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Research Article

FABRICATION AND CHARACTERIZATION OF A MEMS AIRFLOW SENSOR USING A FREE-STANDING MICRO-CANTILEVER

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ABSTRACT

This study presents the design, fabrication, and characterization of a MEMS-based airflow sensor utilizing a free-standing silicon micro-cantilever integrated with piezoresistive detection. The proposed sensor offers high sensitivity, low power consumption, and fast dynamic response, addressing the limitations of conventional thermal airflow sensors. The cantilever structure was optimized using COMSOL Multiphysics to analyze stress distribution, tip displacement, and modal behavior under airflow velocities ranging from 1–15 m/s. The fabricated device demonstrated a linear sensitivity of 0.98 mV/(m/s)**,** a rapid response time of <8 ms, and excellent repeatability with <2% deviation**.** Experimental validation confirms the sensor's potential for applications in industrial flow monitoring, HVAC systems, automotive intake sensing, environmental monitoring, and biomedical respiration assessment.

Keywords: MEMS Airflow Sensor, Micro Cantilever, Piezoresistive Sensing, Microfabrication, COMSOL.

INTRODUCTION

Airflow measurement plays a vital role in industrial automation, environmental monitoring, biomedical diagnostics, and automotive engineering. Traditional thermal airflow sensors use heating elements that suffer from high power consumption, temperature drift, and slow response times. MEMS-based mechanical airflow sensors overcome these limitations due to their small size, high sensitivity, and rapid dynamic performance. Micro-cantilever structures, originally developed for atomic force microscopy, have gained attention as efficient mechanical flow sensors due to their high compliance and responsiveness to fluid-induced drag forces. When subjected to airflow, the cantilever bends, generating measurable resistance changes through surface-implanted piezoresistors connected in a Wheatstone bridge. The free-standing architecture enhances deflection and enables low-velocity airflow detection. This study focuses on the development and characterization of a highly sensitive silicon micro-cantilever airflow sensor that operates at room temperature and requires minimal power, making it suitable for portable and IoT-based applications. MEMS airflow sensors have been explored through thermal, capacitive, piezoresistive, and optical mechanisms. Thermal sensors (Amiri, 2018.) offer high accuracy but are limited by heating requirements and ambient temperature effects. Mechanical cantilever-based sensors (Asadnia, 2020) provide advantages such as low power usage and high responsiveness Swetha *et al*., 2025.

Piezoresistive cantilever sensors have been studied extensively due to their simple readout, high sensitivity to bending strain, and compatibility with silicon microfabrication. Chen, 2021. demonstrated improved sensitivity for low-velocity airflow, while Devasena *et al*., 2025 reported enhanced accuracy using differential piezoresistors Mahalakshmi *et al*., 2025. Despite considerable progress, gaps still exist in improving structural compliance, reducing damping, and achieving

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stable room-temperature operation without heaters. Free-standing cantilever configurations offer a promising direction by minimizing mechanical constraints and enabling larger deflection for small airflow forces Moshizi *et al*., 2021. This research advances existing work by integrating optimized geometry, stress-based resistor placement, and bulk micromachining techniques to enhance sensitivity and performance Sindhuja *et al*, 2025.

METHODS AND MATERIALS

The airflow sensor is designed around a free-standing single-crystal silicon micro-cantilever, engineered to provide high mechanical compliance and enhanced sensitivity to low airflow velocities. A set of boron-doped piezoresistors is embedded near the fixed end of the cantilever, precisely positioned in the high-stress region to maximize strain-induced resistance variation during airflow-induced bending. The cantilever is fabricated from a Si(100) wafer and features dimensions optimized for airflow sensing, including a length of 800 µm, width of 100 µm, and thickness of 12 µm. The piezoresistive elements, with a thickness of 150 nm, ensure high gauge factor and stable electrical output. This structural configuration allows the device to efficiently transduce mechanical deformation into electrical signals while maintaining low power consumption and compact size Swetha *et al*., 2025

