VIBRATION SENSOR FOR WIRELESS CONDITION MONITORING

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ABSTRACT
A microelectromechanical system (MEMS) accelerometer has been manufactured for wireless vibration measurements on AC motors for condition monitoring. The vibration sensor element has been encapsulated with glass using wafer scale adhesive bonding with Benzycyclobutene (BCB). Cavities in the glass allow the moving mass on the silicon sensor to vibrate freely. The wafer scale packaging greatly simplifies the subsequent packaging which includes mounting on a ceramics substrate. The ceramic board with the sensor element is densely packed inside a sensor node together with other components. The battery driven sensor node solution is optimized with regard to small scale and low power consumption to reduce price and extend life time. The sensor element has a linear response up to 30 g with a sensitivity of 0.3 mV/Vg and a resonance frequency of 7.7 kHz. Measurements were performed on a bare, unpackaged die and after glass encapsulation. The only recognizable effect of the glass encapsulation on the frequency response is a moderate damping.

Key words: BCB, wafer bonding, vibration sensor, wireless sensor network

INTRODUCTION

Condition Monitoring

Integrated operations, as understood by the petroleum industry, aim at a better exploitation of competencies across disciplines, location and organization. The expected output is an ability to make correct decisions faster and safer and to increase efficiency in general. Real time data systems and wireless communication are among the tools the industry will employ on a greater scale in order to make decision taking a faster and less location dependent task. On-shore and off-shore personnel interact with higher efficiency by using new working methods.

Condition monitoring means the use of advanced technologies in order to determine equipment condition, and potentially predict failure. At present, the scope of such monitoring is restricted by the cost - either the cost of permanently installing sensors or of manual collection of vibration data using portable equipment. In the future, with the drive towards integrated operations, the demand for condition monitoring data will be greater. New developments in the application of wireless sensors to capture vibration data offer the possibility of a more cost effective approach, which could dramatically alter the scope and practice of vibration monitoring.

A wireless sensor network has been established for vibration sensors within this research project called WiVib. Three types of nodes are present in the network; sensor nodes, relay nodes and a manager node [1]. The sensor node periodically measures the vibration of a motor and transmits the vibration data to the manager node over the air using the WirelessHART standard (a technology based on IEEE802.15.4 2.4GHz radio technology). These radios are designed with low power technology that works well in industrial environments. As an international standard the radios are cost effective and available from multiple sources. In case of limited line-of-sight (which is common on an offshore production facility), the information can be forwarded by relay nodes. The manager node transmits the information further to a server. The sensor node contains analogue electronics that processes the raw signal and reduces the amount of data that must be transmitted. The analysis is performed by the server which runs two applications; a network visualization tool and SKF Machine Suite vibration analysis software [2]. The target of the Wivib research project is to make a cost effective solution for a miniaturized sensor node. This requires that the energy source (the battery) is small, and consequently all components must use the smallest amount of energy possible. Low power consumption, small scale and low cost are thus the guiding targets in the project.

Vibration Sensor

A vibration sensor for condition monitoring of a motor must be able to measure within a broad vibration spectrum. If the motor is not well balanced or misaligned, this will appear as a high energy vibration signal at the frequency near the rotational speed, typically in the range of 50 Hz. If there are bearing defects, a low energy signal at higher frequencies will appear, typically in the range of 1-5 kHz. In order to reveal both kinds of problems with one single sensor, the sensor must have a large bandwidth and a resonance frequency above the interesting range. Actually, the complete **sensor node** that is mounted on the motor for condition monitoring (including **sensor element**, analogue signal filtering electronics, a microcontroller with analogue-to-digital converter (ADC) and memory, radio, antenna and battery) must itself not have any strong natural frequencies below or within the interesting range.

An accelerometer is the most appropriate vibration sensor for an application requiring high frequency monitoring. Velocity and displacement sensors are also used for vibration monitoring, but primarily for low frequency vibrations. The accelerometer proposed in this paper is a silicon based microelectromechanical system (MEMS) device.

