Wafer Level Packaged CMOS-SOI-MEMS Thermal Sensor at Wide Pressure Range for IoT Applications

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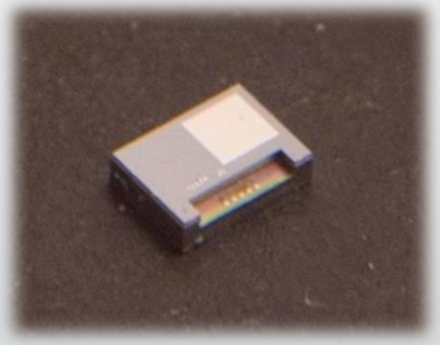
RESEARCH MOTIVATION

- IR sensors have huge markets: IoT, Smart homes, Automotive, etc
- Thermal sensors detect temperature changes induced by remote sensing of IR radiation and provide **uncooled** IR sensors
- MEMS enable high performance **miniature** thermal sensors

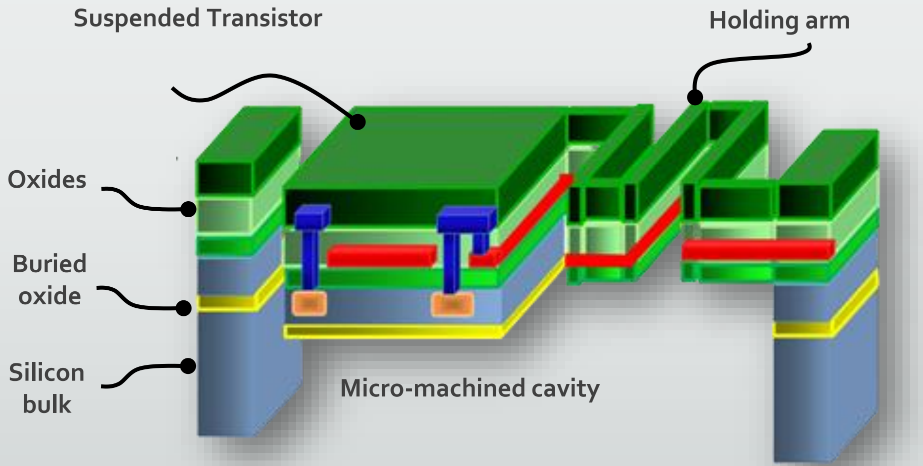
From: https://www.todos-technologies.com/

RESEARCH INNOVATION: TMOS

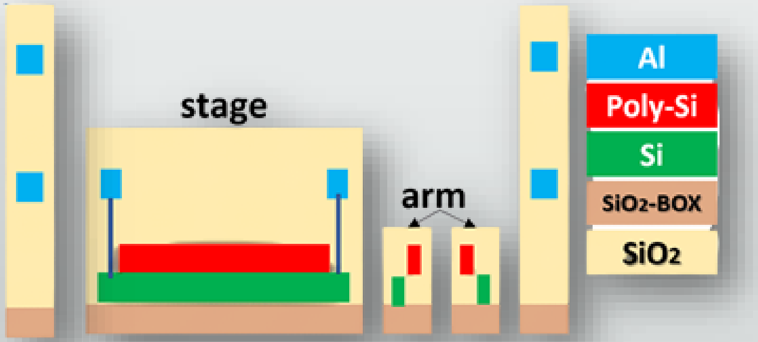
- The TMOS (Thermal-MOS) is a thermal sensor developed at the Technion
- Achieved by CMOS-SOI-MEMS process
- CMOS transistor is the standard building block of CMOS CHIPS manufactured in FABs
- By applying backend machining – TMOS becomes the highest performance thermal sensor (compared to bolometers, PYRO's and thermopiles)
- Operation at subthreshold requires very low power



Fabricated TMOS sensor



3D TMOS pixel Schematic



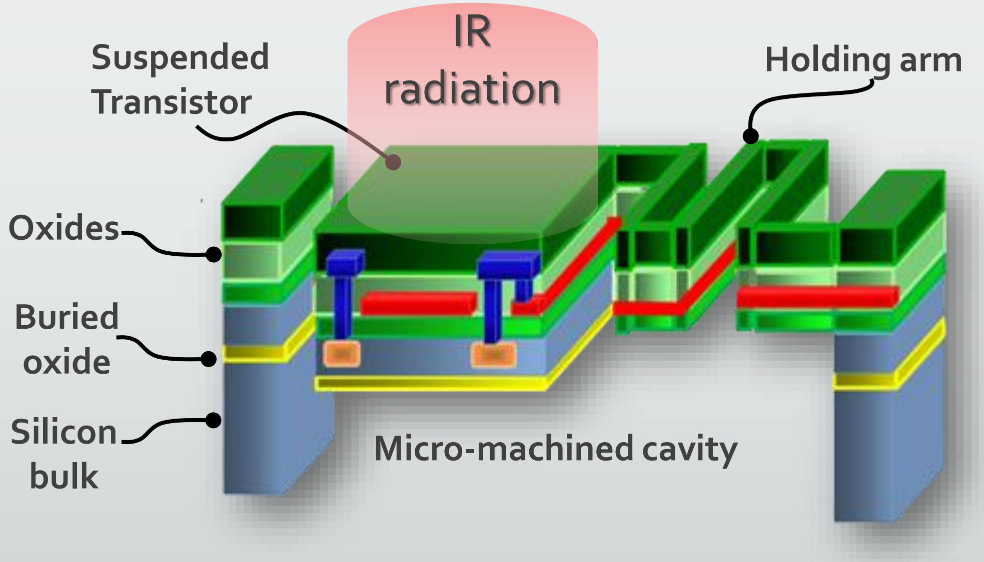
Schematic cross-section of the TMOS layers

