TOWARDS HIGH-RESOLUTION FLOW CAMERAS MADE OF ARTIFICIAL HAIR FLOW-SENSORS FOR FLOW PATTERN RECOGNITION

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ABSTRACT

Next to image sensors, future's robots will definitely use a variety of sensing mechanisms for navigation and prevention of risks to human life, for example flow-sensor arrays for 3D hydrodynamic reconstruction of the near environment. This paper aims to quantify the possibilities of our artificial hair flow-sensor for high-resolution flow field visualization. Using silicon-on-insulator (SOI) technology with deep trench isolation structures, hair-based flow sensors with separate electrodes arranged in wafer-scale arrays have been successfully fabricated. Frequency Division Multiplexing (FDM) is used to interrogate individual hair elements providing simultaneous real-time flow measurements from multiple hairs. This is demonstrated by reconstructing the dipole fields along different array elements and hence localizing a dipole source relative to the hair array elements.

INTRODUCTION

In nature, crickets are fitted with large numbers of tiny hair-sensors residing e.g. on the cerci at the rear of their abdomen. These hair-sensors are amongst the most sensitive hairs in nature forming the sensing part of a cricket's escape mechanism, e.g. during spider-attacks. The hairs density, mechanical properties, preferential direction and the accompanying neural system result in the capability of extracting air movements with high spatial resolution. This assists crickets to detect approaching predators and eventually escape even at small separation distance [1].

Biomimetics is a burgeoning field that examines principles and solutions for challenging environmental interaction problems derived from biological examples. Recently this approach has been used for insect inspired flow-sensors to surpass limited performance of traditionally engineered sensors. Air-hair interaction, geometry of the hair-sensor arrays (hair shape distribution, position, density and compound flow interactions) and functional relevance thereof are not fully understood yet [2]. Therefore, engineered sensor-arrays also aid biologist in understanding the bauplan of hair-sensor arrays.

Inspired by crickets and fish and using MEMS technology, single- and arrays of artificial flow sensors have been designed and implemented successfully in different research groups [3-5]. These designs vary in hair material, detection principle and targeted applications.

Understanding the functioning of hair-sensor arrays and fabrication possibilities of high-density hair-sensor arrays is a prerequisite to uncover a broad range of structures and the large potential for spatio-temporal flow pattern measurements. However, such measurements can only be realized when each array element is interrogated individually. In this work, we present for the first time wafer-scale hair-sensor arrays with separate electrodes enabling the possibility to measure signals from different hairs individually and simultaneously. We focus especially on reducing the complexity of interfacing hair-sensor arrays by minimizing the number of interconnects while maintaining real-time signals and large signal-to-noise ratio (SNR). We demonstrate a Frequency division Multiplexing (FDM) technique as array-addressing scheme. The results confirm the possibility to simultaneously retrieve signals from multiple hair-sensors without deterioration of the performance of individual hair-sensors and we show this for an array made of (5×4) array elements. The virtue of the FDM scheme is especially realized with large numbers of array elements.

ARTIFICIAL HAIR SENSOR

Sensing principle

Figure 1 shows the structure of the mechano-receptive sensory-hairs with their source of inspiration. Hair sensors are fabricated using surface micromachining technology. A poly-silicon sacrificial layer is used with a structural silicon nitride membrane and 1 mm SU-8 hair on top. The detection principle is based on variation of the capacitance between two electrodes, one of them deposited on top of the membrane and the other one being the underlying silicon substrate. Due to the airflow induced drag-torque acting on the hair, the membrane tilts and consequently the capacitance of both halves of the hair-sensor change equally but oppositely. Two out-of-phase AC voltage sources (carrier signals at ~ 1 MHz) are used to detect the changes in capacitance and convert these to voltage signals by modulation of the carrier amplitude (AM signal). Subsequently a synchronous demodulation technique is used to recover the original (baseband) airflow signal.

