Air Damping Characteristics of Integrated Accelerometers with a Single-Side Air Gap

H. Muro, S. Kiyota, S. Uchikoshi and R. Himeno

Nissan Motor Co., Ltd.
1, Natsushima-cho, Yokosuka 237, Japan

Summary

In this paper, damping characteristics of piezoresistive integrated silicon accelerometers, in which a micro-machined seismic mass is suspended by four narrow beams from the surrounding frame that incorporates peripheral circuitry and squeeze film damping effect is provided by a single-side air gap under the seismic mass, were analyzed and numerically calculated. The output waveforms for applied sinusoidal accelerations are different from those of accelerometers with symmetrical air-gap structure when subject to large accelerations. The calculated results are compared with measured characteristics of the fabricated devices.

Keywords: *accelerometer, micromachining, integrated sensor, air damping and squeeze-film effect*

1. INTRODUCTION

With increasing needs for low cost accelerometers for automotive uses, typified by airbag systems, various types of silicon accelerometers using micromachining technology have been developed in recent years[1]-[8]. They have many attractive features concerning the size and productivity with batch fabrication process. Moreover signal processing circuitry can be integrated on the same sensor chip in order to facilitate more compact packaging and improve the reliability[6]-[10].

The piezoresistive accelerometers can be easily fabricated by forming the circuit on a silicon substrate using the conventional IC process and etch the substrate from the back side to construct a seismic mass suspended from the surrounding frame by thin narrow beams [7]-[9]. Electrochemical etching techniques are often used to control the beam thickness, mostly in combination with bipolar process where n-type epilayer is used as the beams [11]. The integration technology is also applied for capacitive ones, although mainly for those using surface micromachining technologies[6].

In developing the available silicon micromachined accelerometers, technologies of oil damping or air damping are usually used to suppress the beam resonance and attain sufficient shock resistivity. Oil damping requires no additional structures and is realized only by immersing the beam and the mass in damping liquid, such as silicone oil, which, however, has large temperature dependence of viscosity[7],[8].

On the other hand, air damping is provided by the squeezed-film effect in a narrow air gap between the moving mass and the planes opposed to it[1]-[4]. The air gaps with only a few micronmeter width can be formed by bonding a base plate and a cap plate, each

with depressions faced to the mass, to both sides of silicon micromachined substrate as shown in Fig.1a. This structure is completed during the wafer fabrication process and the divided chips can be packaged easily compared with the oil damping ones.

For the air damped accelerometers with such a sandwich structure most of the surface area of the frame is consumed for bonding of the cap plate, which makes it difficult to integrate peripheral circuitry on the frame and consequently results in large increase of the chip size for integrating the circuitry.

An alternative choice on air damping in accelerometers is to form only a single air gap at the bottom side of the mass and utilize the frame surface for circuit area as shown in Fig.1b, where the damping may be alleviated for large accelerations when the mass moves away from the base plate. In this paper, the damping characteristics of the accelerometers with a single side air gap are studied theoretically and experimentally.

2. DAMPING CHARACTERISTICS

The dynamic behavior of the mass-spring system, found in the silicon accelerometer, is determined by the following motion equation [1],[2] :

$$m \frac{d^2 x}{dt^2} + \lambda \frac{dx}{dt} + kx = m a(t) \quad \cdots (1)$$

where m is mass, λ is the viscosity damping coefficient, k is the spring constant of the beams, x is the displacement of the mass, and $a(t)$ is the applied acceleration. The viscosity damping is caused by the squeeze film effect in the air gap and can be calculated by solving the Navier-Stokes equation under the assumption of small Reynolds numbers [12],[13]. The

Fig.1 Cross-sectional structures of the silicon micromachined accelerometers with air gaps.

viscosity damping coefficient, λ , is expressed by the form of an infinite series expansion using a squeeze number, σ , as a parameter :

$$\sigma = \frac{12 \mu \omega l^2}{d^2 P_a} \quad \dots (2)$$

in which P_a is the ambient gas pressure, ω is the frequency, μ is the viscosity coefficient, d is the gap width, and l is a characteristic length which in the case of a square mass equals the side length of the mass. At low squeeze numbers, where the oscillation of the mass is slow enough so that compressibility effect can be neglected, the damping coefficient for parallel square plates becomes [14],[15] :

$$\lambda = \frac{0.42 \mu S^2}{d^3} \quad \dots (3)$$

in which S is the area of the plate.

