A "MICRO-MACRO" INTEGRATED PLANAR MEMS TACTILE SENSOR FOR PRECISE MODELING AND MEASUREMENT OF FINGERTIP SENSATION

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ABSTRACT

In this study, a novel "micro-macro" planer MEMS tactile sensor integrating two different scales of tactile sensors has been developed for artificial realization of human's fingertip feeling. The "micro-scale" tactile sensor detects "micro surface shape" and "micro-area frictional force" that are generated and detected at a fingerprint on human's fingertip skin. On the other hand, the integrated "macro-scale" tactile sensor detects "overall contact pressure" and "macro-area sliding friction" that are detected by wide-area on fingertip skin. Since the combination of "micro and macro" tactile information has an important meaning in human's fingertip sensation, this tactile sensor realizes multi-scale tactile detection at the same time and at the same point on the sample surface. It will be a very powerful tool for understanding how humans recognize objects using their fingertip skin sensation.

INTRODUCTION

Artificial realization of human's fingertip sensation has been a great challenge for scientists and engineers. Previous macro-scale tactile sensors employs piezoelectric polymer films such as PVDF [1] and pressure-sensitive rubber sheet, and they cannot divide the force into normal force and frictional force independently. On the other hand, tactile sensors for multi-axis force detection [2-4] have been realized in the MEMS field. However, their sensitivity and spatial resolution are actually insufficient to analyze surface micro texture. A high resolution two-axis MEMS tactile sensor [5] and sensing algorithm [6] have been reported for micro texture analysis by our group. However, their sensitivities are insufficient to evaluate soft materials like clothes that human fingerprint can evaluate.

Also, integration of "micro" and "macro" tactile sensor has not been realized even though it's been strongly demanded for reproduction of fingertip sensation. Figure 1 explains concepts of "micro" and "macro" tactile sensation that human's fingertip senses at active-contact recognition. It consists of tactile sensation at fingerprints and sensation detected by the overall skin of human's fingertip. In micro scale sensation, tactile receptors (Meissner's corpuscle) distributed beside each fingerprint detect its vibration motion caused by micro surface textures. Relationship between micro surface roughness and very local friction are perceived by the fingerprints. On the other hand, wide area skin on the fingertip detects "contact pressure" with Merkel's disk and "slipperiness" with Ruffini ending, which depends on the material surface. It is considered that a human perceives fingertip tactile sensation with both information from micro and macro sensations.

In order to realize "micro-macro" integrated tactile sensing like human's fingertip, a highly sensitive two-axis "micro-area" tactile sensor has been developed for softer materials like clothes. Also, a two-axis "macro-scale" tactile sensor component is first integrated on the same die to obtain the information of "overall contact pressure" and "macro-area sliding friction" in this study.

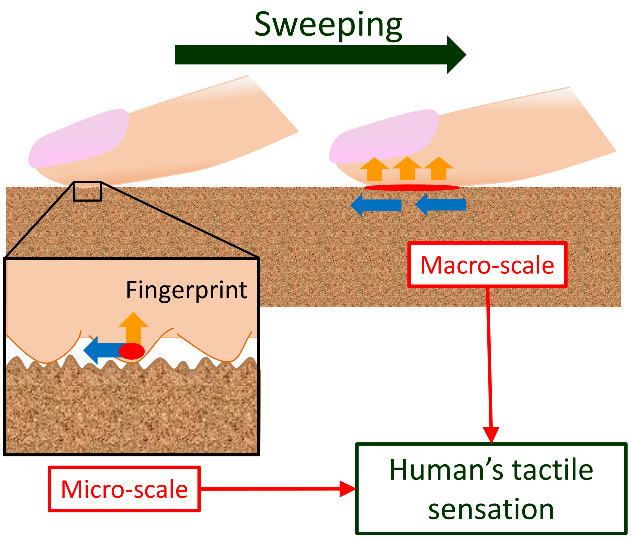

Figure 1: Tactile sensations focusing on "micro-area" and "macro-area". Human's fingertip senses them at active-contact recognition.