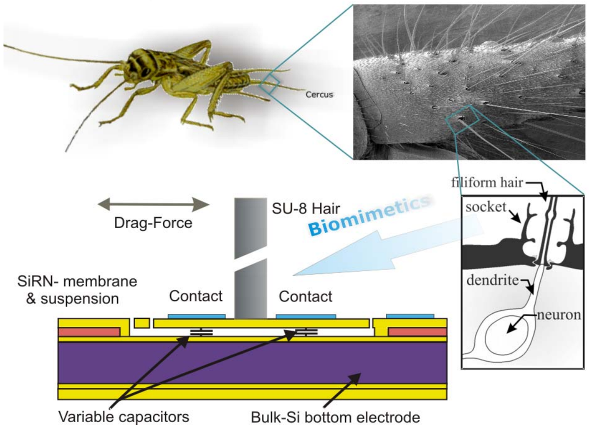

Figure 1: Artificial hair geometry and its biological source of inspiration.

Fabrication

Previously, we have shown advancements in the design and fabrication of flow-sensitive hair-sensors by making high-density hair arrays [6,7] as shown in Figure 2. Averaging the signals of a group of hairs was used to increase the SNR (i.e. adding the common capacitance changes but averaging out noise from similar but independent hairs). However, in that sensor design the underlying silicon substrate forms the common electrode for the capacitors of all integrated hair-sensors. This prevents fabrication of independent sensing electrodes and thereby wafer-scale array addressing.

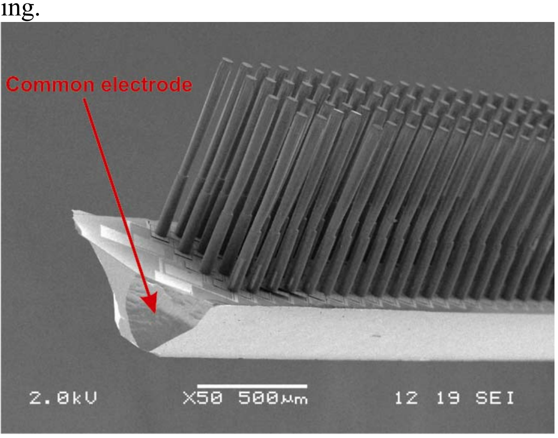

Figure 2: A SEM image of an artificial hair flow-sensor array showing the grouping principle (many hairs arranged in parallel with the substrate as common electrode).

Here we look into possibilities to make high density wafer-scale hair-sensor arrays using a simple fabrication process and which can be interfaced using the same (or comparable) capacitive measurement methods. The use of Silicon-on-Insulator (SOI) wafer technology allows us to redesign the electrode system of the hair sensor and to isolate the sensing electrode of each hair element. This assists in interrogation of each individual hair-sensor with two anti-phase AC-voltage signals. In the current hair-sensor design the carrier signal electrodes are separately defined in the silicon device layer (using deep trenches for insulation) while the common electrode for the output signal is implemented by an aluminum layer on top of the membrane. This enables measuring the signals from individual array elements representing the airflow at the corresponding hair-sensor position without averaging signals over a number of hairs.

Figure 3 illustrates the fabrication process of the hair sensor arrays dedicated to the FDM array-addressing scheme. The fabrication process of the current hair-sensor array starts by etching deep insulation trenches into the 25 μm-thick device layer of the SOI wafer down to the SiO_2 layer by directional reactive-ion etching (RIE), thus forming the bottom electrodes (Figure 3-I). Subsequently a thin nitride (Si_3N_4, 200 nm) layer and a thick poly-Si layer (1400 nm) are deposited by low-pressure chemical vapour deposition (LPCVD) for protection of the bottom electrodes during later sacrificial layer etching (SLE) and for completely filling the isolation trenches separating the bottom electrodes, respectively (Figure 3-II/III). Two wet oxidation runs (1150 °C, 120 minutes) and successive etching in BHF are applied to reduce the poly-silicon layer to 600 nm, the eventual gap distance. Then insulation trenches are patterned into the poly-Si by RIE (Figure 3-III). Next a 1 μm-thick SiRN layer is deposited by LPCVD and etched by RIE to form the actual membranes and torsion beams (Figure 3-IV). A 100 nm thick aluminum layer is sputtered and patterned forming the sensor top electrode (Figure 3-V). This is followed by two sequential exposure procedures of two 450 μm-thick SU-8 layers for the fabrication of 900 μm-long hairs (Figure 3-VI). At the end, the structure is released by etching the sacrificial poly-silicon layer (Figure 3-VII) using XeF_2 (for selectivity purposes).

