A WAFER-BONDED, SILICON-NITRIDE MEMBRANE MICROPHONE WITH DIELECTRICALLY-ISOLATED, SINGLE-CRYSTAL SILICON PIEZORESISTORS

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ABSTRACT

This paper presents the design, fabrication, and testing of a piezoresistive microphone for wind-tunnel acoustic measurements. The microphone was fabricated by an aggressively scaled process which produces a 1500 Å-thick silicon-nitride membrane that supports 850 Å-thick, dielectrically-isolated, single-crystal silicon piezoresistors. Measured results include a linear response up to 155 dB, a sensitivity of -93 dB ($22.4\mu V/Pa$), and a bandwidth of at least 6 kHz.

INTRODUCTION

Compliance with the FAR 36-Stage 3 community noise standard is one of the major factors determining the commercial viability of the High-Speed Civil Transport [1]. Experimental acoustic data from forward-flight, jet-noise experiments plays an important role in verifying noise suppression techniques. Unfortunately, existing microphone technology is insufficient for this application because the signal-to-noise ratio is limited by the flow noise generated by the interaction of the microphone package (*e.g.*, the nose cone) and the wind-tunnel flow. A miniature microphone, flush-mounted to the surface of a laminar-flow airfoil offers the potential to reduce wind noise to acceptable levels. Surface mounting requires that the side length of the microphone be much smaller (≤ 1.0 mm) than the local curvature of the airfoil. In addition, the airfoil thickness places size limitations on the microphone package. These spatial requirements preclude the use of conventional condenser microphones, but are potentially achievable by a microfabricated transducer. Most existing silicon microphones [2,3] were designed for audio applications such as hearing aids [4] and lack the dynamic range and bandwidth requirements for wind-tunnel measurements (Table 1). Specifically, the wind-tunnel environment requires a larger maximum sound-pressure level (SPL), finer spatial resolution, and a larger bandwidth than the hearing aid application.

A microphone is an electro-mechanical-acoustic transducer that transforms acoustical energy into electrical energy. Although many different transduction principles

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	wind tunnel	hearing aid[4]
dynamic range	60-160 dB	27-120 dB
f_{res}	> 50 kHz	≈ 5.0 kHz
temperature range	-7 - 55 °C	-
relative humidity range	10 - 95 %	10 - 95 %
diaphragm size	< 0.5 mm	≈ 3.0 mm

Table 1: Comparative microphone specifications for wind tunnel and hearing aid applications (0 dB = 20 μPa).

have been employed [2], all are based on the detection of a pressure-induced structural deflection. Although most silicon microphones employ capacitive sensing schemes, concerns about narrow-gap condensation, as well as indications of favorable scaling advantages [5] lead to the selection of a piezoresistive sensing scheme over a capacitive scheme for this study. Piezoresistive microphones incorporating various combinations of materials and construction techniques have been fabricated for both acoustics [6,7] and fluid mechanics [8,9] measurement applications. These microphones are not appropriate for forward-flight aeroacoustic measurements because they either lack the proper spatial and temporal resolution [6,7] or possess unacceptably low sensitivities [8,9]. Our microphone design incorporates the transduction advantages of single-crystal silicon piezoresistors [7,9] with the spatial and temporal resolution advantages of thin-film diaphragms [8]. The device structure consists of ultra-thin, dielectrically isolated piezoresistors on top of a silicon-rich, silicon-nitride diaphragm. Several types of pressure-sensors designs have employed single-crystal silicon piezoresistors on silicon-nitride diaphragms by utilizing silicon-under-insulator technology [10] and the BE-SOI technique [11]. The wafer-bond/thin-back process presented in this article is a significant improvement over these processes in terms of diaphragm geometry and piezoresistor placement tolerances and it produces silicon-dioxide encapsulated piezoresistors.

SENSOR DESIGN

A piezoresistive microphone transforms acoustic energy into electrical energy by transducing the strain on the top surface of a deflected membrane, which is deformed by the acoustic pressure, into a corresponding

Figure 1: A schematic of the lumped acoustic model. Note that the microphone vent is exposed to the same pressure fluctuations as the diaphragm.

Figure 2: The equivalent circuit of the lumped acoustic model shown in Figure 1.

change in resistance. Therefore, the behavior of the stress or strain field as a function of loading is of particular importance. The exact characterization of the load displacement field behavior for a micromachined diaphragm is complicated by the presence of large in-plane forces due to processing, thermal expansion, and packaging. For our application, the piezoresistor placement and diaphragm geometry were determined by employing a fundamental structural model [12]. We found that a 1500 Å-thick, 210 μm-diameter silicon-nitride membrane meets the required performance specifications for wind-tunnel testing. The cavity and vent were sized by coupling the structural model into a lumped-element model (Figure 1). In this model, the distributed deflection of the diaphragm is lumped into a rectilinear piston possessing an effective mass (M_{me}) and compliance (C_{me}). In addition, this model incorporates the acoustic impedance due to the cavity compliance (C_a), vent mass (M_{ae}) and dissipation (R_a), and diaphragm radiation mass (M_{rad}). The equivalent circuit for this model is shown in Figure 2. In this electro-acoustic analogy, voltage is replaced by pressure, $p(t)$, and current by volume velocity, $q(t)$. The acoustic sensitivity is $q_c(\omega)/j\omega p(\omega)$. This model predicts a flat, minimum-phase response from 100 Hz–300 kHz with a resonant frequency greater than 1 MHz (Figure 3).

