特集 Super-slim Automotive Acceleration Sensor Applied MEMS Technology*

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Increased performance requirements in terms of the environment, safety and comfort have recently been imposed on automobiles to ensure efficient use of the earth's limited natural resources, as well as safety and comfort in users' lives. To fulfill these requirements, automobiles now incorporate various sensors for feedback control based on the information that these sensors provide. In particular, air-bag technology and other similar safety enhancement technologies, which directly protect human lives, have developed dramatically since they became commercially viable in the late 1980s. An air-bag system incorporates acceleration sensors for collision detection. Such sensors are categorized as critical parts. A current-model automobile with full options would incorporate 10 or more acceleration sensors.

DENSO acquired expertise in MEMS technology when the company first commercialized pressure sensors in 1981. The company made full use of this technology and in 1989 developed and marketed a piezo-resistive semiconductor-based acceleration sensor ahead of its competitors. In the latter half of the 1990s, acceleration sensors used in automobiles had to be miniaturized, intelligent, energy efficient, and be capable of performing self-diagnosis. Of these functions, self-diagnosis was clearly the most important. Various capacitive systems have been developed by applying MEMS technology as well as technology introduced by others.1)2) Subsequently, in 2000 we successfully developed a capacitive semiconductor-based acceleration sensor with a built-in self-diagnosis function, and achieved production growth.

In recent years, however, increased use of automotive acceleration sensors has resulted in increased demand for miniaturization and cost reduction. Under these circumstances, we reconsidered double-sided processing and adopted original surface processing alone, thereby making possible substantial miniaturization and cost reduction.

Key words: Acceleration sensor, Air-bag system, Self-diagnosis function, MEMS technology, Semiconductor sensor

1. EVOLUTION OF THE MEMS PROCESS

DENSO took up proprietary investigation of semiconductor sensors because there was high potential for these in the 1970s. **Figure 1** shows our status of development. We developed a manifold air pressure sensor using MEMS technology that combined a silicon piezo-resistor, liquid phase single crystal silicon deep anisotropic etching, and anodic bonding technology between silicon and Pyrex glass in 1983. Furthermore, in 1989 we commercialized an acceleration sensor for automobile airbag systems with applied pressure sensor technology. Additionally, in 1991 we introduced a single-chip manifold air pressure sensor integrated with bipolar transistor circuit using laser trimmed thin film resistors (**Fig. 2**).

Subsequently, in 1995 we developed high precision pressure sensors using boron aluminum silicate glass that had approximately the same thermal expansion coefficient of silicon. We used the back side process from 1983. In the next generation of these devices, we developed a double sided process using both front and back side processing. We reduced the element area of acceleration sensors to 17% using electrochemical etching technology, and applied this technology to pressure sensors for further miniaturization, and to acceleration sensors for low acceleration velocity.

In the latter half of the 1990s, acceleration sensors had to be capable of performing self-diagnosis. It was not possible, however, to equip piezo-resistive acceleration sensors with a self-diagnosis function. Subsequently, in 2000, we successfully developed a capacitive semiconductor-based acceleration sensor using vertical trench etching and SOI substrate, with a built-in self-diagnosis function. The capacitive acceleration sensors are

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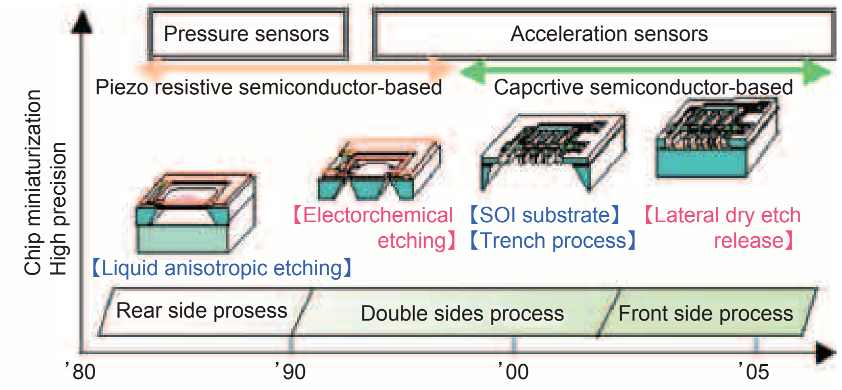


