma_{xx}$ , and  $\sigma_{yy}$  applied to the cube using the symmetry. Here  $\sigma_{xx}$  expresses normal stress along the  $x$  axis, and  $\sigma_{xz}$  expresses shearing stress that is tangential force along  $x$  axis on the top surface of the cube.

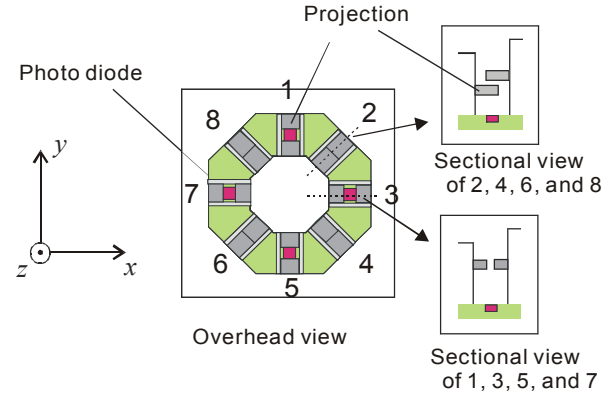


Fig. 4: Structure of the flexible cube with apertures.

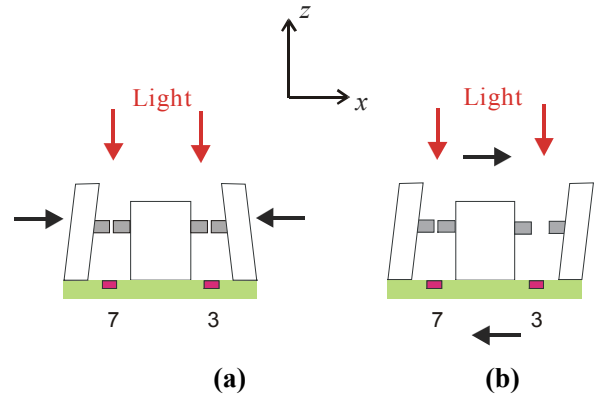


Fig. 5: Sensing normal stress  $\sigma_{xx}$  and shearing stress  $\sigma_{xz}$ .

The principle is explained in Fig. 5. The holes 3 and 7 deform symmetrically for the normal stress along the  $x$  axis, while they deform antisymmetrically for the shearing stress  $\sigma_{xz}$ . Therefore we can obtain equations using constants  $A$ ,  $B$ ,  $C$ , and  $D$  as follows.

$$dp_3 + dp_7 = A\sigma_{xx} + B\sigma_{yy} + C\sigma_{zz} \quad (1)$$

$$dp_3 - dp_7 = D\sigma_{xz} \quad (2)$$

The  $dp_i (i=3,7)$  is the light intensity change detected at the

photo diode  $i$ . The absolute values of the coefficients  $|B|$  and  $|C|$  are smaller than  $|A|$ . From the symmetry we can also obtain

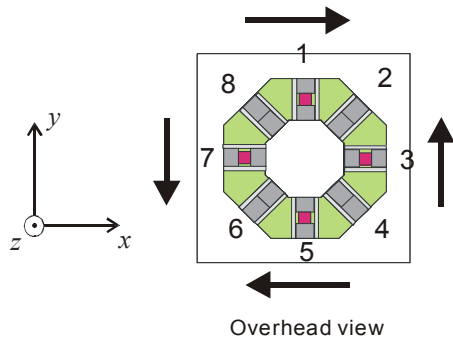
$$dp_1 + dp_5 = A\sigma_{yy} + B\sigma_{xx} + C\sigma_{zz} \quad (3)$$

$$dp_1 - dp_5 = D\sigma_{yz} \quad (4)$$

using the same parameters  $A$  to  $D$ .

The 5th stress  $\sigma_{xy}$  is illustrated in Fig.6. Shearing stress is applied to the side walls. In this case, the light intensity at point 4 and 8 decreases, and that at point 2 and 6 increases. From this symmetry, we can write as

$$dp_2 + dp_6 - (dp_4 + dp_8) = E\sigma_{xy} \quad (5)$$



**Fig. 6:** Sensing shearing stresses  $\sigma_{xy}$ .

The last 6th stress  $\sigma_{zz}$ , the vertical normal stress is illustrated in Fig. 7. The gap distance between the facing projections are mainly sensitive to the normal stress  $\sigma_{zz}$ . Then the parameter  $G$  in

$$dp_2 + dp_4 + dp_6 + dp_8 = F\sigma_{zz} + G(\sigma_{xx} + \sigma_{yy}) \quad (6)$$

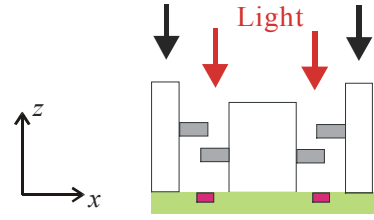
is smaller than  $F$ .