Wafer Level Packaging

Packaging of movable mechanical structures is considered to be one of the largest obstacles for getting MEMS out on the marked at low cost. Encapsulation of single devices is time consuming and inefficient. Wafer bonding, also called zero level packaging or wafer scale packaging, has therefore emerged as a key technology for the success of MEMS. Several different wafer bonding technologies exist. Some technologies use intermediate layers like metals or polymers, whereas other technologies bond the interfaces of two wafers directly together. Some technologies are appropriate for any kind of substrate materials, whereas other demand for instance glass or silicon wafers. Choosing the right bonding technology for the specific application is a critical decision. The choice should be based on the requirements of the encapsulation. In the presented solution, glass wafers are desired as capping wafers for the silicon sensor wafer in order to provide visual inspection after bonding. The bond does not need to be hermetic, and the distance between the capping wafers and the silicon wafer does not have to be extremely well controlled [1]. These rather relaxed requirements make the use of a transparent polymer as an intermediate bonding layer possible. This is called adhesive wafer bonding. The bond will not become hermetic or completely moisture resistant [3]. This is not a constraint for the presented sensor element because the higher levels of packaging of the complete sensor node will take care of required sealing and protection against a possible harsh environment on for instance an offshore production facility.

In adhesive bonding wafers are glued together with an intermediate layer of polymer. Strong bonds can be achieved at low (<300^{o}C) temperatures using moderate tool pressures and some surface topography can be compensated [3]. The polymer is spray or spin coated onto at least one of the wafers to be bonded. The polymer selected for the presented device is Benzycyclobutene (BCB) which is a highly transparent (>90%) thermosetting polymer that undergoes cross-linking during curing [4]. Both photosensitive and non photosensitive BCB are available. The former is more expensive and has a shorter shelf life than the latter, thus the latter was preferred in this case. A smaller volume of BCB is dispensed during spray coating than during spin coating, thus spray coating can minimise the material cost. SU-8 could have been an alternative [5], but bonding with BCB is at present considered as a more mature and less complicated technology than bonding with SU-8. SU-8 is for instance normally cured with UV light rather than with heat.

Patterning of a thermosetting polymer typically requires partial curing (cross-linking) of the polymer during the patterning process (done with dry etching if not photosensitive). Partially cross-linked polymers will re-flow to a much lesser extent during bonding and result in reduced bond yield and reduced bond strength [6]. The design of the encapsulating glass wafers was therefore tailored to allow bonding using unpatterned and uncured polymers which could re-flow during the bonding.

EXPERIMENTAL PROCEDURE

Manufacturing of Sensor Wafer

A design was custom made for the presented vibration sensor in order to get the chip dimensions optimized for a certain sensor node package. The sensor node package should be small and the sensor element should have a low cost, thus the sensor element size was minimized to $3.5 \times 3.5 \times 1.4$ mm^3. Since the sensor node should communicate wirelessly to a network, the power consumption for all components inside the sensor node, including the sensor element and interface electronics, should be low. Therefore a piezoresistive rather than a capacitive sensing principle was selected. A mass was designed to be suspended by four beams with one piezoresistor on each beam. The resistors were organized in a Wheatstone bridge to sense out of plane (z-direction) vibrations. Surface resistors were selected rather than buried resistors to save costs and increase sensitivity. Buried resistors require epitaxial growth of silicon which adds complexity to the device. To bury the resistors under an epitaxial silicon layer is beneficial for extremely long term stability with well controlled off-sets, but off-sets are zeroed out in the presented application using high-pass filtering. The sensitivity was optimized to compensate for the expected noise level from the piezoresistive surface resistors. The sensitivity was maximized by combining a relatively large mass with narrow beams. However, a requirement of shock resistance limited the possible dimensions of the beams relative to the mass. The optimal position, size and value of the piezoresistors were determined by finite element analysis (FEA) using ABAQUS. Figure 1 shows the simulated stress distribution of the moving mass of the vibration sensor. Cross-axis sensitivity (signal detected due to vibrations in the x-y plane) was designed to be less than 5%. The sensor wafers were tested electrically on

[1] The opposite would be the case for i.e. a pressure sensor based on a capacitive sensing principle. For such a device the bonding should be highly hermetic and the distance between the capping wafers and the sensor wafer should typically be only 1-2 μm and controlled within ~10%.

wafer scale on a chuck (non-vibrating) before wafer bonding.

