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Design and Fabrication of Micro-Pillar Based Piezoresistive Flow Sensors

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Adimali Piyadasa, PhD
University of Connecticut, 2017

ABSTRACT

This study is focused on developing a new type of micro-scale gas flow sensors to be used in critical environments such as combustion engines with high pressure high temperature gas flow and integrated micro electro mechanical applications such as lab-on-chip devices. Proposed flow sensor is based on piezoresistivity of Silicon micro column cantilever. Change in resistivity tensor due to gas flow induced stress in the piezoresistive layer results in generating of an output voltage proportional to the gas flow rate in the channel. Current results show that the anisotropic properties of the Silicon can be successfully used in the gas flow sensor to differentiate flow components in different directions. Furthermore the model demonstrates its applicability in measuring local flow fields in high resolution due to its micro-scale
dimensions. Fabrication of the Flow sensor is carried out at the Center for Functional nanomaterials at Brookhaven National Laboratory and Friedrich Schiller University in Germany. With fundamental understanding obtained by the parameter analysis and the experimental process developed for the device fabrication this study provides a useful and timely guidance in designing and fabricating flow sensors with ability to differentiate between local flow directional components at high spatial resolution.
Design and Fabrication of Micro-Pillar Based Piezoresistive Flow Sensors

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2017
Design and Fabrication of Micro-Pillar Based Piezoresistive Flow Rate Sensors

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1 Introduction

Microelectromechanical devices have been widely used these days concurrently with the decades’ fast development in the micro- and nano-electromechanical system (MEMS/NEMS) technology. Availability of a reliable and robust micro-scale gas flow sensor has proven to be a critical instrumentation component for sensing and control in various commercial and engineering applications such as combustion environment in advanced energy generation systems, feedstock utilization in industrial plants, airborne pollution control and medical instrumentation. A majority of the commercially available MEMS based flow sensors can be classified by transduction modes in forms of either thermal, pressure, lift force based, or cantilever based depending on the mechanism used to interact with gas flow. [1]

Developing a flow sensor that can extract information on directional components of the local flow pattern will lead to measuring the flow turbulence where such information can be crucial in safe operation of the various engineering components, machines, and systems.

Macro scale hot wire and optical devices can be regularly used in turbulence measurements, which however are limited by the lack of small or micro (nano-) scale spatial resolution within these demanding environments. [2] On the other hand, the lack of localized direction-differentiation capability is another drawback of flow
sensors used in energy production plants such as nuclear reactors and medical devices such as MEMS drug delivery systems.

In this work, we developed a novel form of piezoresistive flow rate sensors with improved spatial resolution and flow direction differentiation capabilities. This new type of flow sensors can be used to monitor both direction and velocity of the localized flow field in various engineering applications. More importantly the fabrication process of the novel flow rate sensor can be directly integrated into the existing semiconductor fabrication line with standard equipment such as scanners, etchers and ion implanters.

The piezoresistance properties of Si and Germanium (Ge) were first discovered by Smith in 1953 [3] since then numerous studies have been conducted on Si and various other materials attempting to enhance the piezoresistive properties and develop new applications. [4, 5] Si has become a prominent candidate for piezoresistive devices due to multiple reasons, such as its high piezoresistant coefficients, high operating temperature, low cost, etc.

In addition, nanoscale Si structures have electrical properties distinct from those in bulk form owing to a significant change in their electronic structures and therefore behaviors. Particularly low dimensional structures such as nanosheets and nanowires have radically different electromechanical properties. [6] In-situ characterization studies have revealed interesting electromechanical properties of nanostructures strengthening the potential of their applicability in various sensors. [7, 8, 9] Review of
nanowire based sensors is summarized in, [10] discussing the mechanisms and advantages of various nanowire based sensors.

Numerous experiments conducted on p-type Si nanowires in the past decade have revealed its giant longitudinal piezoresistant coefficient, [11, 12] and supported by multiple theoretical studies using first principles calculations. [13, 14]

1.1 MEMS Technology

Traditional integrated circuit manipulates an electrical signal with a combination of several electrical components such as diodes, transistors and capacitors etc. Micro electro mechanical systems (MEMS) on the other hand consist of additional mechanical components that can interact with and manipulate mechanical input/output signals. Integration of mechanical and electrical devises on one small chip enables the path to create some of the smallest machines ever made.

History of MEMS dates back to the late 1950s. On December 29th, 1959 at the American Physical society meeting at Caltech, physicist Richard Feynman gave the lecture “There's Plenty of Room at the Bottom” introducing the power and potential of micro scale devices. Even though the idea was floating around, it only became an achievable reality when the tools and techniques originally developed for fabrication of integrated circuits (IC) became sufficiently advanced in late 1960s and 1970s. Typical process of MEMS fabrication consists of several steps including lithography (electron beam, photolithography etc.), deposition (chemical vapor deposition (CVD),
physical vapor deposition (PVD), electro plating etc.), etching (Reactive ion etching (RIE), wet etching) and polishing. Although this is still an emerging technology, use of MEMS devices are being rapidly increased in various applications such as microfluidics, micro-pumps, micro-mirrors, chemical sensors, pressure sensors, accelerometers, gas sensors, RF switches, energy harvesters, etc. [15, 16, 17, 18, 19, 20, 21, 22] Micro scale devices bring in several advantages compared to their macro scale counterparts due to the reduced dimensions. Two most prominent advantages are the reduced power consumption and material cost. MEMS fabrication process also enables the bulk manufacturing of hundreds of devices on a single silicon wafer cutting down the production time and increasing yield. Furthermore MEMS technology enables the integration of multiple components into a single device making it possible to fabricate new lab-on-chip (LoC) and micro-total analysis systems (I-TAS) that can be used in variety of applications such as wearable medical devices and environmental monitoring devices.

1.2 Background of gas flow sensors

Ability to measure the flow field velocity has become an essential requirement in many applications. Furthermore in some applications such as medical instrumentation, process control and environment monitoring systems it is a critical measurement that demands a high accuracy and precision. Traditional flow rate measuring applications use large-scale mechanical flow meters such as differential pressure flow meters, variable area flow meters or turbine wheel flow meters. But in
recent years variety of MEMS based flow rate sensors has been introduced due to the advancement in MEMS fabrication technologies. These MEMS based flow rate sensors can be classified as either thermal or nonthermal, depending on their mode of operation. Furthermore, non-thermal sensors can be further classified as either differential pressure-based, lift force-based, or cantilever based. [1]

1.3 Thermal flow sensors

Thermal flow sensors are based on the principle of heat transfer. There is a heating element and a temperature sensor. Ideally these should be thermally isolated restricting the heat transfer through substrate or electrical leads to prevent the heat leakage. Since there are no moving parts involved, these systems are quite robust to mechanical failure and can be fabricated using a simple process. Low power consumption, high sensitivity to low flow rates, ability to detect thermal properties of fluid such as thermal conductivity and thermal diffusivity are some other advantages of thermal flow sensors. On the other hand basic thermal flow sensors depend on the constant temperature of the fluid and will require additional components to correct the measurement from a fluid flow with varying temperature. [16] There are three forms of thermal flow sensing: hot-wire and hot-film, calorimetric, and time-of-flight [23]

1.3.1 Hot-Wire and Hot-Film flow sensors

Hot-Wire and Hot-Film flow sensors contain a single resistive heating element and measure resistant change due to convective heat loss from fluid flow. [24, 25, 26, 27]
Both in-plane and out-of-plane heating elements can be used in hot-wire flow sensors. [28] King’s Law can be used to characterize the relationship between voltage change in hot wire system and fluid velocity. The constants $a$, $b$ and $n$ depends on fluid thermal conductive properties and flow geometry hence should be found empirically. [29]

\[ \Delta V(v) = a + bv^n \]  

(1)

Where $\Delta V =$ change in Voltage due to fluid flow  
$v =$velocity  
$a, b, n =$ constants

Figure 1 illustrates the schematic of a hot-wire flow sensor. The resistor serves as both the heating element and the sensing element.

![Figure 1: Schematic of Hot wire flow sensor.](image)

Six operational modes are possible with hot-wire and hot-film sensors by controlling the either the heater power or temperature and observing the heater temperature, power, or temperature difference resulting from fluid flow. [23] Hot-wire and hot-film sensors have to be calibrated initially with known flow rates. It is critical to use the same fluids used in future measurements when calibrating the sensor since the sensor output depends on the thermal conductive properties of the fluid.
1.3.2 Calorimetric flow sensors

In calorimetric flow sensors two temperature sensing elements are placed upstream and downstream of the heating element to measure the temperature profile around the heater. [30, 31, 32, 33, 34] The difference in temperature between two upstream and downstream temperature sensors can be used to measure the flow rate information. [35] Figure 2 illustrates the schematic of a Calorimetric flow sensor.

![Figure 2: Schematic of calorimetric flow sensor.](image)

1.3.3 Time of flight flow sensors

Time of flight sensors consist of one heater and one temperature sensor placed downstream of the heater. A short thermal pulse is sent from heater to the temperature sensor through the fluid flow and the travel time is measured to derive the flow speed. Travel time depends on several factors: the thermal conductivity and diffusivity of the fluid, heater-sensor distance, and average flow velocity. Thermal distribution of the pulse as a function of distance is described in equation (2) by approximation the heater as a line source: [36]

\[
T(x, t) = \frac{q_0}{4\pi kt} e^{-\frac{(x-vt)^2}{4at}}
\]  

(2)

Where: \( T \) = temperature distribution at time \( t \);
$x = \text{distance from heater};$
$t = \text{time};$
$q_0 = \text{pulse signal input strength};$
$k = \text{thermal conductivity of fluid};$
$v = \text{average flow velocity};$
$a = \text{thermal diffusivity}.$

Figure 3: Schematic of time of flight flow sensor.