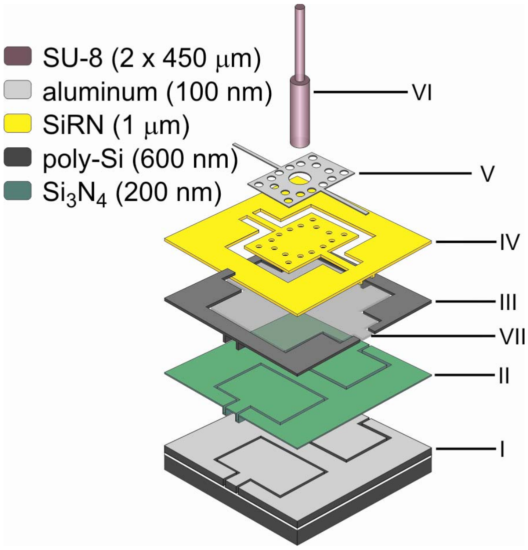

Figure 3: Schematic representation of hair sensor.

ARRAY ADDRESSING USING FDM

As objects move around, their associated flow signals change in amplitude both with time and position i.e. they form characteristic spatio-temporal flow patterns. Observation of these flow patterns would be possible using arrays, extracting flow signals from individual array elements. For large arrays, technical challenges arise in making fast, accurate and parallel interfaces to enable addressing of all array sensors while maintaining a manageable number of readout circuits. As a perquisite for addressing a large number of array sensors the proposed mechanisms should not lead to any deterioration in the performance of individual hair-sensors.

Usually interfacing large numbers of sensors is achieved using multiplexing schemes, either in time or frequency domains, to reduce the number of interconnects. Direct signal acquisition, FDM and, more often, Time Division Multiplexing (TDM) were described in the literature to extract the signals from individually array sensors [8]. FDM acquisition technique has various advantages for:-

- measuring real-time signals;
- reducing hardware complexity (i.e. reducing inter-

connects by factor of 2N*M/2N+M and charge amplifier count by factor of N, where N and M represents array columns and rows respectively;

- reducing electronics integration costs;
- maintaining same SNR;
- scalability i.e. array structure can be extended without deteriorating SNR;
- minimizing possible cross-talk;

This indicates that the use of the FDM scheme is favourable in our case, considering our prerequisite in achieving live measurements.

Using the FDM architecture, illustrated in Figure 4, a bank of oscillators (each with unique bi-phasic carrier frequency) is applied to the columns of the array. The frequency range of the system is divided into a number of sub-bands equalling the number of array columns while maintaining guard intervals (Δf) as shown in Figure 5. Additionally, the series resistance in between hair elements has to be minimized to prevent inter-modulation and hence cross-talks between channels.

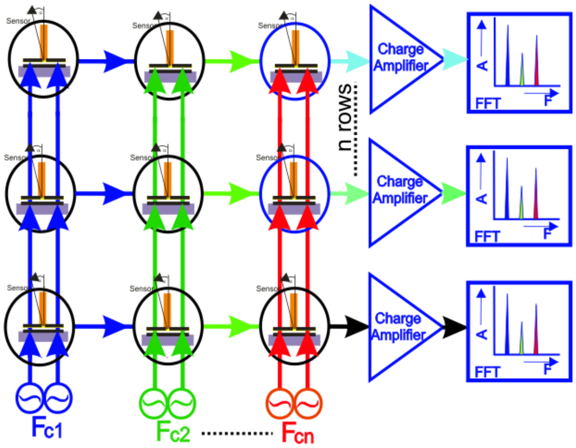

Figure 4: Principle of the FDM addressing technique.