The equations (1), (3), and (6) give the normal stress  $\sigma_{xx}$ ,  $\sigma_{yy}$ , and  $\sigma_{zz}$ . If we neglect  $B$ ,  $C$ , and  $G$ , we can simply write

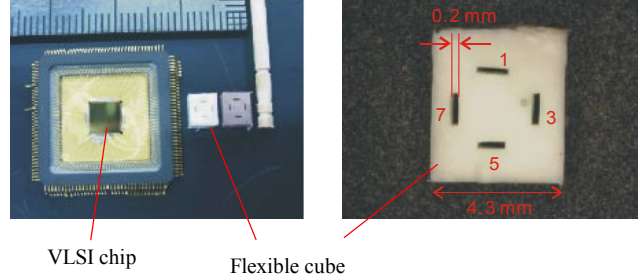
$$\begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \end{pmatrix} = \begin{pmatrix} (dp_3 + dp_7) / A \\ (dp_1 + dp_5) / A \\ (dp_2 + dp_4 + dp_6 + dp_8) / F \end{pmatrix} \quad (7)$$

$$\begin{pmatrix} \sigma_{xz} \\ \sigma_{yz} \\ \sigma_{xy} \end{pmatrix} = \begin{pmatrix} (dp_3 - dp_7) / D \\ (dp_1 - dp_5) / D \\ (dp_2 + dp_6 - dp_4 - dp_8) / E \end{pmatrix}. \quad (8)$$

From above equations, we obtain the all components of stress tensor  $\sigma_{ij}$ .



**Fig. 7:** Sensing vertical normal stress  $\sigma_{zz}$ .



**Fig. 8:** (a): A photograph of a VLSI chip for our prototype sensor chip. (b): A photograph of a flexible cube for 4-component stress measurement.

## 5. Experiments of Stress Sensing

We fabricated prototypes of flexible cube using elastic silicone rubber (Young's modulus =  $3 \times 10^5$  Pa). The edge length of the cube is 4 mm. This prototype has only 4 slits with 0.2 mm gap for detectors 1, 3, 5, and 7.

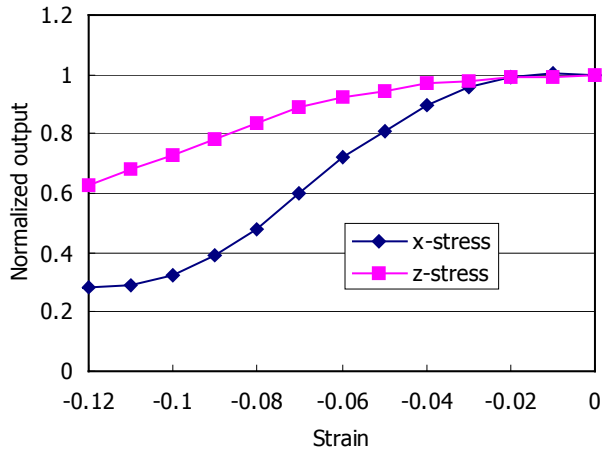
We located the flexible cube so that No. 3 and 7 in Fig. 8 are along the  $x$  axis. And we observed the light intensity at detector 3 when we applied  $\sigma_{xx}$  and  $\sigma_{zz}$ . In this experiment, a discrete photodiode was used for the light intensity detection instead of the photo-detector in the VLSI chip. The plots 'x-stress' in Fig. 9 shows normalized output  $p/p_0$  when we applied horizontal compressive force to the cube faces perpendicular to the  $x$  axis with no stress to other faces. The 'strain' of the horizontal axis means the ratio of the deformed cube length along the  $x$  axis to the original length. The plots 'z-stress' show the detector's output when we applied vertical compressive force to the horizontal cube faces with other faces free. For these plots the strain means the ratio of the length change along the  $z$  axis to the original length. Plots show the detector 3 is more sensitive to horizontal normal stress than to vertical one that implies  $A$  in Eq. (1) is larger than  $B$ .

