

HEWLETT PACKARD'S SEISMIC GRADE MEMS ACCELEROMETER

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ABSTRACT

HP has recently made its plans to develop an ultrahigh-resolution seismic sensing solution public. This solution is being developed with Royal Dutch Shell Corporation for oil and gas exploration [1]. Central to delivering this system is HP's new single axis seismic grade MEMS accelerometer. The HP device uses both bulk micromachining methods and standard thin film technologies as well as HP's new three phase sensing technology. This sensor detects motion when an array of electrodes located on the proof mass moves relative to a stationary array of electrodes across a fixed gap. Initial characterization shows a flat noise power spectral density of < 100 nG/√Hz over a bandwidth of DC-200 Hz. The device exhibits a linear response to +/- 150mG with a sensitivity of over 25 V/g within the specified bandwidth.

INTRODUCTION

Background

The oil and gas industry requires high-quality seismic data to accurately locate and evaluate the viability of new wells. Deep oil and gas deposits require low frequencies to image. A major limitation of geophones and the leading MEMS seismic sensors on the market is that their performance below 10 Hz is limited. The frequency response of geophones rolls off below 10Hz, while MEMS sensors suffer from low frequency noise. An opportunity exists for a low noise, low frequency sensor that can be practically deployed in systems >300,000 nodes. The wasted cost associated with locating and drilling non-productive wells could be substantially reduced with low noise, low frequency MEMS seismic sensors. HP, along with Royal Dutch Shell Corporation, is developing a MEMS based seismic sensor designed to meet this need. In this paper we will present the operation, method of manufacture, and some of the performance characteristics of the device.

Inertial Capacitive Accelerometer

Device performance of an inertial sensor utilizing a capacitance sensing technique is primarily determined by the proof mass size, damping characteristics, and change in capacitance as a function of displacement (dC/dx). The thermal mechanical noise floor is determined by the proof mass size and damping coefficient [2]. In the quasi-static limit of a mass spring damper, the force applied to the proof mass is equal to the restoration force applied by the suspension, shown as

$$kx = ma, \quad (1)$$

where m is the proof mass, k is the spring stiffness of the suspension for the proof mass, a is the applied acceleration and x is the resulting displacement of the proof mass.

Assuming a linear response yields

$$\frac{\delta x}{\delta a} = \frac{m}{k} = \frac{1}{\omega_f^2} \quad (2)$$

where ω_f is the angular resonant frequency of the spring-mass system. The capacitance change per unit of acceleration (dC/da) is then

$$\frac{\delta C}{\delta a} = \frac{\delta C}{\delta x} \frac{\delta x}{\delta a} = \frac{\delta C}{\delta x} \frac{1}{\omega_f^2} \quad (3)$$

which illustrates the importance of a large dC/dx .

Capacitance is linearly proportional to the area, A , of the electrodes and inversely proportional to the gap, g , between them. A sensor can therefore utilize a change in area or gap to get a corresponding change in capacitance. Gap changes can create a relatively large dC/dx , however the response is non-linear. In addition, the dynamic range is inherently limited by the gap. In practice, these limitations are addressed by using a closed loop, force feedback system, which forces a trade off in sensitivity for complexity and higher power consumption. Conversely, capacitive sensors based on an area change can have linear responses; however, achieving a large dC/dx requires a small gap.

