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Characterization and performance estimation of a MEMS spirometer

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Abstract

The electrical characteristics and performance estimation of a MEMS spirometer is reported. The device design incorporates a silicon turbine, integrated magnets, ball bearings, and stators having planar coils. Pneumatic actuation of the turbine with tangential gas flow induces voltages on the stators. Spirometer parameters including breathing flow rate and lung capacity can be determined from the induced voltage amplitude and frequency. Two 12-pole stators with 25- and 50-turns per pole were fabricated. The resistance and inductance values were measured to be 3.9 kΩ and 2.6 mH, and 15.8 kΩ and 10.3 mH, respectively. The expected sensitivity of the devices was calculated to be 0.1 V/lpm and 0.2 V/lpm for the 25- and 50-turns per pole stators, respectively. The integration of all device components will lead to a compact and low-cost spirometer for patient self-monitoring.

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Keywords: MEMS spirometer; flow sensor; stator

1. Introduction

Spirometry is a common practice of measuring exhaled or inhaled air to assess the type and extent of lung malfunctions including COPD and Asthma diseases. Spirometers are relatively bulky devices that are found in

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established healthcare facilities, although expensive portable models exist. To reduce the medical costs associated with the spirometry tests and to enable patient self-monitoring, low-cost and portable spirometers should be developed.

The most important component in a spirometer is the sensing unit that converts fluid flow into an electrical signal, which can be used to determine breathing flow rate and lung capacity. Several types of sensors have been implemented in spirometers so far including thermal sensors, pressure sensors, ultrasound sensors, and turbine-type sensors [1-10]. Turbine-type sensors have major advantages such as linearity, bidirectional flow operation, and insensitivity to ambient temperature and pressure [1]. Accordingly, we have dedicated our efforts to developing a turbine-based MEMS spirometer, which can also be integrated with already-existing electronic devices such as smart watches and cell phones. Initial results on the development of the turbine component was reported in [1-2]. This study focuses on the fabrication and testing of the stator as well as the performance estimation of the device.

2. Design

The device consists of a turbine sandwiched in between two stators as shown in Fig. 1a. The turbine is supported by ball bearings (∅ = 1 mm) that are embedded in trenches, which are etched on the turbine and stators. Turbine blades are defined along the periphery, and permanent magnets are integrated into both turbine faces. Multi-turn planar micro coils are patterned on the stator to facilitate voltage induction. Fig 1.b shows the packaging scheme, where the device is actuated using tangential air flow provided from the air inlet. Pneumatic actuation of the device results in turbine rotation, which leads to voltage induction between coil terminals on the stator. The amplitude and frequency of the voltage can be used to determine the spirometry parameters [1-2].

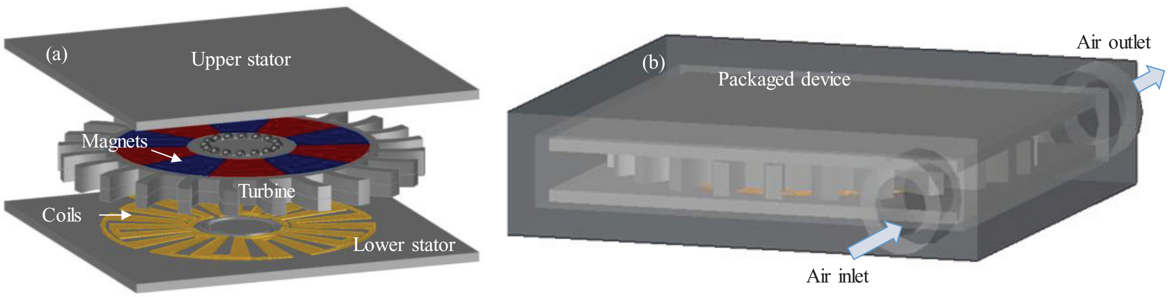

Fig. 1. Schematic of the design, (a) exploded view, (b) packaged device.

3. Fabrication and Test Results

The stators were fabricated using 500 µm-thick, p-type, 1 Ω-cm silicon wafers coated with 2 µm-thick silicon dioxide layer for electrical insulation (Fig. 2a). Initially, AZ5214E negative photoresist was applied and patterned using photolithography. Next, 500 nm-thick Cu was sputtered and lifted off to define the first metal layer that forms the multi-turn planar coils (Fig. 2b). The wafer was coated with a 3 µm-thick SU-8 layer that covers most of the coils and provides openings to be used for connection to the underlying coils (Fig. 2c). AZ5214E was applied and patterned once again, which was followed by the sputtering of another 500 nm-thick Cu layer over the wafer. Next, lift off process was performed, leaving the second metal layer on the wafer that completes the coil structure (Fig. 2d). Finally, the stators were extracted from the wafer using a dicing saw. Two stator designs, namely 25-turns per pole and 50-turns per pole, were fabricated. Photographs of fabricated stators are shown in Fig. 3a and Fig. 3b, respectively.