CONFIGURATION OF THE SENSOR

Figure 2 shows the configuration of the micro-macro integrated tactile sensor developed in this study. It consists of contactor for micro-scale sensing, two suspension units for independent detection of two-axis motion of the contactor, an inner chip frame including a reference plane structure, a macro-area frictional force sensor integrated in the inner chip frame, and a contact force sensor which detects overall contact force applied to the reference plane and the contactor. The "micro-scale" sensor includes surface shape sensor and micro-area frictional force sensor, while the "macro-scale" sensor includes overall contact sensor and macro-area frictional force sensor. The four sensor structures are fabricated by 50μm-thick SOI layer, and the motion of sensors are detected by full-bridge piezoresistor circuits integrated on silicon spring structures. The circuits of full bridge piezoresistors are fabricated by ion implantation process on the suspensions.

The contactor of the micro tactile sensor is designed to realize similar cross-section with a typical human's fingerprint. On the other hand, the "macro-scale" tactile sensor has a wide contact plane to detect macro area tactile information. Design of the new sensor device is optimized for measurement of soft materials.

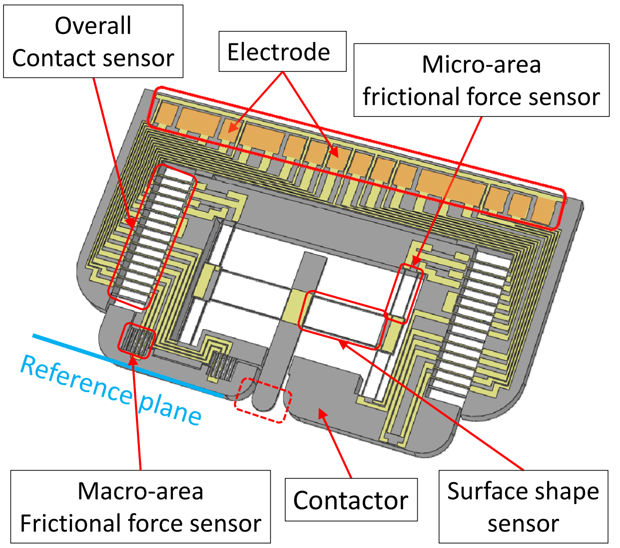

Figure 2: Configuration of the "micro-macro" integrated tactile sensor. The micro-scale sensor includes surface shape sensor and micro-area frictional force sensor, while the macro-scale sensor includes overall contact sensor and macro-area frictional force sensor.

Operation principles of all the sensors in sweeping motion are illustrated in Fig. 3. Normal force (FN) and micro-area frictional force (FMI) are "micro-scale" force inputs that are finally recalculated into "surface shape" and "local frictional force". They are detected by two-axis motion of the contactor. The "overall contact pressure" and "macro-area sliding friction" are calculated from overall contact force (FO) and macro-area frictional force (FMA), respectively. They are detected as vertical motion of the inside frame and sliding motion of the contacting plane. Since these forces are detected by much larger structures than the contactor, "macro-scale" information is detected.

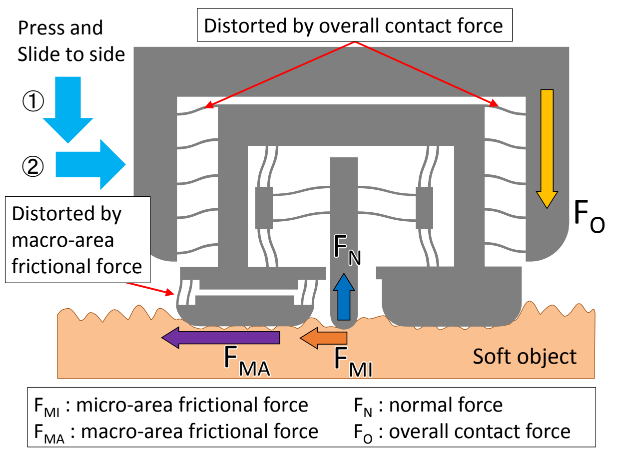

Figure 3: Operation principle of integrated four kinds of tactile sensors under sweeping motion on an object.

Figure 4 shows the CAD layout of the tactile sensor device. The size of sensor chip is 6.0 × 9.9 mm^2. Contactor tip diameter is 500 µm, and it protrudes from the plane of the chip edge by 100 µm. The width of the reference plane to detect the macro tactile information is 7.8 mm. Shapes of components and spring hardness are properly designed for measurement of soft materials like clothes to prevent surface damages and twining of fibers. In our previous device [5], clothes are squashed by the contactor since the spring constant of the suspension units is too high (2.4 mN/µm) to touch soft objects. In this device, since the spring constants of suspension is reduced to 0.05 mN/µm, the contactor can follow the surface of soft samples without large deformation of the shape. Since contact pressure at the contactor is much decreased, frictional force at the contactor tip is reduced too. Therefore, micro-area frictional force sensor is designed to be able to detect small range of frictional force. The reference plane has rounded angle of edge to prevent damage of device coursed by twining of fibers. Full-bridge configuration improves sensitivity and SNR as compared to half-bridge configuration in our previous device.