Fig. 1　Status of development

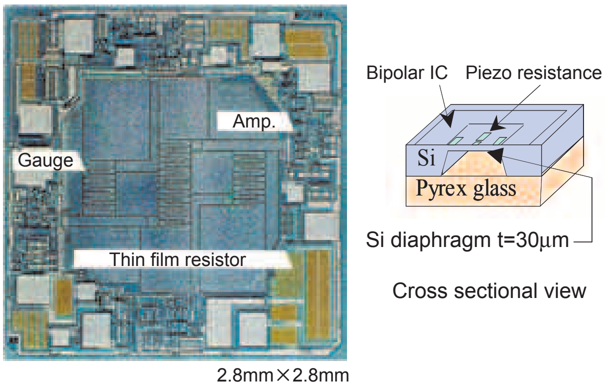


Fig. 2　Integrated pressure sensor

composed of fixed electrodes and moving electrodes attached to a beam that moves in response to acceleration, the capacitance varies as the beam moves, and these variations are converted to electrical signals using a capacitor-voltage converter. We were able to realize self-diagnosis by applying voltage between the fixed and movable electrodes in order to reproduce the application of acceleration.

In recent years, we reconsidered the double-sided processing of wafers needed for conventional capacitive acceleration sensors and adopted original surface processing alone that we called lateral dry etch release, thereby making possible substantial miniaturization and cost reduction.

2. CONSTRUCTION AND WORKING PRINCIPLE OF CAPACITIVE ACCELERATION SENSORS

A cross-sectional view of a comb-sh29.398 mmaped capacitive acceleration sensor is shown in **Fig. 3**. This acceleration sensor consists of a movable electrode that is connected to a beam, a weight, and two fixed electrodes.

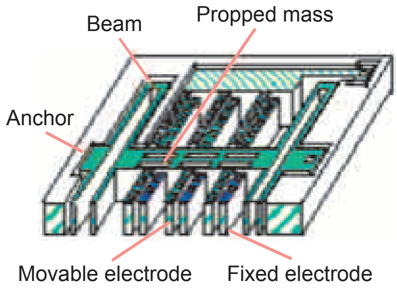


Fig. 3　Cross-sectional construction of capacitive acceleration sensor

The working principle of the capacitive acceleration sensor is shown in **Fig. 4**. When the sensor is accelerated, it detects the acceleration according to the capacity change between the movable and fixed electrodes. As long as the sensor is not subjected to any acceleration, the capacity between the movable electrode and two fixed electrodes C1 and C2 remain unchanged and are equal to each other as shown in **Fig. 4a**. When the sensor is accelerated, the capacities between the movable and fixed electrodes C1 and C2 change as shown in **Fig. 4b**. An accelerometer utilizing this type of sensor determines the acceleration value quantitatively according to the difference between C1 and C2. Capacitive acceleration sensors have the advantage that they can be provided with a self-diagnosis function that is indispensable for automotive applications. The self-diagnosis system produces a pseudo acceleration to check the acceleration sensor for normal functioning. The detectable acceleration range of the sensor can be designed by properly setting the mass of the weight and the spring constant with the beam.

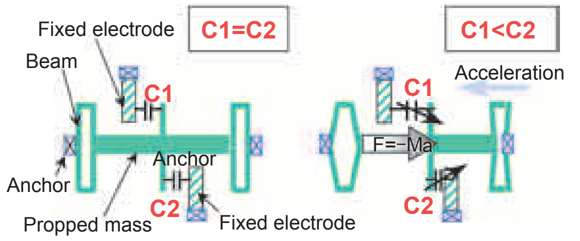


Fig. 4 Working principle of capacitive acceleration sensor
(a) Under no acceleration
(b) Under acceleration

3. CONVENTIONAL ACCELERATION SENSOR FABRICATION PROCESS

A sacrifice layer etching process that removes the oxide film from the wafer surface by etching[3] has been widely used to fabricate general purpose capacitive acceleration sensors. However, this process has the disadvantage that it is likely to disable the accurate functioning of the sensors. Being a wet process that uses HF or other solution, this process permits water to enter into clearances as small as several μm between the beams and between the substrates beneath the movable structures. As the water dries, its surface tension deforms the movable structures and allows the opposing electrodes or substrates to stick to each other, preventing the sensors from functioning normally. Therefore, a dry release process is desirable. We developed a capacitive acceleration sensor fabrication process that releases the movable structures by etching the back surface in a dry condition, and have introduced this process at an international congress.[4]

The wafer process flow we have conventionally used for fabricating capacitive acceleration sensors is shown in **Fig. 5**. Each step is described below.