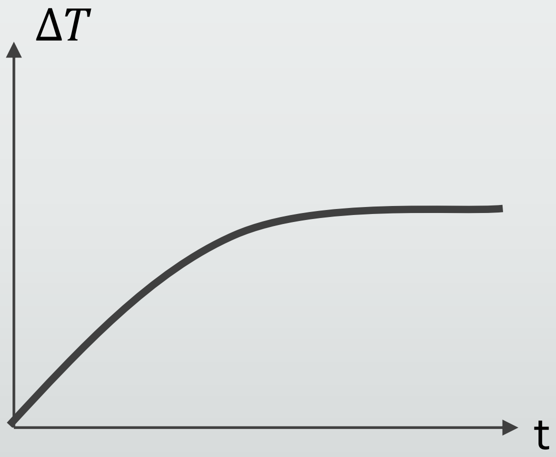
TMOS OPERATION PRINCIPLE

The micro-machined thermally insulated transistor has very low thermal mass and very low thermal conductivity

Absorbed photons increase the TMOS temperature and modify the current-voltage characteristics

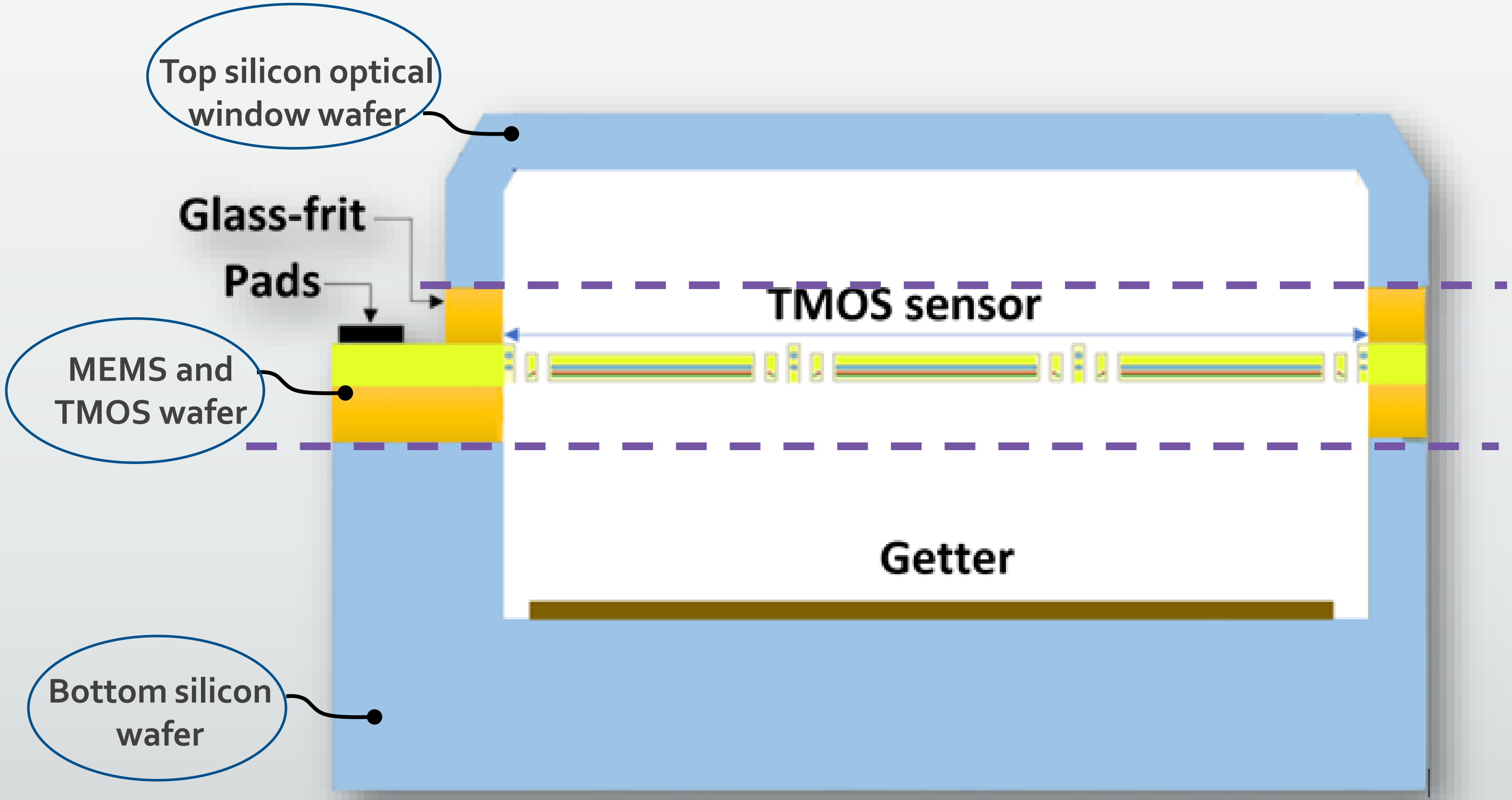
Transistor voltage detects temperature changes at subthreshold





