Integrated CMOS/MEMS Devices

- CMOS Electronics thru standard MOSIS Foundry
- MEMS Post Processing through commercial fabrications and specialized laboratories.
  - Maskless Post Processing – (Mostly sensors)
  - Aligned front and back Post Processing
  - Actuator structures.
A CMOS Thermal Isolated Gas Flow Sensor

- **Basic structures:**
  Two polysilicon resistors sandwiched by a thermally isolated SiO$_2$ membrane and two CVD oxides.

- **Fabrication process:**
  1. CMOS technology
  2. Anisotropic etching as a postprocessing to form the thermal isolated SiO$_2$ membrane.

- **Operation principle:**
  Two polysilicon resistors is used as an electrical heater and a temperature sensor. When a current is passed through the heater, the temperature of the heater element increases, which can be observed by measuring the change in resistance of the sensor element.

### Post-Process Etch for CMOS Micromachining

![Diagram of micromachining process](image)

#### TABLE 4.9 Principal Characteristics of Four Different Anisotropic Etchants

<table>
<thead>
<tr>
<th>Etchant/Diluent/Additives/Temperature</th>
<th>Etch Rate (100) (μm/min)</th>
<th>Etch Rate Ratio (100)/(111)</th>
<th>Remarks</th>
<th>Mask (Etch Rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KOH/water, isopropyl alcohol additive, 85°C</td>
<td>B &gt; 10⁷ cm⁻³ reduces etch rate by 20</td>
<td>1.4</td>
<td>400 and 600 for (110)/(111)</td>
<td>IC incompatible, avoid eye contact, etches oxide fast, lots of H₂ bubbles</td>
</tr>
<tr>
<td>Ethylene diamine pyrocatechol (water), pyrazine additive, 115°C</td>
<td>≥5 × 10¹⁹ cm⁻³ reduces the etch rate by 50</td>
<td>1.25</td>
<td>35</td>
<td>Toxic, ages fast, O₂ must be excluded, few H₂ bubbles, silicates may precipitate</td>
</tr>
<tr>
<td>Tetramethyl ammonium hydroxide (TMAH) (water), 90°C</td>
<td>&gt;4 × 10¹⁰ cm⁻³ reduces etch rate by 40</td>
<td>1</td>
<td>From 12.5 to 50</td>
<td>IC compatible, easy to handle, smooth surface finish, few studies</td>
</tr>
<tr>
<td>Hydrozine water, 115°C</td>
<td>≥1.5 × 10¹⁰ cm⁻³ practically stops the etch</td>
<td>3.0</td>
<td>10</td>
<td>Toxic and explosive, okay at 50% water</td>
</tr>
</tbody>
</table>

*Given the many possible variables, the data in the table are only typical examples.*

**Xenon Difluoride Etching:** XeF₂ is a silicon etch that does not appreciably etch SiO₂ or Al. It can be used as a post-process etch to make silicon a sacrificial layer for CMOS micromachining.
Review of Resistor Design

Resistance of the rectangular block of uniform doped material in figure below is

\[ R = \rho \frac{L}{A} \]

Where \( \rho \) is material’s resistivity

\( L \) and \( A \): the length and cross sectional area of the block.

\( A=Wt \) (\( W \) is width of the sample and \( t \) is the thickness of the sample).

\[ R = (\frac{\rho}{t}) \left( \frac{L}{W} \right) = R_{\square}(L/W) \]

Where \( R_{\square}=(\rho/t) \) is called the sheet resistance of the layer of material and its unit is the ohm. \( L/W \) is unitless.

To avoid confusion between \( R \) and \( R_{s} \), sheet resistance \( R_{\square} \) is given the special unit of ohms per square. The ratio \( L/W \) can be interpreted as the number of unit squares of material in the resistor.

\[ R = \rho \frac{L}{A} \quad \rho = \frac{1}{\sigma} \quad \sigma = q(\mu_{n}n + \mu_{p}p) \]

=> Given the sheet resistance \( R_{\square} \), a circuit designer need calculate the number of “squares” of the resistor in order to define its resistance \( R \).
$R = \rho \frac{L}{A} = \left( \frac{\rho}{\gamma} \right) \left( \frac{L}{W} \right) = R_o \left( \frac{L}{W} \right)$

