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Noise in Piezoelectric MEMS: Modeling and Experimental Characterization

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Summary: This study investigates noise mechanisms in piezoelectric MEMS membranes to identify and minimize performance limitations. A comprehensive noise model is developed, incorporating experimental measurements and the amplifier's noise floor, validated through close agreement with measured noise spectra. The noise is decomposed into distinct sources, which are identified within the developed model. The findings provide valuable insights for optimizing MEMS membrane design, enhancing noise performance, and enabling high-precision applications in sensing and actuation.

Keywords: Piezoelectric MEMS, noise measurement, noise modeling, alumninium nitride, thin-film sensors.

Introduction

Noise refers to unpredictable fluctuations or disturbances in physical quantities that inherently arise, impacting the performance of a system. In the context of microelectromechanical systems (MEMS), noise imposes critical limitations on the accuracy of sensors and actuators, with noise sources broadly categorized as either extrinsic or intrinsic. Piezoelectric MEMS have attracted considerable attention due to their ability to convert mechanical energy into electrical signals and vice versa, making them crucial for precision sensors, actuators, and energy harvesters. However, their performance is often constrained by noise, which can obscure weak signals and degrade measurement accuracy. The multilayer thin-film structures in piezoelectric MEMS, which typically include a piezoelectric layer, electrodes, and additional mechanical or electrical insulation layers, further contribute to noise. Understanding and mitigating noise contributions from these layers, as well as from the piezoelectric origin, is essential for advancing the design and functionality of such devices, particularly in the context of recent advancements in micro-/nanomanufacturing technologies [1].

Materials and Methods

Experimental Setup

The piezoelectric MEMS membrane, characterized by high impedance and low signal output, necessitates a low-noise signal conditioning circuit before interfacing with the data acquisition system. The experimental setup, illustrated in Fig. 1, incorporates a low-noise voltage amplifier to enhance the membrane's signal, given its capacitance in the range of hundreds of Picofarads (pF). The setup spans two dedicated rooms: a measurement room housing data control and environmental monitoring equipment, and a Faraday room designed for noise characterization under room-temperature conditions. Pressure and temperature sensors are employed to ensure stable environmental parameters, which are critical for consistent data collection. The low-noise amplifier (Sierra Amps., SA1) connects the MEMS membrane to a multifrequency lock-in amplifier (MLA-3) for data acquisition. Inside the Faraday room, the MEMS membrane, mounted on a custom PCB, undergoes visual inspection before measurements. SMA connectors and coaxial cables are used to maintain signal integrity within the vacuum chamber hosting the membrane. Temperature and pressure sensors continuously monitor the vacuum chamber to ensure stability during measurements. The low-noise amplifier, with an ultra-low noise floor of 300 $\mathrm{pV}/\sqrt{\mathrm{Hz}}$, interfaces the MEMS device output with the data acquisition unit. The MEMS membrane under investigation is fabricated using a silicon-on-insulator wafer with a 500 nm buried oxide layer and a 2 μm device layer. The fabrication process includes the deposition of a 330 nm oxynitride insulation layer, patterning of Cr/Au electrodes (50/200 nm), sputtering of a 400 nm AlN piezoelectric layer, and subsequent etching steps to release the membranes. The chips are then diced, bonded to a PCB, and each chip hosts multiple piezoelectric membranes dedicated to noise measurements.

Noise Modeling

Noise in piezoelectric MEMS membranes originates from various sources that significantly in-

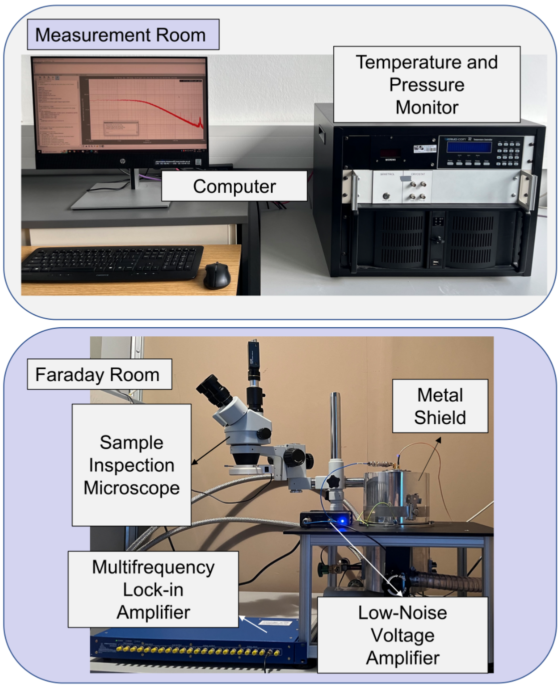

Fig. 1: Experimental setup for noise measurements of piezoelectric membranes, featuring a low-noise voltage amplifier for signal amplification, and a data acquisition system for noise characterization and spectral analysis.

fluence system performance. These sources are broadly classified as intrinsic noise, arising from the piezoelectric material, and extrinsic noise, introduced by the measurement and amplification setup. Thermal noise, also known as Johnson-Nyquist noise, is a fundamental contributor linked to the impedance characteristics of the piezoelectric membrane. This noise results from the random thermal motion of charge carriers within the material and depends on factors such as temperature, material properties, and operating frequency. Beyond thermal noise, the amplifier contributes noise components, including input voltage noise and current noise [2]. The input-referred voltage noise establishes the baseline noise floor of the measurement system, while current noise arises from gate leakage and capacitive coupling effects within the amplifier's input stage. Additional noise sources include the thermal noise of bias and load resistors, which propagate through the system and contribute to the total noise voltage at the amplifier's output. The interplay among these noise sources, the impedance of the piezoelectric membrane, and parasitic elements in the setup collectively determines the overall noise performance of the system. In this context, a model is developed based on individual noise sources that enables the interpretation of different factors that contribute to the total noise measured for the piezoelectric MEMS under investigation here.

Results

The noise spectral density measured at room temperature is presented in Fig. 2, comparing the experimental data, the modeled total noise, and the noise floor of the amplifier. The modeled noise closely matches the experimental measurements across the frequency range, confirming the validity of the noise decomposition. At higher frequencies, the noise approaches the amplifier's noise floor, while at lower frequencies, the measured noise exhibits a characteristic $1/f$ behavior. Peaks in the noise spectrum correspond to the structural resonances of the MEMS membrane, highlighting its vibrational response. The amplifier maintains a stable gain and noise characteristic within the frequency range of 1 kHz to 1 MHz, ensuring consistent noise performance. This comparison between the model and experimental data provides valuable insights into the dominant noise mechanisms and serves as a foundation for optimizing the membrane design and minimizing noise in future applications.

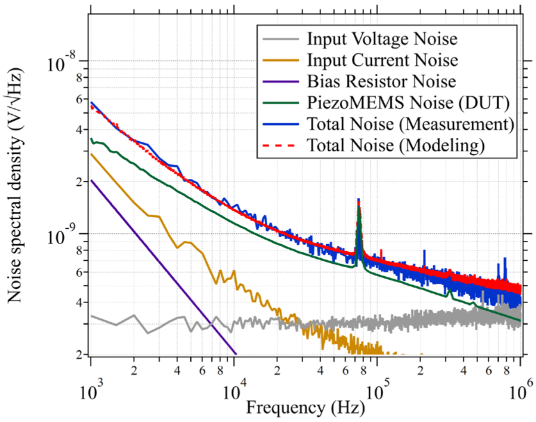

Fig. 2: Noise spectral density showing the total modeled noise compared to the measured noise for the piezoelectric membrane.

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