The plots in Fig. 10 show the normalized output of 3 and 7 when we applied shearing deformation. The 'strain' of the horizontal axis means the shearing strain

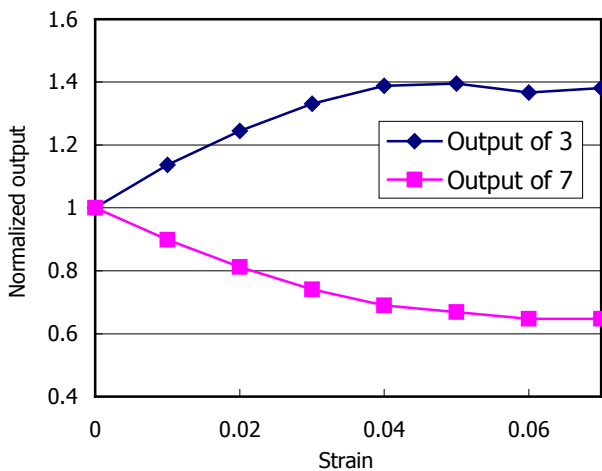
$$u_{xz} = \frac{1}{2} \left( \frac{du_z}{dx} + \frac{du_x}{dz} \right) \quad (9)$$

where  $\mathbf{u}(\mathbf{r}) = (u_x, u_y, u_z)$  is the displacement vector at  $\mathbf{r}$  of the

cube body. The figure shows the slopes of 3 and 7 have opposite signs to each other. These results show the 4 slit detectors can resolve applied stress into  $\sigma_{xx}$ ,  $\sigma_{yy}$ ,  $\sigma_{xz}$ , and  $\sigma_{yz}$  if we neglect the effect from  $\sigma_{zz}$ . If we add one output that is sensitive to  $\sigma_{zz}$ , exact resolution of the stress into the components becomes possible.



**Fig. 9:** Normalized output of photodiode 3 when horizontal compressive force (x-stress) and vertical compressive force (z-stress) are applied to the prototype sensor chip. The 'strain' for 'x-stress' and 'z-stress' implies the ratio of the deformed cube length along the  $x$  and  $z$  axis, respectively, to the original length.



**Fig. 10:** Normalized output of photodiode 3 and 7 when shearing strain is applied to the prototype sensor chip.

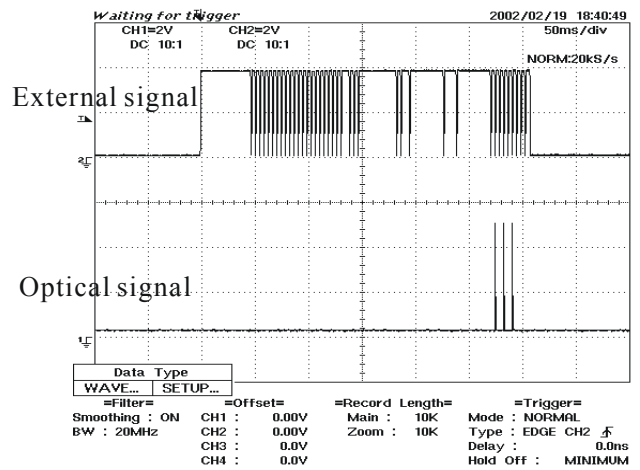
## 6. LSI Chip Operation and Power Consumption

In our design, the VLSI chip operates at 10 MHz and transmits  $8 \times 6$  bit stress data with 1 MHz signal frequency. Signal transmission time for one chip is within  $100 \mu\text{sec}$ . All the chips obtain unique IDs at the beginning of the operation using random number generator, and respond to the

commands with ID transmitted from the LED.

Each chip obtains one sample of stress data by measuring the photon charge generating for 1 ms. Though we have not confirmed the energy consumption of the chip experimentally, we suppose the main power will be consumed by the logic circuit for communication. If we assume  $0.1 \mu\text{W}/\text{MHz}/\text{gate}$ , the average power consumption of our 10 thousand-gate logic circuit ( $0.5 \text{ mm}^2$  square under the  $0.35 \mu\text{m}$  rule) is estimated at  $100 \mu\text{W}$ . If solar cell efficiency is 10 %, a  $0.6 \text{ mm}^2$  solar cell needs  $1.5 \text{ mW}/\text{mm}^2$  light intensity, which Laser can provide.

We are now examining the VLSI chip operation. The lower waveform in Fig. 11 is the response signal of our VLSI chip to test input. In our plan, the output signal from the circuit will be connected to a porous silicon luminescer formed on poly-silicon layer on the chip [3].



**Fig. 11:** An output signal from a VLSI chip for a test input signal.

## References

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