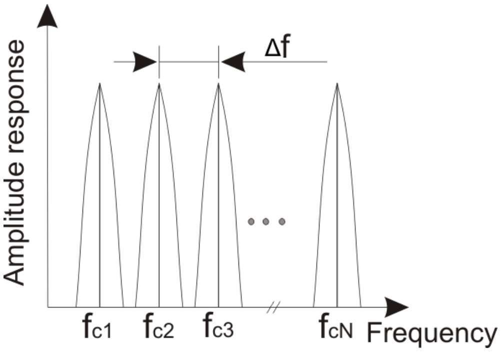

Figure 5: The row signals spectrum using the FDM addressing technique with guard intervals.

The output signal of the hair flow-sensor is an amplitude modulated (AM) signal in proportion to the differential capacitance. The resulting signals along a row are discernable in the frequency domain and can therefore be superposed and transported through a single wire without signal loss. Each row output therefore can be connected to a single charge amplifier which can be retrieved from their carrier using synchronous demodulation.

MEASUREMENTS & RESULTS

In the experimental work an array of (5 × 4) artificial hair-sensors was tested using dipole fields since these are well described in literature [9]. A sphere with radius of 5 cm was harmonically driven at 30 Hz to examine the performance of our hair-sensor array and to localize the source. FDM was utilized to simultaneously measure signals from individual hair-sensors elements (see Figure 6).

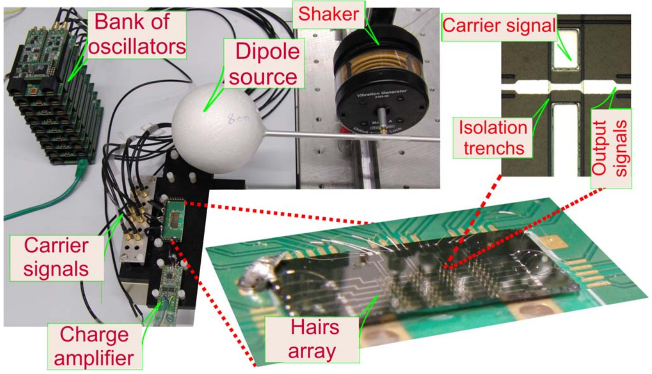

Figure 6: Photograph of the measurement setup and sensor arrays. Isolation trenches are also shown.

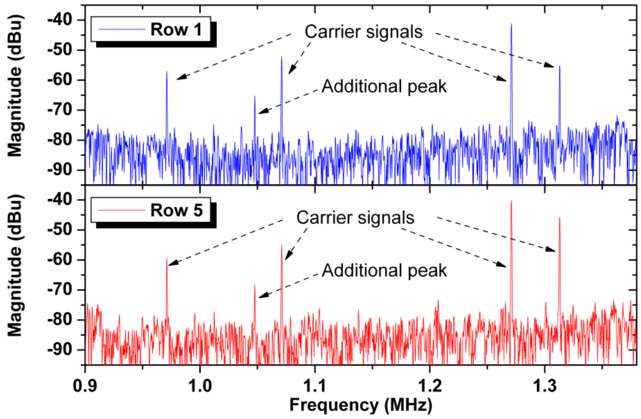

Figure 7: FFT spectrum of AM signals from two rows at the output of the charge amplifiers while employing FDM.

The results show that we were able to retrieve the flow signal, applied to the hair-sensor array, by each hair element while using FDM. Figure 7 shows the frequency spectrum of the signals at the output of the charge amplifier representing the four AM signals for two selected FDM channels. These results clearly confirm the successful implementation of the FDM addressing technique for our hair-sensor array resulting in the benefit of a largely reduced number of interconnects. However, nonlinearities of signals generators (the existence of additional frequency components from the neighbouring channels) can cause cross-talk between FDM components. As a result of that, each hair sensor is not only biased by a voltage at its own frequency, but also at the frequencies of the neighbouring channels i.e. intermodulation (see Figure 7). Thus, the bias frequency has been chosen to be free from additional frequency-components used in other channels.