Corner = 0.56 squares

0.35 squares
## Sheet Resistance of MOSIS

<table>
<thead>
<tr>
<th>AMI</th>
<th>ABN (1.5 micron N-well)</th>
<th>0.80</th>
<th>SCNA, SCNE, SCN, Tight Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS PARAMETERS</td>
<td>N+ACTV</td>
<td>P+ACTV</td>
<td>POLY</td>
</tr>
<tr>
<td>Sheet Resistance</td>
<td>54.8</td>
<td>79.5</td>
<td>30.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AMI</th>
<th>G5N (0.5 micron N-well)</th>
<th>0.35</th>
<th>SCN3M, SCN3ME, Tight Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS PARAMETERS</td>
<td>N+ACTV</td>
<td>P+ACTV</td>
<td>POLY</td>
</tr>
<tr>
<td>Sheet Resistance</td>
<td>81.8</td>
<td>101.1</td>
<td>25.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HP</th>
<th>AMOS14TB (0.5 micron N-well)</th>
<th>0.35</th>
<th>SCN3M, SCN3MLC, Tight Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS PARAMETERS</td>
<td>N+ACTV</td>
<td>P+ACTV</td>
<td>POLY</td>
</tr>
<tr>
<td>Sheet Resistance</td>
<td>2.6</td>
<td>2.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TSMC</th>
<th>0.35 micron 2P4M (4 Metal Polycided, 3.3 V/5 V)</th>
<th>0.25</th>
<th>SCN4ME, Tight Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS PARAMETERS</td>
<td>N+ACTV</td>
<td>P+ACTV</td>
<td>POLY</td>
</tr>
<tr>
<td>Sheet Resistance</td>
<td>81.0</td>
<td>154.1</td>
<td>8.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TSMC</th>
<th>0.35 micron 1P4M (4 Metal Silicided, 3.3 V/5 V)</th>
<th>0.25</th>
<th>SCN4M, Tight Metal</th>
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<tr>
<td>PROCESS PARAMETERS</td>
<td>N+ACTV</td>
<td>P+ACTV</td>
<td>POLY</td>
</tr>
<tr>
<td>Sheet Resistance</td>
<td>4.7</td>
<td>3.4</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Temperature Coefficient of Resistance

\[ R(T) = R_o \left[ 1 + \alpha(T-T_o) \right] \]

where

- \( R(T) \): resistance at temperature \( T \)
- \( R_o \): resistance at temperature \( T_o \)
- \( \alpha \): Temperature coefficient of resistance

\[ \alpha = T_c = \frac{\Delta R}{R_o \Delta T} \]

\( \alpha \sim 1.17 \times 10^{-3}/^\circ\text{C} \) for Poly

Overheat Ratio:

\[ \alpha_R = \frac{\Delta R}{R} \]

Electrothermal Response of Gas Flow Sensor

\[ R(T) = R_0 \left[ 1 + \alpha (T - T_0) \right] \]

\[ T = T_0 + \left\{ \frac{R(T)}{R_0} - 1 \right\} / \alpha \]

Fig. 5. Electrothermal response of the sensor (a) with thermal isolation (b) without thermal isolation.
Test of Gas Flow Sensor

\[ R(T) = R_o [1 + TcT] \]

\[ P = I^2R = I^2R_o [1 + TcT] \]

\[ R \sim I^2 [1 + TcT] \]

Fig. 6. Variation of resistance \( R_2 \) with \( I^2(1 + TcT) \).

Fig. 7. The response of the sensor to flows (a) 0, (b) 5, and (c) 12.5 m/s.
Thermal Structures

• Systematical design:

Thermal resistance \( R_{th} = \Delta T/P \) (unit: KW\(^{-1}\))

To optimize the conversion of the power \( P \) to the temperature difference \( \Delta T \).

Heat conduction:

Power \( P = \) heat flux \( Q = \kappa A \Delta T/L \)

\[ R_{th} = \frac{\Delta T}{P} = \frac{L}{(\kappa A)} = \frac{L}{(\kappa D W)} = \frac{1}{(\kappa D)}(L/W) \]

Thermal resistance:

\[
R_{th} = \left( \frac{L}{W} \right) \left( \frac{1}{\kappa D} \right)
\]

Thermal sheet resistance:

\[
R_{st} = (\kappa D)^{-1}
\]

<table>
<thead>
<tr>
<th>material</th>
<th>( \kappa [\text{W/(°C-cm)}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO(_2)</td>
<td>0.014</td>
</tr>
<tr>
<td>Si</td>
<td>1.57</td>
</tr>
<tr>
<td>Al</td>
<td>2.36</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
</tr>
</tbody>
</table>
Electrical-Thermal Analogies

Thermal power and electrical power are equivalent in physical sense, but they are not equivalent in the above analog.