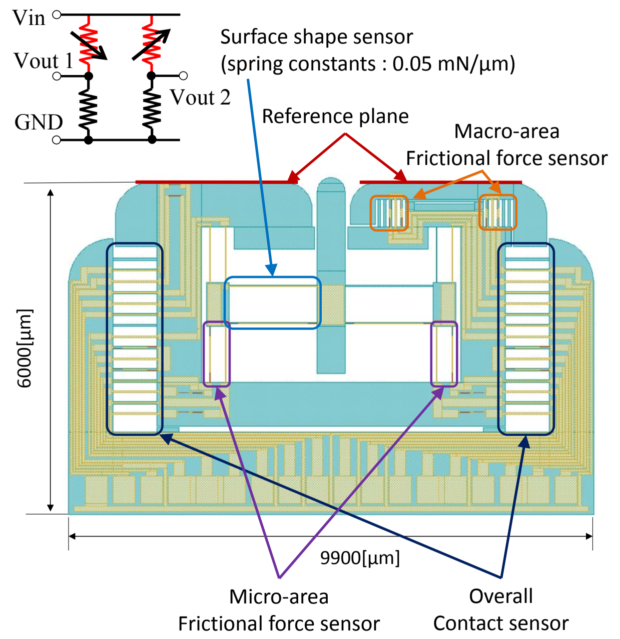

Figure 4: CAD layout of the tactile sensor device.

FABRICATION OF THE SENSOR

Figure 5 shows the fabrication process flow of the tactile sensor. Patterning of the diffusion layer for circuit wiring is performed first on the device layer of SOI wafers using photolithography step. The highly doped diffusion layer is formed by a thermal phosphorus diffusion process for circuit wiring (a). The piezoresistor parts are fabricated by ion implantation process of phosphorus and annealing (b). Cr films are sputtered on both the active layer surface and the back side surface of wafer. They are patterned to form hard mask for the following Deep-RIE (d). The first deep-RIE of the device layer is performed to fabricate the movable structures (e). It is followed by the second deep-RIE process to etch the handle layer under the movable sensor structures. Finally, the BOX layer is etched by HF solution to release the movable structures (f).

Figure 6 shows photographs of the fabricated micro-macro integrated tactile sensor and the details of the sensor chip. As shown in the photographs. The contactor tip, the macro-area sensor integrated in the reference plane, and 17µm-width silicon suspension unit integrating piezoresistors are successfully fabricated as designed.

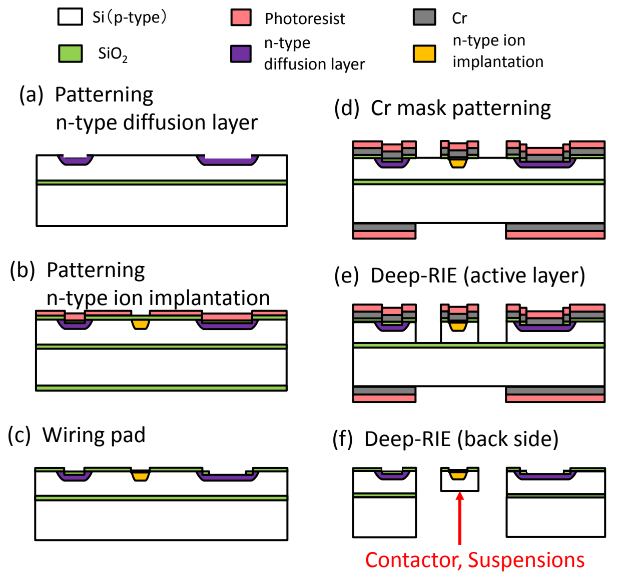

Figure 5: Fabrication process of the tactile sensor device.