1.4 Non-Thermal Flow Sensors

Non-thermal flow sensors can be separated into four main categories namely resonating, differential pressure-based, lift-force based and cantilever-based.

1.4.1 Resonance based flow rate sensors

Resonant flow sensors measure the change in natural frequency of a heated micro machined membrane due to forced convection from gas flow in the channel and convert the frequency signal into flow rate. Figure 4(a) shows the Operation of the resonating microbridge mass flow sensor, suspended inside the flow channel, with resistors for thermal excitation and piezoresistive detection of the vibration, this electrical two-port forms an oscillator with off-chip drive circuitry, the oscillation frequency is dependent on the temperature elevation of the heated microbridge, which is a function of the mass flow. Figure 4(b) shows the Experimental set-up with
on-chip resistive heater and strain gauge and off-chip gain/phase analyzer for measuring the transfer function of the sensor. [37]

Figure 4: (a) Operation of the resonating flow sensor, (b) experimental set-up with a gain/phase analyzer for measuring the transfer function of the resonating flow sensor. [37]

Resonance based flow rate sensors requires an AC input and some off the chip frequency analyzer to analyze the resonance frequency which will result in a delayed measurement. Resistive heaters and on chip strain gauges to measure vibration frequency adds up to a more cumbersome apparatus requiring a complicated fabrication process.

1.4.2 Differential pressure based flow rate sensors

Differential pressure flow sensors use the induced pressure difference due to flow speed given by Bernoulli principle. Figure 5 shows the schematic of a differential pressure flow meter (a) without flow and (b) deflection on the membrane due to flow in the channel. It can be shown that the change in capacitance between boss
and the Pyrex glass layer due to deflection in thin silicon membrane is proportional to the square of the flow velocity in the channel (equation 3). [38]

\[ \nu \propto \sqrt{|\Delta C|} \]  

(3)

Figure 5: Schematic of a differential pressure flow meter (a) without the flow, (b) deflection due to flow in the channel. [38]

Compared to the thermal flow sensors pressure based flow sensors are less prone to the corrosion problems since the electrical components are insulated from the fluid flow. Also, removal of the heater greatly reduces the power consumption of the device.

1.4.3 Lift force based flow rate sensors

Lift force based flow rate sensors are fabricated with a membrane placed at an angle to the flow direction. The fluid flow in the channel will apply a lift force on the angled membrane and induce a strain on the membrane that can be measured with attached strain gauges. Figure 6 illustrates a schematic diagram of a lift force based flow rate sensor with integrated heaters that act as a thermal flow rate sensor.
It is shown that the lift force based flow rate sensor has a higher sensitivity at higher flow rates while thermal flow rate sensor has a higher sensitivity at lower flow rates (Figure 7). By combining these two types of sensing mechanisms in one device N. Svedin et al increased the range of sensitivity. [39]
1.4.4 Cantilever based flow rate sensors

Basic mechanism of the cantilever based flow rate sensor is to measure the deflection of a cantilever placed in the flow channel using attached strain gauges. Figure 8 illustrates a basic cantilever based flow rate sensor.

![Figure 8: Schematic illustration of cantilever based flow rate sensor. [40]](image)

Change in the resistance of the sensor due to change in its length from the cantilever deflection can be approximated in following form. [40]

\[
\frac{dR}{R} \approx \frac{dl_R}{l_R} (1 + 2\nu)
\]  

(4)

Where:

- \( R \) — Resistance
- \( l_R \) — Length of the resistor
- \( \nu \) — Poisson’s ratio
2 Computational and Experimental approach and methods

When designing a physical system such as mechanical, electrical or thermal the first step involves building a model of the system. This will help in understanding and resolving the possible complications that might arise during the fabrication or building process. The model can also be used to prove the applicability of the proposed concept and improve important aspects of the system such as efficiency and sensitivity by analyzing the effect of different parameters in the system on its efficiency, sensitivity etc.

Usually the physical systems are described using partial differential equations (PDEs) with multiple variables. For majority of the real world geometries and problems these PDEs cannot be solved analytically thus requires numerical methods with some approximations to obtain feasible solutions. Finite element method (FEM) is one such method that can be used to solve PDEs in complex geometries.

2.1 Introduction to Finite element method

Finite element method was originated as a method to solve complex elasticity and structural analysis problems in civil and aeronautical engineering. In early 1940s Russian-Canadian Structural Engineer Alexander Hrennikoff [41] and German-American mathematician Richard Courant [42] independently proposed Finite Element Method to numerically solve PDEs. In 1960s and 1970s with computers becoming more available, applicability of FEM became more feasible and started
developing a rigorous mathematical basis for FEM in various engineering applications.

Figure 9 shows the work flow of finite element analysis study. In general first step of the finite element study is to create a model of the geometry using a computer aided design (CAD) tool. Next step is to identify the required physics modules and define corresponding governing equations and parameters for each physical phenomenon we expect to model. After setting up the physics modulus, boundary conditions have to be defined at each boundary of the geometry. Then geometry is divided in to finite number of elements that can be used to numerically solve the problem. Process of dividing the geometry is called meshing and the chunked up geometry is called mesh. Next the system of governing equations is solved using numerical techniques and results are evaluated for accuracy. Finally, explore the possible paths to improve the model performance such as refining the mesh or numerical techniques.
1. Create CAD geometry model of the system.
2. Define required physics modules and parameters.
3. Define boundary conditions.
4. Mesh the geometry with appropriate parameters.
5. Solve the system.
6. Evaluate the results for accuracy.
7. If necessary refine the mesh and solve again.

Figure 9: Work flow steps used in Finite Element analysis model.
3 Designing micro column based silicon flow rate sensors using finite element analysis

The basic principle of the flow sensor consists of fluid flow in the channel, pressure applied on the micro pillars due to fluid flow and the induced voltage due to piezoresistivity of the material. In order to model the full functionality of the flow rate sensor one has to couple the effect from each individual component.

3.1 Fluid Flow

The single-phase fluid-flow is modeled using the Navier-Stokes equations, which in their most general form can be written as,

Continuity equation representing conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$  \hspace{1cm} (5)

Vector equation representing conservation of momentum:

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla [-pI + \tau] + F$$  \hspace{1cm} (6)

And, equation representing the conservation of energy, formulated in terms of temperature ($T$).

$$\rho C_p \left( \frac{\partial T}{\partial t} + (u \cdot \nabla) T \right) = -(\nabla \cdot q) + S - \frac{T}{\rho \frac{\partial p}{\partial t}} \left( \frac{\partial p}{\partial t} + (u \cdot \nabla) p \right) + Q$$  \hspace{1cm} (7)

Where:

* $\rho$ is the density (SI unit: kg/m$^3$)
• \( u \) is the velocity vector (SI unit: m/s)

• \( p \) is pressure (SI unit: Pa)

• \( \tau \) is the viscous stress tensor (SI unit: Pa)

• \( F \) is the volume force vector (SI unit: N/m3)

• \( C_p \) is the specific heat capacity at constant pressure (SI unit: J/(kg·K))

• \( T \) is the absolute temperature (SI unit: K)

• \( q \) is the heat flux vector (SI unit: W/m2)

• \( Q \) contains the heat sources (SI unit: W/m3)

• \( S \) is the strain-rate tensor:

\[
S = \frac{1}{2} \left( \nabla u + (\nabla u)^T \right)
\]  

(8)

The operation “:\=” denotes a contraction between tensors defined by

\[
a: b = \sum_n \sum_m a_{nm} b_{nm}
\]  

(9)

This is sometimes referred to as the double dot product.

For a Newtonian fluid, which has a linear relationship between stress and strain, Stokes [43] deduced the following expression for viscous stress tensor:

\[
\tau = 2\mu S - \frac{2}{3}\mu (\nabla . u) I
\]  

(10)

For incompressible fluid with constant or nearly constant density \( \rho \) the mass and momentum conservation equations can be re written as,

\[
\rho \nabla . u = 0
\]  

(11)

\[
\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla \cdot \left[ -pI + \mu (\nabla u + (\nabla u)^T) \right] + F
\]  

(12)
3.2 Structural mechanics

3.2.1 Stress-Strain Relationship

Strain or deformation of an object depends on the direction, position and magnitude of the applied stress. The stress strain relationship for one dimensional stress can be written as (Hooke’s Law),

\[ \frac{\Delta L}{L} = \varepsilon , \quad \frac{F}{A} = \sigma \]  

(13)

\[ \sigma_{axial} = E\varepsilon_{axial} , \quad \sigma_{shear} = G\varepsilon_{shear} \]  

(14)

Where,

\( \sigma_{axial} , \sigma_{shear} \) = axial / shear stress

\( \varepsilon_{axial} , \varepsilon_{shear} \) = axial / shear strain

\( E \) = Young’s modulus

\( G \) = shear modulus

Poisson’s ratio \( \nu \) is defined as ratio of lateral strain to axial strain:

\[ \nu = \left| \frac{\text{lateral strain}}{\text{axial strain}} \right| \]  

(15)

The relationship between \( E , G \) and \( \nu \) for isotropic material can be written as,

\[ G = \frac{E}{2(1+\nu)} \]  

(16)
By measuring $E$, $G$ and $\nu$ independently and verifying of the above relationship can give an idea of how isotropic the material is.

