Microelectromechanical Vibration Sensor with Optical Interconnects

Erwin Peiner, Dirk Scholz, Klaus Fricke, Andreas Schlachetzki, and Peter Hauptmann

Abstract—A resonant vibration sensor realized using silicon micromachining for wear monitoring of rotating machinery is described. It comprises a mechanical resonator, piezoresistive bridge, and components for fiber-optical signal readout by an infrared light-emitting diode. The performance of the microsystem is demonstrated by its static and dynamical behavior. The results confirm that the described sensor has the potential for on-line vibration control of rotating machinery operated under the conditions of industrial production. [257]

Index Terms—Bulk-micromachined piezoresistive transducer, fiber-optical readout, mechanical vibrations.

I. INTRODUCTION

MAINTENANCE and repair of machinery leading to outage times of highly productive lines are important cost factors of industrial production. Therefore, on-line control of wear is required to predict failure and avoid accidental shutdown. The conditions of operation and state of rotating machinery can be characterized by the solid-borne vibration spectrum [1], [2]. Vibration spectra of rolling element bearings may exhibit so-called kinematic frequencies due to irregularities on the rolling elements, retainer ring, or the inner or outer roller race of the bearing. As an example, in the case of a calender roll operated in an industrial production line for nonwoven fabrics, kinematic frequencies caused by an imperfection of the inner race appear in the vibration spectra [3]. These characteristic vibrations can be measured with high sensitivity using a bulk-micromachined piezoresistive sensor operated close to resonance [4], [5]. Fig. 1 shows a typical time-domain vibration signal, which is essentially dominated by two spectral components of the corresponding vibration spectrum: the resonance frequency of the sensor and the characteristic frequency $f_i = 23.9$ Hz of the bearing. The corresponding excitation amplitude amounts to $a_i = 0.046g$, where $g$ is the acceleration due to gravity. Both values are in close agreement with the conventional spectrum analysis [4]. Thus, the amount of data of complex vibration spectra is reduced to the significant information, and the evaluation procedure for wear monitoring is considerably simplified. However, vibration measurements in the harsh environment of an industrial plant are affected by electromagnetic interferences (EMI’s), a problem which becomes more serious at lower signal levels.

Optical interconnection of electronics is of high potential for high-bit-rate digital systems as well as for advanced sensor applications, e.g., microelectromechanical systems (MEMS) [6]–[8]. In the first case, the benefits of optical interconnects include high reliability, small volume, low power requirements, high bandwidth, and high-density input/output [6]. With respect to low production cost and high conversion efficiency of electric energy to optical energy, monolithic fabrication technologies are very attractive. Following this approach, high-performance laser diodes and photodetectors were realized using heteroepitaxy of III/V compound semiconductors on Si (see [9] and [10]). In the case of MEMS, optical interconnections between the sensor head and the controller provide immunity against EMI [7]. Further advantages are the intrinsic safety of insulating connections and the ability of operation at elevated temperatures [8]. Compared to all optical sensors, this approach has the advantage of compatibility with the well-developed technology of electromechanical transducers.

Optical fibers when used in local-area networks can meet the stringent requirements for signal transmission in the harsh environment of an industrial plant, e.g., impairment by particles, humidity, temperature load, hazardous ambient, and EMI. For electrooptical signal conversion, a light source can be integrated on the sensor chip. Light emitters fabricated in Si technology, e.g., using porous Si [11] or Si diodes operated near avalanche breakdown [12], however, suffer from low-power-conversion efficiency. For optical interrogation of sen-

![Fig. 1. Time-domain vibration signal of an aged rolling element bearing of a calender roll measured by a bulk-micromachined piezoresistive vibration sensor operated close to resonance.](image-url)
sors, therefore, hybrid GaAlAs/GaAs infrared-emitting diodes (IRED’s) are presently most promising. From these devices, light power in the range of a few milliwatts can be launched into a multimode fiber of 200-μm core diameter [7]. The coupling efficiency can be further improved by integration of a microlens [13]. As electronic driver of the IRED, a heterojunction bipolar transistor (HBT) can be monolithically integrated.