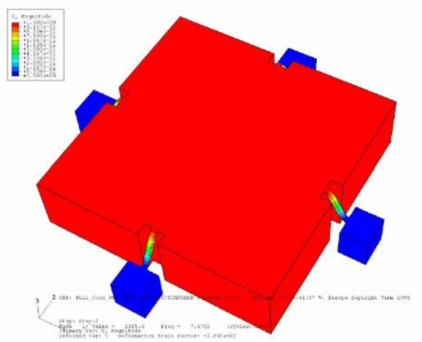

Figure 1: **FEA of the stress distribution of the moving mass of the vibration sensor. The stress is localised in the beams where the piezoresistors are positioned.**

The device was made using single crystalline silicon which is a perfectly elastic and thus highly reliable material. This is a great advantage for a continuously vibrating device. 100 mm BSOI (bonded silicon on insulator) wafers with a total thickness of 390 µm were processed. Conductor lines and piezoresistors were defined by boron ion implantation. The metal routing layer was aluminum. The buried oxide (BOX) layer was used as stopping layer for the dry etching defining the beams and the mass. A Bosch type process was developed in an AMS200SE I-Speeder from Alcatel which is an inductively coupled plasma (ICP) based dry etching tool.

BCB Wafer Bonding

Dicing of the processed sensor wafer and release of singularized sensor elements from a dicing tape were expected to be demanding. The sensor wafer was therefore wafer scale bonded. Glass wafers (Borofloat 33, similar to Pyrex 7740) were patterned in HF using a NiCr/Au hard mask. Cavities (60-80 µm deep) were defined in the top and bottom glass capping wafers. A cavity was defined both above the moving mass and above the contact pads on the top wafers. Only a cavity below the moving mass was defined in the bottom wafer as shown in Figure 2. The selected depth of the cavities was needed to assure a safe stop height for the dicing blade during release of the contact pads. The mass was estimated to move less than 10 µm out of plane.

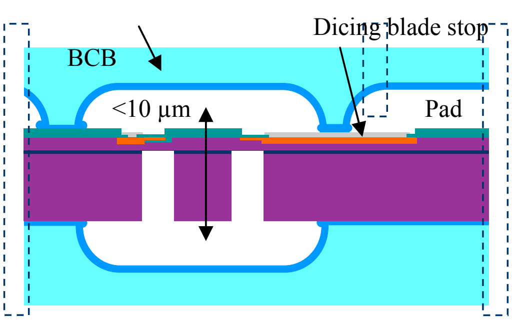

Figure 2: Wafer bonding of the vibration sensor with glass capping wafers using BCB. No lithographical patterning of the BCB is needed in this encapsulation process. The dicing blade is stopped inside the 60-80 µm deep cavity for pad release.

The requirements for the wafer bonding are summarised in Table 1. The capping wafers were coated with a layer of 3 µm BCB (Cyclotene® 3022). The BCB film was only soft cured and not patterned before bonding to retain its full re-flow capability. Topography on the sensor wafer of ~1 µm had to be compensated. The BCB did not accumulate inside the cavities either during spin or spray coating.

Table 1: Specifications for the wafer bonding of the presented sensor element.

Parameter	Value
Hermetic	Not required
Moisture resistant	Not required
Wafer distance control	Not critical
Bond strength	> 5 MPa
Yield	High
Bonding atmosphere	N_2
Surface topography on sensor wafer	Conductor lines, ~1 µm
Temperature tolerance of finalized bond	-50°C to +130°C
Accepted stress induced from bonding	Uncritical as off-set will be zeroed

The capping wafers were aligned and bonded to the sensor wafer in a commercial wafer bonding tool (SB6e from Suss MicroTec). A bonding tool pressure of 300 mbar and a temperature of 250°C were used for the bonding. After bonding, the wafers were diced. A glass encapsulated sensor element was cross sectioned for visual inspection.

