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# POLYMER-BASED CARDIOVASCULAR SHEAR STRESS SENSORS

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## ABSTRACT

This paper describes a polymer-based cardiovascular shear stress sensor built on catheter for atherosis diagnosis. This flexible sensor detects small temperature perturbation as fluid past the sensing elements leading to changes in the resistance, from which shear stress is inferred. MicroElectroMechanical System (MEMS) surface manufacture technology is utilized for fabrication of the devices with biocompatible materials, such as parylene C, Titanium (Ti) and Platinum (Pt). The temperature coefficient of resistance (TCR) of the sensor is 0.11%/$^{o}$C. When a catheter-based sensor is positioned near the wall of the rabbit aorta, our 3-D computational fluid dynamic model demonstrates that flow disturbance is negligible under steady state in a straight segment. The sensor has been packaged with a catheter and will be deployed into the aorta of NZW rabbits for real-time shear stress measurement

## INTRODUCTION

Coronary artery disease remains the leading cause of death in the US and is the emergent global health issue within the next 15 years. Hemodynamic forces, specifically, fluid shear stress, play an important role in the biological activities of cardiovascular endothelial cells. At arterial bifurcations where inflammatory processes prevail, the fluid mechanical environment is distinct from the laminar pulsatile environment present in the long and straight regions of the vessel or the medial wall within bifurcations. At the lateral walls of arterial bifurcations, disturbed flow, including oscillatory flow (bidirectional net zero forward flow), is considered to be an inducer of vascular oxidative shear stress that promotes the initiation and progression of atherosclerosis.

Measuring the vessel wall shear stress precisely remains as a challenging issue for engineers, although several methods have been developed for wall shear stress measurement, including, micro force sensing element or ultrasonic Doppler measurement. However, these methods are either too difficult to fabricate or lack the resolution. There is another method which is thermal anemometry based on the heat transfer principle to be discussed in the ensuing paragraph. The advantages of this technique are simplicity in fabrication, avoidance of moving elements, and high sensitivity

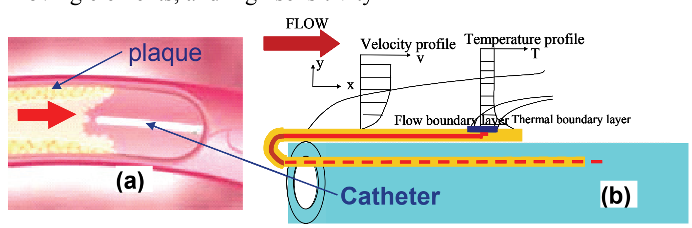


**Fig. 1**. **(a)** A polymer-based shear stress sensor in a model of rabbit aorta. **(b)** Packaging of sensors on the catheter in relation to thermal boundary layer.

When an electric current passes through the heated element, the heat convection from a resistively heated element to the flowing fluid is measured, from which a value for shear stress is inferred. Over past decade Dr. Ho and Tai [1] have been developed polysilicon based the MEMS surface micromachined sensors for shear stress sensing in air and liquid.

In previous research [2,3], our labs have developed and tested bulk micromachined silicon-based MEMS sensors that have enabled us to measure intravascular physical parameters; specifically, real-time shear stress, temperature, pressure and velocity with high spatial and temporal resolution. This abstract describes our recently developed and tested bio-compatible, flexible polymer-based MEMS sensors for real-time measurements of shear stress and velocity with catheter **(Fig. 1)**

## DEVICE AND RESULTS

The micro polymer-based vascular sensors are composed of resistive heating and sensing elements that are encapsulated by biocompatible polymer (parylene C). The sensor detects small temperature perturbation as fluid past the sensing elements leading to changes in the resistance, from which shear stress is inferred. Biocompatible

 

Titanium (Ti) and Platinum (Pt) are used as the heating and sensing elements to be exposed to blood flow. The Ti/Pt sensing element offers low resistance drift, large range of thermal stability, low 1/f noise without piezoresistive effect, and biocompatibility and resistance to corrosion/oxidation. Moreover, Ti/Pt is deposited at room temperature, allowing for integration with flexible parylene fabrication process.

