ENGINEERING MINIATURIZED HAIR CELL SENSORS FOR AUDITORY SYSTEM

Mohsen Asadnia[1], Ajay G. P. Kottapalli[2], Majid E. Warkiani[3], Jainmin M. Miao[4] and Michael S. Triantafyllou[5]
[1]Department of Engineering, Macquarie University, Sydney, Australia
[2]Singapore MIT Alliance for Research and Technology, Singapore
[3] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney
[4]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
[5]Department of Mechanical Engineering, Massachusetts Institute of Technology, Boston, USA

ABSTRACT

Mechanosensory haircells are well-evolved biological sensors found in nature. In this paper, we present a novel artificial NEMS stereovilli sensor developed through novel fabrication techniques. The NEMS stereovilli sensor fabrication combines soft-polymer material synthesis methods and nanofiber generation techniques with conventional microfabrication methods to form novel flow sensors. The sensor fabrication mainly consists of three major steps which are 1) fabrication of artificial stereovilli of varying aspect ratios, 2) formation of nanofiber tip-links through electrospinning of PVDF material and 3) development of biomimetic HA-MA hydrogel cupula. These artificial sensors closely mimic stereovilli and achieve ultrahigh sensitivities through a biomimetic design. The sensors achieve a sensitivity and threshold detection limit of 300 mV/(m/s) and 8 μm/s, respectively.

INTRODUCTION

Mechanosensory haircells are well-evolved biological sensors found in nature. The basic internal structural organization and sensing principles of the stereovilli in the neuromasts of fishes shares a high similarity with the haircells in the auditory system of mammals which function as microphones. Mechanosensory haircells are not just limited to the lateral-lines of fishes but are also found as sensors and transducers in various sensing systems in mammals. Haircells are a basic biological sensing system found in auditory and vestibular systems (that render a sense of balance) of all vertibrates [1, 2]. It is rather surprising to notice a high level of functional overlap between the auditory haircells found in the inner ears of mammals and the lateral-line haircells found in fishes and amphibians [3]. In the bio-inspired sensors developed in the past [4-9], the haircells have been mimicked using a single high-aspect ratio vertical pillar. However, in reality, the biological haircell is a much more complex structure consisting of multiple soft pillars of varying heights (figure 1) [10]. The intricate morphological organization of the haircell with varying heights of the stereovilli is rather complex and could be quite challenging to achieve through micro-fabrication techniques. This could be the reason that among all the superficial neuromast (SN)-inspired flow sensors developed so far, the haircell has always been approximated as a cylindrical pillar [11, 12]. Most of the researchers who developed artificial lateral-lines in the past undertook a bio-inspired approach by developing devices that emulate the flow sensing functionality of the SNs [5, 13, 14]. In recent years, bio-inspired MEMS flow sensors have become an interest to be used for many applications including navigation and object detection on autonomous underwater vehicles (AUV) [15-17], flow measurement in biomedical such as in breath monitoring and intravenous (IV) infusion, as well as in liquid dispensing system. Their advantages in terms of light weight, low powered, high resolution and surface mountable are more favorable compared to the traditional detection devices such as sonar and optical devices that are often low resolution and large in size. Many researches have been done to develop robust and highly sensitive MEMS flow sensors for these applications. On a contrary, this paper presents a biomimetic approach of development of artificial SNs which achieves the desired flow sensing functionality by developing devices that closely mimic the structure, sensing principle and materials involved in the biological inspiration. This paper, through true biomimetic designs, presents the development of a novel haircell sensor that mimics the structural organization of stereovilli and kinocilium. The tip-links that form the core sensing elements in the individual haircell bundle act as sensing elements in the artificial stereovilli MEMS device.

