# HIGHLY LINEAR, ULTRA SENSITIVE BIO-MEMS FORCE SENSORS WITH LARGE FORCE MEASUREMENT RANGE

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## ABSTRACT

We have designed, fabricated, and characterized a set of displacement based micromechanical force sensors. These sensors combine high force resolution (50-500 pN) with large force measurement range (100 nN- 1 μN) and have highly linear force-displacement characteristics. In addition, we have established a novel scheme to avoid capillary forces during the immersion and removal of these sensors from aqueous environments that make them highly suitable for biological studies. As a demonstration of their versatility, these sensors are used to measure the mechanical response of embryonic Drosophila (fruit fly) axons *in vivo*.

## INTRODUCTION

In recent years, advances in instrumentation have led to remarkable progress in our understanding of cell mechanotransduction [1]. Several studies have unambiguously established that living cells respond to mechanical stimuli from their micro environment respond both mechanically and biochemically [2]. The most common techniques used to study single cell mechanical response are atomic force microscopy, magnetic twisting cytometry, micropipette aspiration, optical trapping and optical stretching [3]. These techniques usually study cell response to small deformations (1-2 μm) or have small force measurement range (~1 nN). But large cell deformations are physiologically relevant and to study cell response in such cases a new set of microfabricated sensors were developed [4]. These micromechanical force sensors used a system of thin flexible beams to measure forces up to 1 μN. However, these sensors used a complex fabrication procedure and had limited force resolution (~ 1 nN) and linear range.

Here, we present a new class of displacement based micromechanical force sensors that combine high force resolution with large force measurement range. In addition, these sensors have a highly linear force-displacement response and are fabricated by a simple two mask process that significantly reduces the number and complexity of processing steps. Furthermore, we have developed a simple scheme to avoid capillary forces during the immersion and removal of these sensors from aqueous environments that make them highly suitable for biological studies.

## FORCE SENSOR DESIGN

The force sensors comprise of a system of identical flexible beams attached to a rigid probe and a fixed beam that serves as a reference for displacement measurement (Fig. 1). The principle of operation of the force sensor is as follows. When subjected to an external force, the beams deform and their total deflection is found by optically measuring the relative displacement of the probe with respect to the fixed reference beam. The external force is then given by the total deflection of the beams multiplied by their combined stiffness. The combined stiffness of the beams is calculated from their geometry and independently verified by calibration.

As evident from Fig. 1, the basic repeating element of the force sensor is a frame, which is comprised of two flexible beams connected at their ends by a thick, rigid bar. The frame structure was chosen because it substantially increases the in-plane rotational stiffness of the force sensor. This ensures that the probe deflects only along the x axis and the structural integrity of the sensor is maintained. The advantage of using the frame structure can be understood by comparing the rotation of a single beam and a frame when they are subjected to a moment M. The rotation of a single beam is given by

$$\theta_s = ML/EI \quad (1)$$

The corresponding rotation for the frame is

$$\theta_f = ML/2E(I+I^*) \quad (2)$$

Here, E = 170 GPa is the Young's modulus of silicon, $I = hb^3/12$ and $I^* = bhs^2/4$. h, b, and L are the depth, width and length of the beams whereas s is the distance between beams in a frame. In our force sensors, s~10b and therefore the rotation of the frame is about 600 times lower than that of single beam. The typical dimension of the beams in the force sensors are h = 30-40 μm, b = 2-4 μm, L = 2-3 mm, while the number of frames (N) is around 20.

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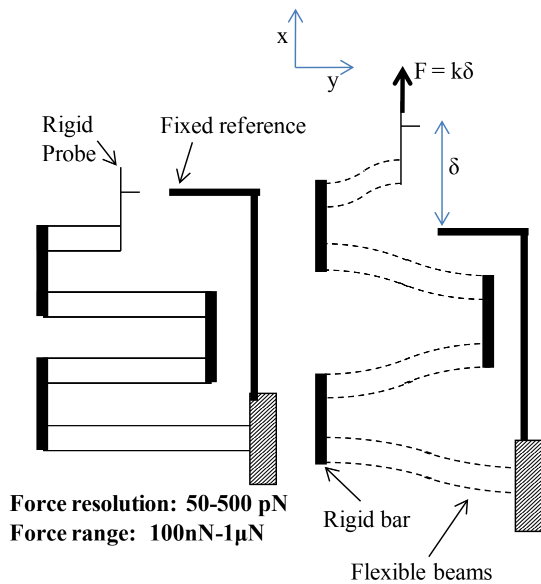


Figure 1: Schematic of the force sensor. Because of the frame design, the force sensor deflects only along the x direction.