In three dimensions stress and strain becomes symmetric tensors and can be generalized using displacement vector $u$ ($u_x, u_y, u_z$).

Total strain tensor:

$$\epsilon = \frac{1}{2} (\nabla u + \nabla u^T)$$  \hfill (17)

Or in components:

$$\epsilon_{mn} = \frac{1}{2} \left( \frac{\partial u_m}{\partial x_n} + \frac{\partial u_n}{\partial x_m} \right)$$  \hfill (18)

The relationship between stress: $\sigma$, strain: $\epsilon$ and elasticity: $C$ tensors:

$$\sigma_{ij} = C_{ijkl} \epsilon_{kl}$$  \hfill (19)

Where,
These tensors consist of three normal and \((\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz})\) and six (three, if symmetry is used) shear \((\sigma_{xy}, \sigma_{xz}, \sigma_{yz}, \varepsilon_{xy}, \varepsilon_{xz}, \varepsilon_{yz})\) components. Since stress and strain tensors are symmetric this can be written in voigt notation.

\[
\begin{bmatrix}
\sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy}
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{xz} \\ \varepsilon_{yz}
\end{bmatrix}
\] (20)

For isotropic material elasticity tensor can be written in terms of Young’s modulus \(E\) and Poisson ratio \(\nu\):

\[
C = \frac{E}{(1+\nu)(1-2\nu)}
\begin{bmatrix}
1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2}
\end{bmatrix}
\] (21)

### 3.3 Fluid structure interaction

When fluid flows through the channel it applies a force on the micro-pillar resulting in a strain and change in resistivity tensor due to piezoresistive effect of the material. The force exerted on the solid boundary by the fluid is the negative of the reaction force on the fluid.
Since the fluid flow is solved in the deformed frame above force has to be transformed in to the undeformed frame to be used in as the boundary force on pillars. This transformation can be done via,

\[ F = f \cdot \frac{dv}{dV} \]  \hspace{1cm} (23)

Where \( dV \) and \( dv \) are the mesh element scale factors for the undeformed and deformed frame respectively. On the other hand the force due to fluid flow will deform the micro-pillar resulting in a moving wall for the fluid flow. For large deformations Fluid-Solid interface boundary has to be coupled to reflect this effect.

For small displacements in the solid the Fluid-Solid boundary can be considered stationary and one-way coupling will be sufficient to accurately represent the physical system. In one-way coupled models, fluid flow is solved first to find the induced boundary force and then the solid mechanics system is solved using the induced boundary force as input.

### 3.4 Piezoresistivity

Electrical resistance of an object depends on the resistivity of the material and the geometry of the object (Figure 10). In early strain gauges, thin metal strips were used to measure the tensile and compressive strain. Tension and compression on the metal will change its dimensions by stretching or compressing, resulting in a change in the resistance proportional to the strain.
Figure 10: Electrical resistance of a solid cylinder as a function of its material resistivity, length and cross sectional area.

\[
Resistance \ (R) = \text{Resistivity} (\rho) \times \frac{\text{Length} \ (L)}{\text{Area} \ (A)}
\]

Figure 11: Schematic of a strain gauge utilizing resistivity change of strain sensitive wire.

In anisotropic materials resistivity is represented by a tensor rather than a scalar. Due to the asymmetry in the crystal structure the resistivity in different directions...
depends on the crystal orientation. In Piezoresistive materials resistivity tensor is changed by applied stress. In general piezoresistive materials are semiconductors. Strain in the crystal lattice will change the band structure in semiconductors. This change in the band structure will alter the career mobility and number density resulting in changing the resistivity tensor.

The relationship between the electrical field, $E$, and the current, $J$, within a piezoresistor is given by the following formula:

$$ E = \rho \cdot J + \Delta \rho \cdot J $$ \hspace{1cm} (24)

In tensor form:

$$ \begin{bmatrix} \mathbf{E}_x \\ \mathbf{E}_y \\ \mathbf{E}_z \end{bmatrix} = \begin{bmatrix} \rho_{xx} & \rho_{xy} & \rho_{xz} \\ \rho_{yx} & \rho_{yy} & \rho_{yz} \\ \rho_{zx} & \rho_{zy} & \rho_{zz} \end{bmatrix} \begin{bmatrix} \mathbf{J}_x \\ \mathbf{J}_y \\ \mathbf{J}_z \end{bmatrix} + \begin{bmatrix} \Delta \rho_{xx} & \Delta \rho_{xy} & \Delta \rho_{xz} \\ \Delta \rho_{yx} & \Delta \rho_{yy} & \Delta \rho_{yz} \\ \Delta \rho_{zx} & \Delta \rho_{zy} & \Delta \rho_{zz} \end{bmatrix} \begin{bmatrix} \mathbf{J}_x \\ \mathbf{J}_y \\ \mathbf{J}_z \end{bmatrix} $$ \hspace{1cm} (25)

Where $\rho$ is the resistivity and $\Delta \rho$ is the induced change in the resistivity which is related to the stress, $\sigma$, and piezoresistive tensor $\Pi$ by the constitutive relationship:

$$ \Delta \rho = \Pi \cdot \sigma $$ \hspace{1cm} (26)

When there is no stress applied on the system resistivity tensor takes a diagonal form. Applying external stress on the micro column will change the resistivity tensor and non-diagonal elements will gain non-zero values depending on the external stress and piezoresistive tensor of the material. New resistivity tensor of the material under stress can be written as the sum of initial resistivity tensor and change in resistivity tensor.
Due to the symmetry, change in resistivity can be written as a function of external stress and piezoresistivity tensor using voigt notation.

\[
\begin{bmatrix}
\Delta \rho_{xx} \\
\Delta \rho_{yy} \\
\Delta \rho_{zz} \\
\Delta \rho_{yz} \\
\Delta \rho_{xz} \\
\Delta \rho_{xy}
\end{bmatrix} = \begin{bmatrix}
\Pi_{11} & \Pi_{12} & \Pi_{13} & \Pi_{14} & \Pi_{15} & \Pi_{16} \\
\Pi_{21} & \Pi_{22} & \Pi_{23} & \Pi_{24} & \Pi_{25} & \Pi_{26} \\
\Pi_{31} & \Pi_{32} & \Pi_{33} & \Pi_{34} & \Pi_{35} & \Pi_{36} \\
\Pi_{41} & \Pi_{42} & \Pi_{43} & \Pi_{44} & \Pi_{45} & \Pi_{46} \\
\Pi_{51} & \Pi_{52} & \Pi_{53} & \Pi_{54} & \Pi_{55} & \Pi_{56} \\
\Pi_{61} & \Pi_{62} & \Pi_{63} & \Pi_{64} & \Pi_{65} & \Pi_{66}
\end{bmatrix} \times \begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{yz} \\
\sigma_{xz} \\
\sigma_{xy}
\end{bmatrix}
\] (28)

Considering the crystal symmetry (m3m) of Si, [44] the above formula reduces to:

\[
\begin{bmatrix}
\Delta \rho_{xx} \\
\Delta \rho_{yy} \\
\Delta \rho_{zz} \\
\Delta \rho_{yz} \\
\Delta \rho_{xz} \\
\Delta \rho_{xy}
\end{bmatrix} = \begin{bmatrix}
6.6 & -1.1 & -1.1 & 0 & 0 & 0 \\
-1.1 & 6.6 & -1.1 & 0 & 0 & 0 \\
-1.1 & -1.1 & 6.6 & 0 & 0 & 0 \\
0 & 0 & 0 & 138.1 & 0 & 0 \\
0 & 0 & 0 & 0 & 138.1 & 0 \\
0 & 0 & 0 & 0 & 0 & 138.1
\end{bmatrix} \times 10^{-11} \times \begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{yz} \\
\sigma_{xz} \\
\sigma_{xy}
\end{bmatrix}
\] (29)

It can be seen that the non-diagonal elements in \( \Delta \rho \) tensor have following relationships with the stress components.

\[
\Delta \rho_{xz} = 138.1 \times 10^{-11} \times \sigma_{xz}
\]
\[
\Delta \rho_{yz} = 138.1 \times 10^{-11} \times \sigma_{yz}
\]
\[
\Delta \rho_{xy} = 138.1 \times 10^{-11} \times \sigma_{xy}
\] (30)

Considering the applied voltage (input) in z-direction,

\[
J_x = 0 \\
J_y = 0 \\
J_z > 0
\] (31)

The induced electrical fields can be written as:
\[
E_x = \Delta \rho_{xz} \times J_z \\
E_y = \Delta \rho_{yz} \times J_z \\
E_z = (1 + \Delta \rho_{zz}) \times J_z
\]

\[
V_x = E_x \times X = \Delta \rho_{xz} \times J_z \times X \\
V_y = E_y \times Y = \Delta \rho_{yz} \times J_z \times Y \\
V_z = E_z \times Z = (1 + \Delta \rho_{zz}) \times J_z \times Z
\]

\[
V_x = 138.1 \times 10^{-11} \times \sigma_{xz} \times J_z \times X \\
V_y = 138.1 \times 10^{-11} \times \sigma_{yz} \times J_z \times Y \\
V_z = (1 + (-1.1 \cdot \sigma_{xx} - 1.1 \cdot \sigma_{yy} + 6.6 \cdot \sigma_{zz}) \times 10^{-11}) \times J_z \times Z
\]

As seen in the above formulae, electrical field induced in the x and y directions will depend on their respective stress components, piezoresistive values and current density in z direction.