In this study, fabrication and performance of a micro-machined vibration sensor with fiber-optical readout is described. We specially concentrate on the electrooptical signal conversion by a hybrid combination of an IRED and a metal–oxide–semiconductor field-effect transistor (MOSFET) as the driver as well as the light coupling into a standard multimode fiber. With respect to packaging cost as one of the main obstacles for wide-spread use of optical technologies, we discuss the tolerance requirements for assembly.

II. SENSOR STRUCTURE

In Fig. 2, a schematic of the sensor chip is displayed. The mechanical resonator as the sensing element consists of a seismic mass supported by two thin suspensions comprising close to their clamping a symmetric piezoresistive Wheatstone bridge for signal conversion. By deflection of the mass, mechanical stress is applied to the piezoresistors, and the Wheatstone bridge is detuned by $\alpha n m U_b$. $\alpha n m$ is the effective piezoresistive coefficient, and $U_b$ is the supply voltage of the bridge. An additional semiconductor resistor of 17 kΩ is utilized for temperature sensing. MOSFET stages are integrated for signal amplification and as driver for an optoelectronic interface.

A schematic of the optoelectronic setup is shown in Fig. 3. An AlGaAs/GaAs double-heterostructure IRED (OECA, VQ502) of $360 \times 360 \times 180$ μm$^3$ in size is positioned onto a square via hole in the sensor chip. The optical power at an emission wavelength of $\lambda = 870$ nm is specified as 8 mW at a drive current of $I = 50$ mA. Conductive epoxy resin of a specific resistivity of $10^{-3}$ Ω·cm (2400 circuit works) is employed as a glue for electrical contact formation between the chip metallization and the bottom and top electrodes of the IRED, i.e., wire bonds are avoided. Insulation between the conductive paths is achieved by nonconductive epoxy resin (EPO-TEK 353ND). This epoxy resin, which is transparent at $0.7 \mu m \leq \lambda \leq 0.9 \mu m$, is also used for fixing a standard graded-index optical fiber (Siecor) of core and cladding diameters of 50 and 125 μm, respectively. No optical components are employed to focus the IRED radiation onto the fiber. This structure is suitable for mass production using a fiber-sensor assembly machine [14].

III. SENSOR FABRICATION

The vibration sensor is realized using silicon micromaching on [100]-oriented n-type Si of a specific resistivity of 2–4 Ω·cm. The parameters of the resonator as required for the application and the resulting resonance frequency $f_0$ are given in Table I. The entire fabrication process comprises five steps.

1) The Si wafer is simultaneously etched from the front side and the back side using KOH (30 w/o) at 60 °C to predefine resonator structure and grooves employed as aids for fiber alignment, mask alignment (two-side lithography), and dicing. A thermally grown 1.6-μm-thick SiO$_2$ layer structured using buffered hydrofluoric acid solution is utilized as the etching mask.

2) Boron diffusion from a silica emulsion (emulsitone, borofilm 100) is performed at 1100 °C to realize the piezoresistors, temperature sensor, and source/drain re-
of the mechanical resonator after KOH etching. The etch rates were 24.4 \mu m/h for (100)-Si, 0.08 \mu m/h for SiO\textsubscript{2}, and 0.04 \mu m/h for Au/Cr. The most critical parameter for the resonance frequency and the sensitivity is the thickness of the resonator suspension. Resonator suspensions of 30 \mu m were fabricated within bounds of \pm 2 \mu m. Dynamical characterization of the sensor was performed using a 1-W loudspeaker at accelerations ranging from 0.02 to 0.10 g and a signal analyzer (HP 3561A) to acquire the spectrum. The measured resonance frequency of 92.4 Hz closely agrees with the desired value of 96.8 Hz, which is close to the third harmonic of the characteristic frequency of the sensor.