In the force sensors, the frames are connected together in series. Therefore their combined stiffness in the x direction is 1/N times the stiffness of each frame. As a result, the force sensor can have high sensitivity even if the stiffness of the individual frames is not very low. In addition, the sensitivity and range of the force sensors can be altered simply by varying N without changing the dimensions of the beams that comprise the force sensor. More importantly, this design leads to a highly linear force-displacement relationship for the sensor (Fig. 2). This is so because even when the overall deflection (δ) is large, the deflection of individual beams is still small (δ/N) and hence non linear effects are negligible.

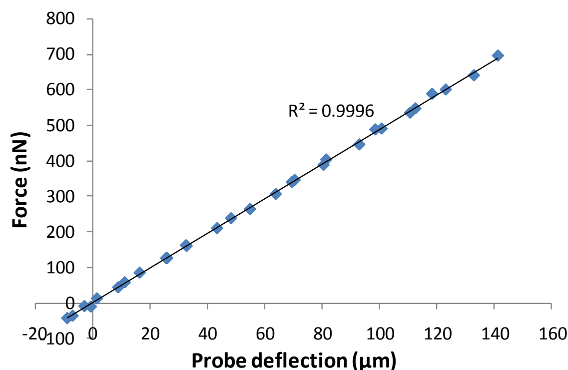


Figure 2: Force-deflection characteristics of a force sensor (k = 4.8nN/μm) showing the linearity of the response over a large range of deformation (~150μm). A displacement resolution of 100nm leads to a force resolution of ~500pN.

## FABRICATION PROCESS

The MEMS force sensors are fabricated from 150 μm thick (100) oriented silicon wafers using a simple two mask process. Before processing, the silicon wafer is cleaned thoroughly to get rid of any particles on the surface. In the first step, photoresist is spun on both sides of the wafer and patterned by photolithography. The top and bottom patterns are identical except that the bottom pattern does not have the force sensing beams. In the next step, the wafer is etched from the bottom side using ICP-DRIE (Inductively Coupled Plasma – Deep Reactive Ion Etching) to a depth of about 120 μm. After this the photoresist on the bottom side is removed by oxygen plasma and a thin layer of aluminum (~50 nm) is sputter deposited on it. In the next step, the wafer is etched from the top side using ICP-DRIE until the aluminum layer is reached, in the process creating the force sensing beams. Finally, the photoresist on the top side is removed by oxygen plasma. The aluminum layer performs a two-fold function. It prevents damage to the force sensing beams during venting in the ICP-DRIE process. In addition, the aluminum layer prevents damage from capillary forces when the force sensor is initially immersed into liquid. A scanning electron microscopy (SEM) image of the force sensor is shown in Fig. 3.

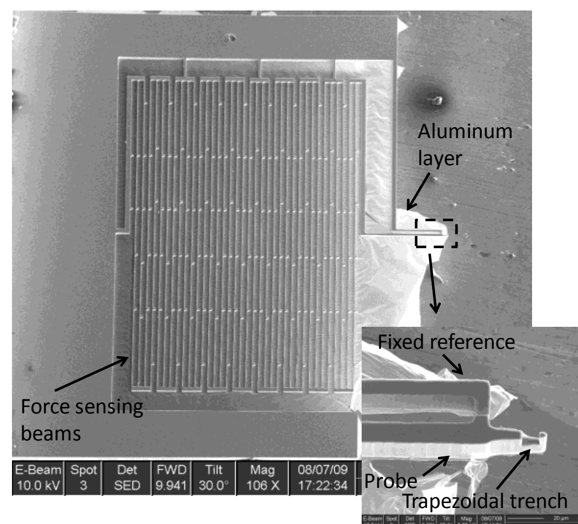


Figure 3: SEM image of a force sensor containing 18 frames in series (N=18). For the *in vivo* experiments on Drosophila embryos, trapezoidal trenches were cut into the probe using focused ion beam milling to enable easy gripping of the axons.