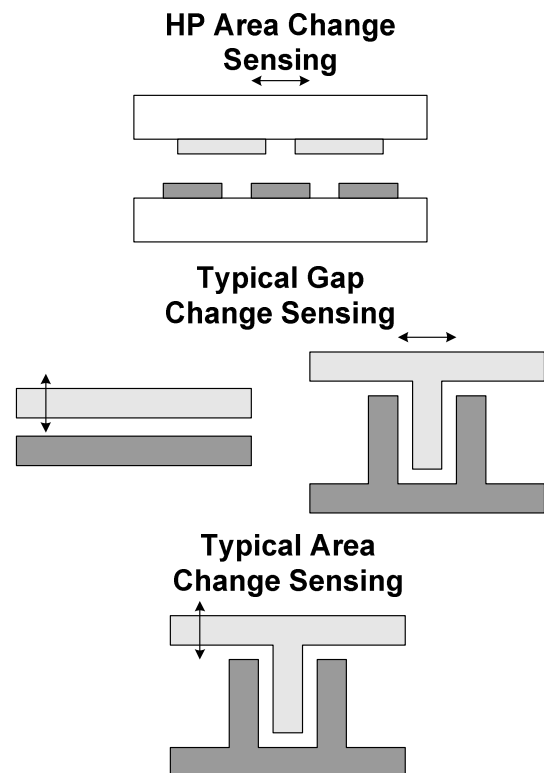


Figure 1: HP sensing scheme compared to typical gap and area change designs

There are several ways to measure the variable capacitor, including quantifying the charge build-up due to a fixed potential, monitoring the output of a feedback loop which maintains a constant electric field across the capacitor, or measuring the attenuation of an AC signal passing through the capacitor. The HP accelerometer utilizes the third method because of its ability to measure a DC response and does not require increased complexity and power consumption of a closed loop force feedback system.

DEVICE OPERATION

The majority of bulk micro-machined multi-wafer MEMS accelerometers utilize a gap closing scheme between device wafers or a comb finger sensing scheme on a single device wafer [3,4]. The travel of these devices is inherently limited to the size of the gap between the plates or combs. HP's accelerometer is unique because the axis of sensing is orthogonal to the gap and electrodes [5], illustrated in Figure 1.

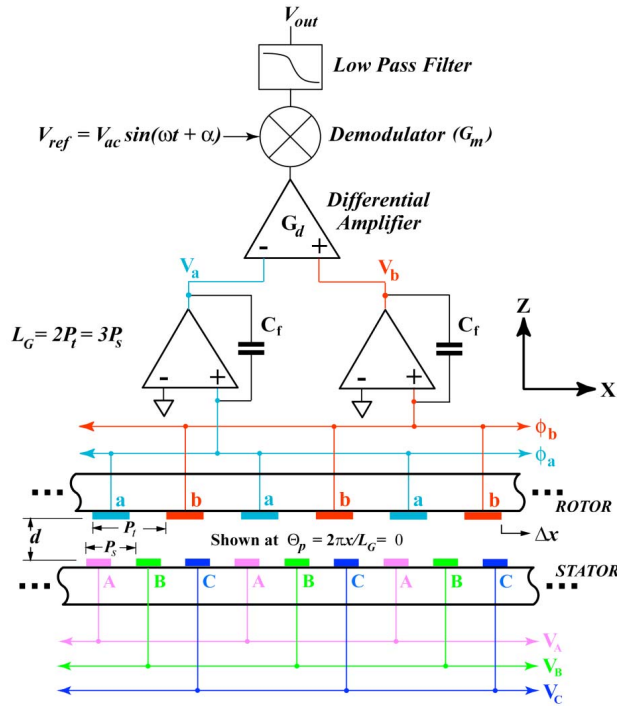


Figure 2: HP's three phase capacitive sensing electrode arrangement combined with output AC amplifiers, differential amplifiers, demodulator and low pass filter [6].

The HP sensing scheme, called three phase sensing, enables a purely electrical method for compensation of fabrication tolerances [6]. This same method is also used to trim the sensor output for cancelling biases or nulling offsets, allowing the sensor to be operated in a regime of maximum sensitivity and linearity regardless of overall orientation, fabrication errors, or other effects [6]. A schematic of the electrodes with accompanying electronics can be seen in Figure 2 and a cross section of an electrode

test structure can be seen in Figure 3. In the three-phase electrode arrangement, there are six variable capacitors between the five electrodes and each capacitance value is shifted 120° from each other [6].

