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Array of Biomimetic Hair Sensor Dedicated for Flow Pattern Recognition

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Abstract- Flow sensor arrays can be used to extract features from flow fields rather than averaging or providing local measurements provided the sensors in the array structure can be interrogated individually. This paper addresses the latest developments in fabrication and array interfacing of biomimetic artificial air-flow sensors. Hair flow sensors in wafer level arrays have been successfully fabricated using SOI wafers with deep trench isolation structures. Using a Frequency Division Multiplexing (FDM) technique, we were able to simultaneously measure flow signals at multiple sensor positions. By virtue of FDM, once signals are retrieved from all individual array elements, spatio-temporal flow patterns can be reconstructed, while few system interconnects are required.

I. INTRODUCTION

Biological hair-sensors are amongst the most sensitive sensors appearing in nature. For crickets, two large mechano-sensory hair-arrays reside on the cerci at the rear of their abdomen forming the sensing part of a cricket's escape mechanism, e.g. during spider-attacks [1]. The large numbers of hairs, the array density, the hair's mechanical properties as well as their directivity result in a smart system capable of extracting the direction of approaching predators by virtue of the aerodynamic representations as sensed with high spatial resolution of the air movements.

Engineering often takes its inspiration from biology in order to design, fabricate and characterise micro-mechanical sensing systems [2]. Inspired by crickets and using MEMS technology, single and arrays of artificial flow sensors have been designed and implemented successfully within different research groups [3,4,5]. The arrangement of many hairs in a dense array structure allows for a broader design range of structures than for single hairs and thereby a wider range of spatio-temporal measurements.

In this work, the Frequency Division Multiplexing (FDM) technique is demonstrated as sensor addressing technique in hair-sensor arrays. Performing parallel signal acquisition from the individual hair flow sensors with a reduced number of connections to improve the sensor performance is the main design target. The advantage of the present scheme is realized in facilitating large number of array elements.

II. ARTIFICIAL HAIR SENSOR ARRAYS

Hair flow-sensors were fabricated using sacrificial poly-silicon surface micro-machining technology to form a suspended silicon nitride membrane with ≈ 1 mm long *SU-8* hairs on top. The electrode deposited on top of the membrane form capacitors with the underlying electrodes, namely the silicon device layer of an Silicon on Insulater (SOI) wafer. Due to viscous drag torque acting on the hairs, the membrane tilts and in consequence the capacitors, on both halves of the sensor both change but with opposite signs. These capacitive changes are measured differentially to provide measurements for air flows surrounding the hair.

The fabrication starts with patterning of the bottom electrodes into the highly-conductive device layer (25 μm) by anisotropic reactive-ion etching (RIE) down to the isolating SiO_2 layer of the SOI wafer. Afterwards, a thin nitride (Si_3N_4) layer and a thick poly-Si layer (1400 nm) were deposited for the isolation of the bottom electrodes during later sacrificial layer etching and for completely filling the isolation trenches separating the bottom electrodes, respectively. Two wet oxidation runs and successive etching in BHF were performed to reduce the poly-silicon layer to 600 nm thickness before patterning isolation trenches into the poly-Si. The patterning of the membranes, aluminum electrodes and processing of *SU-8* hairs is identical to fabrication of previous devices described in e.g. [6]. Fig. 1 shows the artificial hair geometry and its biological source of inspiration.

III. ARRAY ADDRESSING

During propagation, flow signals change in amplitude both with time and position i.e. they form flow patterns. Recognising specific flow patterns would be possible by extracting flow signals from the individual array elements. Hence, methods for separating and rapid read-out of the sensors signals have been considered. Usually,

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interfacing large numbers of sensors is achieved by using different multiplexing schemes, either in time or frequency domain, to reduce the number of required connections. FDM and, more often, Time Division Multiplexing (TDM) are described in the literature to extract the signals individually from an array of sensors [7]. Each addressing scheme has various technical advantages and trade-off. These advantages and drawbacks lie in the sensor and system bandwidth, the complexity of the system, the effect of noise and cross-talk. It was found that the use of the FDM addressing scheme is favourable in our case. Unlike the TDM, the FDM technique is not sensitive to propagation delays. Channel acquisition techniques and hardware needed for the FDM are therefore not as complex as those for TDM. Hence, the array structure can be extended in number of hair-sensors and dimension without harming the integration time and thus the signal-to-noise ratio.

