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学位論文題目	Study on Silicon Capacitive Microsensors and Electrostatic Microactuators:Towards a Micro Electro Mechanical System (MEMS) （シリコン静電容量形マイクロセンサと静電マイクロアクチュエータの研究：微小電気機械システム（MEMS）の実現へ向って）
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論文内容要旨

Sensors and actuators play a key role in a control and measurement system. Recent progress in silicon micromachining technology has succeeded in fabricating various three-dimensional microstructures in a silicon substrate. Silicon has also been well known as a good material suitable to mechanical structures due to its excellent mechanical properties. These features lead the silicon microsensors and microactuators to having higher-performance, as well as being smaller in size, than ones which used to be fabricated before. By integrating control and detection circuitry on the same chip as sensors and actuators, less than a millimeter-sized in an overall, a highly functional mechanical system is expected to be realized, which will have a wide application in use for down-sizing portable equipment and medical surgery tools etc. This dissertation describes a study on several critical issues related to silicon sensors and actuators: design as to material and structure selection, manufacturing, and detection and drive circuitry for silicon capacitive microsensors and electrostatic microactuators. Capacitive detection and electrostatic driving methods have been chosen from system consideration in a micron size range.

These selected methods are suitable to making a system smaller, simpler and more effective: Structure similarity of electrostatic microactuators to capacitive microsensors is very useful to simplify an overall system. Good isolation thin films are commonly used in silicon IC process. In a range of less than 5 μm, a high electrostatic field (3×10^{8}V/m) can be used, which corresponds to such a strong force as the magnetic drive force.

At an initial stage in designing the silicon sensors and actuators, knowledge regarding mechanical properties, Young's modulus and residual stress, is essential. A novel measurement technique has been developed, which is based on the rapid collapse of a doubly-supported beam on exerting an electrostatic force load. Only the electric measurement of a pull-in voltage, causing the beam of collapse, provides a value of Young's modulus and residual stress in a thin layer. Preliminary measurement for a heavily boron-doped silicon layer has shown that heavily-boron silicon has a Young's modulus of 2.2×10^{12}dyne/cm^2 (30% higher than that of non-doped bulk silicon) and a residual stress of 1.83×10^{8}dyne/cm^2. Since the test structures occupy a small area, they can be integrated on the same chip as the sensor and actuator chips, providing a test vehicle for process condition monitoring.

Based on thorough knowledge regarding mechanical properties of thin layers, three kinds of capacitive sensors have been developed: pressure sensor (single transducer element), array sensor, and active array sensor.

1) The capacitive pressure sensor form is that of a silicon pressure-sensitive thin diaphragm structure bonded onto a glass substrate. A 1mm square, 3~10 μm thick, silicon diaphragm with a bossed structure on the center has been fabricated, using a deep boron-diffused etching stop technique in conjunction with silicon anisotropic etching technique and silicon-to-glass electrostatic bonding. A small diaphragm deflection in proportion to the pressure is detected by measuring the change in capacitance between a silicon diaphragm plate and a metal plate on a glass. The capacitive sensor has been found to have higher sensitivity and more stable temperature dependence than piezoresistive ones. The temperature dependence for the capacitive pressure sensor has as small a value (60ppm/℃) for offset temperature drift as that for sensitivity in a fabricated CMOS integrated piezoresistive pressure sensor that was carefully trimmed according to measurements on its temperature characteristic. More important, individual sensors have uniform characteristics due to their simple structure, thus producing a very high yield. Switched capacitor-based detection circuitry has been found to greatly suppress the parasitic capacitance induced through the signal line, providing the minimum detectable resolution for a capacitance change as small as 3fF even in the form of hybrid circuitry.

2) A 1024 (32×32)-element capacitive array sensor has been fabricated on the basis of the good knowledge of the capacitive pressure sensors. Individual silicon sensors, having a novel doubly-supported beam structure bonded on a glass substrate, are arranged in an X-Y matrix on

0.5mm centers. The imager chip is fabricated by wet hybrid micromachining: The silicon transducer elements are patterned using deep boron diffusion and bonded on a glass substrate, followed by the silicon wafer dissolution process, which etches an overall silicon wafer except for a boron diffused area. This process features 1) single-sided wafer processing for standard silicon wafers, 2) only four noncritical masking steps for the silicon and two for glass, 3) low-resistance batch lead transfers between silicon row lines and metal lines on glass, 4) very high yield and uniformity in a highly reproducible process, and 5) very high density. Individual force transducer elements in the array have a measured sensitivity of 0.27pF／gf／element with a maximum operating force of about 1gf. The imager, together with the readout circuitry based on a switched capacitor, offers an overall force resolution of 6bits and can be read out at a 15-20μsec／element rate, thus offering a 5.1msec total frame rate using four parallel readout circuitries. This silicon-glass structure has been compared with the polysilicon surface or silicon fusion structures from the view points of process complexity and the scaling behavior concerning sensitivity and resolution. The result indicates that the silicon-glass structure offers the simplest process, has the highest yield and can provide resolution and required for a wide variety of applications. In addition, the coupling effect of packaging related to a glass substrate and a thin plastic film cover has been studied by calculating the cross-talk among individual transducer elements, using a SPICE model. The results have shown that a glass substrate isolates adjacent transducer elements very well and that the coupling through a plastic cover is very small: The transient response due to the substrate bounce voltage is less than 50nsec even for a 1μm thick polymer covered with an aluminum layer. The high-density tactile imager is expected to find a practical application in use for enabling robots to implement parts orientation and identification, bin picking, and sorting, in use for prosthetic gloves used by the handicapped, and in use for finger print detection.