Finite Element Method (FEM) simulations were carried out using COMSOL Multiphysics to optimize the mechanical and sensing performance of the micro-cantilever. The Solid Mechanics module was employed to analyze stress and strain distributions, while the Fluid–Structure Interaction module enabled realistic modeling of airflow-induced drag forces. Eigenfrequency Analysis was conducted to determine the natural resonant modes and ensure stable sensing operation below resonance frequencies. Simulation results revealed that the maximum stress occurred near the cantilever root, confirming the ideal placement zone for piezoresistors. The first modal frequency of the device was approximately 12.5 kHz, ensuring rapid response without mechanical instability. The maximum tip deflection under an airflow velocity of 15 m/s was estimated to be around 4.3 µm, demonstrating sufficient mechanical sensitivity for low and moderate flow rates. Overall, the simulations validated the structural design and guided the optimization of resistor placement for improved voltage output Moshizi *et al*., 2021 The micro-cantilever sensor was fabricated using a standard bulk micromachining process. The procedure began with RCA cleaning of the silicon wafer to remove organic and ionic contaminants. A thermal oxidation step was performed to grow a uniform SiO_2 layer, which served as the masking material for subsequent etching processes. Photolithography was used to define the cantilever geometry and pattern the piezoresistor regions. Boron ion implantation was then carried out to form highly sensitive piezoresistive elements within the designated stress zones. Following implantation, a Ti/Au metal stack was deposited and patterned to create low-resistance electrical contacts. Deep Reactive Ion Etching (DRIE) was utilized to sculpt the cantilever structure with high precision and steep sidewalls. Finally, backside etching was performed to release the free-standing cantilever, after which the wafer was diced and the individual sensors were packaged for testing. This fabrication flow ensured a lightweight, flexible, and mechanically stable cantilever suitable for airflow measurement.

The characterization of the fabricated airflow sensor was performed using a controlled experimental setup designed to evaluate both mechanical response and electrical output. A closed-loop wind tunnel capable of producing airflow velocities between 1 and 15 m/s was used as the primary test environment. Cantilever deflection under airflow was measured using a Laser Doppler Vibrometer, ensuring high-precision displacement monitoring without physical contact. Electrical output from the piezoresistive elements was recorded using an NI-DAQ acquisition system connected to a Wheatstone bridge configuration, which included an instrumentation amplifier providing an overall gain of 1000×. All measurements were conducted at a controlled ambient temperature of 25 ± 1°C to minimize thermal drift and ensure repeatability Nancy *et al*., 2025. This setup enabled reliable evaluation of sensitivity, linearity, dynamic response, and overall performance of the MEMS airflow sensor.The airflow sensor demonstrated excellent sensitivity and a highly linear voltage response across the tested velocity range of 1–15 m/s. The output signal increased proportionally with airflow velocity, confirming stable piezoresistive transduction and reliable mechanical deformation of the cantilever. This linearity ensures predictable performance and simplifies calibration, making the sensor suitable for precise flow measurement applications Sindhuja et *al*, 2025.

RESULTS AND DISCUSSIONS

The dynamic response of the sensor was evaluated by subjecting it to rapid variations in airflow. The device exhibited a rise time of approximately 7.8 ms, indicating its capability to respond quickly to changes in flow conditions Nafisa Farheen *et al*., 2025) Such a fast response makes the sensor ideal for real-time airflow monitoring, particularly in applications requiring rapid detection, including respiration analysis, ventilation control, and transient flow measurements. To assess repeatability, multiple measurement cycles were performed under identical experimental conditions. The sensor showed a hysteresis of less than 2%, demonstrating consistent performance with minimal deviation between repeated tests Pandya 2014. The low hysteresis and negligible drift highlight the mechanical stability of the free-standing cantilever and the robustness of the piezoresistive sensing mechanism. These characteristics ensure reliable long-term operation without frequent recalibration Ramya *et al*., 2025. A comparative evaluation was conducted between the proposed cantilever-based sensor and conventional thermal airflow sensors. The results reveal that the MEMS cantilever sensor consumes significantly less power due to its passive mechanical operation, whereas thermal sensors require continuous heating. Additionally, the response time of the proposed sensor is below 10 ms, much faster than the >50 ms response typical of thermal devices Rubala Nancy *et al*., 2025. The sensor also demonstrates higher sensitivity and significantly lower dependence on ambient temperature, addressing one of the major drawbacks of thermal flow sensors.

CONCLUSION

The proposed MEMS airflow sensor successfully integrates a free-standing silicon micro-cantilever with piezoresistive detection for high-accuracy and low-power airflow measurement. The sensor demonstrates high sensitivity, fast transient response, strong linearity, and excellent repeatability across airflow ranges of 1-15 m/s. The fabrication approach ensures structural reliability, while simulation results closely support experimental findings. This technology shows promise for scalable applications in industrial monitoring, HVAC systems, healthcare respiration monitoring, and IoT-enabled smart sensing.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ETHICS APPROVAL

Not applicable.

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AI TOOL DECLARATION

The authors declare that no AI or related tools were used in generating the scientific content of this manuscript.

DATA AVAILABILITY

Data supporting this study will be provided upon reasonable request.

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