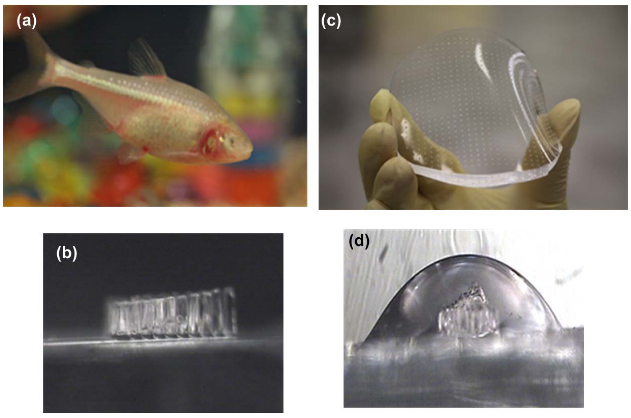

Figure 1. Inspiration from blind cave fish in developing flow sensors (a) A photograph of the blind cave fish which uses thousands of such haircells for flow sensing. (b) flexible PDMS pillars fabricated for the artificial stereoville sensor (c) A flexible PDMS wafer with thousands of NEMS flow sensors (d) An optical microscopic image of a complete single NEMS biomimetic SN flow sensor

ARTIFICIAL STEREOVILLE SENSOR

The biomimetic NEMS stereoville sensor presented in this work is designed on the same structural basis as that of the biological stereovilli sensor. A bundle of high-aspect ratio polydimethylsiloxane (PDMS) pillars positioned close to each other perform similar function as that of the stereovilli. PVDF nanofibers form the tip-links connecting all the consecutive tips of the stereovilli and the kinocilium. A soft-polymer cupula developed from hyaluronic acid methacrylic anhydride (HA-MA) acts as a cupula. The HA-MA hydrogel polymer encapsulates all the stereovilli. A very thin layer of conductive epoxy is used to form contact pads on both the sides of the haircell bundle for collecting signal generated from the nanofibers. The NEMS stereovilli sensor mainly consists of three major structural parts which are 1) hydrogel cupula that interacts with the external flow, 2) stereovilli bundle that transduces the flow to the tip-links and 3) PVDF nanofiber tip-links that are the actual sensing elements. The following sections describe the dimensional design of all these three sub-components of the NEMS flow sensor (see figure 2).

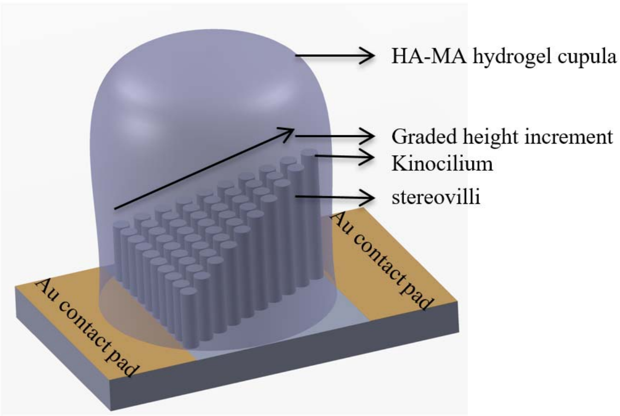

Figure 2: A schematic describing the artificial stereovilli device structure and the various materials used in the device fabrication.

A single artificial haircell bundle consisting of 55 PDMS stereovilli arranged into 10 columns is developed. The device consists of a one tallest pillar (kinocilium) and the number of stereovilli in each column increase as the distance from the kinocilium increases (see figure 3). Pillars in each column have the same height and all the columns are graded in height. The height of pillars in each column reduces as the distance from the kinocilium increases. The column the shortest pillars is the farthest column from the kinocilium. Each stereovilli of a successive column of higher height falls at the center of the two stereovilli of the preceding shorter column. This arrangement maximizes the number of tip-links generated between the pillars and also ensures that all the tip-links have similar length which is equal to the distance between the columns. This arrangement and dimensional design of the stereovilli is inspired by the studies by the biologists on the biological stereovilli that have been conducted in the past [19, 20]. Each PDMS stereovilli has a diameter of 50µm and the successive stereovilli are spaced at 25µm distance. As depicted in figure 3, the entire distance between the tallest kinocilium and the shortest stereovilli that is located farthest from the kinocilium spans a length of 725µm. Although in reality the size of the biological stereovilli are much smaller, the dimensions of the artificial stereovilli are chosen in order to be feasible to fabricate through micro-lithographic techniques and PDMS moulding processes. The graded height increment of the PDMS pillars ranges from 200µm for the shortest pillar column to 400µm for the tallest pillar (kinocilium).

Sensing principle

Flow disturbances in water cause the artificial cupula of the sensor to bend in response. Since all the PDMS stereovilli are infused into the hydrogel cupula, the bending of the cupula causes all the stereovilli to bend.