## SCHEME TO AVOID CAPILLARY FORCES

A major impediment to the use of micromechanical force sensors in biological applications is the damage caused by capillary forces during their immersion and removal from aqueous environments. The capillary forces arise because the meniscus that forms between the water surface and the force sensor needs to be broken for the sensor to be immersed or removed from water. We have established a novel scheme to avoid damage to the force sensors from capillary forces.

First, the bottom side of the force sensor, with the aluminum film (see Fig. 3) still intact, is glued to a 150 µm thick glass slide (5 mm by 7 mm). The glass slide with the sensor is then and immersed into a beaker containing a diluted solution of AZ 327-MIF developer. During the immersion, the aluminum film protects the beams against damage from capillary forces. Once the sensor is immersed, the developer etches the aluminum film slowly, in the process releasing the flexible beams. Then the developer is replaced with water by repeated dilution while ensuring that the sensor remains wetted at all times. When the glass slide is removed from the beaker it retains a droplet of water due to the increased hydrophilicity contributed by the sensor die. Therefore, the sensor remains inundated and is not exposed to the capillary meniscus. When the glass slide is immersed into another aqueous solution for biological experiments, the solution first contacts the water droplet keeping the sensor inundated. Therefore, the sensor is not exposed to the capillary meniscus either during its immersion or removal from water and thus avoids structural damage from capillary forces.

## IN VIVO MECHANICAL RESPONSE OF DROSOPHILA AXONS

Recent experiments have shown that mechanical tension is necessary for accumulation of neurotransmitters in the presynaptic terminal of Drosophila axons [5]. To understand the mechanics of this tension regulation, we used the force sensors to study the in vivo mechanical response of embryonic Drosophila axons subjected to varying amounts of deformation.

The probes of the force sensors were specially modified for these experiments. Before releasing the beams, a trapezoidal trench was made in the probe (Fig. 3) using focused ion beam milling to enable easy gripping of the axons. The procedure described in the previous section was then used to release the force sensing beams and the sensor was mounted on a 3 axis Piezo stage to apply deformation on the axons. Figure 4 shows the force sensor being used to apply large deformation (~50 µm) on an axon while measuring sub nN forces. The relaxation of the force in the axon with time is shown in Fig. 4c.

## CONCLUSIONS

We have designed, fabricated and calibrated highly sensitive micromechanical force sensors with large force measurement range. A novel scheme has been established to avoid capillary forces during the immersion and removal of these sensors from aqueous environments to enable their use in biological studies. As a demonstration of their capability and versatility, these force sensors were used to measure sub nN forces in Drosophila axons subjected to large deformation (~50 µm) *in vivo*.

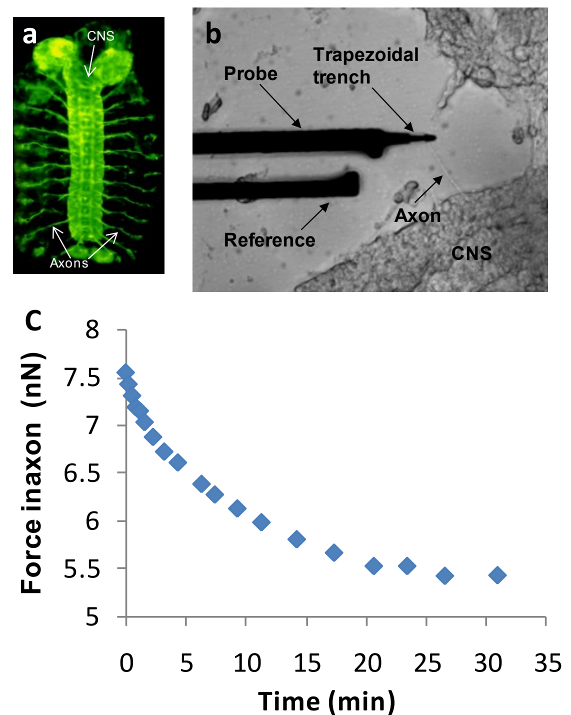


Figure 4: a) Fluorescence image of the Drosophila nervous system showing the CNS (central nervous system) and axons. b) Optical image of the force sensor deforming an axon. c) Force relaxation in an axon measured using a sensor with a stiffness of ~0.5 nN/µm.

## ACKNOWLEDGEMENTS

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