3) A silicon electrostatic ultrasonic transducer has been studied as an example of an active capacitive sensor. The sensor utilizes an electrostatically-generated elastic film vibration to send an ultrasonic wave to a targeted object. It subsequentially receives an ultrasonic wave reflected from the targeted object, which is electrically detected on the basis of a capacitance change measurement. Individual transducer elements performance is strongly dependent both on the size of the holes formed under the vibrating film and the thickness of the isolation layer between the two metal electrodes. One is formed on the film, while the other is patterned on the silicon substrate. The size of individual holes is precisely fabricated using silicon anisotropic etching. The thickness of the isolation layer is precisely defined using a silicon dielectric layer formation, providing a very small distance and good isolation between the two electrodes. The process is very simple and suitable to an array sensor. More importantly, the sensor structure operated in the transmitter mode is very similar to one worked in the receiver mode, where only

a circuit connection to the sensor is different. This simplicity is obtained due to the feature of structure similarity for the capacitive sensor to that for the electrostatic actuator. The transition between the two modes is carried out during the transition time when the ultrasonic wave is transmitting between the transducer and the targeted object. The transducer with a 1 μm thick insulator and 5320-element 40×40 μm squared holes offers the sending sensitivity of 19.1dB (0dB=1 μbar/V) at the vibration frequency of 150kHz and the flat receiving sensitivity of approximately 0.47mV/Pa in a wide frequency range, 10~130kHz. Note that such a high sensitivity has been achieved under as low as a 30V bias. The transducer doesn't provide such a long ringing in the transient characteristic as that of a conventional piezoelectric device, offering such a short minimum detectable distance range as 1.7cm. A linear array of transducer elements can carry out an electrostatic sector scanning using the phased array principle. A preliminary experiment has shown that the main beam direction can be scanned in the ±42 degree range using a 100kHz ultrasonic wave, while keeping half-power beamwidth of the main lobe at 9.0 degrees. This ultrasonic transducer is expected to be used as a proximity sensor enabling robots to achieve a function of collision free movement and accurate approach to a targeted object.

The vibration of a thin polymer film in the ultrasonic transducer has a movement vertical to the substrate surface with a small limited range (less than 1 μm). The movement lateral to the surface with a large distance is realized by silicon microactuators, which are driven by the electrostatic force. Several kinds of silicon microactuators were studied mostly focused on their fabrication technology. On the contrary of a well-known polysilicon surface micromachined micromoter, in this research, a novel fabrication process has been developed for microactuators with much thicker (~20 μm) structure. The microactuators are fabricated by etching a single-crystal silicon wafer and bonding it on a glass substrate. The critical narrow gaps between rotors and stators are formed to be less than 1 μm using anisotropic dry etching and, following the silicon-to-glass electrostatic bonding, silicon wafer dissolution process (dry hybrid micromachining). This process offers an acute vertical wall, while the wet hybrid micromachining forms a rounded shape suitable to sensor structure. A silicon linear microactuator (120 μm wide, 655 μm long, and 10 μm thick) and a 50 μm diameter rotational micromotor have been fabricated using the new process. They have been found to successfully move by the electrostatic force generated by electrostatic voltage. The silicon microactuators represent the first single crystal silicon actuators that are fabricated without any aid from individual parts assembly.

The sensor, actuator and circuit fabricated in silicon features very small size and excellent performance. Due to the structure similarity between the capacitive sensor and the electrostatic actuator, the device structure is greatly simplified. The elaborate combination of these three components is expected to offer a high-performance micro electro mechanical system (MEMS) in the near future. It will be used as a key device in diagnosis and treatment in a small opening tube in a machine or in a human body without serious damage and in use for magnetic／optical disc head or an automatic aligning and focusing scanner in optical equipment. Such a silicon technology-based microsystem will be developed towards the achievement of an "intelligent" micro system in the future.

審査結果の要旨

半導体集積回路に用いられる単結晶シリコンは電子材料としてだけでなく機械材料としても用いることができ，これに微細加工技術を適用することで微小電気機械システムが実現できる。本論文は対向電極構造を基本とした静電容量形マイクロセンサおよび静電マイクロアクチュエータに関するもので，これらの設計指針となる微細構造体の機械特性，触覚センサや超音波センサにおける集積化の問題など，材料からシステムまで総合的に微小電気機械システムの研究を行い，その成果を取りまとめたもので，全編10章よりなる。

第1章は緒論である。

第2章ではシステムをマイクロ化する意義について考察している。

第3章では，シリコンの微細構造を用いたセンサの設計に関して，構造および検出方法の点から検討を加えている。

第4章では，機械的設計に必要な自己支持薄膜構造の機械的な特性を知るため，新しい測定方法を開発して研究を行い，有用な知見を得ている。

第5章では，微小電気機械システムの製作に用いるシリコンの微細加工技術に関して述べている。

第6章では，具体的なシステムとして触覚イメージャを製作した結果について述べている。1024個の力センサを2センチメートル角に配列させた従来にない高密度のセンサが実現されている。

第7章はシリコンの静電マイクロアクチュエータに関するものであり，立体的な構造に作られている点で従来の研究よりも大きく進歩したものである。

第8章では，シリコン基板上に形成した対向電極構造を，超音波を発生するアクチュエータおよび超音波を検出するセンサとして用いる研究についてまとめている。これはセンサとアクチュエータを多数集積化した能動型センサで，ロボット用の近接センサなどとして役立つものである。

第9章は微小電気機械システムに向けて，問題点を明らかにし将来を展望している。

第10章は結論である。

以上要するに本論文では，シリコンの微細加工技術を用いたセンサとアクチュエータを集積化した微小電気機械システムに関して，新しいシステムを具体化することを通して実証的に研究を行い，その設計指針を明らかにしたもので，精密工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。