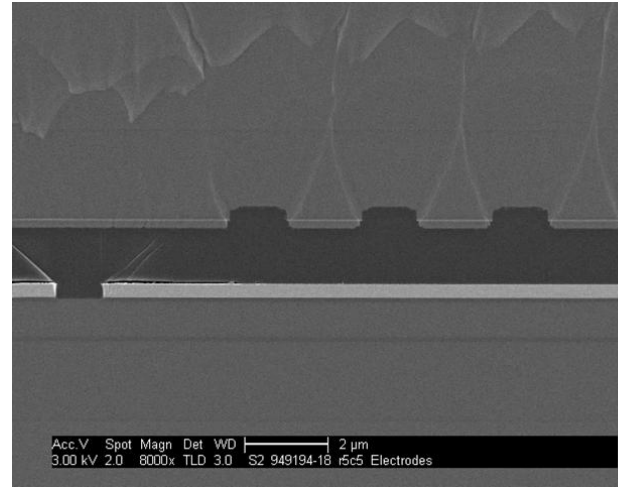


Figure 3: SEM image of electrode test structure cross section.

The electrodes are placed on a mechanical structure which is shown in Figure 4 and a zoomed in image of the flexure suspension can be seen in Figure 5. This structure consists of a proof mass and four double folded springs. The double folded springs provide good axial stiffness and linearity throughout the operational deflection range.

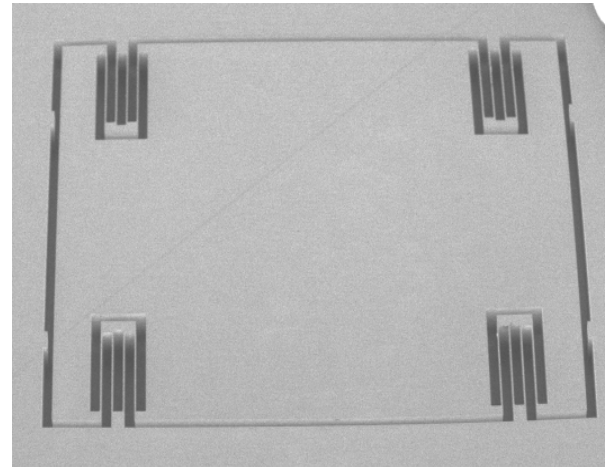


Figure 4: Accelerometer flexure suspension.

All features are etched through the thickness of the device wafer. The high aspect ratios of the suspension allow for a large cross axis sensitivity rejection. The spring stiffness in the sense direction is proportional to

$$k_s \propto \frac{tw^3}{L^3}, \quad (4)$$

and the stiffness out of plane is proportional to

$$k_o \propto \frac{wt^3}{L^3}. \quad (5)$$

The cross axis sensitivity rejection is then defined as

$$\frac{k_0}{k_s} = \left(\frac{t}{w}\right)^2. \quad (6)$$

To achieve rejections over 60 dB the aspect ratio of the suspension needs to be greater than 31 which are capable with the HP device architecture.

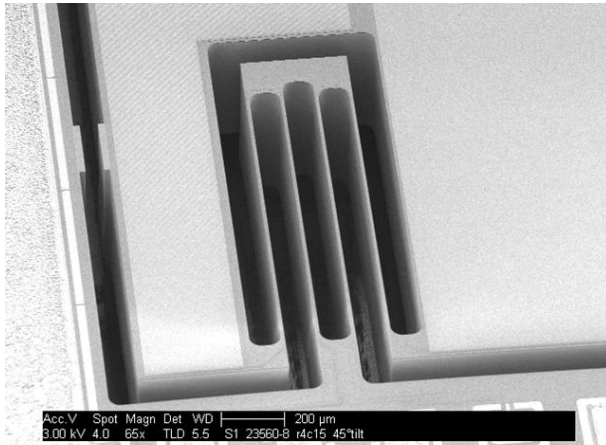


Figure 5: SEM image of suspension etched through device wafer.