B. Fiber-Optical Readout

After mounting the IRED and before the optical fiber was attached, we measured the optical power emitted through the opening in the Si chip using a powermeter (Advantest TQ8210). We found a linear dependence of the optical power on the drive current \( I \) with a slope of 0.0175 W/A. The light intensity per unit area (and per drive current) emitted by the IRED through the opening in the chip was \( N/I = 100W/(A \times r \times cm^2) \), The part of this intensity which can be launched into a graded-index fiber of core radius \( a \) and numerical aperture \( A_N \) is approximately given by \( P = 0.5 \times N \pi a^2 \tau A_N^2 \) [16]. For the employed fiber of \( a = 25 \mu m \) and \( A_N = 0.21 \), we find \( P = 6.8 \mu W \) at \( I = 50 \) mA corresponding to a coupling loss of \(-21.1 \) dB. \( P \) was measured using a calibrated Ge-photodiode (laser monitoring systems) operated at open circuit of a sensitivity of 0.93 \times kV/W. In Fig. 4, the diode voltage \( U \) and \( P \) are displayed in dependence on \( I \) exhibiting typical features like the cut-in voltage and linear dependence above. At \( I = 50 \) mA, we find a coupling loss of \(-24.1 \) dB close to the above theoretical estimate. The power conversion efficiency is \(-45 \) dB. Within wide bounds, these results are not affected by the alignment of the fiber to the IRED. We found that the coupling efficiency decreases by less than \(-1.5 \) dB when the distance between IRED and fiber is increased to 0.3 mm. In lateral dimensions, the fiber is passively aligned by the tilted side walls of the opening in the Si chip. These results are important for automatic sensor fabrication using a fiber-chip assembly machine as required for mass production [14].

The performance of the optoelectronic interface after integration on the sensor chip was investigated using a single

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IV. SENSOR CHARACTERIZATION

A. Vibration Sensor

The technological steps 1)–3) of the Si process were controlled by optical inspection of the geometrical dimensions of the MOSFET's leading to a surface hole concentration of \( 2.5 \times 10^{15} \) cm\textsuperscript{-3} and a diffusion depth of 4.1 \mu m. Subsequently, the wafer is thermally oxidized at 1100 °C. The realized field-oxide and gate-oxide thicknesses are 0.5 \mu m and 60 nm, respectively. Finally, layers of Cr (30 nm) and Au (300 nm) are deposited by e-beam evaporation and structured using lift off. This metallization is resistant against an etching attack by KOH (30 w/o) at 60 °C for at least 2 h as necessary for the following step.

3) A second KOH etching step (30 w/o, 60 °C) is performed during which the resonator structure is released at one end for free movement out of the chip plane. No additional layer to protect the electronic components is employed. The etching time is given by the residual thickness of the suspensions after step 1). Simultaneously, the via hole for vertical fiber-to-IRED attachment (cf. Fig. 3) is opened.

4) The wafers are cleaved into dies, which are mounted into carriers (KOVAR) and electrically connected by ultrasonic bonding using an Al/Si (1%) wire of 100-\mu m diameter.

5) As the last step, the optoelectronic interface (cf. Fig. 3) is assembled. For this purpose, the IRED is positioned by a micro gripper onto the via hole in the sensor chip (Fig. 3), where it is fixed by a small amount of conductive epoxy resin. To improve fixing and insulation transparent epoxy resin is used. Finally, conductive epoxy resin is deposited for electrical contact to the top electrode. The lateral positioning accuracy amounts to \pm 10 \mu m, thus meeting well the tolerance requirements of around \pm 50 \mu m given by the dimensions of the IRED and the via hole. Further improvement is possible by micromachined alignment aids fabricated, e.g., by anisotropic etching [15]. Passive alignment by the inclined side walls of the via hole is used to position the optical fiber with respect to the IRED. Transparent epoxy resin baked at 60 °C for 30 min is utilized for fixing. For pull relief of the connection the fiber is attached to the chip carrier.
common-source MOSFET stage to drive the IRED. In Fig. 5, the electronic circuit is displayed, which can be operated at a single voltage supply of \( U_0 = -12 \) V. Since in the present configuration the MOSFET is dc coupled to one of the branches of the Wheatstone bridge, only one half of the output signal is exploited. The resistances \( R_1 \) and \( R_2 \) for adjusting the supply voltage of the Wheatstone bridge to \( U_b = 2.5 \) V (\( R_1 + R_2 = 380 \) \( \Omega \)) and the dc input voltage \( U_g \) of the driver stage can be realized by MOSFET’s. In Fig. 6, the drain current \( I_d \) of the driver MOSFET and \( P \) are plotted versus \( U_g \). At \( U_g \leq -6 \) V, the characteristic is linear changing to \( I_d \sim (U_g - U_T)^2 \) close to the threshold voltage. Similarly, the transfer function \( P(U_g) \) of the optoelectronic interface is linear below \(-6 \) V. The electrical signal of the sensor generated by detuning the Wheatstone bridge is converted into an optical signal at the fiber output with an efficiency of 0.58 \( \mu \)W/V.