### 3.5 Micro column array flow rate sensor

The main obstacle in modeling large devices with arrays of micro columns is the lack of computational power need to include the entire device in the model. When modeling the micro column array devices we have limited the number of columns to 9 (3 x 3 array) in order to reduce the computational time. Figure 12 shows the displacement filed in micro columns due to gas flow distribution in the channel. Color of the velocity streamlines represents the magnitude of the total velocity vector. Slip boundary condition has been applied to the two side walls and top wall of the flow channel while non-slip boundary condition has been applied to the bottom wall to represent the friction from the substrate. The inlet flow velocity is set to 50m/s and it can be seen that the flow velocity is reduced at the sides of the micro columns (due
to friction) and increased above them. When looking at the distribution of the total displacement in micro columns it can be seen that the maximum displacement is at the two outer micro columns directly facing the gas flow. This is a drawback of the array type stress based flow rate sensors; most of the stress is generated from the outer columns while the contribution from the inner columns is fairly low due to screening effect from the outer columns facing the flow field.

Figure 12: Gas flow distribution in channel and displacement field of Silicon micro columns in micro column array based sensor.
Figure 13: Mesh pattern for finite element analysis model in micro column array based sensor.

Figure 13 shows the mesh used in finite element analysis. Complete mesh consists of 66575 tetrahedral domain elements, 8006 boundary elements, and 1368 edge elements.

3.5.1 Stress analysis on the base

Displacement of the micro columns due to gas flow in the channel will induce stress on the base of the micro column array.
Figure 14: Change in average induced stress (shear stress components) on the base of micro column array when increasing gas flow velocity in y direction.

Figure 14 shows the three induced shear stress components $\sigma_{xy}$, $\sigma_{xz}$ and $\sigma_{yz}$ due to gas flow in $+y$ direction, averaged over the entire volume of the base. It can be seen that the $yz$ component of the shear stress is much higher than the other two components. In order to use the $yz$ shear stress we need to electrically couple the $y$ and $z$ directions. This can be achieved by sending current in $z$ direction and measuring induced voltage in $y$ direction. When the flow direction is changed to $x$ the highest induced stress component will switch to $xz$ component of the shear stress. This directional dependence of the stress as shown in Figure 15, gives sensor the capability to differentiate flow direction as well as flow speed. In order to apply a current in $z$ direction a grid shaped electrode is deposited in between the micro columns. While grid electrode serves as one terminal back side of the base serves as the other terminal. Figure 16 shows four other terminals attached to the base to measure induced voltages in $x$ and $y$ directions.
3.6 Single micro column flow rate sensor

Single micro column devices with both circular and cross shaped cross-sections have been developed to test and compare the performance. Figure 17 shows the schematic of the single column flow rate sensor device with gas flow in the y direction.
direction. At the Inlet gas velocity is set to 100m/s while closer to the bottom of the micro pillar the velocity approaches 0m/s due to frictional forces from the bottom surface. Non-slip boundary condition (velocity = 0) has been applied on the entire bottom surface of the gas channel and zero friction boundary condition has been applied on the other three side walls.

![Diagram of the Single micro column device with gas flow in y direction showing micro column deflection due to flow pressure.](image)

Figure 17: Schematic of the Single micro column device with gas flow in y direction showing micro column deflection due to flow pressure.

σ_{xy} shear stress distribution on the base with changing gas flow direction

Single column flow rate sensor is based on the induced stress on the base of the micro column due to the gas flow in the channel. First a gas flow was simulated
within the flow channel and used to study the stress distribution on the base due to interaction between flow field and the micro column.

Figure 18: $\sigma_{xy}$ shear stress distribution on the base, a) cross shaped column with flow in y direction, b) cross shaped column with flow in x direction, c) cylindrical column with flow in y direction, d) cylindrical column with flow in x direction.

Figure 18 shows the induced shear stress in xy direction ($\sigma_{xy}$) in both cross shaped (a, b) and cylindrical (c, d) micro columns with gas flows in x and y directions. In all four systems the inlet velocity is kept at constant 50m/s. Comparing Figure 18 (a) and (b) to (c) and (d) it can be seen that the cross shaped column induces higher stress on the base compared to cylindrical column. Change in the gas flow direction from y to x will result in changing the stress distribution pattern. This direction dependent stress distribution as seen in Figure 19 can be used to measure the flow direction as well as its velocity.
Figure 19: Induced shear stress component $\sigma_{xy}$ in four piezoresistive sensors with changing gas flow direction for cylindrical shaped single micro column device.

Positioning of piezoresistive sensors around micro column for maximum sensitivity

Figure 20: Schematic showing position of four piezoresistive sensors around cylindrical and cross shaped micro columns.
By looking at the induced stress distribution in Figure 18, four piezoresistive sensor elements has been placed at optimum position to maximize the strain $\sigma_{xy}$ values as shown in Figure 20. In the following sections dependence of stress and sensor output on various parameters were analyzed to optimize the sensor performance. Four sensors on the base were numbered as shown in Figure 21.

![Image of stress distribution](image)

Figure 21: Orientation of four piezoresistive sensors in cylindrical and cross shaped single micro column devices.

**Variation of $\sigma_{xy}$ shear stress with gas flow speed in channel**

Increase in the gas flow velocity in the channel will increase the pressure on the micro column wall and result in an increased stress on the base. The gas flow velocity is increased from 0[m/s] to 50[m/s] keeping all the other parameters constant.
Figure 22: Change in Induced shear stress component $\sigma_{xy}$ with flow velocity for cylindrical shaped micro column device.

Figure 23: Change in Induced shear stress component $\sigma_{xy}$ with flow velocity for cross shaped micro column device.
In Figure 22 and Figure 23 it can be seen that the flow velocity has a somewhat linear relationship with the stress tensor component $\sigma_{xy}$. In Figure 22 for cylindrical shaped column, two out of four sensors have close to zero stress components while other two have high negative and positive stress components due to directional dependency of the induced stress. Comparing the stress induced on cylindrical shaped column and cross shaped column from Figure 22 and Figure 23 it can be seen that cross shaped column results in a higher induced stress value than the cylindrical shaped column. This can be attributed to the shape of the cross shaped column where its fins provide a better resistance to the flow field compared with the curved smooth surface of the cylindrical column. Also, when comparing the location of the sensor components, cross shaped column has more closely packed sensors located within its fins giving them the ability to transfer higher stress values while cylindrical column’s more spread out sensors limiting the transferred stress values from the column to sensor.
Variation of $\sigma_{xy}$ shear stress with column height

Figure 24: Change in Induced shear stress component $\sigma_{xy}$ with micro column height for cylindrical shaped micro column device.

Figure 25: Change in Induced shear stress component $\sigma_{xy}$ with micro column height for cross shaped micro column device.
As seen from above Figure 24 and Figure 25 height of the column has a close linear relationship with the induced stress. Increased height of the micro column will increase the pressure due to flow field on its surface, resulting in a higher induced stress on its base.

**Variation of $\sigma_{xy}$ shear stress with column width**

![Graph showing variation of shear stress with column width](image)

*Figure 26: Change in Induced shear stress component $\sigma_{xy}$ with micro column width for cross shaped micro column device.*
As seen from above Figure 26 and Figure 27 column width has a nonlinear relation with the induced stress. Wider columns will greatly decrease the induced stress in both cross shaped and cylindrical configurations. Even though wider columns will result in an increased surface force due to flow field, it will also increase the cross section area of the root where micro column connects to the base thus reducing the induced stress on its base. It can be concluded that the shape and area of the roots cross section has a major effect on the induced stress of a micro column flow rate sensor.
3.6.1 Analysis of Induced voltage in single column flow rate sensor

Induced output voltage with gas flow speed

Figure 28: Change in output voltage with gas velocity in channel for cylindrical shaped micro column device.

Figure 29: Change in output voltage with gas velocity in channel for cross shaped micro column device.
Induced output voltage with column height

Figure 30: Change in output voltage with column height for cylindrical shaped micro column device.

Figure 31: Change in output voltage with column height for cross shaped micro column device.
Induced output voltage with column width

Figure 32: Change in output voltage with column width for cylindrical shaped micro column device.