SENSOR FABRICATION

The microphone device structure consists of 850 Å-thick, silicon-dioxide encapsulated (150 Å-thick), single-crystal silicon piezoresistors on top of a 1500 Å-thick,

Figure 3: Theoretical Bode diagrams of dynamic response, $H(\omega) = q_c(\omega)/j\omega p(\omega)$ (0 dB = acoustic sensitivity at 1 kHz).

210 μm-diameter silicon-nitride membrane. Figure 4 is a SEM of a the top view of the microphone and Figure 5 is the corresponding cross-sectional schematic. Pressure equilibration is achieved by a 10 μm × 10 μm × 2.25 mm-long, channel which is vented to the surface. The U-shaped aspects of the vent intensify the viscous losses per unit length. This winding vent design conserves chip real estate while achieving the desired acoustic resistance. The arc-shaped and tapered resistor design results in piezoresistors that possess equal mean resistance, but respond with an equal and opposite change in resistance for a given deflection. This permits the use of both constant-current and constant-voltage excitation for fully-active and half-active Wheatstone bridges to maximize sensitivity and minimize thermal drift. Advantages over previous piezoresistive microphone designs include: superior gauge factors and reduced 1/f noise of single-crystal silicon compared to polycrystalline silicon [6,8], and no temperature-dependent leakage currents compared to diffused piezoresistors [7]. The microphones were fabricated using a silicon-nitride/silicon fusion-bond and thin-back process outlined in Figure 6. To begin the process, a 150 Å-thick passivating oxide is grown on a SIMOX handle wafer. The membrane material, 1500 Å of silicon-rich silicon nitride, is deposited and polished in preparation for bonding (A). The cavity and vent are etched into the handle wafer using a DRIE and 7000 Å of thermal oxide is grown as a bonding layer (B). The wafers are bonded in a 20% O₂ / 80% N₂ ambient and annealed at 1100 C for one hour (C). The bonded pair are first ground back to eliminate most of the substrate and then etched back to the buried oxide on the device wafer using a 20% KOH solution at 90 C. The piezoresistors are ion-implanted

Figure 4: A SEM of a half-active, full-bridge microphone.

Figure 5: A cross-sectional schematic of the microphone device structure (not drawn to scale).

with boron ($2E18/cm^3$) and the buried oxide is stripped using a 7:1 BOE. The piezoresistors are patterned using a plasma etch and a 150 Å-thick top passivation oxide is grown (D). Contact cuts are made, followed by metalization, venting, and die separation (E).

This process yielded oxide-encapsulated single-crystal piezoresistors on top of a silicon-rich, silicon-nitride diaphragm using standard step and repeat projection lithography. Process features include strict diaphragm geometry tolerances ($\pm 3\%$) and $0.25 \mu m$ piezoresistor alignment (Figure 7). The process also eliminates one packaging function by compactly integrating the cavity and vent on chip.

RESULTS AND DISCUSSION

The acoustic sensitivity and linearity was determined by testing the microphone with a reference microphone (B&K 4138) in a plane-wave tube. The test setup permits the independent variation of both SPL (50 Pa- 1100 Pa) and frequency (200 Hz- 6000 Hz). Figure 8 demonstrates a linear response up to 155 dB at 1 kHz. The measured sensitivity is $-93 \text{ dB} \pm 3 \text{ dB}$ ($0 \text{ dB} = 1 \text{ V/Pa}$) for a 10 V excitation and 0.7 mW power consumption (Figure 9). This represents over a five-fold increase in sensitivity and a two-order-of-magnitude decrease in power con-

Figure 6: A schematic of the microphone fabrication sequence. Note that for simplicity the winding vent was not drawn.

Figure 7: A SEM of the diaphragm region of a fully-active, full-bridge microphone.

Figure 8: The output voltage of a fully-active, full bridge microphone as a function of SPL at 1 kHz for an excitation voltage of 10 V.

Figure 9: The acoustic sensitivity of a fully-active, full bridge microphone as a function of frequency for an excitation voltage of 10 V. The response is flat to within the calibration of the plane-wave tube.

sumption over commercially available devices [9]. The measured and predicted sensitivity agree to within 3 dB. The predicted noise floor of this device due to Johnson noise is 63 dB. Acoustic sensitivity testing at NASA-Langley Research Center's Jet Noise Laboratory confirms our sensitivity results while noise measurements indicate a noise floor of 92 dB. We believe that this high level is mainly due to noise pick-up via the package and cabling.

CONCLUSIONS

A piezoresistive microphone for wind-tunnel measurements has been developed. The devices were fabricated using a novel wafer-bonding process that permits the fabrication of sub-micron thick, silicon-dioxide encapsulated, single-crystal silicon piezoresistors on a silicon-nitride membrane. The microphone was designed by using coupling a fundamental structural model and a lumped-element dynamic model. This device has been tested at both MIT and NASA-Langley. The measured acoustic sensitivity is in good agreement with predicted

values, but the noise floor is higher than expected. Currently, detailed sensitivity and noise testing are ongoing at NASA-Langley and the University of Florida.

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