Bottom-Up Life-Cycle Assessment of MEMS Piezoresistive Pressure Sensors

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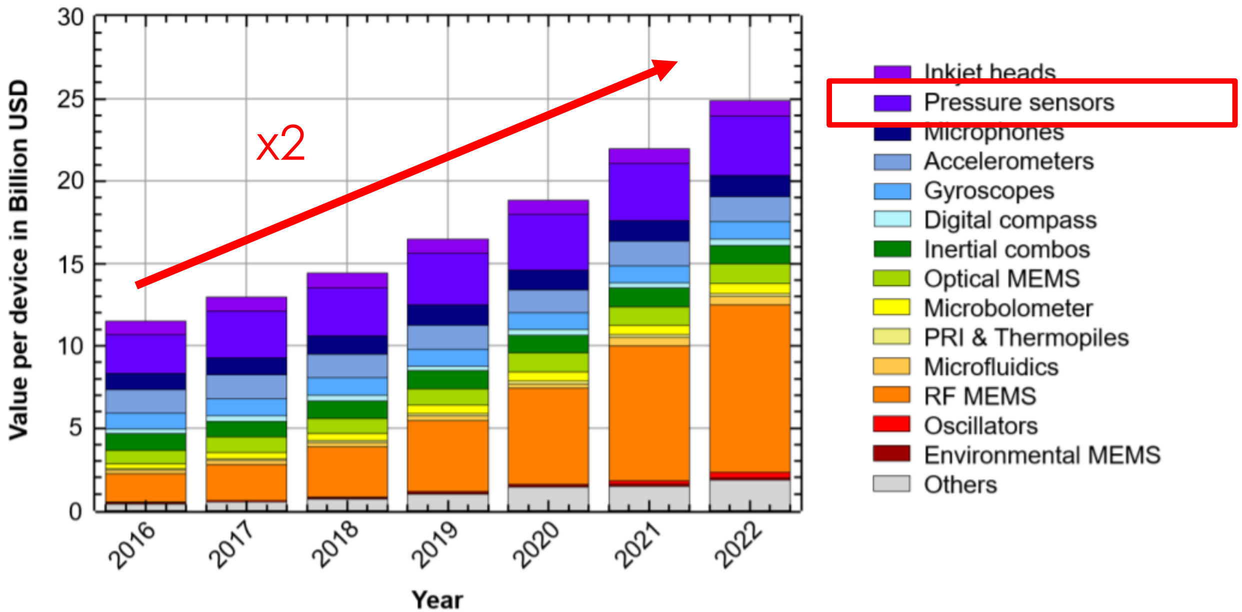
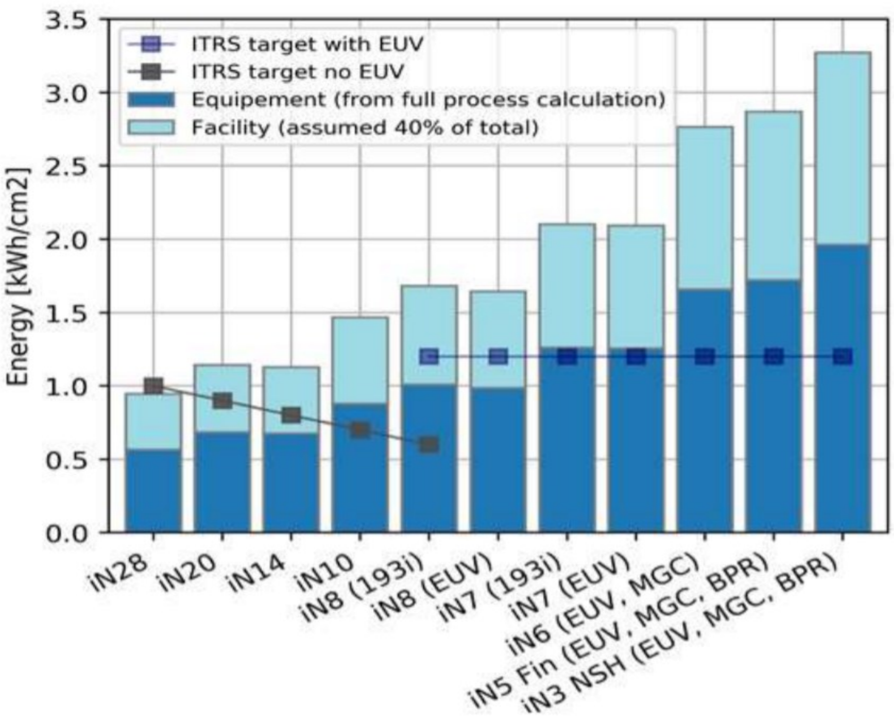
Introduction