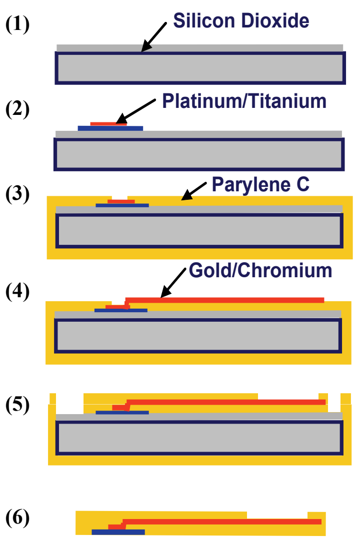


**Fig. 2.** Fabrication process of polymer-based micro vascular sensor.

The fabrication process of the sensor is as follows (Fig. 2): (1) thermal growth of $SiO_2$ on Silicon wafer and deposition (or coating) of a thin layer of Silicon (1  m); (2) deposition and patterning of $SiO_2$ (0.3μm)and Pt/Ti layers (0.1μm) for the heating element on the surface of the Silicon; (3) deposition of Parylene C and etching of a hole to form electrode contact (4) deposition and patterning of a metal layer of Au/Cr for electrode leads (2μm); (5) deposition and patterning of a thick layer of Parylene C to form the device structure; and (6) etching the underneath Silicon sacrificial layer leading to the final device-a flexible parylene C-based sensor.

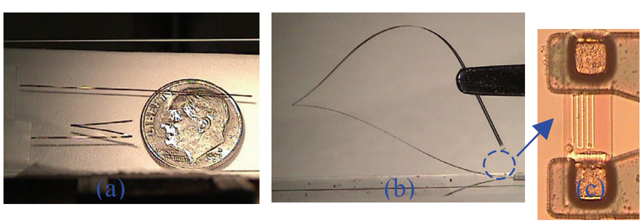


**Fig. 3.** (a) The sensor is flexible, assuming linear or zigzag fashions. (b) The sensor is folded by a tweezers without structural or functional damage. (c) The sensing element is made of 2μm wide Pt/Ti thin film line

The fabricated sensors are shown in fig. 3, where the dimension of the sensing element of the flexible parylene-based sensor is proximally 160 μm in length and 80μm in width, while whole sensor has 4 cm in length, 320 μm in width and 21 μm in thickness. Given that parylene offers the structural stiffness and sturdiness to encapsulate the electrodes, the sensor is easily conformed to various anatomic curvatures with excellent mechanical strength

The resistance of the sensing element is about 1.0 kOhm, and the temperature coefficient of resistance (TCR) is at 0.11%/°C, compatible for blood Rheology.

Under a fully developed laminar flow, the boundary layer velocity profile determines the rate of heat transfer from a heated resistive element to the surrounding fluid field. Thus, a linear relationship is established between $V^2/R$ and $\tau^{1/3}$ **(Fig. 4).**

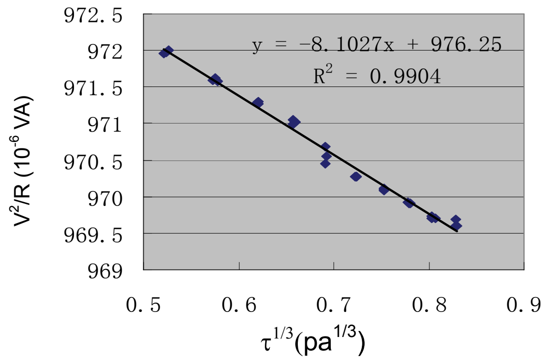


**Fig. 4** Circuit signal vs. shear stress

A 3-D CFD model using the FLUENT software demonstrates that flow disturbance is negligible under steady flow in a straight segment if a catheter integrated with the sensor is placed near the wall of the rabbit aorta **(Fig. 5)**. The sensor has been bonded with catheter guide wire with biocompatible conductive epoxy for electrode connection and insulating epoxy for protecting the sensor body, which will be deployed into the aorta of NZW rabbit.

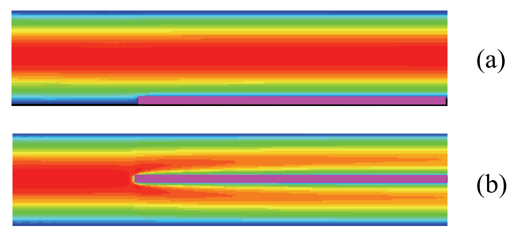


**Fig. 5** The catheter is placed (a) attaching the blood vessel wall for accurate wall shear stress with minor disturbance to the flow, (b) in the middle of blood vessel with totally changed flow profile from its disturbance.

## SUMMARY

A biocompatible polymer-based shear stress sensor has been developed for precisely measurement of cardiovascular wall shear stress. Owing to its flexibility and working principle, it can also be utilized to measure other intravascular physical parameters, such as flow velocity and temperature with high spatial and temporal resolution.


## ACKNOWLEDGMENT

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