Bare, unpackaged sensor elements were mounted on simple TO-cans for mechanical testing. Small pieces of silicon were glued under the bare dies as spacers to allow the mass to move freely. Glass encapsulated sensor elements were mounted on ceramic substrates. The glass encapsulated dies were mounted with glue, Epotek GE116-1, and the wire bonds were coated with silicone, Dow Corning Q1-9379. A more advanced ceramic substrate with several components included were drawn for the final sensor node, but has not yet been tested. Mechanical tests performed on bare and glass encapsulated sensor elements were compared. The TO-cans and the ceramic substrates were placed on a shaker table together with a calibrated reference accelerometer to establish the transfer functions of the sensor elements.

EXPERIMENTAL RESULTS

A total of 15 sensor wafers were manufactured, see an example of a sensor element in Figure 3.

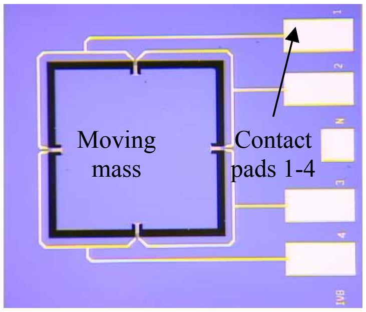

Figure 3: A microscope image of a bare sensor element before wafer bonding.

The definition of the beams was the most critical process step, as can be understood by studying the scanning electron microscope (SEM) image in Figure 4. The etch from the back side of the wafers (which releases the mass) was not perfectly isotropic. The so called "bow" of the etch resulted in flaps of silicon, but these were not expected to have a large impact on the device performance.

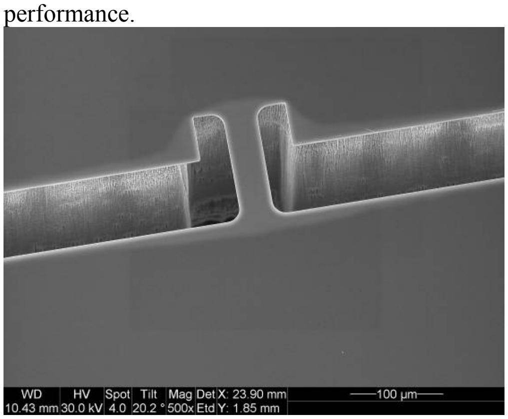

Figure 4: A SEM image of the thin beams. The light grey areas surrounding the beam are also thin due to the nature of the back side etch.

The wafers could be studied in light microscope after bonding since the BCB was transparent as shown in Figure 5.

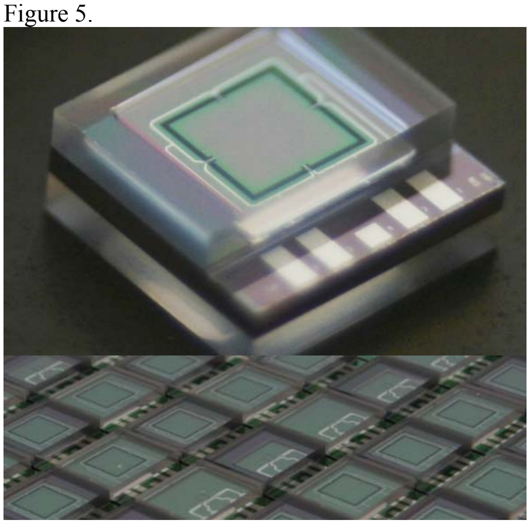

Figure 5: Sensor wafer packaged on wafer scale with glass capping wafer after dicing. Dicing of the uppermost glass wafer is used to release the contact pads.