Figure 33: Change in output voltage with column width for cross shaped micro column device.
Induced output voltage in the four sensors of single column flow rate sensor is modeled to study its dependency on other parameters. Figure 28 and Figure 29 shows the change in output voltage with the change in gas flow speed in cylindrical column device and cross shaped column device respectively. Sensor 3 and 4 in cylindrical column device and all four sensors in cross shaped column device have somewhat of a linear relationship with the flow speed in the range of 0-50m/s. Sensor 1 and 2 in cylindrical column device has zero output voltage due to crystallographic orientation of the sensors, these will have a non-zero induced voltage when the flow is changed to x-direction from y-direction. From Figure 30 and Figure 31 it can be seen that the change in induced voltage due to change in column height has a close linear relationship in the range of 10um to 20um column heights. Increasing height results in increased boundary force on micro column which in turn increases the base stress and induced voltage. Figure 32 and Figure 33 shows the effect of column width on induced voltage. Increasing the column width will effectively increase the surface area facing the gas flow and increase the net boundary force acting on it. But, at the same time increasing the micro column width will increase the cross sectional area of the micro column base which in turn reduce the pressure on the base resulting in reduced output voltage. It can be seen that output voltage has a nonlinear relationship with column width that rapidly decreases with increasing column width in the range of 0.5um to 2um.
**Induced voltage with doping concentration**

Increasing the Doping concentration will increase the conductivity of the sensor which will increase the current through it. At the same time increasing doping concentration will decrease the piezoresistive coupling coefficient of the silicon. As shown in previous chapter 3.4, induced voltage depends on both current through the sensor and piezoresistive coefficient of the material. Since doping concentration affects these two properties in opposite ways, effect of current increase cancels out by the decrease of piezoresistive coefficient resulting in no net change in induced voltage.

**4 Fabrication of micro column based silicon flow rate sensors using MEMS fabrication techniques**

4.1 MEMS Fabrication process

Fabrication of MEMS devices employs a similar process as used in regular semiconductor integrated circuits fabrication. In addition to the standard process techniques some additional fabrication techniques are used to realize other components such as mechanical components with moving parts and optical components for photonics applications. Typical semiconductor fabrication process involves several key process steps such as lithography, material deposition, doping, ion etching and cleaning/polishing.
4.1.1 Fabrication process steps

Figure 34: Process flow followed in the fabrication of the micro column flow rate sensors.
Figure 34 illustrates the process flow used in fabrication of the micro column flow rate sensor. First step of the process is to clean the wafer to remove any contaminants or organic residue from the wafer surface. Then the wafer is spin coated with e-beam resist and prebaked on hotplate to remove excessive solvents in the resist. Patterning of the resist is done using electron beam lithography which changes the chemical composition of the resist upon incident electrons. Change in chemical composition results in change in solubility of the resist thus allowing us to remove the resist areas exposed to the electron beam by dissolving it in developer chemical. Pattern obtained using the developed resist is called a soft mask (soft polymer resist) and is not suitable as a mask for ion etching. Prior to ion etching step the soft mask has to be converted to a hard mask that can withstand the accelerated ions and protect the underneath silicon wafer. Hard mask is obtained by depositing a metal layer (chromium) on top of the previously developed soft mask and liftoff process. After depositing the metal layer on soft mask it will cover all the areas including soft mask and bare silicon pattern exposed after developing the soft mask. Liftoff process is the process of chemically removing the soft mask along with metal layer on top of it while keeping the metal layer deposited on bare silicon pattern. This method will result in a hard (metal) mask which is the opposite (not) of the soft mask. After getting the hard mask (Chromium) patterned on the wafer next step is to etch the silicon using reactive ion etching. In this step the patterned wafer is bombarded with ions that will result in removing the exposed silicon area by both physical etching (momentum of the ions) and chemical etching. Next step of the
process is to dope the wafer to create piezoresistive sensing areas and conductive paths. It is required that the piezoresistive areas to be placed at predefined locations with given dimensions. This is achieved by another soft mask created using the same process (spin coat, prebake, exposure and develop) mentioned earlier. Spin coating at this stage requires several process adjustments to achieve a good uniform layer of resist on the wafer due to uneven wafer surface resulting from etched micro/nano patterns from the previous step. Typically a sufficient uniformity in resist layer can be achieved by using a thinner photoresist and a reduced spin rate. When creating this second soft mask it is critical to align it with the existing pattern on the wafer. Alignment is done using alignment marks placed during the first step. This alignment exposure step is critical to place the piezoresistive sensors at predefined locations and requires a tight tolerance less than 50nm. After the second soft mask and development step the sample is doped using an ion implantation system. Ion beam will implant dopant atoms in the exposed silicon wafer while the other areas are protected by the soft polymer mask resulting in a localized doping pattern. Bombarding wafer with dopant ions will result in point defects in the silicon lattice. After the ion implantation and stripping the soft mask these point defects are repaired by an annealing step. [45] Following the ion implantation and annealing steps next and final part is to deposit electrodes for the electrical connections. Same as the previous step of ion implantation, electrode deposition requires a high accuracy of pattern overlay (alignment tolerance of less than 50nm). Alignment marks placed during the initial patterning stage and used in the second patterning
stage for ion implantation will be used in this final step of electrode deposition. After exposure and development of the soft mask a bilayer of metal (Titanium 5nm and Gold 25nm) is deposited as the electrodes. Finally another liftoff step is carried out to remove the soft polymer mask and create the electrode pattern.

4.1.2 Wafer cleaning

Wafer cleaning is carried out using several steps to remove oils and organic residues that appear on wafer surfaces.

Steps:

1. Place the silicon wafer in the warm (50°C) acetone bath for 10 minutes.
2. Sonication in methanol for 2–5 minutes.
3. Remove and rinse with IPA and DI water.

4.1.3 Spin coat resist and pre bake

![Figure 35: Schematic of the e-beam resist coating process using spin coating system and pre bake.](image)

Recipe parameters:

- Resist : ZEP520A
- Dilution: 1:1 in Anisole - D.R (Dilution Rate) = {Original Resist(g)+Solvent(g)}/original Resist(g)
- Spin:
- Step 1: 500 rpm for 5 sec
- Step 2: 3000 rpm for 45 sec
- Prebake: 180 °C hot plate for 3 min

ZEP520A is high performance positive EB resists which show high resolution and dry etch resistance. Initially the resist is diluted 1:1 with Anisole (weight ratio) which provide sufficient film thickness and prevent resist waste. Film thickness dependence with spin rate for different dilution rates is shown in Figure 36. [46] Figure 35 illustrates the spin coating process flow. Small puddle of diluted resist is dropped on the center of the wafer and spun at a low rpm (500) for 5 seconds to spread the resist over the wafer. Then the spinning rate is increased to 3000 rpm and kept for 45 seconds to obtain a uniform film thickness. Finally the wafer is annealed at 180°C on a hot plate for 3 minutes to evaporate the solvent and harden the resist film.
4.1.4 Lithography

Lithography is the process of patterning silicon wafer. There are several different methods used in patterning such as electron beam lithography, photo-lithography and Interference lithography, each having their own advantages and disadvantages.

**Photolithography**

Photo lithography uses a photon beam to pattern the resist. Photon beam is send through a pre patterned mask to transfer the pattern on photoresist. This is a parallel process where the entire pattern can be transferred to the resist at once; hence this is a high throughput process. This is the primary lithography technique used in semiconductor integrated circuits industry. Major disadvantage of photolithography is that undesired photon diffraction and interference patterns limit the systems resolution.

**Interference lithography**

Interference lithography is used to create line patterns using the interference of two photon beams. The advantage of this type of a system is its simple apparatus requirements. It mainly requires a laser, beam splitter and couple of mirrors to set up an interference lithography system. It is limited only to line patterns, but one can create other uniform patterns by rotating the lines on wafer surface. another disadvantage of this system is that it requires a perfect alignment of photon beams that can take a lot of time and effort to achieve. Figure 37 shows the schematic
diagram of a laser interference lithography system and patterns obtained by two-beam setup. [47]

**Figure 37**: Schematic diagram of laser interference lithography system and patterns obtained by two rotated exposures.

**Electron beam lithography**

In electron beam lithography a focused beam of electrons is used to draw patterns on the wafer. This is a serial process in which a single beam is traversing the path making the exposure pattern; hence this process is very time consuming. The main advantage of this method is that it can create any arbitrary pattern without the use
of a mask. This method is mainly used in the research facilities where researches continuously change the pattern to optimize the process or functionality of the device. This can also be used in custom fabrication facilities producing small number of units. JEOL JBX-6300FS electron beam lithography tool in center for functional nanomaterials in Brookhaven national laboratory has been used to expose the patterns required for fabrication of micro column flow rate sensors. This tool can operate at 100, 50 and 25 keV and is available with patterning of feature sizes as small as 8 nm. It also provides capability for high-speed, large area exposures (1mm+) and sub-20 nm overlay and stitching accuracy.

There are several process parameters to consider during the exposure step.

**Beam current**

Beam current is an important parameter that has to be adjusted for proper exposure patterns. Higher beam currents will speed up the writing process but will have negative effect on smaller features due to scattering of electrons in the photoresist as shown in Figure 38.

**Acceleration Voltage**

When electrons travel through the resist some of them will scatter at small angles, an effect known as forward scattering. This will significantly widen the exposure area and reduce the feature resolution. Figure 38 shows the Monte Carlo simulation of electron scattering at two different acceleration voltages. Left figure correspond to
lower acceleration voltage of 10kV and can be seen to have a wider effective exposure area due to high scattering. Figure on the right has higher acceleration voltage hence low scattering events giving a much narrower exposure area within the PMMA (resist) layer. Using a thinner resist can also reduce the beam broadening due to forward scattering.