Our conventional capacitive acceleration sensors are fabricated from SOI wafers having an SOI thickness of 15μm, a laminated oxide film thickness of 2μm, and a substrate thickness of 625μm. To assure ohmic contact with Al, an N-type zone is formed on the SOI layer by diffusing phosphor and then an Al film is formed. After patterning, bonding pad electrodes are formed (a). After the wafer is cut and polished on the back surface, a SiN film is formed on the back surface and patterned (b). After the SOI layer surface is patterned using a resist, the surface is vertically etched in a comb shape by an ICP-RIE apparatus using the resist mask until it reaches the buried oxide (c). This ICP-RIE process uses successive etch and passivation steps to make the vertical comb electrode. A protective resist is applied over the wafer surface. Using the SiN film that was previously formed on the back surface as the mask, the Si substrate is unisotropically etched with KOH solution until the buried oxide film appears (d). The resist is then removed from the surfaces (e). The buried oxide film is removed by dry plasma etching that uses an etching gas containing CF4/CHF3, and the movable structures are released from the back surface of the wafer (f). Since this process releases the movable structures in a completely dry condition, these structures never stick to each other. However this process inevitably leaves tapered edges on the back surface because of isotropic Si etching with KOH solution, which obstructs chip size reduction. This process also has the disadvantage that it consists of many steps because it treats both surfaces.

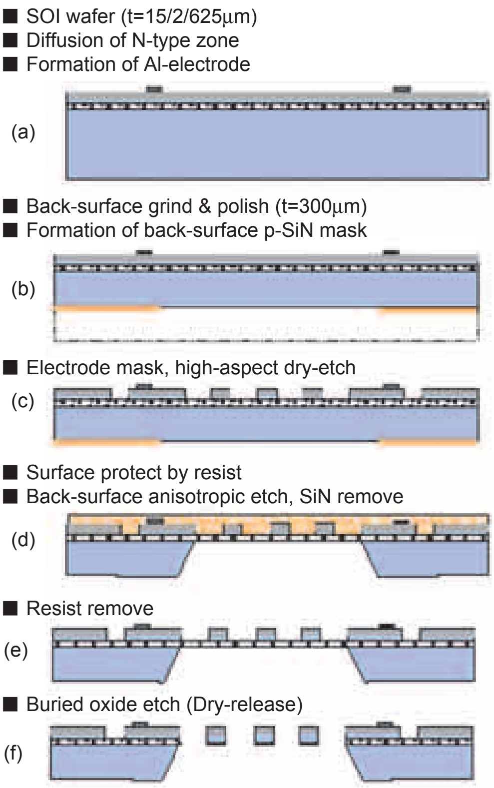


Fig. 5 Process flow of conventional capacitive acceleration sensor

4. SUPER SLIM AUTOMOTIVE ACCELERATION SENSOR

Today, the demand for smaller-sized and lower-priced acceleration sensors is increasing. To meet such user demands, we recently improved our conventional acceleration sensor fabrication process by introducing surface MEMS technology, and developed a super-slim automotive acceleration sensor. In the new process, we combine two innovative techniques to process single-crystal SOI wafers: a vertical Si etching technique using ICP-RIE, and a lateral etching technique along the buried oxide film. SOI interface to release movable structures.5)

4.1 Wafer process flow

The new wafer process flow for capacitive acceleration sensor fabrication is shown in **Fig. 6**. Each process step is described below.

The raw materials for these sensors are SOI wafers having an SOI thickness of 18µm, a laminated oxide film thickness of 2µm, and a substrate thickness of 400µm. Compared with wafers used in our conventional process, the new wafers feature a thinner substrate to ensure size reduction and a thicker SOI layer to assure sufficient capacity even after size reduction. To assure ohmic contact with Al, an N-type zone is formed on the SOI layer by diffusing phosphor and then an Al film is formed. After patterning, bonding pad electrodes are formed (a). After the SOI layer surface is patterned using a resist, the surface is vertically etched in a comb shape with an ICP-RIE apparatus until it reaches the buried oxide, in the same way as the conventional process (b). The removable structures are released by lateral etching along the oxide film-SOI interface. The resist is finally removed by O_2 ashing (c).

Table 1 compares the new process with the conventional process in terms of the number of process steps. Requiring only three masks, the new process dramatically reduces the number of process steps.

