Sensors and Actuators A 160 (2010) 69–77

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A multifunctional integrated silicon tactile imager with arrays of strain and temperature sensors on single crystal silicon diaphragm

Hidekuni Takao[a,b,*], Masaki Yawata[b], Kazuaki Sawada[b], Makoto Ishida[b]

[a] Micro-Nano Structure Device Integrated Research Center, Kagawa University, 2217-20, Hayashi-cho, Takamatsu 761-0396, Kagawa, Japan
[b] Department of Electrical and Electronic Engineering, Toyohashi University of Technology, 1-1, Hibarigaoka, Tempaku-cho, Toyohashi 441-8580, Aichi, Japan

ARTICLE INFO

Article history:
Received 27 July 2009
Received in revised form 3 March 2010
Accepted 24 March 2010
Available online 7 April 2010

Keywords:
Tactile sensors
Silicon-MEMS
Smart sensors
Microsensors
Multifunctional integration

ABSTRACT

In this study, a silicon multifunctional tactile imager with the simultaneous detection abilities of '3D surface shape' and 'temperature distribution' of touching object has been realized with silicon LSI/MEMS technology. The pixel circuit array including a piezoresistor and a temperature sensor is integrated on elastic surface of pneumatically swollen silicon diaphragm. Also, elasticity detection of touching object has been simultaneously realized with signal processing in frequency domain. Prototype tactile imagers with a 3.1 mm × 3.1 mm sensor diaphragm integrating 420-μm pitch multifunctional sensor pixel array have been fabricated. In the evaluation experiments, the shape of a 1.5 mmϕ soft tube was successfully detected. Also, simultaneous measurement of surface shape and temperature distribution was performed using a heated metal pipe. The detectable lower-limit of vibration in this tactile imager was below 1.0 μm with signal bandwidth more than 2 kHz. Using the ability of vibration detection, the three kinds of materials with different elasticity (0.59–7.04 mN/μm) were successfully distinguished with the tactile imager. The highly sensitive and multifunctional tactile imager with versatile detection ability has been realized by sophisticated integration ability of silicon-MEMS technology.

1. Introduction

Human fingertip can detect the various physical information of touching object as distributed and dynamic images. Various kinds of tactreceptors are distributed under the skin of human fingertip at a high density. In haptic/tactile sensing applications, tactile imager devices will have the role of front-end device in future 3D surface shape recognition system based on direct touching measurement. It is considered that high-density sensor pixels for tactile imaging are necessary to obtain high resolution tactile images like human fingertip. Some tactile sensors with polymer materials like pressure sensitive conductive rubber [1–4] and combination with organic-FET switches [5] have been reported as force distribution sensing devices. In general, such devices are suitable for large area applications with low spatial resolution because of their flexibility and low cost per unit area. Unfortunately, the obtainable spatial resolution of such organic sensors is not so high and typically around a few milli-meters.

On the other hand, distributed micro-force/pressure sensor array devices based on silicon-MEMS technology have been reported also for tactile sensing applications that require high spatial resolution. They are configured as the integrated arrays of individually separated micro-mechanical sensor pixels [6–14], or integrated as strain sensitive MOSFET arrays in bulk-CMOS integrated circuit [15]. Most of the silicon tactile image sensors can detect only force or pressure distribution by the sensor array. Also, it is difficult to cover the 3D surface of an object using previous silicon-MEMS integrated sensors, since mechanical stroke of such small sensor pixels are usually very short. Typical mechanical stroke of micro-mechanical force sensors is around 1 μm because of their sizes of structures. Short mechanical stroke and inflexible surface of silicon tactile image sensors have been limitations in 3D surface shape recognition using tactile sensors, even though they have much higher spatial resolutions than the organic tactile sensors. In order to realize high-density sensor pixel array with the flexibility of sensor surface, we have reported a novel tactile image sensor with integrated piezoresistor pixel array on a pneumatically swollen single diaphragm structure [16,17]. In our previous study, multi-point force detection ability and obtainable spatial resolution using a continuous diaphragm structure with integrated piezoresistor pixels were discussed. Also, the detectable force range of thin silicon diaphragm structure was analyzed and evaluated for tactile sensing [17].