![Figure 38: Monte Carlo simulation showing how electrons scatter in resist on a silicon substrate at a) 10 kV and b) 20 kV. [48]](image)

**Dose to clear**

Dose to clear is the amount of electrons required to completely expose a unit area of resist that gives best resolution without overexposure. It can be calculated using following formula.

\[
Dose \text{ to Clear} = \frac{I \times t}{s^2} \quad (35)
\]

Where:

- \( I \) – Beam current
t – Dwell time
S – Step size

Dwell time is automatically calculated for a given dose, current and step size.

**Step size**

Step size defines how far apart the beam will shoot electrons when exposing an area.

Figure 39 shows a Monte Carlo simulation of different step sizes. Steps between point-a and point-b are too close and overexpose towards the bottom of the resist. Steps between point-d and point-e are too far apart and underexpose towards the top of the resist. Points c and d are kept at optimum position to deliver correct dose amount to achieve best resolution.

![Figure 39: A Schematic representation of the step size parameter using Monte-Carlo simulation.](image)

**Exposure parameters:**

- Beam current 15nA
- Dose 350 μC/cm²
- Step size 8nm

**4.1.5 Resist properties and development**

ZEP 520A is a positive tone high resolution electron beam resist with a molecular weight of 55,000. It is manufactured by Zeon Chemicals (Japan).
Figure 40 shows the Schematic of the chemical structure of ZEP 520A, a copolymer of α-chloromethacrylate and α-methylstyrene. [50] Exposed resist is developed for 90 seconds in Amyl Acetate and then thoroughly rinsed with isopropyl alcohol and DI water before blow drying with nitrogen.

4.1.6 Metal deposition

There are several common techniques used for metal deposition such as sputtering, electron beam evaporation and thermal evaporation. Electron beam evaporation has been used in the fabrication of micro column flow rate sensor.

In electron beam evaporation a beam of electrons is focused on to a metal target placed on the crucible. The entire setup is kept under vacuum (5E-6 Tor) and the substrate is placed on top of the target facing downwards such that the evaporated metal vapor-plume gets deposited on it. 30nm layer of chromium was deposited as the hard mask for reactive ion etching and a bilayer of Titanium (5nm) and gold (25nm) was used as the electrodes for electrical characterization.
4.1.7 Liftoff process

When depositing the chromium layer on the developed soft mask, some of the metal will be deposited on the bare silicone where the exposed pattern is developed and removed while the rest will be deposited on the soft polymer mask. During the liftoff process the soft mask is chemically dissolved resulting in the removal of metal layer on top of it leaving only the metal layer deposited on the bare silicon. For a successful liftoff the metal layer thickness should not be greater than one third of the soft polymer mask thickness.

Liftoff process parameters:

- Microposit® remover 1165
- 80°C - 1 hour

4.1.8 Etch process

Liftoff process results in a hard metal mask on the silicon wafer that can be used as a protective shield during etch process. As shown in Figure 41 etching can be separated in to two main categories as wet etching and dry etching.
4.1.8.1 Wet Etching

Wet etching is the process of chemically removing material using a liquid solution bath or spray. As shown in Figure 42 wet etching is an isotropic process resulting in undercutting.
Plasma etching

Figure 43 shows the plasma etching process of silicon using Fluoride radicals. RF excitation in plasma etching system used to ionize variety of source gases in vacuum. Fluoride radicals are created from SF$_6$ gas and free electrons in the plasma. These Fluoride radicals diffuse towards the silicon surface and react with it to create volatile SiF$_4$ gas removing silicon atoms from the surface. This process of chemical etching is isotropic and not ideal for MEMS fabrication.

![Figure 43: Schematic illustration of isotropic dry plasma etching process using reactive radicals.](image)

Sputtering / ion milling

On the other hand etching silicon using ion bombardment is highly anisotropic. Ion bombardment is purely physical process and silicon atoms are removed from the
surface by momentum transfer of the directional ion beam accelerated using an externally applied electric field. Energetic noble gas ions such as Argon (Ar+) created in plasma is used to bombard the wafer surface. Ion bombardment has a poor selectivity and known to damage the wafer surface creating large defects that are not desirable for MEMS fabrication. [51, 52] Figure 44 illustrates an ion milling process.

![Figure 44](image)

**Figure 44: Schematic illustration of anisotropic ion milling process on a masked solid substrate.**

**Reactive ion etching**

Reactive ion etching (RIE) is a dry etching process for removing material using plasma of ions and chemically reactive radicals. This etch process is developed by combining both physical and chemical techniques to overcome the drawbacks of plasma etching.
and ion bombardment to achieve highly anisotropic features with no surface defects. During RIE process chamber is filled with low pressure gas mixture such as SF$_6$/Ar and plasma is created by externally applying a RF electric field, typically with 13.56MHz frequency. This RF field will oscillate the free electrons in plasma and collide them with neutral gas molecules creating more free electrons, ions and radicals (electron avalanche effect). [53] Argon ions and fluorine radicals are created in plasma as shown in following equations. [54, 55]

\[
Ar + e \rightarrow Ar^+ + 2.e \quad (36)
\]

\[
SF_6 + e \rightarrow SF_5^+ + F + 2.e \quad (37)
\]

Radicals in plasma chemically react with the surface material that needs to be removed and create gaseous molecules that desorbs from the surface. Silicon atoms on the wafer surface react with fluorine radicals to create volatile SiF$_4$ molecules as shown in following equation. [56]

\[
Si + 4F \rightarrow SiF_4 \quad (38)
\]

At the same time RF field will accelerate the light argon ions in plasma causing the ions to remove surface silicon atoms from physical bombardment. Physical etching due to ion bombardment and chemical etching due to fluorine radicals can be controlled independently by adjusting the gas ratio in the chamber. Furthermore surface passivation techniques are used to improve the anisotropy of etch profile. Surface passivation is achieved by introducing C$_4$F$_8$ (Octafluorocyclobutane) in to the source gas stream which yields SiO$_x$F$_y$ functional groups that condense on the
sidewalls to protect them from lateral etching. Schematic of capacitively coupled plasma – reactive ion etching system (CCP-RIE) is shown in Figure 45.

Major disadvantage of capacitively coupled plasma is that ion current cannot be decoupled from the ion density. Introducing inductively coupled plasma systems overcome this drawback by using separate electromagnetic induction coil to create plasma and another electric RF system to accelerate the ions. [57] ICP coil is supplied with an alternating current to produce an oscillating magnetic field which in turn moves the electrons in the plasma to continue the ionization process. ICP system is separated from the etching area so that he ion oscillations due to ICP will not affect the etch profile. Schematic of inductively coupled plasma – reactive ion etching system (ICP-RIE) is shown in Figure 46.
Cryogenic ICP-RIE systems are introduced to further control the etching process and improve the feature quality. Cryogenic ICP-RIE systems are equipped with liquid helium cooled substrate holders that can cool down the substrates to temperatures below -100°C. Cryogenic process enhances the anisotropic etching by promoting the adhesion of surface passivation layer.

4.1.9 Doping process

Doping is an important step in fabrication of semiconductor devices. Doping process alters the carrier density of the semiconductor changing its electrical properties such as conductivity and piezoelectric effect. Diffusion and ion implantation are the two main doping methods used in the industry.
Diffusion

Diffusion moves impurity atoms due to concentration gradient. This is commonly observed when smell of perfume spreads through air or ink drop spreads changing color of water. For a silicon crystal, impurity atoms have to move through a solid lattice. When diffusing in a solid lattice, impurity atoms can travel by moving in to an empty space in lattice or moving in between atoms in lattice or exchanging the position of impurity atom and silicon atom as shown in Figure 47.

![Image of lattice diffusion mechanisms]

**Figure 47:** Schematic illustration impurity transport mechanisms through crystal lattice.

Diffusion rate of the dopants depend on following factors.

- concentration gradient
- temperature
- dopant material
- substrate material
- crystallographic orientation of the substrate

Diffusion can be carried out using an exhaustible source (limited one time supply) or inexhaustible source (continuous supply). Inexhaustible source will ensure a constant
concentration of dopants on the substrate surface resulting in gradually decreasing dopant concentration from top to bottom in the wafer while using exhaustible source will decrease the doping concentration on the substrate surface over time. Fick’s first law describes this dopant redistribution and its flux dependence on the concentration gradient.

Diffusion of dopants in to Silicon wafer can be carried out using a gas, liquid or solid source. In gas phase diffusion a gas containing dopant atoms is passed over the wafer at elevated temperatures diffusing them in to the substrate at constant concentration. When it is a liquid source a stream of carrier gas such as nitrogen is bubbled through the liquid source. If the source is in solid form the carrier gas will pass over a heated solid source and flow towards the substrate giving a uniform dopant concentration on the wafer surface. Diffusion processes are advantages due to simultaneous processing of many wafers but can be disadvantageous due to isotropic diffusion in the wafer resulting in lateral spreading of dopants.

**Ion implantation**

Compared to the diffusion techniques, ion implantation can precisely control the dopant profile and concentration. Ion implantation is carried out using a stream of charged dopant ions accelerated in to the substrate. This has several advantages over the diffusion method such as no lateral diffusion and precise depth control. On the other hand the limitations on ion beam width can restrict the throughput of the process.
Figure 48 shows the schematic of an ion implanter setup. Ion source produces ionized dopants in gaseous state. Ionized dopants then accelerated in to the mass separator and filtered according to the desired mass using magnetic deflection. Beam control slit is used to screen the deflected dopants. Then the filtered dopant ions are accelerated using the acceleration tube and pass through the horizontal and vertical deflectors to hit the target wafer.