In this feasibility study, we realized a Wheatstone full bridge and a MOSFET monolithically on chip. However, in the measurements we utilized only one branch of the bridge. In order to exploit the full potential of the bridge, the electronic circuit can be easily extended toward a differential amplifier.

In Fig. 7, the amplitude spectrum of the resonator deflection periodically excited at 0.1 g is displayed. The upper and lower traces were measured at the output of the Wheatstone bridge and of the optical fiber, respectively. The driver MOSFET was operated at \( U_g = -6.5 \) V. The solid curves are fits to the measured data using the dynamical behavior of the classical oscillator with the resonance frequency and the quality factor as the fitting parameters for which we obtained 92.4 and 90 Hz, respectively. Close to resonance we observe voltages from 0.3 to 30 mV at the output of the Wheatstone bridge. This voltage range is typically observed with aged rolling bearings (Fig. 1). Taking the voltage-energy conversion efficiency of the optoelectronic interface of 0.58 \( \mu \)W/V and the sensitivity of the photodetector of 0.93 V/W into account, this corresponds to \( P \) ranging from -67 to -47 dBm at the fiber output and from -136 to -96 dBV at the Ge photodiode. Thus, the transmitted power is well above the noise-equivalent power of \(-116 \) dBm/(Hz)\(^{1/2}\) of the Ge photodiode. Our measurements of the photodiode output are restricted to more than -120 dBV due to the sensitivity limit of the signal analyzer.

Since at \( U_g = -6.5 \) V undistorted signal transmission by the optoelectronic interface is possible up to an input voltage swing of \( \pm 0.5 \) V (see Fig. 6), an amplifier stage can be integrated at the input of the driver MOSFET. The necessary amplification of the bridge output signal can be achieved by a two-stage common-source MOSFET circuit. Furthermore,
by reducing $U_T$ to $-2$ V, the linear region of the $L_d(U_g)$ characteristic was extended to around $U_g = -3$ V.

The power conversion efficiency of the optoelectronic readout can be improved by using fibers of larger core diameter, e.g., plastic optical fibers (POF’s) of $2a = 750$ μm. Fluorinated POF designed for wavelengths ranging from 0.6 to 1.3 μm are under development [17]. Alternatively, the active area of the IRED can be reduced to the fiber-core cross section leading to substantial reduction of power consumption by the IRED. In this case, monolithic integration of the IRED on the sensor chip is possible to keep fabrication efforts and cost low. III/V-based optoelectronic components can be realized by selective-area growth, which is compatible with bipolar MOS Si technology [18], [19]. Compatibility with KOH etching can be achieved using a Au/Cr metallization, which is suitable for ohmic contacts on Si as well as on InGaAs [20].

V. CONCLUSIONS

A micromachined vibration sensor with an optoelectronic interface was described. It was designed for resonant operation close to a vibration eigenmode characterizing irregularities of the inner race of a rolling element bearing. The performance of the sensor was investigated in static tests as well as dynamically at excitation strengths, which corresponds to progressed aging of the bearing. From the presented results, we conclude that both the conditions of sensitivity and immunity against EMI can be satisfied by the described resonant sensor with fiber-optical readout. A considerable potential of this sensor for on-line vibration control of calender rolls operated under the conditions of industrial production is expected.

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REFERENCES


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