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A miniaturized wireless accelerometer with micromachined piezoelectric sensing element

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ABSTRACT

A miniaturized wireless accelerometer using a piezoelectric micro sensing element is designed, theoretically analyzed, and demonstrated for remote mechanical vibration monitoring. The micro sensing element comprises a micromachined monolithic silicon seismic mass and multiple silicon beams coated with in-plane polarized (Pb, La)(Zr, Ti)O_3 (PLZT) ferroelectric thin film. A low profile compact package is obtained for accommodating all the micro sensing element, charge amplifier and signal processing circuits, radio frequency module, and battery. The electrical output linearly proportional to the vibration acceleration is amplified, digitalized and transmitted to a remote base unit through radio frequency communication. The effects of the device package on the dynamic response of the wireless piezoelectric accelerometer including shielding of ambient interference are investigated.

1. Introduction

Vibration monitoring is often carried out for the purposes of machines fault diagnosis or as regular checkup to determine if maintenance is required [1,2]. The state of the art vibration monitoring process usually requires time consuming installation of multiple accelerometers on various locations on the machine. The manual and repetitive installation not only involves substantial manpower cost but also causes inconsistency in the measurement results; and, sometimes, the installation has to be carried out under dangerous condition as the machines cannot be shutdown during the installation process. Current accelerometer design also requires long cables between the accelerometer and signal analysis unit. Careful routing of the cables must be taken to avoid interfering with the machine operation. Accelerometers with wireless communication function and battery powering in the same package are thus highly demanded for machine condition and structural health monitoring [3].

Compared to piezoresistive and capacitive accelerometers, a piezoelectric accelerometer has some important advantages for condition monitoring applications such as broad frequency response range, large linear amplitude range, and low power consumption. Wireless piezoelectric accelerometers (WPA) emerging in the market are mainly based on bulky piezoelectric materials [4–6]. The large mass and size of the commercial accelerometers can cause substantial interference to the operation of the machine to monitor, making them not suitable to monitor small machine parts. Besides, the protruding profile and antenna design limit their application at high response frequency or when only small space is available. The rapid development of piezoelectric microelectromechanical systems (piezoMEMS) technique and wireless sensor network technology has opened new opportunities for miniaturized wireless accelerometers [7–9]. There have already been some published proof-of-concept studies. McGinnis reported a miniaturized wireless inertial measurement unit (IMU) for the free-flight dynamics analysis of a rigid body [10]. Mo demonstrated a ZigBee-based wireless wearable multi-sensor integrated measurement system for in-situ humane physical activity measurement [11]. In paper [12], a low power consumption wireless digital output piezoelectric sensor node was reported for animal movement analysis. A self-powered wireless transducer was disclosed in [13] for monitoring excessive vibrations in a bearing, in which the design utilizes a single piezoelectric transducer for both vibration sensing and energy harvesting. The accelerometers in the publications above are used for low frequency vibration monitoring. There is no consideration in the miniaturized wireless piezoelectric accelerometer design to achieve a high dynamic range and to minimize electromagnetic interference (EMI).

This paper aims at achieving a miniaturized, low profile wireless battery-powered accelerometer system utilizing a piezoelectric

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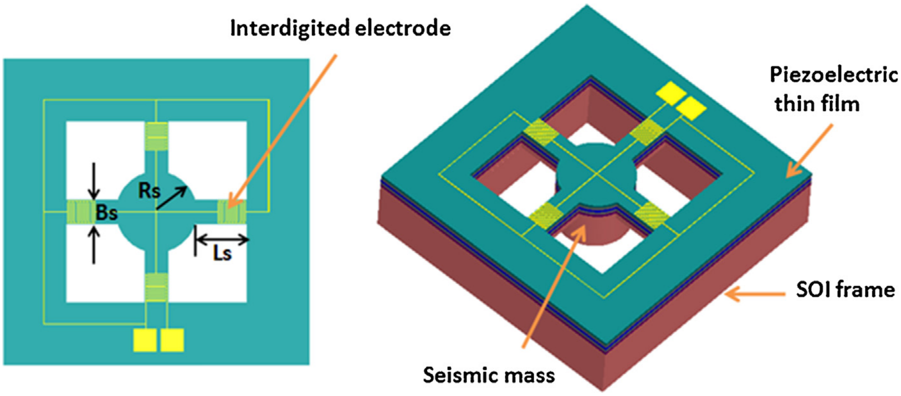

Fig. 1. Schematic of the bending mode piezoelectric micro sensing element.