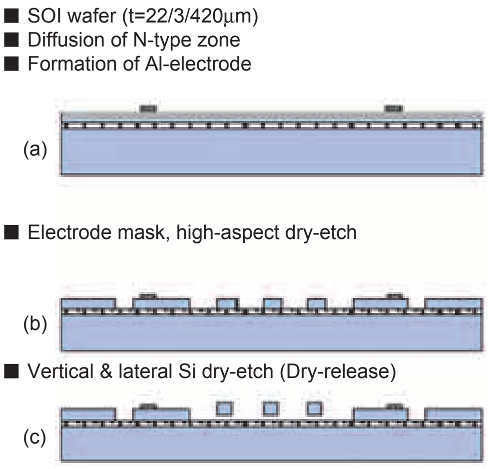
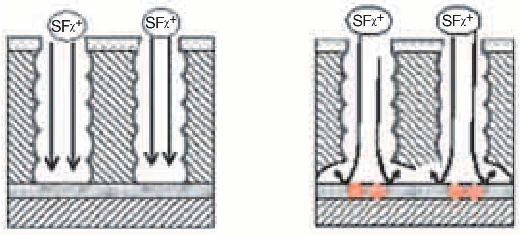


Fig. 6　Process flow of super-slim automotive acceleration sensor

Table 1　Comparison of the number of process steps

	Conventional	Super slim
Chip size	1.8 x 1.8mm	1.4 x 1.4mm
Number of process step	20	12
Photolithography	4	3
Deposition	3	2
Oxidization/Diffusion	3	3
Back side grinding	1	0
Etching	9	4



(a)　(b)

Fig. 7　Mechanism of lateral etching

4.2 Newly introduced lateral etching

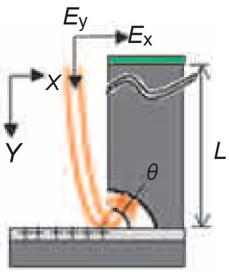
The lateral Si etching mechanism, which is the outstanding feature of our new process, is shown in **Fig. 7**. In lateral etching, high aspect ratio vertical Si etching is first carried out. This vertical Si etching is widely used in MEMS processing. Following this step, the ICP-RIE apparatus performs lateral Si etching along the SOI film-buried oxide film interface to release the movable structures. For lateral etching, the buried oxide film is electrically charged to reflect and laterally repel the incoming etching ions. The repelled ions etch the substrate in the lateral direction.

Our new etching mechanism is characterized by the following features. During vertical etching, an antistatic function is activated so that the electrode bottom (buried oxide film interface) will not produce any notches. Therefore, the vertical walls (electrode side faces) are etched without notch formation (**Fig. 7a**). Following this step, the antistatic function is deactivated to electrify the buried oxide film so that lateral etching will progress along the buried oxide film-SOI interface (**Fig. 7b**) until the movable structures are released.

Since the etching ions are positively charged during etching, the buried oxide film is also charged positively as the etching progresses. The positive electric charge reflects and laterally repels the incoming etching ions. The repelled etching ions laterally etch the buried oxide film–SOI interface as shown in **Fig. 8**. The etching ion reflection angle θ can be determined from Equation 1. Since the incident speed Vs is proportional to the lead-in voltage, etching along the buried oxide film-SOI interface can be controlled by controlling the lead-in power.

$$\tan\theta = \frac{E_y(V_s^2 - 2eE_yL)^{1/2}}{E_x\{V_s - (V_s^2 - 2eE_yL)^{1/2}\}} \quad \text{(Equation 1)}$$

We carried out an experiment to clarify the effect of ion lead-in voltage on the etched shape. The results of the experiment are shown in **Fig. 9**. We used etching height H and etching width L as the etched shape evaluation parameters. As the lead-in power decreased, the reflection angle decreased and deteriorated the lateral shape. As the lead-in power increased, the aspect ratio (H/L) of the etched shape increased and finally exceeded 1.0. This means that a large lead-in power will excessively etch the upper portion of each electrode and will thereby lower the acceleration sensor performance. The above experimental results show that an ideal etched shape having an aspect ratio of nearly 1 (which means that etching height is almost equal to etching width) can be obtained by suitably controlling the lead-in power.