The characteristics of squeeze film damping will be modified when the displacement of the mass become significant with respect to the gap width. The viscosity damping coefficient with a large displacement can be calculated by multiplying it by a displacement factor as [15] :

$$F_D = (1 - \epsilon)^{-\frac{3}{2}} \quad \dots (4)$$

where ϵ is the ratio of the mass displacement to the gap width.

Although these analyses are mainly focused on symmetrical damping for sinusoidal accelerations, the accelerometers with a single side air gap as shown in Fig. 1b will be asymmetrically damped for large accelerations, that is, the moving mass is less damped when displaced away from the base plate. In order to evaluate this effect on the damping characteristics by simple numerical calculations, the motion equation (1) was modified by replacing the gap width, d , used in the damping coefficient by that under the mass displacement, $x + d$, resulting the following equation.

$$m \frac{d^2 x}{dt^2} + \frac{\lambda}{(1 + \frac{x}{d})^3} \frac{dx}{dt} + kx = m \alpha(t) \quad \dots (5)$$

or

$$\frac{d^2 x}{dt^2} + \frac{\beta}{(1 + \frac{x}{d})^3} \frac{dx}{dt} + \omega_0^2 x = \alpha(t) \quad \dots (6)$$

where ω_0 is the resonant frequency $= (k/m)^{1/2}$ and β is the ratio of the viscosity damping coefficient to the mass $= \lambda / m$. β is related to the 3dB cutoff frequency, ω_a , through the equation :

$$\beta^2 = \frac{\omega_0^4 + 2\omega_a^2 \omega_0^2 - \omega_a^4}{\omega_a^2} \quad \dots (7)$$

The damping characteristics for sinusoidal accelerations were calculated by solving the differential equation (6).

3. DEVICE FABRICATION

The prototype of the integrated accelerometer was designed to detect medium range acceleration of about 50G with frequency response up to several hundred Hz. Fig.2 shows a photograph of the fabricated accelerometer chip. Silicon seismic mass with a area of 1.5mm×1.5mm and weight of about 1.4mg is suspended from the surrounding support by two pairs of thin silicon beams from both sides. The beams are 400 μ m long, 340 μ m wide, 9 μ m thick and arranged along the <110> direction of the silicon substrate. A pair of p-type piezoresistors are formed on each beam near both ends of the beam to construct a Wheatstone bridge circuit with cross-sensitivity compensation. The applied acceleration is detected piezoresistively through a change in the bridge output voltage.

On the frame, the peripheral circuitry is integrated for signal conditioning of the bridge output, whose sensitivity is about 150 μ V/G. These circuits are formed by conventional bipolar process, whose epilayer is also used as the beams by applying electrochemical etching. The fabrication process of this integrated accelerometer is shown in Fig.3.

(a) The starting material is (100) 10 Ω cm both-side

Fig.2 A photograph of the fabricated integrated accelerometer.

Fig.3 A fabrication process flow diagram of the integrated accelerometer.

polished p-type silicon substrate with a $2\Omega\text{cm}$, $9\mu\text{m}$ thick n-type epilayer. Several diffusions are performed to form bipolar circuitry. The piezoresistors are formed by implanting boron with a dose of $3 \times 10^{15}/\text{cm}^2$.

(b) After forming aluminum interconnections, the back side silicon oxide layer is patterned. The p-type substrate is electrochemically etched from the back side by hydrazine solution using the three-electrode method. During the etching process n-type epilayer was positively biased to create an etch stop and the beams. (c) Pyrex glass is used for the base plate, where grooves are etched in the regions of the air gap by buffered HF. The glass substrate is bonded to the sculptured silicon substrate using the anodic bonding

technology, resulting in an air gap of about $1.8\mu\text{m}$ width under the released mass.