- Thermal conductance: \( G = \frac{1}{R_{th}} = \frac{P}{\Delta T} \) (unit: \( \text{WK}^{-1} \))

- Thermal capacitance: \( C = \frac{dH}{dT} = mC_p \) (unit: \( \text{JK}^{-1} \))

<table>
<thead>
<tr>
<th>Thermal Parameter</th>
<th>Electrical Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature: ( T ) (K)</td>
<td>Voltage: ( V ) (V)</td>
</tr>
<tr>
<td>Heat flow, Power: ( P ) (W)</td>
<td>Current: ( I ) (A)</td>
</tr>
<tr>
<td>Heat: ( Q ) (J = W s)</td>
<td>Charge: ( Q ) (C = A-s)</td>
</tr>
<tr>
<td>Resistance: ( R ) (K/W)</td>
<td>Resistance: ( R ) (( \Omega = V/A ))</td>
</tr>
<tr>
<td>Conductance: ( G ) (W/K)</td>
<td>Conductance: ( G ) (( S = \Omega^{-1} ))</td>
</tr>
<tr>
<td>Capacity: ( C ) (J/K)</td>
<td>Capacitance: ( C ) (( F = A\cdot s/V ))</td>
</tr>
<tr>
<td>Thermal resistivity: ( \rho_{th} ) (K-m/W)</td>
<td>Electrical resistivity: ( \rho_{el} ) (( \Omega \cdot m ))</td>
</tr>
<tr>
<td>Thermal conductivity: ( \kappa ) (W/K-m)</td>
<td>Electrical conductivity: ( \sigma ) (( S/m ))</td>
</tr>
<tr>
<td>Specific heat: ( c_p ) (J/kg-K)</td>
<td>Permittivity: ( \varepsilon ) (( F/m ))</td>
</tr>
</tbody>
</table>
Thermal Model (I)

- **Suspension SiO₂ beams:**
  \(1/R_{\text{beam}}\): thermal conductance of the suspension beams.

- **Floating SiO₂ membrane:**
  \(G_{\text{film}}\): parasitic conductance for the undesired heat loss in the SiO₂ membrane caused by convection, conduction and radiation through the gas or substrate.
  \(C_{\text{film}}\): heat capacity of the membrane.

- **Polysilicon sensor:**
  \(G_{\text{sen}}\): the desired conductance created by the physical signal (i.e. heat convection of the sensor caused by gas flow).

\[
C \frac{dT}{dt} = P - G \Delta T_{\text{film}}
\]

\[
G = \frac{1}{R_{\text{beams}}} + G_{\text{film}} + G_{\text{sen}}
\]
\[ C \frac{dT}{dt} = P - G \Delta T_{film} \]

\[ G = \frac{1}{R_{beams}} + G_{film} + G_{sen} \]

In a steady state situation:
\[ \Delta T_{film} = T - T_{ambient} = \frac{P}{\left( \frac{1}{R_{beams}} + G_{film} + G_{sen} \right)} \]

In a transient situation:
\[ \Delta T_{film}(t) = \frac{P}{1/R_{beam} + G_{film} + G_{sen}} (1 - \exp(-t/\tau_{film})) \]

\[ \tau_{film} = \frac{C_{film}}{G_{film} + G_{sen} + 1/R_{beam}}. \]
**Suspension SiO$_2$ beam:**

Field Oxide = 0.6 $\mu$m

$O_{X1}=0.8$ $\mu$m  \{D=2.0 $\mu$m\}

$O_{X2}=0.6$ $\mu$m

$L/W=3$

$\kappa=0.014 [W/(^\circ C-cm)]$ for SiO$_2$

$$R_{\text{beam}} = \left(\frac{L}{W}\right)\left(\frac{1}{kD}\right) = (3)\left(\frac{1}{0.014 \times 2.0 \times 10^{-4}}\right) = 1.07 \times 10^6$$

$$R_{\text{beams}} = \frac{R_{\text{beam}}}{4} = 2.68 \times 10^5 \, [^\circ C/W]$$

Assume no heat loss in membrane $G_{\text{film}} = 0$ and no flow $G_{\text{sen}} = 0$

$$R_{\text{th}} = R_{\text{beams}} = \frac{\Delta T}{P}$$

$$P = \frac{\Delta T}{R_{\text{beams}}} = \frac{300}{2.68 \times 10^5} = 1.12 \text{mW}$$

$\Rightarrow$ only 1.12 mW power required to raise the temperature 300$^\circ$C:
Thermal RC Circuit and Time Constant

\[ \Delta T_{\text{flm}}(t) = \frac{P}{1/R_{\text{beam}} + G_{\text{flm}} + G_{\text{sen}}} (1 - \exp(-t/\tau_{\text{flm}})) \]

\[ \tau_{\text{flm}} = \frac{C_{\text{flm}}}{G_{\text{flm}} + G_{\text{sen}} + 1/R_{\text{beam}}} \]
Sensor Signal and Interface

Constant current mode:

Saturation: \( V_{ds} = V_{gs} - V_t \)

\[
I_{ds} = \frac{\beta}{2} (V_{gs} - V_t)^2 
\]

Eq(2-5) in Ch1

Free standing polysilicon resistor \( R \)

Apply current \( I \) ⇒ self heating by \( P = I^2R \)

Flow velocity \( v \) ⇒ Cool by convection ⇒ Resistance ↓ (positive TCR)

\[ \Rightarrow V_{\text{sensor}} = IR \]