![Schematic illustration of the ion implanter setup for doping process.](image)

Ion Implanted dopant atoms are generally not electrically active due to their interstitial lattice placement during implantation process. To activate these dopant atoms samples are annealed at high temperatures (>900°C) in a low pressure (10^{-4} mbar) environment. Elevated temperature will generate lattice vacancies in silicon that facilitate the movement of dopant atoms from interstitial positions to vacant lattice sites (substitution). High temperature annealing will also remove the lattice defects formed from ion beam damage and recrystallize the lattice.
4.2 Fabrication results

Device fabrication includes several steps. In following sections we will discuss the parameters in each step and how they affect the device quality.

4.2.1 Electron beam exposure and development

Electron beam exposure is a critical step at the front end of the fabrication process. Quality of the features directly depends on the resolution limit of the exposure instrument. For larger patterns, stitching quality and accuracy of the exposure instrument plays an important role too. Even with state of the art instruments user has to specify numerous process parameters to obtain the best possible feature quality.
Figure 49: SEM images of exposure results after development at various dose levels a) 350μC/cm², b) 325μC/cm², c) 300μC/cm², d) 275μC/cm², e) and f) 175 μC/cm².
Figure 49 shows the SEM images of exposure at 4 different dose levels, a) 350μC/cm², b) 325μC/cm², c) 300μC/cm², d) 275μC/cm², e) and f) 175 μC/cm². All the exposures were done on spin coated PMMA while keeping all the other parameters at constant. Figure 49a shows a considerably large over exposure resulting in decayed features during development process. As seen on sub figures b, c and d, when decreasing the dose level the feature quality increases, but further decreasing the dose will result in under exposure. Without sufficient charge to penetrate through the resist it will not completely remove the resist from exposed regions as shown in sub figures e and f.

4.2.2 Metal deposition and liftoff

When feature size decreases and feature density increases while keeping the other exposure parameters such as current and dose at constant, it reduce the quality of the patterned features.
Figure 50: SEM images of liftoff quality at different feature sizes and densities.

Figure 50 shows the SEM images of several samples after liftoff with different feature sizes and separation. All the samples were processed while keeping other parameters constant. It can be seen that high feature densities and small dimensions result in quality decreases by losing feature sharpness.

4.2.3 Reactive ion etching

The outcome of reactive ion etching process is very sensitive to its parameters. A little change in one of the parameters can result in drastically different outcome. Two of the most critical parameters are the temperature and ratio between input gases. Cryogenic silicon etching process is usually carried out below -100°C temperature.
This low temperature is required to form the passivation layer from oxygen that prevents sidewall etching. Increasing the process temperature will result in desorption of oxygen from the feature walls and thinning the passivation layer and undercutting of the side walls. On the other hand lowering the temperature below the optimum level will result in a thicker passivation layer and non-vertical (tapered) etch profile.

Input gas ratio also plays a major role in etch profile. Our input gas mixture consists of Sulfur hexafluoride (SF₆) for chemical etching and Oxygen (O₂) for passivation layer. Increasing Sulfur hexafluoride ratio will result in accelerated etching and undesired undercutting while increasing Oxygen ratio will promote micro masking resulting in black silicon grass. A method of determining successful etch parameters using black silicon “Black silicon method” has been reported by Jansen et al in 1995. [58]

![Figure 51: Schematic illustration of positive, vertical and negative etch wall tapering from RIE etching.](image)
Figure 52: Temperature dependence of etch angle for Silicon RIE using SF₆ and O₂ mix.

Figure 53: Oxygen flow rate dependence of etch angle for Silicon RIE using SF₆ and O₂ mix.
Figure 51 shows a schematic of positive, vertical and negative etch tapering effect. Positive etch tapering occurs due to high rate of wall passivation. There are several reasons identified as responsible for high rate of wall passivation. As described earlier low temperature and high oxygen flow rate will result in increased side wall passivation. Furthermore, forward bias also plays an important role in side wall passivation. Reactive ion etching utilizes both chemical and physical etching mechanisms to achieve its an-isotropic etching properties without damaging the substrate from ion bombardments. To attain this, RIE uses radicals to chemically etch the substrate and a passivation layer to protect the side wall from etching. This formation of the passivation layer is an isotropic process and covers the entire substrate including the horizontal surfaces that needs to be etched. Ion bombardment in RIE is used to remove this passivation layer in horizontal etch surfaces and clear the path for radicals to do their job and chemically etch the substrate. In inductively coupled plasma source ions are accelerated with the use of second RF supply called Forward bias. Decreasing the forward bias power will hinder the ion milling of the passivation layer on horizontal etch surfaces resulting in a positively tapered side wall. Low forward bias power will also result in increasing the chance of forming black silicon grass on substrate. On the other hand high forward bias power will damage the substrate by increasing the ion milling process. Increasing the forward bias power in samples with soft masks such as PMMA will increase the mask etch rate and limit the maximum etch depth, but for hard masks such as chromium this will not be a big concern.
Figure 52 shows the temperature dependence of etch angle for both cylindrical and cross shaped micro columns. The study was conducted while keeping all the other parameters constant as shown in Table 1. Etch angle dependence on the temperature for both cylindrical and cross shaped columns can be identified as linear in the range of -90°C to -115°C giving vertical etch profile around -105°C. As mentioned before this change in etch angle can be explained by the temperature dependent surface adsorption and desorption rates of the passivation layer. High temperatures will promote the surface desorption of passivation layer while low temperatures will promote the surface adsorption resulting in positively tapered side walls. When comparing the cylindrical column with cross shaped column it can be seen that cross shaped column has more sensitivity to the temperature variation. This high temperature dependence in cross shaped columns is due to thin fins in the cross shaped column. Thin fins having smaller feature size compared to the cylindrical column with the same diameter will increase the temperature dependence of cross shaped column.

Oxygen flow rate in the etch chamber is another important parameter in controlling side wall angle. Figure 53 shows the effect of changing Oxygen flow rate on etch angle. This study was conducted while keeping all the other parameters constant as shown in Table 2. Increasing the Oxygen flow rate will promote the passivation layer and result in positive etch angle while decreasing Oxygen will decrease the passivation layer thickness resulting in a negative etch angle. As previously seen in the temperature dependent etch angle graph, cross shaped column has a higher
sensitivity to the oxygen flow rate compared to the cylindrical column. This can also be explained by the smaller feature size of fins in cross shaped column. The relationship between oxygen flow rate and the etch angle can be identified to have a positive linear trend in the range of 4sccm to 8sccm flow rates. Both micro columns show vertical side wall profile when the oxygen flow rate is close to 6sccm.

<table>
<thead>
<tr>
<th>Column diameter</th>
<th>10um</th>
<th>Oxygen flow rate</th>
<th>6.5sccm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF₆ flow rate</td>
<td>40sccm</td>
<td>RF power</td>
<td>20W</td>
</tr>
</tbody>
</table>

Table 1: Process parameters used in temperature dependent etch angle study.

<table>
<thead>
<tr>
<th>Column diameter</th>
<th>10um</th>
<th>Temperature</th>
<th>-110 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF₆ flow rate</td>
<td>40sccm</td>
<td>RF power</td>
<td>20W</td>
</tr>
</tbody>
</table>

Table 2: Process parameters used in oxygen flow rate dependent etch angle study.
Figure 54: SEM images showing etch tapering effect on Silicon cylindrical micro columns after RIE.
Figure 55: SEM images showing etch tapering effect on Silicon cross shaped micro columns after RIE.
Figure 54 shows the SEM images of etch tapering effect on cylindrical micro columns. All three structures in subfigures a, b and c was etched by varying oxygen flow rate while keeping other parameters at constant as shown in Table 2. Subfigure a) was etched at low oxygen flow rate (5sccm) resulting in a negative etch angle while subfigure b) etched at 6sccm oxygen flow rate turns out to be the optimum flow rate for vertical side walls. Subfigure c) shows a small positive etch angle due to slight increase in oxygen flow rate at 6.5sccm.