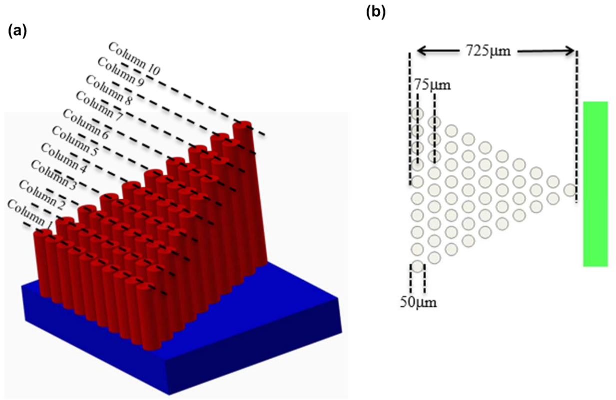

Figure 3. Artificial stereovilli design (a) A schematic showing the number of stereovilli and their organization in each biomimetic NEMS sensor (b) Top-view of the NEMS sensor showing various dimensions used in the sensor design.

Due to the different heights of the pillars in each column of the bundle, there is a difference in the displacement of the pillars of various columns. Due to the difference in the displacements of the pillars of successive columns, there will be a resultant stress induced on to the PVDF nanofiber that connects the pillars. This stretching occurs at all the nanofiber tip-links connecting every pillar to the longer pillar of the successive column. The charges generated in the nanofiber are collected at both the ends through contact pads as a voltage output. Figure 4 describes a simplified scenario of bending of displacement induced in stereovilli of same height as compared to stereovilli with height gradient. Due to a 2D representation, each pillar in reality represents an array of pillars into the plane of the paper. Fabrication process of the sensor is illustrated in figure 5.

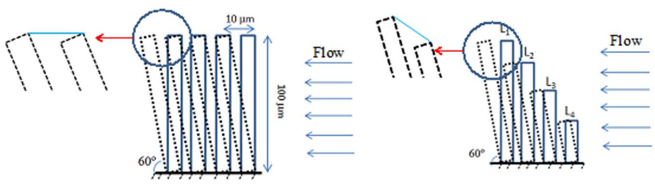

Figure 4: A schematic describing the basic sensing principle of sensing of the biomimetic NEMS sensor. (a) If pillars of all the columns are designed to have the same height there would be no resultant stress generated on the nanofibers (b) Pillars with height gradient result in stress in each unit tip-link that connects a pillar to its successive taller pillar.

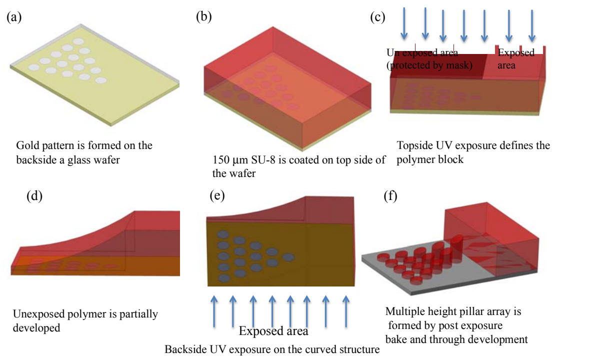

Figure 5: Fabrication of artificial PDMS stereovilli (a) Lift-off process to form Au circular patterns. The glass wafer with Au patterns acts as a substrate as well as a mask (b) A 750µm thick SU-8 layer of uniform thickness (c) A exposed (hardened) region of SU-8 created right at the edge of the longest pillar (kinocilium) in order to generate an exponential gradient of SU-8 that is needed to form pillars of varying heights (d) A gradient in SU-8 formed through partial time-controlled developing process (e) Exposure from the backside of the glass wafer through Au patterns to form the stereovilli (f) Final developing process to form the stereovilli of varying height.

EXPERIMENTAL RESULTS

The goal of the characterization is to determine the sensitivity, threshold sensing limits and the sensing accuracy of the sensor. Experiments to determine the direction dependence of the sensor output are also illustrated in this section. Unlike other piezoelectric sensors fabricated using bulk piezoelectric material, these sensors do not need to be poled with high electric field. This is because the poling is conducted in situ while the electrospinning process applies high electric field to generate nanofibers. In order to tap the output voltage generated by the sensor two probes are connected to the contact pads as shown in figure 6. The experimental results section is mainly divided into three main experiments. In all the experiments, a dipole stimulus described is used to generate oscillatory flows of various amplitudes and frequencies underwater.