4. EXPERIMENTS

The bonded wafers were divided and each chip was mounted and sealed at atmospheric pressure with a standard metal package. The packaged sensor was attached to a shaker and the output waveform from the sensor was monitored by a digitizing oscilloscope. The vibration frequency was scanned from 100Hz to 10kHz with acceleration level up to 100G (980m/s^2). The measured outputs were expressed in gravity unit, G, by dividing them by the sensitivity measured at input acceleration of 10G.

Fig.4 and Fig.5 show the measured output waveforms of the fabricated accelerometer with vibration conditions of 500Hz/50G and 2kHz/100G, respectively. The waveforms calculated by the equation (6) with the fitting parameters of $\beta = 143\text{kHz}$ and $\omega_0 = 50\text{kHz}$, which agree reasonably with the values calculated using the device dimensions, are also shown by dotted lines. As the amplitude and frequency of the input accelerations increase, the air damping effect increases, resulting in asymmetrical output waveforms. These asymmetrical responses were evaluated by measuring the output amplitudes of maximum and minimum values as shown in Fig.6. The frequency responses of measured amplitudes, V_H and V_L , at input accelerations of 50G and 100G were plotted in Fig.7 with the corresponding calculated curves. As the acceleration frequency increases, V_L begins to decay at frequency higher than 500Hz, while the frequency response of extends beyond 1kHz,

Fig.4 Output waveforms at 500Hz/50G.

Fig.5 Output waveforms at 2kHz/100G.

Fig.6 Waveform parameters, V_H and V_L .

Fig.7 Frequency responses of V_H and V_L at 50G and 100G accelerations.

whose 3dB cutoff frequencies lie in 2~4kHz. (These frequency bandwidths are sufficient for various practical applications such as airbag systems.) As expected, V_H and V_L curves behave as if they had different damping coefficients, where the difference increased with input accelerations. The measured results agree reasonably with the calculated ones, although there are considerable measurement errors at frequencies higher than 2kHz due to the parasitic resonances of the attachment or the shaker itself.

5. CONCLUSIONS

In this paper, a piezoresistive integrated accelerometers with a single side air gap under the seismic mass have been described. The damping characteristics of such accelerometers were numerically calculated simply by modifying the motion equation. The prototypes of such accelerometers were designed and fabricated, whose measured results agreed reasonably with the calculated ones.

6. ACKNOWLEDGEMENTS

The authors wish to thank the members of the Electronics Production Department, Nissan Motor Co., Ltd. for their help in the fabrication of the devices.

(Manuscript received March 29, '96, revised August 30, '96)

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Hideo Muro

He received his B.S. and M.S. degrees in electrical engineering from Tokyo university, Tokyo, Japan, in 1976 and 1978, respectively. Since joining Nissan Motor Co., Ltd. in 1981, he has been engaged in developing silicon sensors.

Shigeyuki Kiyota

He received his B.S. and M.S. degrees in electronic engineering from Keio university, Kanagawa, Japan, in 1987 and 1989, respectively. He has been working at Nissan Motor Co., Ltd. since 1989.

Susumu Uchikoshi

He received his B.S. and M.S. degrees in physics from Keio university, Kanagawa, Japan, in 1989 and 1991, respectively. He has been working at Nissan Motor Co., Ltd. since 1991.

Ryutaro Himeno

He received his B.S. and M.S. degrees in electrical engineering from Kyoto university, Kyoto, Japan, in 1977 and 1979, respectively. He joined Nissan Motor Co., Ltd. in 1979. He served as a researcher at the Institute of Space and Astronautical Science, Japan, from 1984 until 1986. He received his D.E. degree in applied physics from Tokyo university, Tokyo, Japan, in 1988. He is currently a Senior Researcher in Computational Fluid Dynamics at Nissan Research Center.