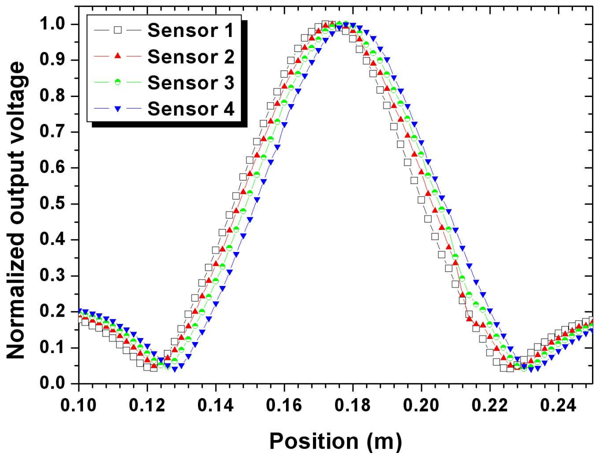

Figure 8: Flow field measurement vs dipole position simultaneously detected by 4 hairs in one row. The separation between peaks matches with the hair separation.

As demonstration for successful reconstruction of flow fields by the hair-sensor array the dipole fields were measured along different rows and the relative positions of the dipole source to the array elements were determined. Figure 8 represents the dipole field detected by each hair-sensor by means of a virtual lateral line system (shifting the dipole source in discrete steps to construct a lateral line system [10]). The shift in peak positions represents the column separation distance between sensors and perfectly matches the physical design distance between the elements (2 mm).

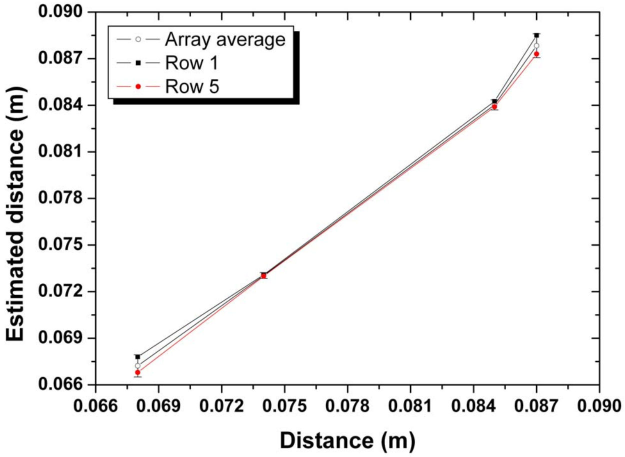

Figure 9: Dipole source localization by hair-sensor array while using FDM.

This proofs that each hair element faithfully reflects the dipole field, at its position, while employing the FDM technique. The source localization process using signals from various array rows as well as averaging signals over the same rows (simultaneously with FDM) are shown in Figure 9. The source localization is achieved according to the methods described in [10]. The results show a clear linear relation between the real and estimated distances. This demonstrates the hair-sensors ability to localize the relative positions of the dipole source to either each hair element or the entire array accurately (using the virtual lateral line arrangements). This opens possibilities to perform spatio-temporal flow field measurements.

CONCLUSIONS & FUTURE WORK

In conclusion, this contribution details the advancements of a "flow-camera" based on biomimetic flow-sensor arrays. SOI based fabrication technology in combination with FDM has opened up the possibility to simultaneously interface multiple hair-based flow-sensors adding new dimensions to flow-imaging of the surrounding environment with potential application in e.g. robot guiding.

In future work, air flow patterns will be investigated using larger number of hair-sensors. Such systems will allow the determination of various object parameters, such as position and direction of movement, by the spatio-temporal flow signatures as measured over the array structures. Additionally, arranging large numbers of sensitive hairs in high-density arrays allows for a broad range of hair structures. These developments will be beneficial to sensing and controlling functions of vehicles by imaging the surrounding environment even in total darkness.

ACKNOWLEDGEMENTS

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