WAFER LEVEL PROCESSING AND VACUUM PACKAGING

- Currently on 8-inch wafers and 0.13μm CMOS-SOI PROCESS
- 3 silicon wafers are bonded
- vacuum of 10^{-5} atm
- stable over 5 years



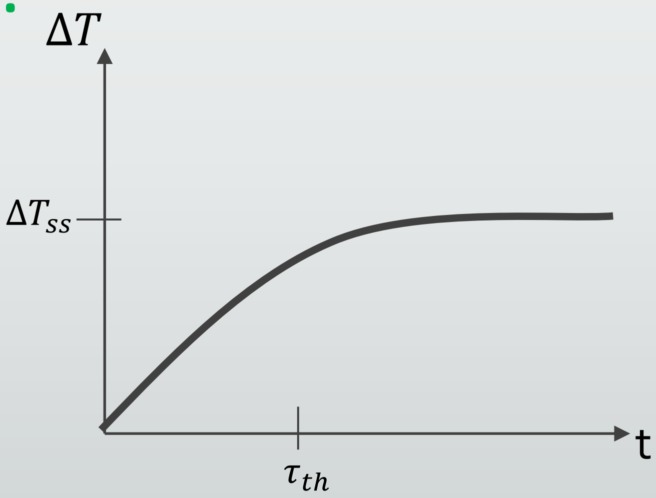
THE RESEARCH QUESTION

- **Residual pressure determines the thermal conductance - G_{th}**

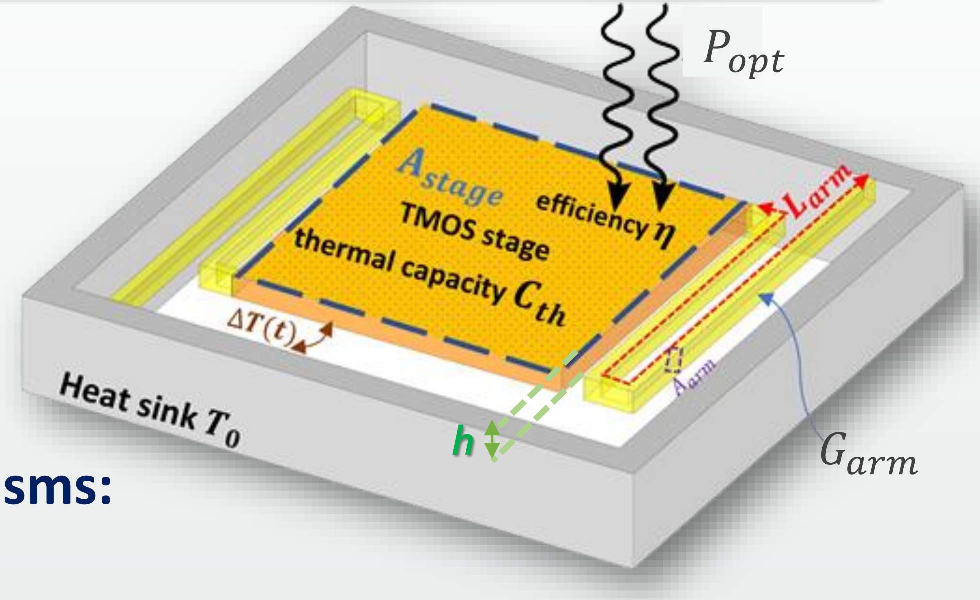
- **thermal time constant $\tau_{th} = \frac{C_{th}}{G_{th}}$**

- **What is the effect of the residual vacuum upon performance?**

- **What pressure is critical for the proper performance of the device?**



THERMAL MODELING OF THE PACKAGED TMOS SENSOR



- **The power balance equation:**

  $\eta P_{opt} = C_{th}\big(d\,(\Delta T(t))/d\,t\big) + G_{th}\Delta T(t)$

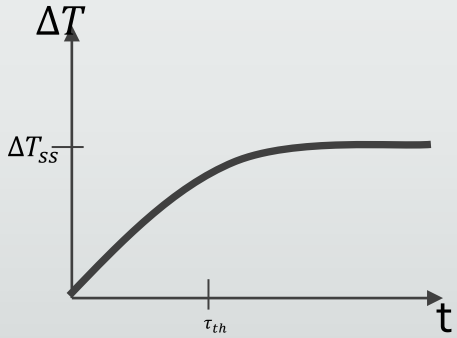
- **In steady-state:** $\Delta T_{ss} = \frac{\eta P_{opt}}{G_{th}}$