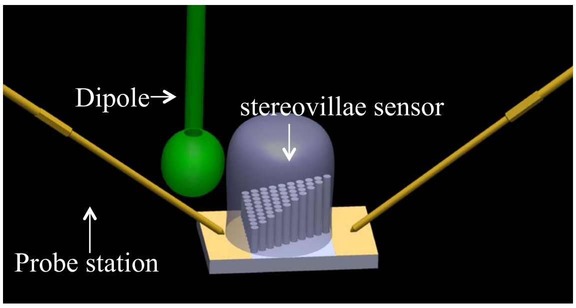

Figure 6: Experimental set-up in water showing probes that connect to the contact pads of the stereovilli sensor and the dipole in the vicinity of the sensor

The dipole stimulus is calibrated to determine the velocity of vibration for various sinusoidal signal amplitudes using a LDV. In order to determine the sensitivity and velocity detection threshold of the sensor the vibration of the dipole is varied from a velocities as low as 1µm/s to 80mm/s. The dipole is vibrated at a constant amplitude of 35Hz and the amplitude of vibration is varied in order to generate varying flow velocities. The sensor is positioned at a distance of 25mm from the dipole and the output of the sensor is amplified by 500 times using SRS low-noise pre-amplifier. Figure 7 shows the flow velocity calibration of the sensor. The results presented are average results of 5 runs. The sensor's output varies linearly with respect to the amplitude of the sinusoidal source signal as expected. The sensor demonstrates a threshold sensing limit of 8.24µm/s below which the sensor's response starts to become noisy, due to the reason that the sensor output is hitting the noise floor. The sensor demonstrates a sensitivity of 0.286 mV/(mm/s) for sensing water flow. The threshold sensing limit achieved by this sensor is extremely low even compared to that of the biological neuromast counterpart [12]. In figure 7b it can be observed that the linear increase in sensor output is very gradual for water flow velocities up to 20mm/s, after which, the rate of increase of sensor output is much higher. This is due to a skin friction on the standing pillar, generated at velocities below 20mm/s (corresponding to a Reynolds's numberRe≈50), that majorly contributes to the sensor output. At the range of velocities below 20mm/s, the drag force that contributes to the output is linear to flow velocity.

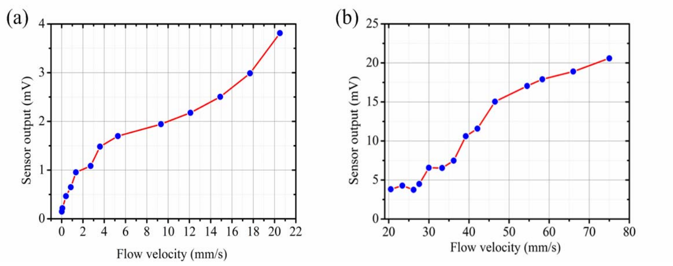

Figure 7: Flow velocity calibration of the NEMS stereovilli sensors for (a) low flow velocities and (b) higher flow velocities

CONCLUSION

In this paper we describe the development of an artificial SN which is the closest biomimetic to the haircell bundle that have been developed so far. The device structure consists of a series of 55 PDMS pillars that are organized into 10 columns with a gradient in height between each column. All these PDMS stereovilli were connected to each other through nanofiber tip-links. Piezoelectric PVDF nanofibers that are aligned from the shortest stereovilli column to the longest kinocilium are developed through electrospinning process. Due to the difference in the displacements of the pillars of successive columns, there will be a resultant stress induced on to the PVDF nanofiber that connects the pillars. This stress induced causes a voltage out-put that is acquired. The sensors are calibrated for flow velocity sensing underwater using a dipole stimulus. The sensors demonstrated a high sensitivity of 0.286 mV/(mm/s) and an extremely low threshold detection limit of 8.24μm/s.

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CONTACT

*M. Asadnia, tel:+612 9850 9528,
mohsen.asadnia@mq.edu.au