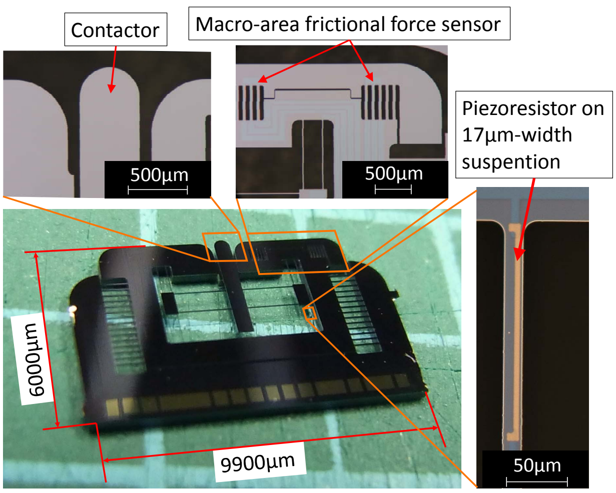

Figure 6: Chip photographs of the fabricated micro-macro tactile sensor device and the details.

DEVICE EVALUATION

Figure 7 shows the experimental setup of device evaluation and a video frame of experiment measuring "plain stitch" sample. The sensor device is fixed to the opposite side of the measured sample, and the measured sample is fixed on the one-axis linear motion stage controlled by a measurement PC. The contactor tip and the reference plane is pushed to the sample surface, and the sample on the movable stage is swept at a constant speed. The scanning speed is controlled to be 1mm/sec in this experiment. During the sweeping motion, the contactor moves up and down according to surface shape of soft plain stitch thanks to the low spring constants. Also, the contactor roles from side to side according to the local frictional force generated at the contactor tip. Damage of the device is not observed after sweeping it on the cloth since edge shapes of the reference plane is designed to prevent catching on the fiber structure of cloth. All the integrated tactile sensors smoothly operated on the soft cloth, even though there are many yarns on the surface that are easy to be entwined with the device.

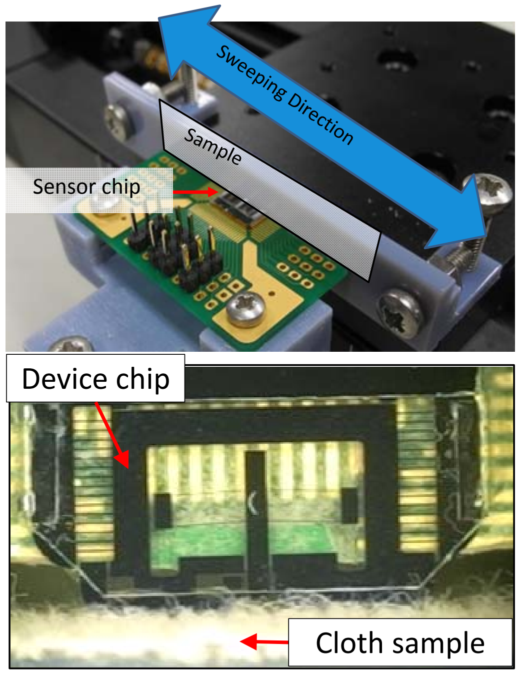

Figure 7: Experimental setup of device evaluation and a video frame of "plain stitch" measurement.

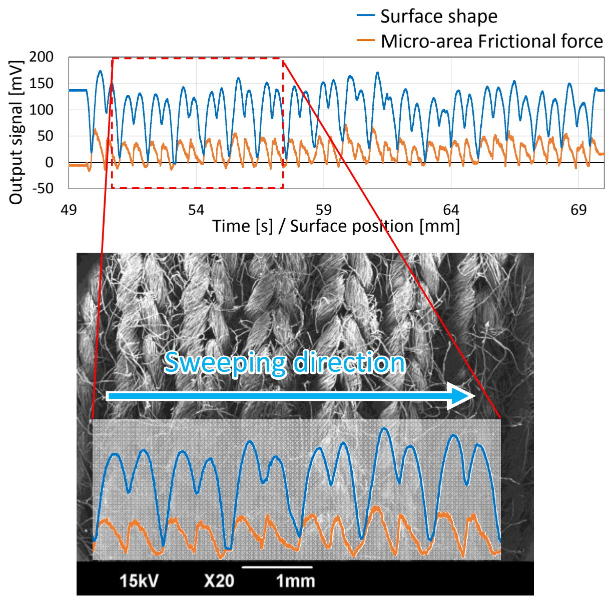

Figure 8: Obtained outputs of the micro-area tactile sensors from "Plain Stich" and comparison with the SEM image.