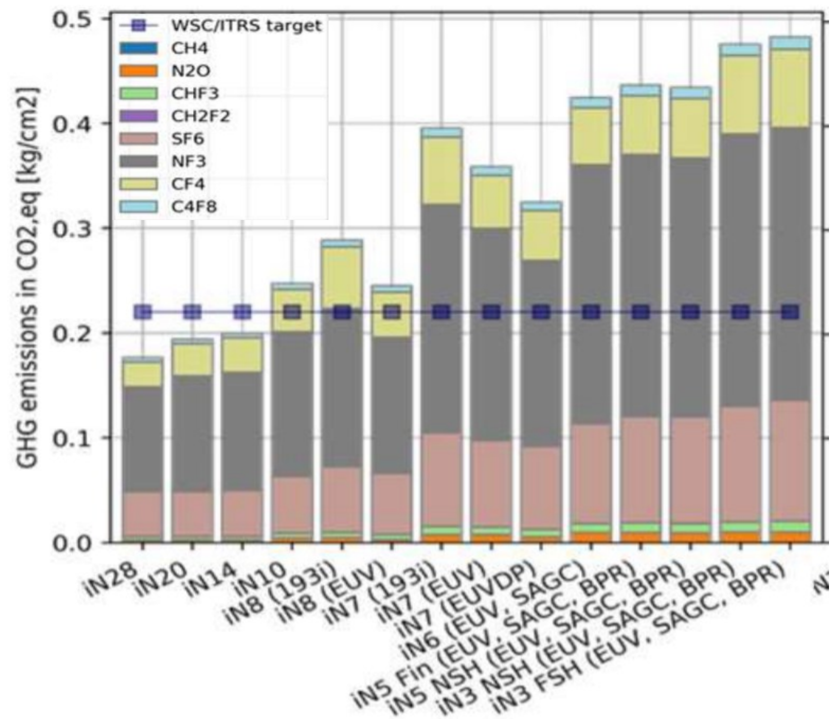
- MEMS Market should rise tremendously [1]



Pressure sensors should have been the biggest part until 2018

Introduction





We need to be careful because advanced technologies often come with increased Energy Demand and GHG emissions: for example CMOS [2]