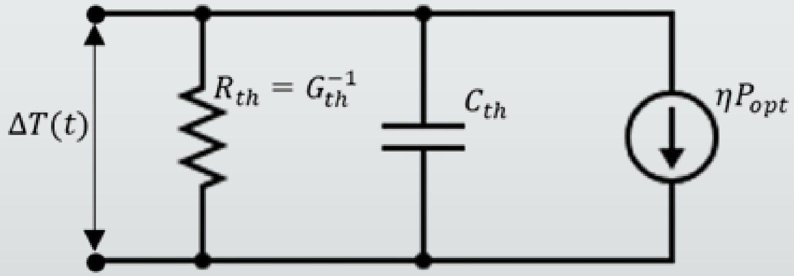
- **The thermal conductance is determined by three mechanisms:**

  $G_{th} = G_{solids} + G_{gas} + G_{radiation}$

- **The thermal capacitance:** $C_{th} = \rho c' A_{stage} h$

- **The thermal time constant:** $\tau_{th} = \frac{C_{th}}{G_{th}}$





$\boldsymbol{parameters\ and\ constants}: \rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] - \text{mass density}, \mathrm{c}'\left[\frac{\mathrm{J}}{\mathrm{kg}\cdot K}\right] - \text{specific heat capacitance}, \eta - optical\ efficiency, \mathrm{h} - \text{stage height [m]}$

THERMAL MODELING – SOLID CONDUCTION AND RADIATION

- **Body emits radiation according to its temperature:**

$$P_{rad} = \varepsilon\sigma A_{total} T_s^4 \approx \varepsilon\sigma\left(2\cdot A_{stage}\right)T_s^4$$

- **Hence, the thermal conductance due to thermal radiation:**

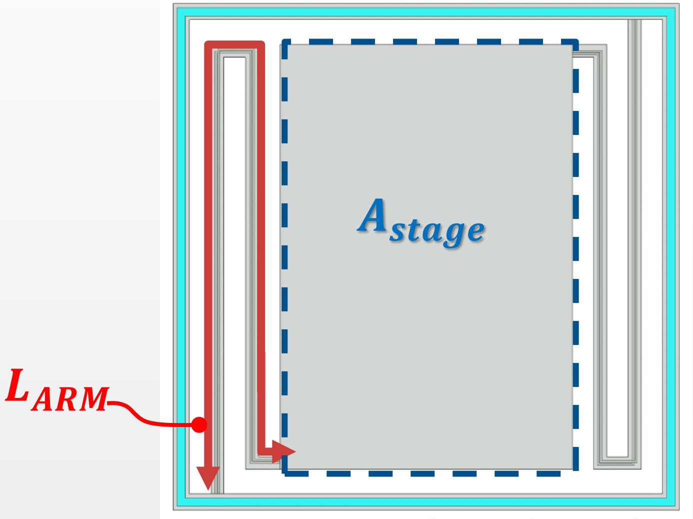
$$G_{rad} = d\,P_{rad}/d\,T \;= 8\varepsilon\sigma A_{stage} T_s^3$$

- The thermal conduction through a material is derived from Fourier law and equals to:

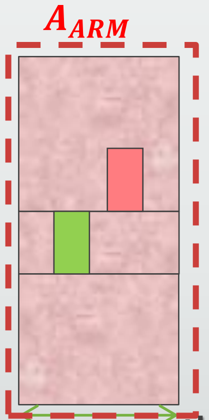
$$G = \frac{Q}{\Delta T\cdot\Delta t} = k\cdot\frac{A}{L}$$

- **For example, in our device, the thermal solid conduction is governed by the holding arm:**

$$G_{arm} = k_{arm}\cdot\frac{A_{arm}}{L_{arm}}$$



TMOS top view schematic



Arm cross-section

parameters and constants:

ε – body emmisivity, $\sigma = 5.67\cdot10^{-8}\left[\frac{W}{m^2\cdot K^4}\right]$ – Stefan–Boltzmann constant, $\mathrm{k}\left[\frac{\mathrm{W}}{\mathrm{m}\cdot K}\right]$ – thermal conductivity, $\mathrm{A_{stage}}$ – stage area$[\mathrm{m}^2]$, $\mathrm{L_{arm}}$ – arm length[m]

Q – *thermal energy* $[J]$, T – *temperature*$[K]$, t – *time*$[s]$, A – *area*, L – *length*$[m]$