Material flow due to the heat and the applied tool pressure during bonding was studied on the cross sectioned sample. The BCB was found to gather in the corners as shown in Figure 6, but sufficient volume was reserved for the material flow in the design. The observed BCB flow was not expected to influence the mechanical behavior of the sensor element since the flow did not reach the moving mass or the thin beams.

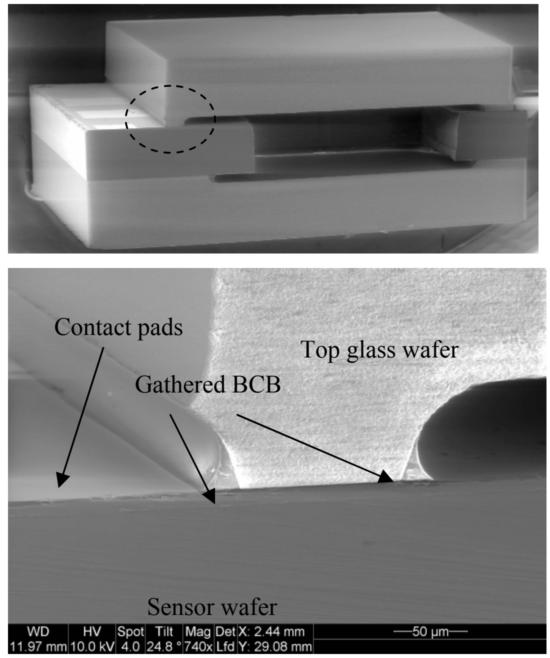

Figure 6: SEM images of a cross section of the glass wafers bonded to the sensor wafer using BCB (overview and zoomed). BCB is found to gather at the corners (see arrows). The glass has been removed above the contact pads by dicing.

The transfer function for the bare sensor element, established from mechanical tests, could be roughly described as a second order system with a Q factor above 750. Analytical calculations were compared with measurements showing a reasonable overlap, as shown in Figure 7 a. Calculations with a Q factor of 150 best fitted the measurements on the glass encapsulated sensor element, as depicted in Figure 7 b.

a)

b)

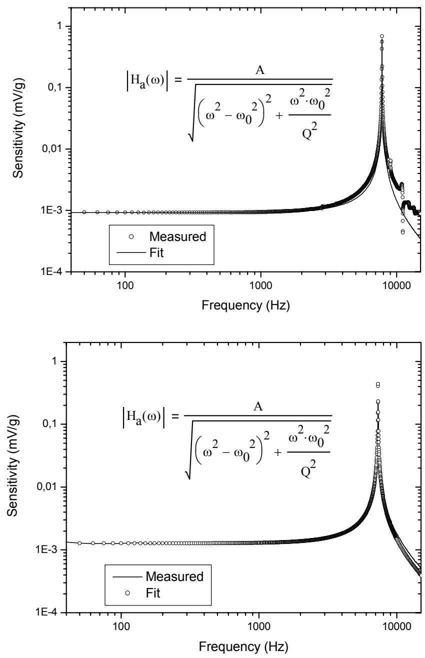

Figure 7: a) Absolute value of the transfer function for a bare sensor element and b) for a glass encapsulated sensor element. The resonance frequency and sensitivity are fitted to the curve for a second order system (see the formula in the figures).

The reduced Q factor indicated a moderate damping due to the glass encapsulation. The Q-factors were found by fitting the phase response as shown in Figure 8 for both a bare and a glass encapsulated sensor element.

$$\theta_a(\omega) = \theta_0 + \operatorname{atan}\left[\frac{\omega \cdot \omega_0}{Q \cdot (\omega^2 - \omega_0^2)}\right]$$

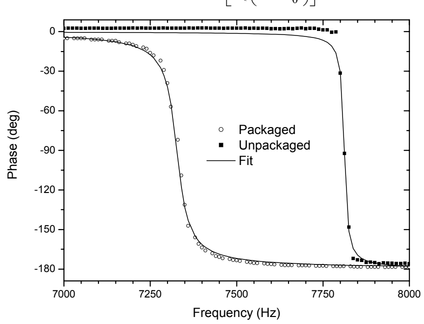

Figure 8: The phase shift measured for a bare (unpackaged) and for a glass encapsulated (packaged) sensor element. Comparison is made to modelled curves with Q-factors of 750 and 150 respectively. The f_0=2πω$_0$ were 7815 and 7327 Hz.