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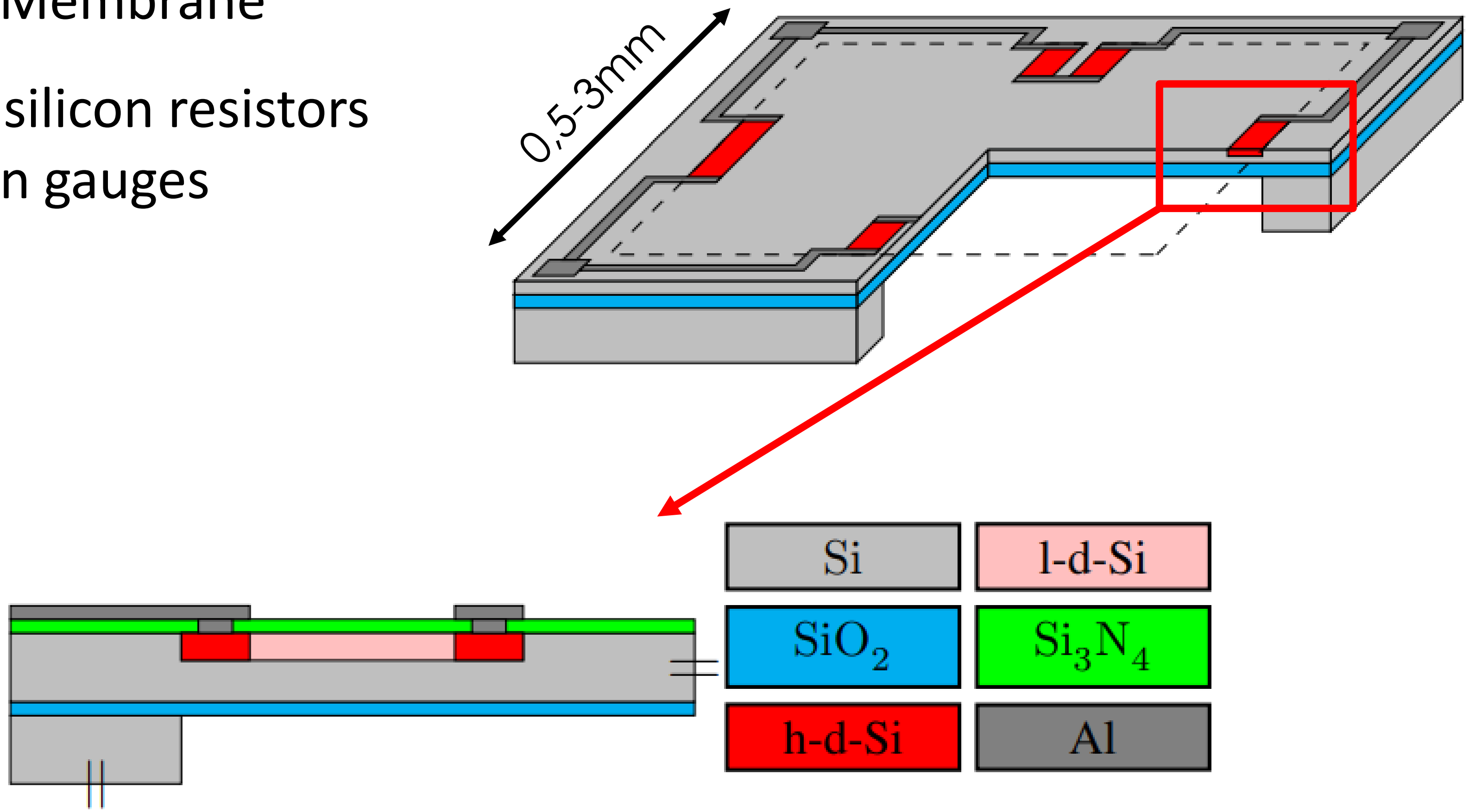
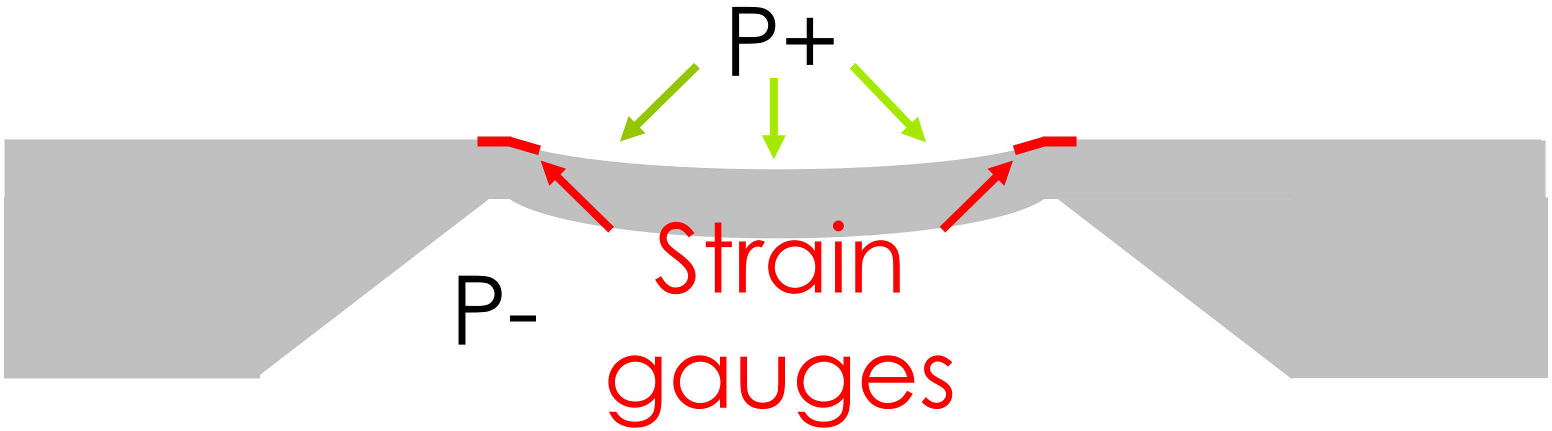
MEMS Piezoresistive pressure sensor: Principles and Process flows