Since "tactile sense" includes various information and physical signals concerned with touching operations, integration of multifunctional detection ability is an important subject for tac-

---

* Corresponding author at: Micro-Nano Structure Device Integrated Research Center, Kagawa University, 2217-20, Hayashi-cho, Takamatsu 761-0396, Kagawa, Japan. Tel.: +81 87 864 2331; fax: +81 87 864 2331.
E-mail address: takao@eng.kagawa-u.ac.jp (H. Takao).

0924-4247/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2010.03.039

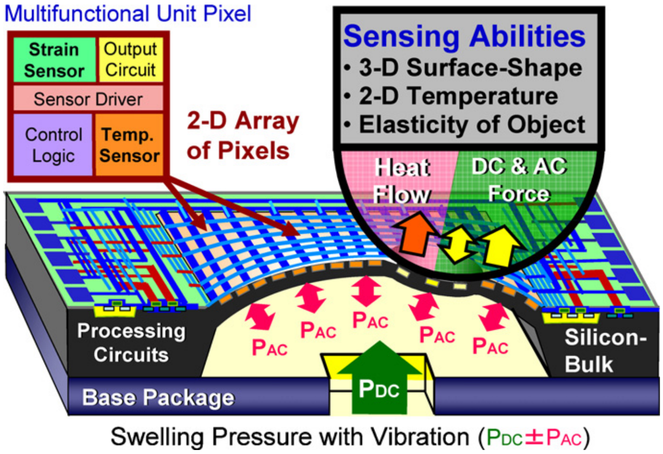

Fig. 1. Schematic diagram of this multifunctional tactile imager device with integrated strain and temperature sensor arrays on single air-pressurized silicon diaphragm.

tile sensor devices. Different kinds of sensors are necessary to extract different physical information from the touching object. In recent years, simultaneous and independent measurement of stress and temperature using single MOSFET-based sensor structure has been reported with small sized and high-density sensor pixel array [18,19]. Also, active tactile sensor elements for hardness and force detection have reported with pneumatic and magnetic actuators [20,21]. The new elements of technologies for multifunctional tactile imaging have been developed and established step by step.

In this study, a new silicon multifunctional tactile imager with the sensing abilities of surface shape, temperature distribution, and the elasticity of touching object has been investigated. Mechanical structure and dimensions of the tactile imager is the same with our first tactile imager device [17] integrating only a piezoresistor array. However, both a temperature sensor and a piezoresistor are integrated with their control/driving circuits in each sensor pixel of the new tactile imager. The first fabrication results of the multifunctional tactile imager are reported in a conference proceeding [22]. After that, a multifunctional tactile imager with the detection ability of surface elasticity has been developed and reported [23]. In this paper, the detailed principles and the latest evaluation results of the silicon multifunctional tactile imager are presented and discussed systematically for the first time.

2. Detection principle of the multifunctional tactile imager

2.1. Simultaneous detection of 3D surface shape and the temperature distribution

The multifunctional tactile imager in this study has a continuous single diaphragm structure to realize flexible contact face and a larger mechanical stroke. Fig. 1 shows a schematic diagram of the tactile imager in this study. The diaphragm is pneumatically swollen from the backside in order to realize surface flexibility and convex shape of the contact face. The area of the diaphragm is 3.1 mm × 3.1 mm. Depending on the diaphragm dimension and the swelling pressure, the center height of swollen diaphragm (i.e. mechanical stroke) reaches from a few ten microns to a few hundred microns. In each pixel circuit of the sensor array, two kinds of different sensors are integrated. The temperature sensor is used for the detection of temperature distribution, and the piezoresistor is used for the extraction of 3D surface shape and the surface elasticity of the touching object.