THERMAL MODELING – GAS CONDUCTION AT HIGH PRESSURE

- **The thermal conductivity of gas at high pressure is independent on the pressure and equals to a constant for a given temperature (like solids):**

$$\boldsymbol{k_{high-pressure} = constant\left[\frac{W}{K\cdot m}\right]}$$

- **The thermal conductivity of the gas is given by:**

$$k_{gas} = \boldsymbol{\frac{1}{3}\rho c' v_{mol} \cdot l_{mfp}} = G_0'' \cdot \frac{p}{p_0} \cdot l_{mfp}\left[\frac{W}{K\cdot m}\right]$$

- **At high pressure where the collision distance between two gas molecules is much smaller than the device typical dimensions. Therefore, the mean-free-path is governed by the molecule collision distance**

- **In this case, at high pressure, the mean-free-path is proportional to the inverse number of molecules - $\boldsymbol{l_{mfp} \propto n^{-1}}$, and the pressure is proportional to the number of molecules - $\boldsymbol{p \propto n}$, where n is the number of molecule**

- **For air at high pressure, the value of k_{air} is well established and equals to $0.026\left[\frac{W}{m\cdot K}\right]$ at 300°[K]**

$\boldsymbol{constants\ and\ parameters}: p - pressure[Pa], \rho - mass\ density\left[\frac{kg}{m^3}\right], c' - specific\ thermal\ capacitance\left[\frac{J}{kg\cdot K}\right],$

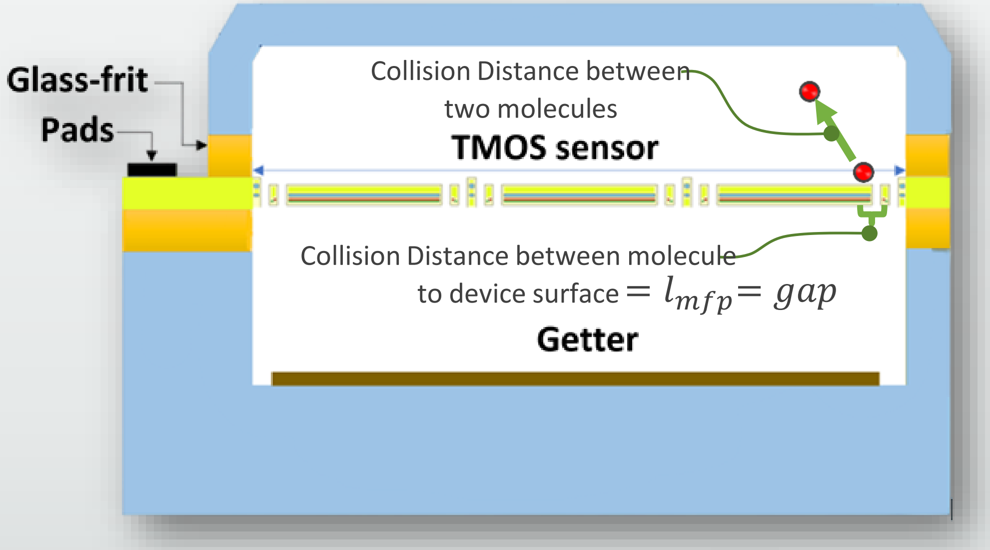
$v_{mol} - molecule\ velocity\left[\frac{m}{s}\right], l_{mfp}[m] - mean\ free\ path, G_0''\left[\frac{W}{K}\right] - normalized\ thermal\ conductance\ for\ p_0 = 1[Pa]$

THERMAL MODELING – GAS CONDUCTION AT LOW PRESSURE

- **The thermal conductivity by the gas is given by:**

$$k_{gas} = \frac{1}{3}\rho c' v_{mol} \cdot l_{mfp} = G_0'' \cdot \frac{p}{p_0} \cdot l_{mfp} \left[\frac{W}{K \cdot m}\right]$$

- **At low pressure where the collision distance between two gas molecules is much larger than the device typical dimensions. Therefore, the mean-free-path is governed by the device smallest typical dimension**