θ: reflection angle
Vs: incident speed ∝ lead-in voltage
E(x,y): electric field
∝quantity of electric charge
L: electric field range

Fig. 8　Reflection of etching ions

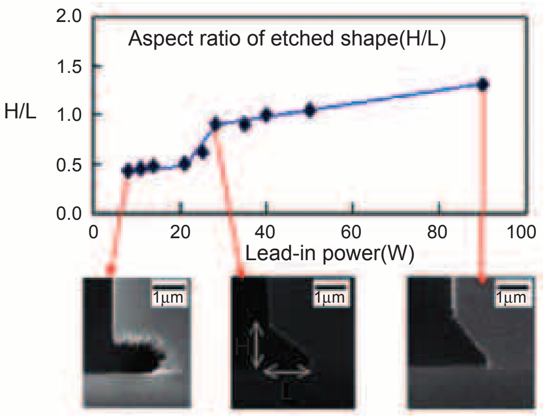


Fig. 9　Lead-in power vs. aspect ratio of etched shape (H/L)

5. PRODUCT EVALUATION RESULT

Photographs of a conventional acceleration sensor and a sensor chip made by the newly developed process are shown in **Fig. 10**. We successfully fabricated sensor chips as small as 1.4mm×1.4mm, which is 40% smaller than conventional 1.8mm×1.8 mm chips.

An SEM photograph of the sensing element of a sensor chip made by the new process is shown in **Fig. 11**.

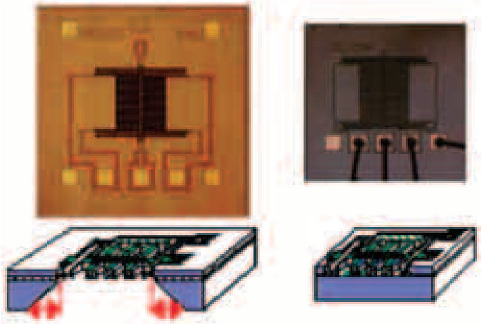


Fig. 10　Conventional vs. super-slim sensor chips
(a) Conventional sensor
(b) Super-slim sensor

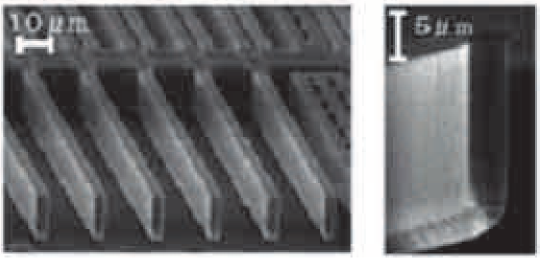
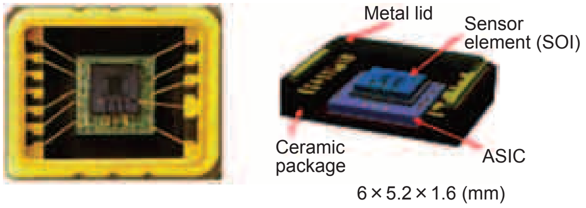


Fig. 11　Sensing element of sensor chip made by the new process
(a) Cross-sectional view of movable electrode
(b) Enlarged view of movable electrode

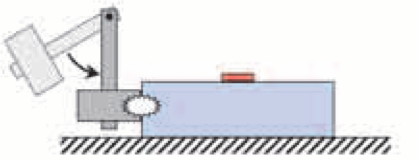
Photographs of a newly developed acceleration sensor assembly are shown in **Fig. 12**. The new sensor assembly consists of a ceramic package in which a censor chip is stacked on an ASIC.

The shock response test result for a new sensor is shown in **Fig. 13** as an example of its output characteristics. The shock response test method is shown in (a) in the figure. A shock load is applied to the specimen with a pendulum and the output was compared with the reference curve. The result is shown in (b) in the figure. As can be understood from the figure, the sensor output closely correlates with the reference curve with a correlation factor of 99.5%.

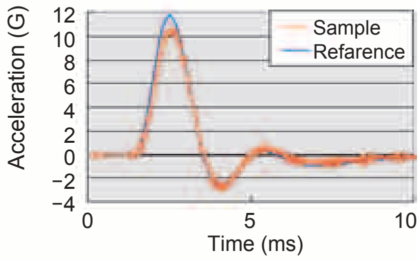


(a) (b)

Fig. 12 Assembly of newly developed acceleration sensor
(a) Package
(b) Cross-sectional view



(a) Pattern diagrams of the test



(b) The results of the test

Fig. 13 Impact response test

6. CONCLUSION

We developed an extremely small-size (super-slim) acceleration sensor fabrication process by applying surface MEMS technology and have already put the sensors into volume production. Our acceleration sensor fabrication process uses SOI wafers, and combines a vertical Si etching technique using an ICP-RIE apparatus, and an innovative lateral etching technique that enables dry release of the movable structures. The new acceleration sensor is 40% smaller than this conventional capacitive acceleration sensors. Requiring only three masks, our innovative sensor fabrication process has dramatically reduced the number of process steps.

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