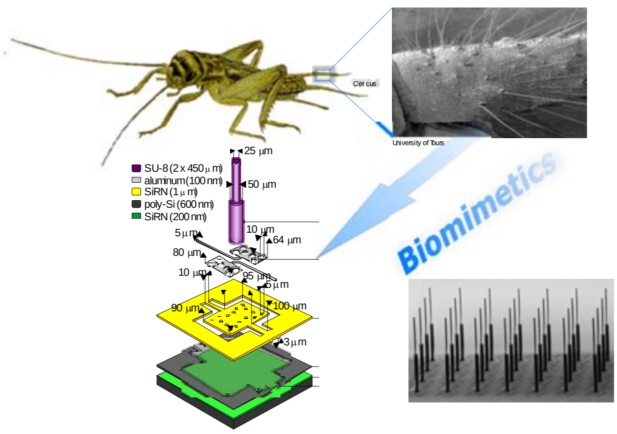

Fig. 1. Artificial hair geometry and its biological source of inspiration.

Using the FDM architecture, a bank of oscillators is applied to feed signals to the columns of the array. Along the rows the signals are collected from all of the individual sensors. The basic principle of the FDM technique for hair-sensor array addressing is shown in Fig. 2. The FDM technique is beneficial here when large groups of analog channels are required to be transmitted off-chip simultaneously since FDM is an inherently parallel addressing technique, with no synchronisation between signals during the transmission and receiving required and with no reduction in sensor bandwidth or sensor performance (when selecting appropriate carrier frequencies).

To facilitate FDM in our cricket-inspired hairs sensor, the fabrication process is adapted from the process in [6] in patterning the 25 µm thick device layer by etching trenches, to isolate the signal electrodes of each hair sensor. This allows fabricating arrays on wafer level in which each sensor can be measured individually. Fig. 3 shows an image of the artificial hair sensor array dedicated for FDM technique used in this study.

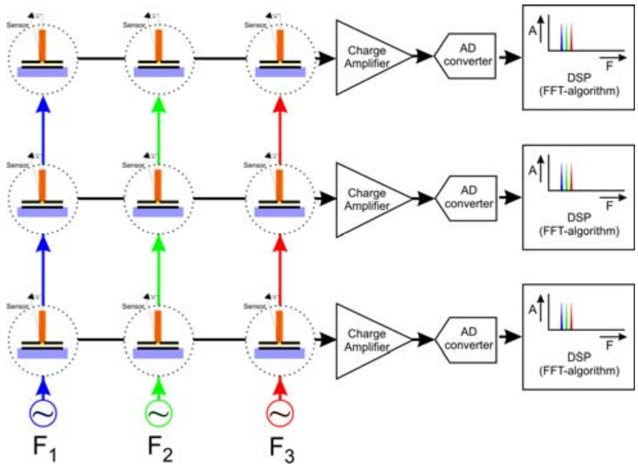

Fig 2. Basic principle of FDM technique for hair-sensor array addressing.

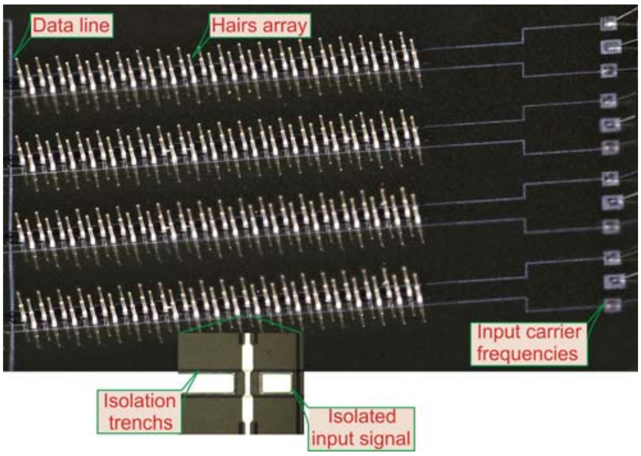

Fig. 3. Image of the artificial hairs sensors array dedicated to FDM addressing experiments.

IV. Experimental Results

Inspired from crickets and using MEMS technology, arrays of (1 × 4) artificial flow sensors have been fabricated to demonstrate the proposed FDM array addressing technique. The measurements were conducted using a loudspeaker to generate a 75 Hz sinusoidal air flow to the hair sensors. A bank of oscillators (1.05, 1.10, 1.15, 1.20 MHz) was used to feed different excitation signals to the array columns. Each column has a unique excitation frequency which allows amplitude modulation (AM) and shifting the flow signals to different carrier frequencies. Along the row, a single charge amplifier is used to pick up the AM signals from the entire array. Further, synchronous demodulation and low-pass filtering techniques were used to extract the original flow signal detected by each sensor individually. Fig. 4 shows the experimental setup used in this study.