Figure 55 shows the SEM images of etch tapering effect on cross shaped micro columns. All three structures in subfigures a, b and c was etched by varying oxygen flow rate while keeping other parameters at constant as shown in Table 2. Subfigures a, b and c corresponds to flow rates 5sccm, 6sccm and 6.5sccm respectively. From subfigure c) it can be seen that the etch tapering angle for column diameter is different from that of the fin width. Width of the fin has much higher positive tapering towards the bottom compared to the tapering effect on the diameter of the micro column. This is a good example that shows the tapering angle dependence on the feature size. Due to this, controlling the etch angle of structures with varying feature dimensions can be a difficult task.
Figure 56: SEM image showing etch tapering on circular shaped micro column arrays.
Figure 57: SEM images showing etch tapering on cross shaped micro column arrays.
Table 3: Etch parameters for studying density and feature size effect on etch angle in both cylindrical and cross shaped micro column arrays.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>-110°C</th>
<th>Oxygen flow rate</th>
<th>6.5sccm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF$_6$ flow rate</td>
<td>40sccm</td>
<td>RF power</td>
<td>20W</td>
</tr>
</tbody>
</table>

Figure 56 shows the etch tapering effect on cylindrical micro column arrays. Samples in subfigures a, b and c were all etched in constant etch parameters as shown in Table 3. The change in etch angle is due to the change in density and feature size between each sample. Etch tapering and feature binding becomes more prominent with increasing feature densities and decreasing feature sizes. This is mainly due to the restriction of mass transport of fluorine radicals in the cramped space between micro columns. Main mechanism of mass transport of radicals required in the chemical etching process is due to the diffusion, and the diffusion process is hindered at tight spaces limiting the radicals available for etch process resulting in positively tapered side walls. Figure 56 b) shows that the outer wall of the micro column has a lower tapering angle compared with the inner wall; this is a direct consequence of mass transport disparity between two sides of the column. Figure 57 shows both positive and negative etch angles on cross shaped micro column arrays. Figure 57 a) has a more spread out features with low density, hence more radicals can reach in between the features and contribute to the etch process resulting in over etched features having negatively tapered side walls. Figure 57 b) on the other hand has just the right amount of spacing for radical diffusion allowing it to etch vertical side walls. From Figure 57 c) it can be seen that the spacing between micro columns is too tight resulting in positive etch tapering. This can be corrected by increasing the forward
power which will drive ions into the tight space between micro columns clearing the passivation layer for chemical etching. Decreasing the oxygen flow rate will also reduce the passivation layer thickness and promote the chemical etching by radicals.

4.2.4 Spin coating on existing micro structures

Spin coating resist on a substrate will create a thin film due to centrifugal force on resist by its rotational motion. To spin coat a uniform thin film on a substrate it requires a smooth substrate surface ensuring the unobstructed flow of resist while spinning. This condition is usually satisfied at the very beginning of the fabrication process when a new wafer is patterned for the first time. But, after the initial patterning, for subsequent spin coating steps this smooth surface condition is hardly ever satisfied due to previously patterned structures on the wafer surface. These patterned structures on the wafer surface presents somewhat of a challenge to achieve uniform resist coating.

Figure 58 Shows the SEM images of spin coated resist and subsequent lift off result with preexisting structures. As seen in Figure 58-a individual or adequately spaced structures will have minimal effect and still be able to totally cover the surface of the structures as well as the horizontal wafer area using the standard spin coating recipe. But, dense structures such as micro column arrays shown in Figure 58 -b will not get coated uniformly due to resist being blocked from reaching the center area by the surrounding structures. When metal layer is deposited on this for liftoff purpose, the metal will come in contact with the exposed region in the middle of the array and
adhere to it preventing the removal of metal layer during the liftoff as shown in Figure 58 -c. There are several mechanisms to overcome this problem and achieve a uniform layer of resist on preexisting structures. One method is to use spray coating or immersion coating method that ensures a uniform coating on 3d substrates. Spray coating requires special equipment that are not available in many cleanroom facilities and immersion coating is a wasteful method that requires large quantities of expensive resist thus increasing the cost of fabrication. The other method is to adjust the spin coating recipe to achieve the desired uniformity on preexisting structures. In our experiments it is found that diluting the resist with anisole and reducing the spin speeds will improve the results to an acceptable level of resist layer uniformity. Even though the recipe has to be tweaked several times for different structures depending on their dimensions, this method can utilize existing equipment and prevent the resist waste. Figure 59 and Figure 60 shows the SEM images of completed micro column array and single micro column devices respectively.
Figure S8: SEM images showing spin coating resist and subsequent liftoff process on existing micro structures.
Figure 59: SEM images showing completed micro column array devices.
Figure 60: SEM images showing completed single micro column devices.
5 Performance testing and parameter tuning of the novel piezoresistive flow rate sensors

Figure 61 shows the change in output voltage with increasing flow velocity for cylindrical column flow sensor device. Graph shows a linear trend between sensor output and flow velocity. The column has a height of 10\(\mu\)m and a diameter of 2\(\mu\)m. Dopant concentration of the sensor devices is 1.078\(x10^{19}\) (cm\(^{-3}\)). It can be seen that the experimental values are about 40% lower than the calculated output. The sensitivity is defined as the change in voltage with the unit change in flow speed. In the range of 5m/s to 20m/s flow speeds the sensitivity is calculated as follows.

\[
\text{Sensitivity} = \frac{\Delta\text{Voltage}}{\Delta\text{Speed}} = 7.5 \frac{\mu\text{V}}{\text{ms}^{-1}}
\]
Figure 62: Pulsed flow response from cylindrical column flow rate sensor.

Figure 62 shows the change in induced output voltage with a pulsed gas flow for a single cylindrical column flow rate sensor. The column has a height of 10\(\mu\)m and a diameter of 2\(\mu\)m. Dopant concentration of the sensor devices is 1.078\(\times\)10\(^{19}\) (cm\(^{-3}\)). Gas flow is set at 15m/s and switched on/off every 10 seconds. When the gas flow is turned off, mean output voltage oscillates around 0V and when the flow is turned on it increases to 0.09mV. The output is measured only at one of the four sensors in the device.
Figure 63: Change of induced voltage in cylindrical column sensor 1 and 3 with varying gas flow direction.

Figure 63 shows the direction dependence of the single cylindrical column flow rate sensor. The column has a height of 10μm, diameter of 2μm and sensor areas with dopant concentration of $1.078 \times 10^{19}$ (cm$^{-3}$). Output voltages from sensor 1 and sensor 3 are measured while changing the flow speed and keeping the flow velocity constant at 15m/s. It can be seen that the output voltages from two sensors depend on the flow direction as suggested in the finite element model. Sensor 1 shows a higher output voltage compared to the sensor 3, this can be due to the variations in fabrication steps such as contaminants or off alignment during electrode deposition and liftoff process.
6 Summary and Outlook

Flow rate sensors have become a very important class of components in modern technological equipment. They have a wide variety of applications ranging from medical instruments such as drug delivery systems to critical control systems used in nuclear reactors. There are numerous types of flow rate sensors based on different flow measurement techniques such as rotating turbines, ultrasonic, and thermal, etc.

This dissertation research is focused on design and fabrication of novel microscale gas flow rate sensor, utilizing the piezoresistive properties of Silicon. Two main types of designs were analyzed and fabricated, one design using only a single micro column and the other one using an array of micro columns. The design of the flow rate sensor and its parameter optimization has been carried out using finite element analysis in COMSOL Multiphysics. Parametric study has shown that columns with small diameter and large length (high aspect ratio) have a higher flow rate sensitivity compared to the wider and shorter columns. Taller micro columns will have a higher boundary force resulting in a higher induced stress and output voltage while increasing the column width will reduce the induced stress and output voltage due to increased cross sectional area at the base of the column. Two different shapes of micro columns have been tested, one with a circular cross section and the other one with a cross shaped cross section. When comparing the shape of the micro column, the one with cross shaped cross section showed a higher output voltage than the one with the circular cross section. This can be attributed to the higher flow resistance and reduced cross sectional area in the cross shaped column.
Array type devices are more robust to mechanical failure due to use of multiple columns compared with the single column device. The major drawback of the array type device is its distribution of $\sigma_{xy}$ induced shear stress on the wafer surface. In single column devices, four piezoresistive sensors were fabricated around the micro column to capture the directional dependence of the induced $\sigma_{xy}$ shear stress. But in array type device $\sigma_{xz}$ or $\sigma_{yz}$ shear stress component has to be utilized with additional terminals in the z direction. Furthermore, columns in array have to be sufficiently spaced out to reduce the screening effect from the outer micro columns. On the other hand increased gap between micro columns will reduce the induced stress and output voltage.

Second part of this study is focused on developing a fabrication process for the novel flow rate sensor. It is critical that the fabrication can be integrated in to the standard MEMS process flow, to be readily available for new equipment such as lab on chip devices. Proposed fabrication process involves standard micro/nano fabrication techniques such as lithography, electron beam evaporation, reactive ion etching and ion implantation. Fabrication process was developed and process parameters were optimized using the clean room facility at the Center for Functional Nanomaterials in Brookhaven National Laboratory. Samples were doped using ion implantation at the Friedrich Schiller University Jena in Germany. Several single column and multiple column devices have been fabricated and tested for sensitivity and directional dependent output. The experimental results show that the proposed mechanism for novel flow rate sensor and fabrication process can be successfully used to integrate
micro scale flow rate sensors into future lab on chip applications. Proposed new micro column based flow rate sensor has several advantages over the existing thermal, differential pressure or laser based flow rate sensors. Its micro meter size dimensions give it the capability to take high resolution in-situ measurements of flow velocities and its directional dependent output can be used to measure local turbulence patterns. Furthermore the cost effective and straightforward fabrication process can be readily integrated in to existing MEMS fabrication lines. The sensitivity and the performance of the sensor can be controlled via changing the micro column dimensions and piezoresistive material used in the sensor. Future research on this novel sensor technology can test the applicability of other piezoresistive materials such as Germanium and Zinc Oxide to replace the silicon piezoresistive sensor. The effect of size dependency on piezoresistive coefficients can be used to enhance the sensor performance by changing the geometry and/or reducing the dopant layer thickness of the sensor. This novel piezoresistive based micro column flow rate sensor introduces a robust, easy to fabricate and cost effective sensor for micro scale flow rate and direction measurements.
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