Figure 8 shows the measured signals of plain stitch obtained from the "micro-scale" tactile sensors. Since the sensor device was swept across the weave of cloth in the experiment, measured surface shape signal (blue line) is expressing the weaving structure of the cloth. As seen in the figure, SEM image of the measured cloth is well corresponding with the shape of the waveform. On the other hand, the waveform shape of local frictional force (orange line) has quite different shape from the waveform shape of the surface shape. This difference is very interesting to understand the mechanism of human feeling of touch. The difference is clearly shown by applying signal processing to the raw signal waveforms.

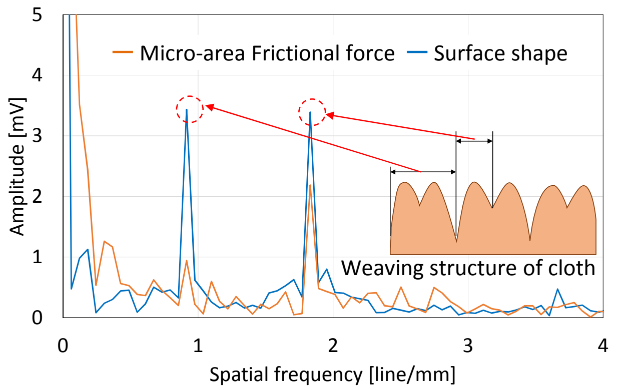

Figure 9: Spatial frequency components in micro-area signals of "surface shape" and "frictional force".

Figure 9 shows the FFT spectrums calculated from the measured waveforms shown in Fig. 8. The blue and orange lines correspond to spatial frequency spectrums of the surface shape and frictional force including characteristic frequencies of the plain stitch, respectively. In the blue line (i.e. surface shape signal), two frequency peaks are appearing at 1mm^{-1} and 2mm^{-1}. The lower frequency peak corresponds to the pitch of plain stitches, while the higher peak corresponds to the pitch of yarn in the stitches. In the orange line (i.e. micro-area frictional force), the lower frequency peak is disappeared in the spectrum. This difference corresponds to the difference of waveforms observed in Fig. 8. These are the features of micro surface texture in the "Plain Stich" that are felt by the micro-area tactile sensor referring human's fingerprint cross-section. The measured resolutions of surface shape and transversal frictional force are 1.25 μm and 0.38 mN, respectively.

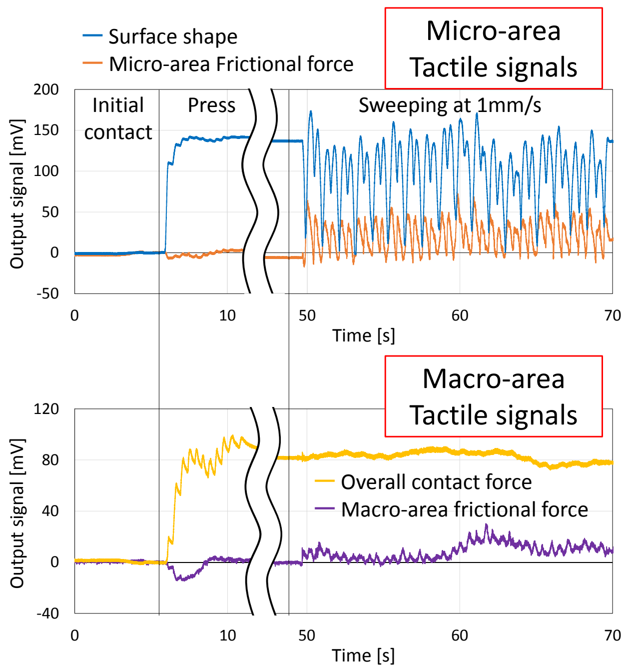

Figure 10: Measured output waveforms of "micro and macro" tactile sensors at the same time and at the same point on the touching object.

"Macro-area" tactile signals was successfully obtained at the same time at the same point in the same experiment as shown in Fig. 10. As seen in the waveforms, overall contact force varies irregularly during the sweep motion. Also, macro-area friction is important in the feeling of touch of cloth. Since soft materials like cloths are deformed by contact pressures, relationship between micro-area tactile signals and the macro-area tactile signals is very important for measuring the tactile sensation of soft materials. Controlling the overall contact pressure in stable, micro-area tactile sensing results are also stabilized.

CONCLUSION

In this paper, a novel "micro-macro" integrated tactile sensor device has been realized to measure "micro surface texture" and "macro-area tactile information" at the same time. The detailed surface shape and the related frictional force of "soft cloth sample" has been successfully analyzed by the fabricated device for the first time.

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