The results show that the sensors are moving as a

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result of the loudspeaker-induced air displacements. We were able to retrieve the air flow signal, applied to 1 × 4 wafer level array sensors, from each sensor simultaneously using the FDM technique. Fig. 5a shows the FFT spectrum of the AM signals detected at the output of the charge amplifier and Fig. 5b shows the FFT spectral of the original signal from the source and the demodulated signal detected by hairs sensors.

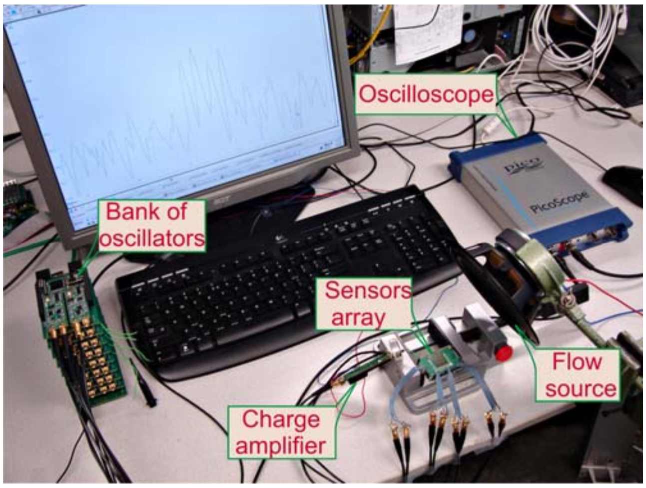

Fig. 4. Experimental setup used to demonstrate FDM technique.

V. CONCLUSIONS

In this study we presented our progress in addressing artificial hair flow-sensors arranged in array structures. Our flow sensitive-hair sensors are based on mimicking the cricket's hair-sensors and are fabricated using surface micro-machining technologies. Artificial hair-flow sensors were successfully implemented in wafer level array structures. The FDM addressing technique has been successfully demonstrated using an array consisting of (1 × 4) hair sensors to reduce the required number of electrode connections. This opens possibilities for the determination of various flow signatures from the spatial flow distribution over the array structure.

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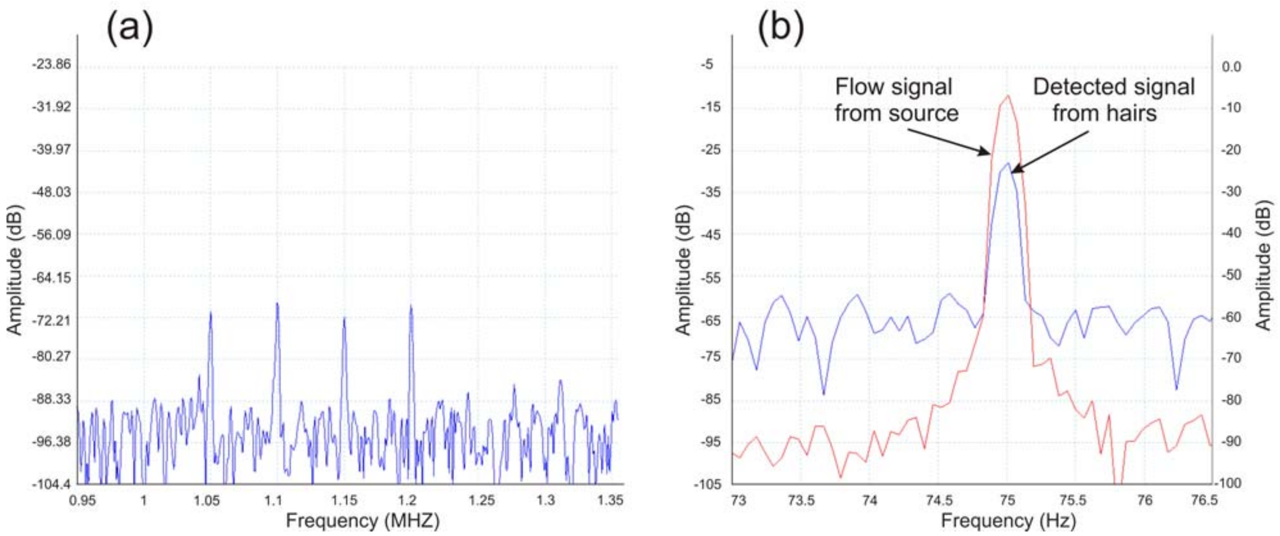

Fig. 5. The FFT spectral of (a) AM signals acquired at the output of single charge amplifier (b) flow signal from the source and demodulated flow signals detected by hairs sensors while using FDM technique with 1 × 4 hairs sensors array.

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