- **In this study, $l_{mfp} = gap = 3\mu m$ and $\frac{G_0''}{p_0} \approx 2$**

- Therefore: $k_{low-pressure} = 6 \cdot p \left[\frac{W}{m \cdot K}\right]$

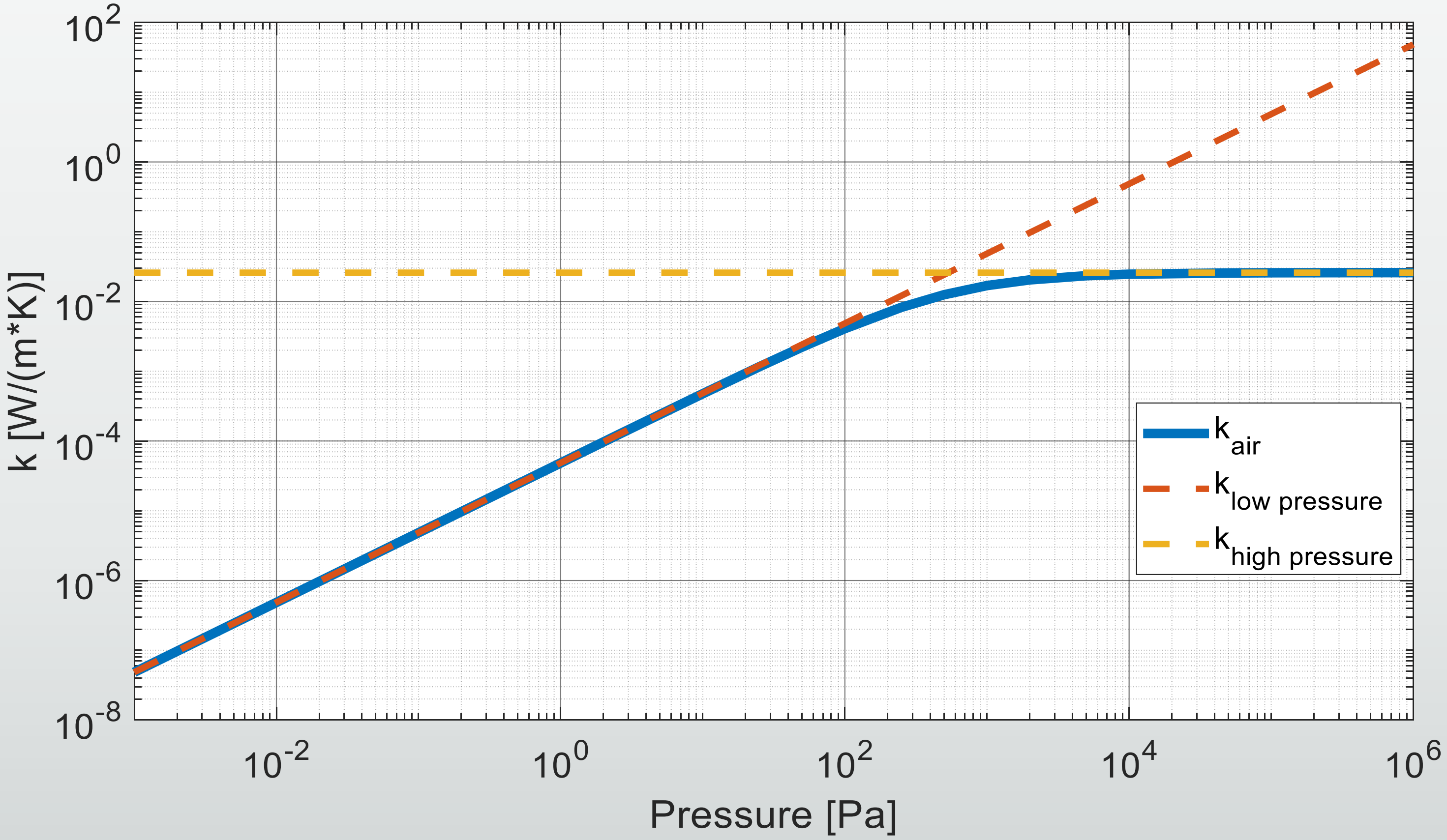
$\boldsymbol{constants\ and\ parameters}: p - pressure[Pa], \rho - mass\ density \left[\frac{kg}{m^3}\right], c' - specific\ thermal\ capacitance \left[\frac{J}{kg \cdot K}\right],$

$v_{mol} - molecule\ velocity \left[\frac{m}{s}\right], l_{mfp}[m] - mean\ free\ path, G_0'' \left[\frac{W}{K}\right] - normalized\ thermal\ conductance\ for\ p_0 = 1[Pa]$

THERMAL MODELING – GAS CONDUCTION AT INTERMIDATE PRESSURE

- At intermediate pressure, the thermal conductivity is given by the parallel combined of the both mechanisms:

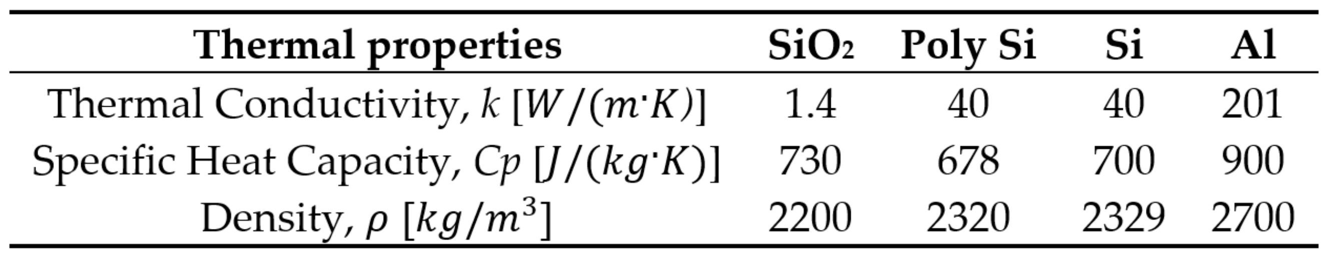
$$\frac{1}{k_{gas}} = \frac{1}{k_{high-pressure}} + \frac{1}{k_{low-pressure}}$$