FABRICATION

The HP MEMS accelerometer is manufactured using standard silicon micromachining technologies and consists of a hermetically sealed three wafer stack. As shown in Figure 6, the first wafer consists of a deep cavity etched in the bulk silicon (a). The second wafer is bare silicon and is plasma bonded onto the cavity wafer (b). This wafer will contain one set of the sensing electrodes along with the associated interconnects (c). Once the thin film layers have been deposited and patterned the proof mass and suspensions are formed (d). A Bosch etch is used to release the proof mass and form the suspensions. The electrical connect to the electrodes on the proof mass are obtained by running metal conductors along the top of the silicon springs. A low pressure environment is important to the functioning of this device. Hermeticity is obtained by using a high temperature metal eutectic bond. In addition, this eutectic bond will form the interconnects between this wafer and the wafer containing the opposing set of sensing electrodes. This third wafer is processed separately and consists of the opposing set of sensing electrodes and eutectic bond metal (e). Oxide standoffs are used to set the electrode-to-electrode gap and to form a dam to contain the bond metal once the eutectic point is reached. Once the final eutectic bond is completed (f), the devices are singulated and packaged.

There are several key advantages to this process. First, the electrode-to-electrode gap is controlled almost exclusively by thin film depositions. These types of processes are generally well controlled with very good uniformities. Since the sensitivity of the device is directly affected by the electrode-to-electrode gap, accuracy and consistency are crucial. Secondly, by using a eutectic bond

metal process, it is possible to vary the package pressure by controlling the pressure during bonding. This provides a method to effect the operational specifications of the device without changing the design. Finally, with some modifications to the process, a getter material can be incorporated if needed.

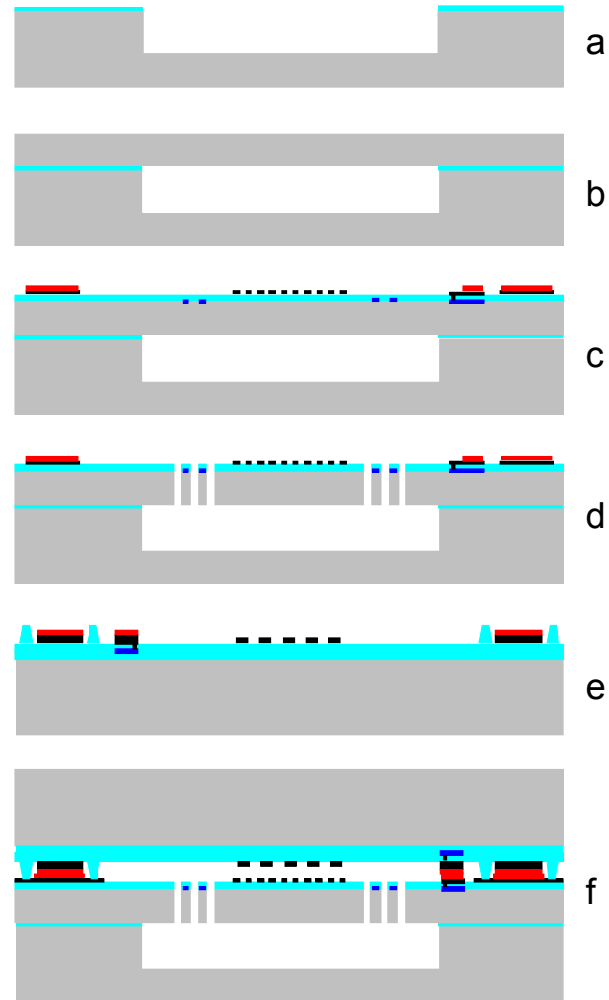


Figure 6: Fabrication process flow

CHARACTERIZATION

To verify the operational space of our device, the maximum and minimum detectable signal, as well as the flat band frequency response, were measured. To measure the maximum detectable signal, the device was placed in a high precision rotary stage that is rotated to apply various accelerations to the sensor. The results from this test can be seen in Figure 7. HP's seismic accelerometer has a linear range of +/- 150mG. Within this range, the sensitivity of the device is 26.2 V/G. The device was then placed into a low noise environment, which has an ambient noise characteristic below the intrinsic noise of our sensor. In these noise conditions, the output voltage is inherent to the sensor, and the minimum detectable signal (MDS) can be measured. The sensor demonstrated a dynamic range of 108dB and a noise power spectral density (PSD) of 70

nG/rtHz. Figure 8 shows the noise PSD of the flat band region as well as the resonance of the mechanical structure. Finally, the frequency response function of the device was tested. The device showed a flat frequency response from DC to 200 Hz and can be seen in Figure 9.

