Sensors and Actuators A 153 (2009) 155–161

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Design, process and characterisation of a high-performance vibration sensor for wireless condition monitoring

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ARTICLE INFO

Article history:
Received 16 December 2008
Received in revised form 2 April 2009
Accepted 9 April 2009
Available online 24 April 2009

Keywords:
Vibration sensor design
DRIE
Wireless sensor network
BCB
Wafer bonding

ABSTRACT

A microelectromechanical system (MEMS) accelerometer has been developed for wireless vibration measurements on AC motors for condition monitoring. It should be a part of a cost-effective solution for a miniaturized sensor node. The requirements for such the sensor are a resonance frequency of at least 10 kHz, a highly linear response up to ±30 g and low noise floor of 5 mg RMS. For the sensor design a trade-off has been made between cost-effective development and manufacturing and the necessary higher performance of the sensor for the application compared to available off-the-shelf sensors. The sensor has been designed for manufacturing with a specially developed DRIE (deep reactive ion etch) bulk micromachining process with piezo-resistive read-out. The vibration sensor element has been encapsulated with structured glass using wafer scale adhesive bonding.

Because of the design dependence of the DRIE process two manufacturing runs have been performed, regarding observed etch profiles from the first run in an improved design for the second run. Both the effects of the packaging and the imperfections of the production process on the device performance were thoroughly investigated. The sensor elements show a sufficient linear response (non-linearity <0.15% FS) up to 30 g with a sensitivity of 0.19 mV/(V g) and a noise floor equivalent to 5 mg RMS. The resonance frequency of 7.7 kHz of sensors of the first batch could be increased to 10.3 kHz for the second batch. This allows the usage of the sensor in this demanding application with the necessary bandwidth.

1. Introduction

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 condition data using portable equipment. 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. 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 developed for vibration sensors within this research project called WiVib [1]. A sensor node periodically measures the vibration of a motor and transmits the vibration data to the manager node using the WirelessHART standard (a technology based on IEEE802.15.4 2.4 GHz radio technology). These radios are designed with low power technology that works well in industrial environments. The sensor node contains 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].

Besides high installation costs for wired and existing wireless solutions the price per sensor unit is also significant. Today's solutions use conventional sensors, mostly piezoelectric ones. These sensors are very well suited for this application regarding performance, but they are quite bulky and costly (∼200US$) [3]. There is a growing interest to substitute such conventional sensors with MEMS based sensors for condition monitoring applications [3–5]. Studies with available MEMS sensors have been performed by us and others [3,5] for this demanding application. The conclusions of these studies have been that available off-the-shelf MEMS sensors are very competitive regarding price (∼15–20US$/unit)[3], but that they are limited in some respects regarding performance, especially dynamic range and maximum measurable acceleration.

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doi:10.1016/j.sna.2009.04.011

The target of the Wivib research project has been to make a cost-effective solution for a miniaturized sensor node meeting the requirements for wireless vibration monitoring. This requires an inexpensive high-performance accelerometer on one hand and a cost-effective and power efficient solution for the whole system on the other hand. Low power consumption, small scale and low cost by meeting the demanding requirements at the same time are thus the guiding targets in the project.

1.1. 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, front-end amplifier, 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 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. The design requirements for this sensor can be found in Table 1.

Table 1
Design requirements for the vibration sensor.

Parameter	Specified value
Eigenfrequency, f_0	10 kHz
Noise floor	5 mg RMS
Measurement range	0–30 g
Shock resistance	1000 g
Cross-axis sensitivity	<5%
Non-linearity	<0.2% FS

1.2. Initial sensor design

A seismic mass was designed to be suspended by four beams with one piezoresistor on each beam. This sensor concept has been investigated before (e.g. [6]), though mainly for structures manufactured with anisotropic wet etch and not for such a demanding application. This kind of configuration is especially beneficial regarding reduction of cross-axis sensitivity. In our case the targeted process was an advanced bulk DRIE SOI process, which allows for a compact design with minimized area compared to an anisotropic wet-etch process. The resistors were organized in a Wheatstone bridge to sense out of plane (z-direction) vibrations. Surface resistors were selected for achieving high sensitivity. The mechanical sensitivity was optimized to compensate for the expected noise level from the piezoresistors. The sensitivity was maximized by combining a relatively large mass with full wafer thickness with thin, narrow beams.

At first, a coarse dimensioning of the mechanical structure has been performed. Analytical expressions for the eigenfrequency and the mechanical sensitivity (expressed by the maximum stress $\sigma_{\max}$ on the beam surface) from the literature have been adapted for our structure [7]:

$$\omega_0 = \sqrt{\frac{4E_{Si}wt^3}{ml^3}} \tag{1}$$

$$\sigma_{\max} = \frac{3l}{4wt^2}ma \tag{2}$$

In these formulas m is the seismic mass of the accelerometer, t, w, l are the thickness, width and length of one beam, E_{Si} is the

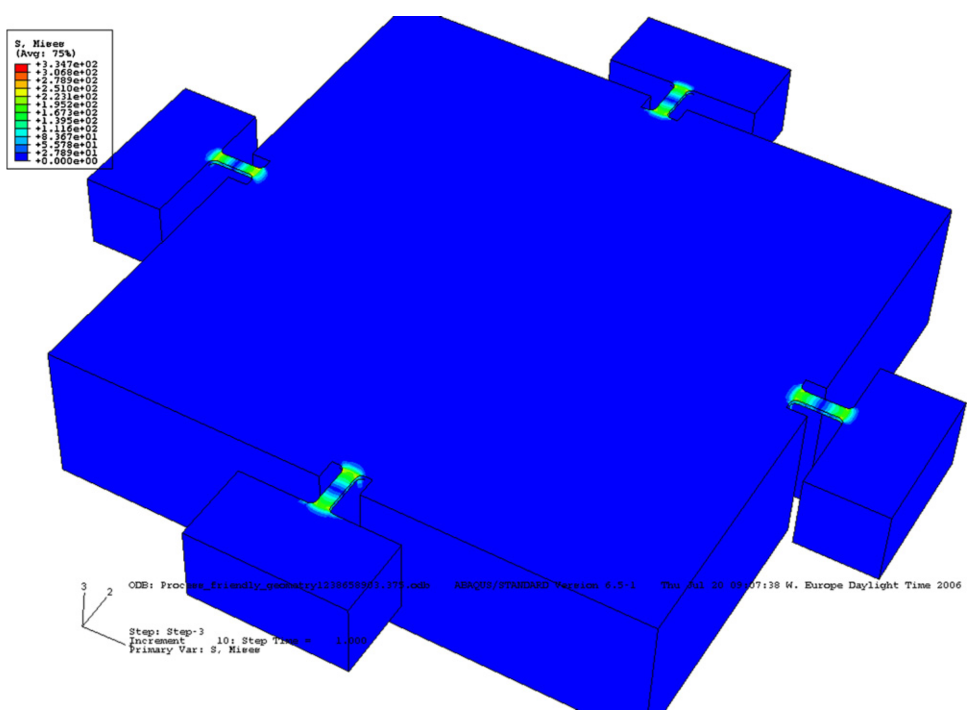

Fig. 1. FEA of the v.Mises stress distribution of the moving mass of the vibration sensor. The stress is localised in the beams where the piezoresistors are positioned.