THERMAL MODELING - SUMMARY

- **The holding arm conduction does not depend on pressure**

- **Typical CMOS-SOI thermal properties required for thermal simulation:**



Thermal properties	**SiO_2**	**Poly Si**	**Si**	**Al**
Thermal Conductivity, k $[W/(m{\cdot}K)]$	1.4	40	40	201
Specific Heat Capacity, Cp $[J/(kg{\cdot}K)]$	730	678	700	900
Density, ρ $[kg/m^3]$	2200	2320	2329	2700

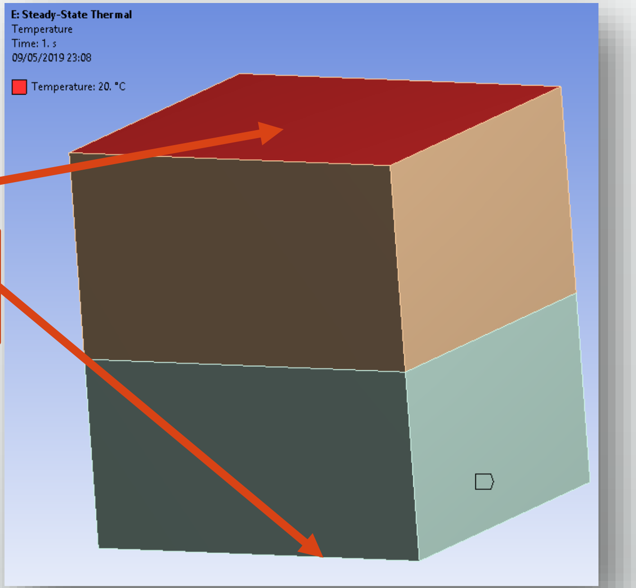
- **Air conduction is governed by two mechanisms: at low pressure and high pressure**

- **This study evaluates this pressure impact on the thermal conductance of the packaged device**

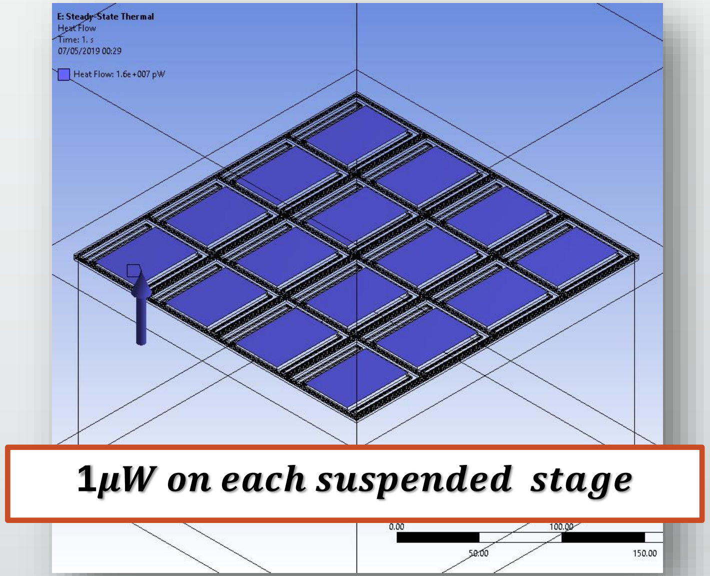
- **The air thermal properties calculated by the ideal gas law and by the method showed in the previous slides**

THERMAL MODELING – BOUNDARY CONDITIONS

- 3D model of the device was generated in FEA software
- Materials thermal properties were assigned
- Applying boundary conditions to our packaged model:



Constant temperature of $20^{0}[C]$ on the outer package



$1\mu W$ *on each suspended stage*

- Simulations for wide pressure range values were performed

MEASUREMENT AND SIMULATIONS RESULTS OF τ_{th} AND G_{th}

Steady-state thermal simulations yield the increase of the sensors temperature:

$$\Delta T$$

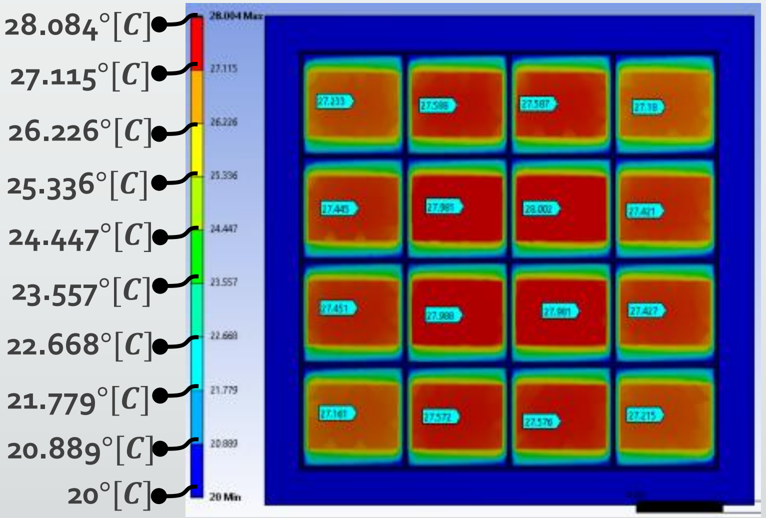
The thermal conductance obtained from the heat balance equation:

$$G_{th} = \frac{P}{\Delta T}$$

The thermal time constant can be obtained by transient simulation or can be evaluated by:

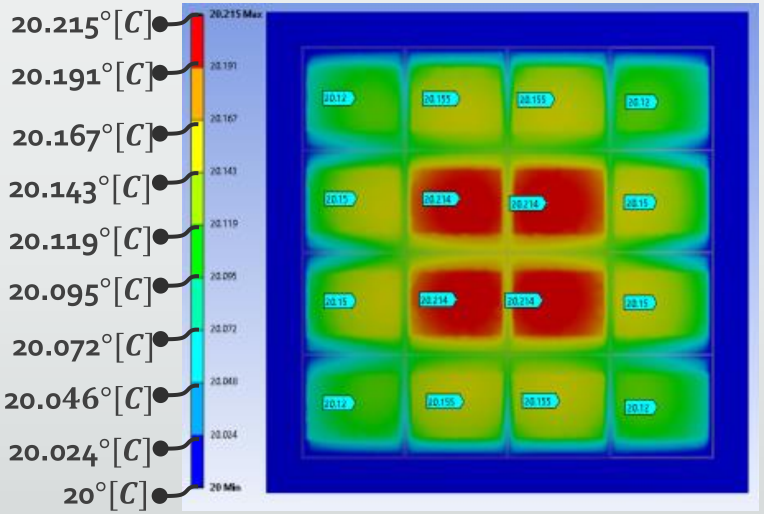
$$\tau_{th} = \frac{C_{th}}{G_{th}}$$

- There is no simple way to measure the temperature of the physical device
- Best way to measure or evaluate the thermal performance of the device is by measure the thermal time constant



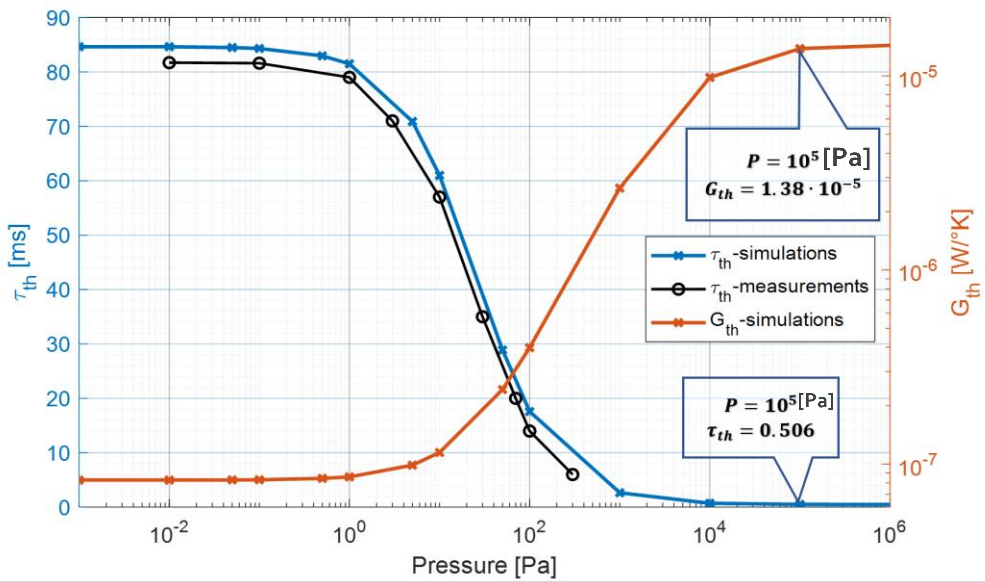
$p = 2.5[Pa]$

$tempetature\ range\!: \ 20° - 28°[C]$



$p = 10^5[Pa]$

$tempetature\ range\!: \ 20° - 20.215°[C]$



$P = 10^5$[Pa]
$G_{th} = 1.38 \cdot 10^{-5}$

$P = 10^5$[Pa]
$\tau_{th} = 0.506$

CONCLUSIONS

- **With this modeling the optimal pressure may be selected**
- **Highest performance devices require residual pressure of few pascals**
- **The modeled, simulated and measured thermal time constant are in good agreement**

ACKNOWLEDGMENTS

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- **The devices were fabricated and packaged at ST Microelctronics. The excellent work of all the engineers supporting this work is highly appreciated**