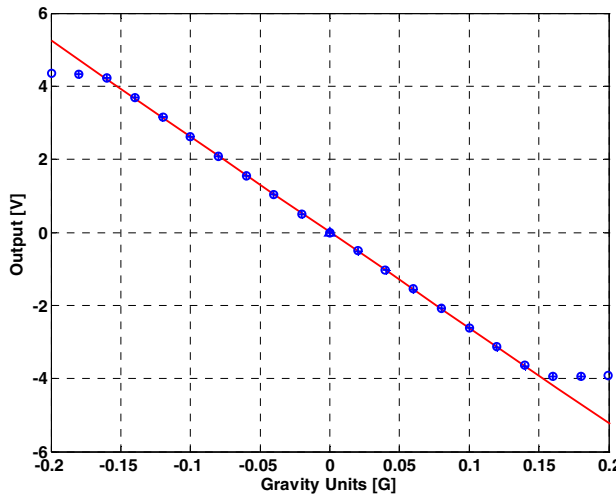


Figure 7: Voltage response to a static acceleration load on a precision stage.

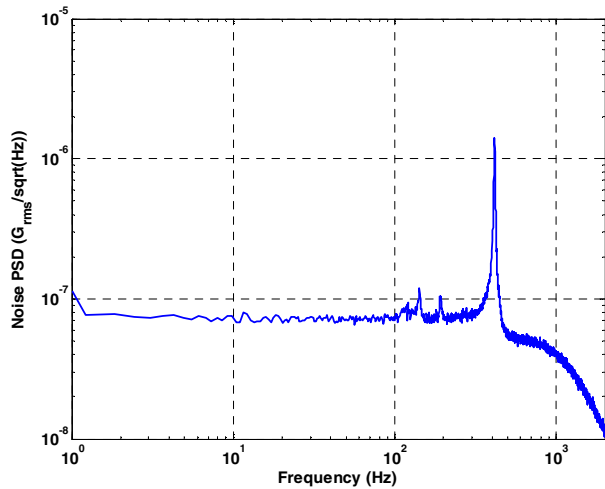


Figure 8: Noise power spectral density of the seismic accelerometer.

Table 1: HP Accelerometer Specifications

Specification	Value	Units
MDS	70	nG/rtHz
Dynamic Range	108	dB
Max Signal	150	mG
Bandwidth	DC-200	Hz

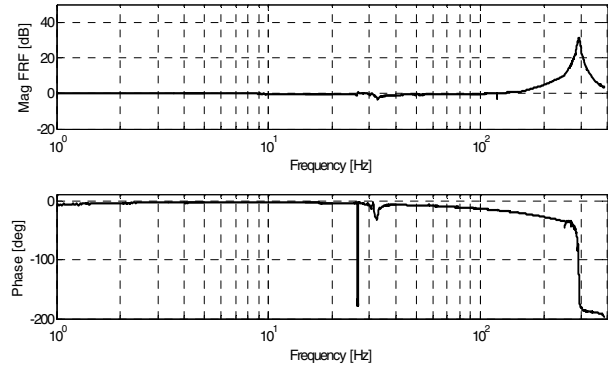


Figure 9: Frequency response function

CONCLUSIONS

HP has recently developed an inertial grade MEMS accelerometer in conjunction with Royal Dutch Shell Corporation. This device is the first to implement HP's three phase sensing scheme, which enables the device to be electrically adjusted to balance any offsets and to allow operation at the point of maximum sensitivity. Accompanying electronics can adjust dynamically to account for changing measurement conditions. Specifications can be found in Table 1. Initial characterization shows a flat noise power spectral density of < 100 nG/ $\sqrt{\text{Hz}}$ over a bandwidth of DC-200 Hz. The device exhibits a linear response to ± 150 mG with a sensitivity of over 25 V/g within the specified bandwidth.

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