The average resonance frequency of 9 measured sensors was 7.7 ± 0.2 kHz (6 measured before and 3 after glass encapsulation). The spread in the natural frequency was believed to be related to variations of the oscillating mass, caused by processing nonuniformity across the wafer. The average resonance frequency did not change after glass encapsulation, indicating that the wafer bonding did not introduce significant tensile nor compressive stress in the beams.

The linearity of a bare, unpackaged sensor element was tested by gradually increasing the peak acceleration at three different frequencies. The sensor had a linear response from 1-30 g with a sensitivity of ~0.3 mV/Vg, as shown in Figure 9. The noise level was found to be 90 dB below the signal at 30 g and 2.5 kHz.

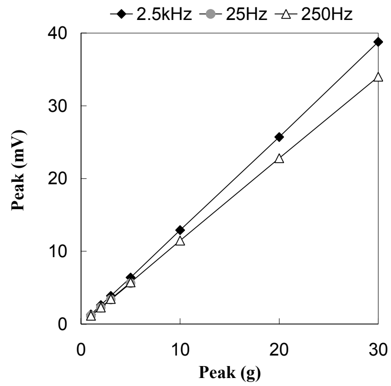

Figure 9: Linear response for a bare sensor element mounted in a TO can.

The cross-axis sensitivity was measured and found to be well below the specified 5% for a bare sensor element.

DISCUSSION

The measured sensitivity, linearity and noise level for the sensor element were satisfactory and so was the small cross-axis sensitivity. However, the resonance frequency should still be increased. When studying the analytical expression for the transfer function, one will find that the stiffness of the beams must be increased or the mass must be reduced in order to achieve this. The most efficient choice is to increase the beams stiffness because this will have a relatively smaller negative impact on sensitivity than a mass reduction. This was confirmed by FEA analysis. The beams can be made stiffer by increasing the device layer thickness of the BSOI wafers. Thicker beams will result in a more robust device which is an advantage for any device to be applied in a harsh environment.

The presented BCB wafer bonding procedure is straight forward and is expected to contribute positively to the low cost of the device. The BCB wafer bonding procedure will be applicable for several other devices not requiring a hermetic seal. A well controlled stand-off height (within a few μm) may be difficult to achieve, but can be controlled to a certain extent by curing the BCB more before bonding. Generally, thickness control and alignment is improved by curing the BCB before bonding at the sacrifice of the capability to compensate for surface topographies. The wafer scale packaging of the presented device makes the subsequent packaging a simpler task. The moving mass is well protected inside the glass cavities during mounting onto a ceramic board. No additional packaging of the glass encapsulated sensor element on the ceramic board is needed except for the final outer housing of the sensor node.

CONCLUSIONS

A MEMS accelerometer intended for wireless vibration measurements on AC motors for condition monitoring has been manufactured. The vibration sensor element has been packaged on wafer scale using glass wafers with deep cavities coated with BCB. The BCB was only soft cured and unpatterned before bonding, which improved the ability of the polymer to compensate for topography on the wafers and resulted in a good bond. The wafer scale packaging greatly simplified the subsequent packaging for the sensor element which included mounting on a ceramic substrate. The transfer function for the sensor element was measured on a bare, unpackaged sensor element and after glass encapsulation. The sensor element had a linear response from 1-30 g with a sensitivity of 0.3 mV/Vg and a resonance frequency of 7.7 kHz. The only recognizable effect of the glass encapsulation on the frequency response was a moderate damping. The sensor element will be part of a fully autonomous sensor node which includes wireless communication to a central unit.

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