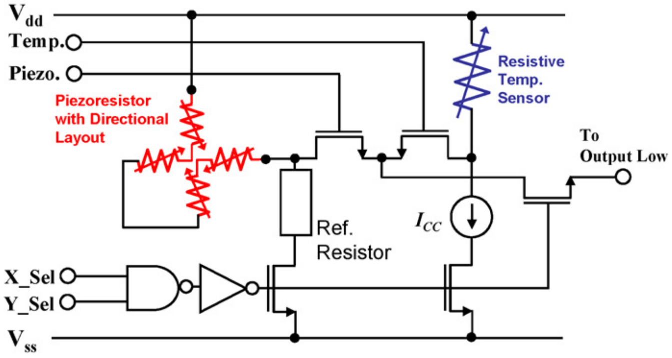

Fig. 2. Circuit configuration of the multifunctional sensor pixel including piezoresistor and resistive temperature sensor. Pixel select logic circuits, sensor driver, and output select switches are also included.

Fig. 2 shows the circuit configuration of the sensor pixel in the tactile imager. The sensor pixel circuit is sensitive to both strain and temperature applied from the touching object. The drive current of the two sensors is supplied through the MOSFETs. The logic circuits have the function of the pixel selection. Sensors in each pixel are only activated during the period which the selection signal of X_Sel and Y_Sel are active (V_{dd}) for the pixel. One of the sensor signals is selected and transferred to the output low by the two switches. A dummy pixel for the reference signal is also integrated around the swollen diaphragm area, which is basically insensitive to the applied input force and temperature of the touching object. The final sensor signals from each pixel are extracted by subtracting the reference signals from the sensor output voltages. The surface shape and the temperature distribution of touching object can be obtained simultaneously by the signals of piezoresistors and temperature sensors in the array.

The operation principles of the two kinds of sensors are explained as following. Contact-force distribution on the sensor diaphragm surface is measured with the piezoresistor array similarly with our previous tactile sensor [17]. The spot of contact-force on the diaphragm creates the spot of surface indentation from the initial surface position in proportion to the force amplitude. Therefore, the surface shape of the touching object can be estimated directly from the image of obtained 2D contact-force distribution. The initial operating point of the pixel output voltage is determined by a divided voltage by the piezoresistor and the reference polysilicon resistor which has relatively negligible stress sensitivity. According to the sensitivity analysis in our previous literature [17], the output potential voltage of the piezoresistor in each pixel can be expressed as the following equation.

$$V_{\text{Pix\_Str}} = \frac{R_{\text{REF}}}{R_{\text{PR\_0}} + R_{\text{REF}}} \cdot (V_{\text{dd}} - V_{\text{ss}}) - \pi_{n\langle 110\rangle} \cdot \frac{V_{\text{dd}} - V_{\text{ss}}}{R_{\text{PR\_0}} + R_{\text{PEF}}} \cdot R_{R_{\text{PR\_0}} \| R_{\text{REF}}} \cdot k \cdot F_X \quad [\text{V}], \qquad (1)$$

where R_{REF} is the poly-silicon resistor, $R_{\text{PR\_0}}$ is the initial resistance of piezoresistor, $\pi_{n\langle 110\rangle}$ is the piezoresistive coefficient of n-type silicon in ⟨110⟩ direction current flow, k is the conversion factor from the average pixel contact-force (F_X) into signal component of stress change on the pixel region, and $R_{R_{PR\_0}\|R_{Poly}}$ is the combined resistance of parallel connection of $R_{\text{PR\_0}}$ and R_{REF}. If an object contacts to the diaphragm surface, the membrane stress is redistributed depending on the shape of the object surface and the total force applied. Surface tensile stress decreases because of the diaphragm bending stress. The corresponding signal is created by the piezoresistive change of n-type piezoresistor as expressed in the second term of Eq. (1). The surface shape of the diaphragm can be obtained as the image of distributed force, which is corresponding to the surface shape of the touching object.