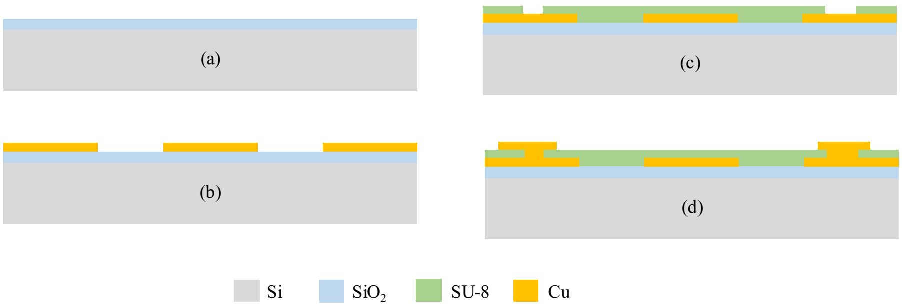

Fig. 2. Fabrication process of the device, (a) starting wafer, (b) deposition and patterning of the first Cu layer, (c) SU-8 lithography, (d) deposition and patterning of the second Cu layer

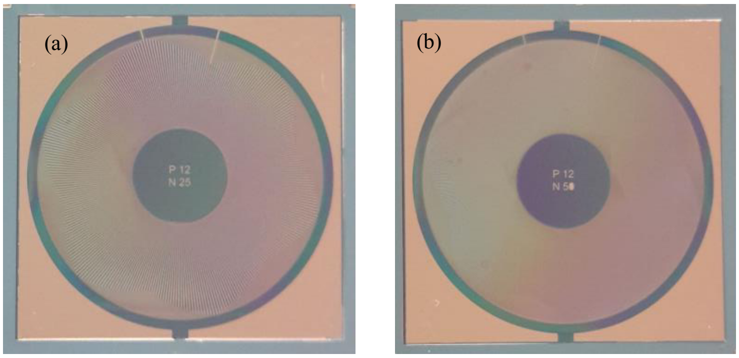

Fig. 3. Photographs of fabricated stators (a) 25-turns per pole stator, (b) 50-turns per pole stator.

Both stators were tested for their electrical parameters using Cascade Microtech PM-5 probe station and Keithley 4200 SCS Semiconductor Parameter Analyzer. The resistance and inductance of the 25-turns per pole stator were measured to be 3.9 kΩ and 2.6 mH, respectively. The values for the 50-turns per pole stator were determined to be 15.8 kΩ and 10.3 mH, respectively. The quadruple increase in the resistance and inductance is attributed to the increase in the total coil length as well as the inner and outer connection parts of the coils. Based on these results and our previous work on turbine development and characterization in [1-2], the expected voltage amplitude was calculated and plotted as a function of flow rate in Figure 4. The sensitivities were calculated to be 0.1 V/lpm and 0.2 V/lpm for 25- and 50-turns per pole stator designs, respectively.

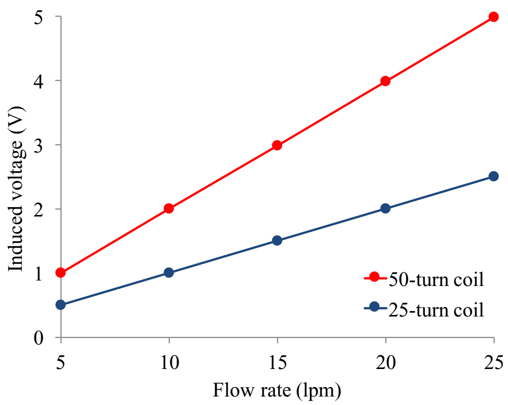

Fig. 4. Estimated voltage vs flow rate graph

4. Conclusion

The development of the stator component of a MEMS spirometer is reported. The device utilizes electromagnetic induction to convert normal breathing into electricity, which can be used to measure breathing flow rate and lung capacity. The stator was fabricated through a series of thin film deposition and patterning processes. Electrical measurements revealed that the resistance and inductance values are 3.9 kΩ and 2.6 mH, and 15.8 kΩ and 10.3 mH for the 25-turns per pole and 50-turns per pole designs, respectively. The sensitivity of the two stator designs was calculated to be 0.1 V/lpm and 0.2 V/lpm, respectively. The near-future integration of the turbine and stators will lead to a very compact and low-cost spirometer that can be used by patients at home for self-monitoring their diseases. The size of the device also lends itself for integration into portable electronic devices such as cell phones.

Acknowledgements

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