MEMS sensing element to meet the increasing industry demands for miniaturized WPAs. The accelerometer is expected to be left on the machine, without the need of being reinstalled each time a measurement session is required. Such a wireless accelerometer system will significantly reduce the time and manpower cost required for vibration measurement, enhance the consistency of measurements, and realize continuous real-time machine condition monitoring. The paper also discusses on the configuration of different functional modules in the package, design consideration to achieve small size while maintain high dynamic range, and the effect of different EMI mitigation measures.

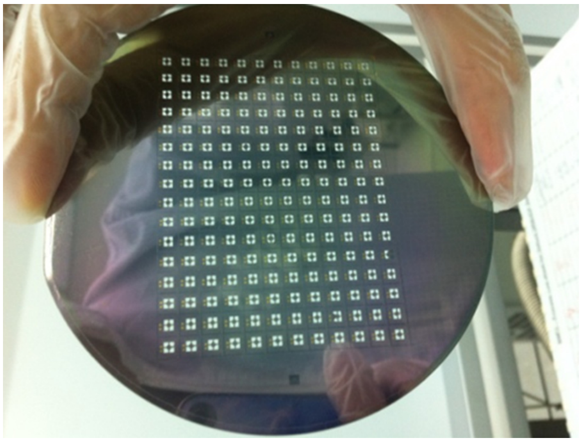

Fig. 2. Piezoelectric sensing elements micromachined on one 4-in. wafer.

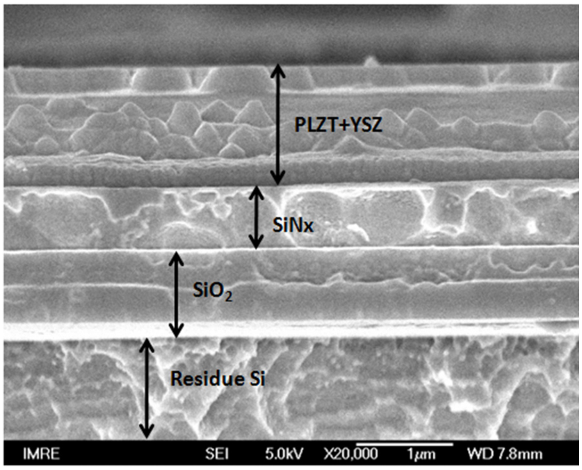

Fig. 3. Cross-sectional FESEM image of a piezoelectric sensing beam.

2. Piezoelectric sensing element

The MEMS sensing element comprises a frame, four suspending beams, and a seismic mass, as shown in Fig. 1, all made of one monolithic silicon single crystal. The structure and electrodes of such MEMS sensing element have been selected after analysis to obtain high signal-to-noise ratio and robustness at small sizes [14]. The geometric dimensions of the sensing element are given in Table 1. The detailed batch fabrication process of the sensing elements from 4-in. SOI (silicon on insulator) wafer is similar to the report in the literature [14]. The beams have a multilayered structure with the layer of (Pb, La)(Zr, Ti)O_3 (PLZT) ferroelectric thin film and its interdigital electrodes, on the top of YSZ/SiN_x/SiO_2/Si layer (YSZ: yttrium stabilized zirconia). The PLZT film was dry etched through reactive ion etching (RIE) process to define the beams. The seismic mass moves in response to the vibration to bend the four beams and thus electrical charges are generated in the strained ferroelectric PLZT film through its piezoelectric effect. The four sets of interdigital (IDT) electrodes on the four beams respectively collect the charges and constructively generate the electrical output proportional to the acceleration of the seismic mass.

Fig. 2 presents a 4-in. wafer containing 192 sensing elements. The cross section of a piezoelectric sensing beam was examined with field-emission scanning electron microscopy (FESEM), as shown in Fig. 3.

The ferroelectric property of the PLZT thin film in the multilayer structure after all the micromachining process was characterized by a Radiant standard ferroelectric testing system. With the in-plane configuration using the interdigital electrodes, which is different from the commonly used sandwich capacitor configuration, the effective area of the capacitor is calculated from the PLZT film thickness and the spacing between the neighboring electrode fingers is taken as the capacitor's effective thickness. Fig. 4 shows a typical polarization-electric field hysteresis loop of the PLZT film in a bending mode sensing element. An effective remnant polarization P_r of 19 $\mu C/cm^2$ and the coercive electric field E_c of 57 kV/cm can be read on the hysteresis loop measured at 180 kV/cm. The PLZT films were poled under 150 kV/cm for 4 min at room temperature.

A finite element method (FEM) model was built for analyzing the bending mode sensing element using ANSYS (Version 10.0, Ansys Inc., Canonsburg, PA). Simulation was conducted using 3D structural element SOLID92 and piezoelectric element SOLID226 for one fourth of the structure considering the 4-fold axial symmetry of the structure. The IDTs were modeled by coupling the electric potential in the IDT area. The four cantilever beams were assumed to be fully clamped at the ends. The material properties for each layer are