Working principle

- Silicon Membrane
- Doped silicon resistors as strain gauges

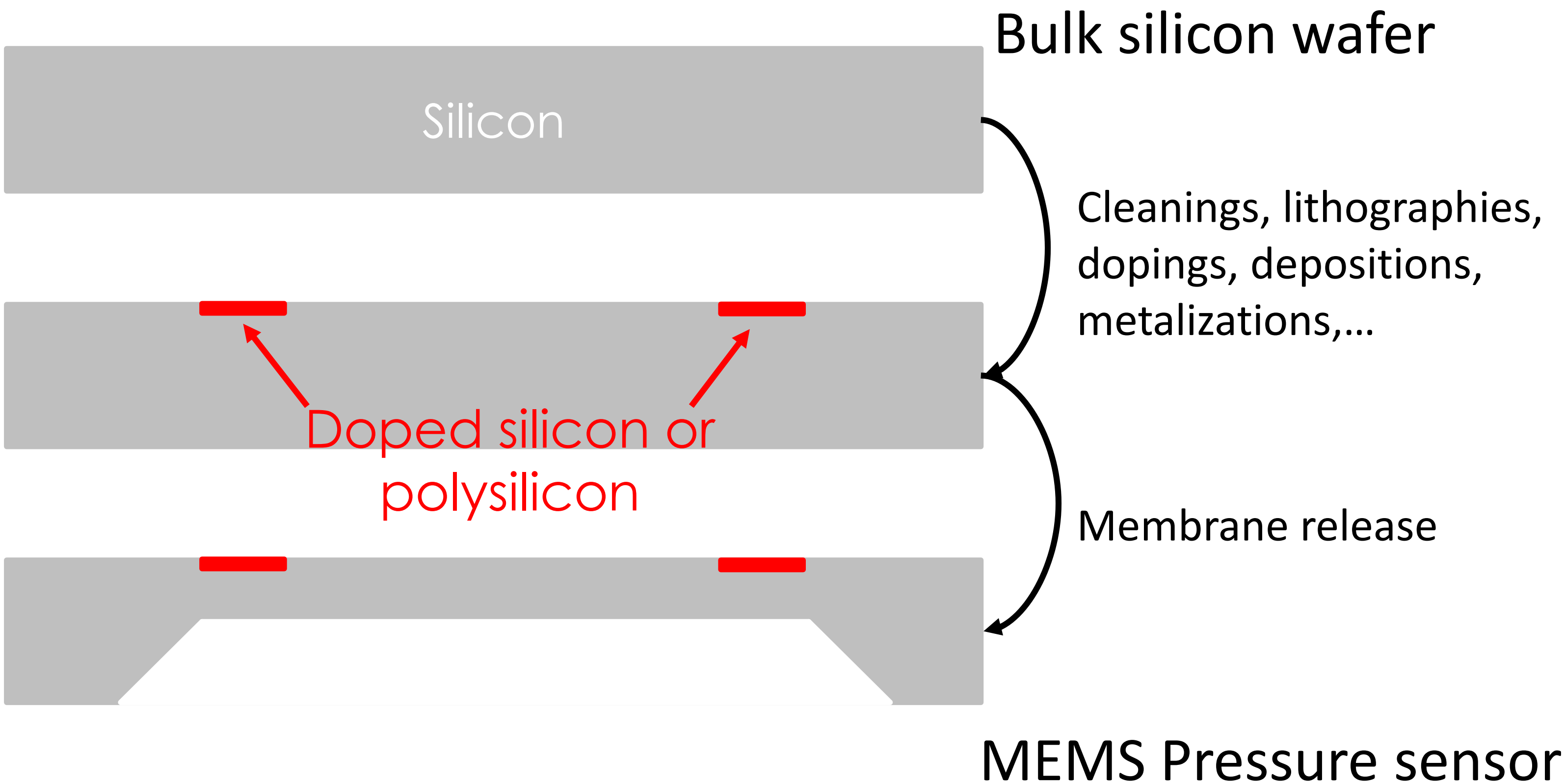


Working principle



- Differential pressure sensing
- Variable resistors as strain gauges

Basis of process flows



Basis of process flows

Membrane released by anisotropic wet etching (KOH, TMAH)

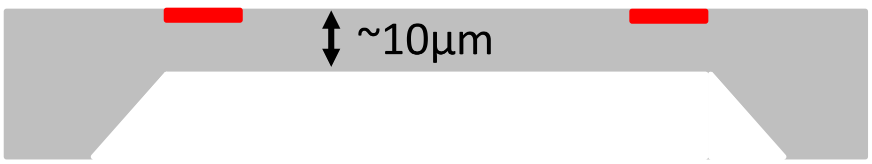
Membrane released by anisotropic dry etching (SF_6 - DRIE)

- Reduced Area thanks to no slope side walls

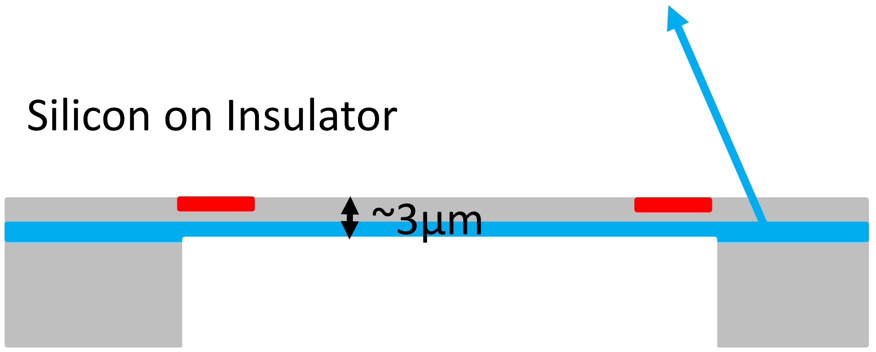
Basis of process flows

Burried oxide layer (BOX)

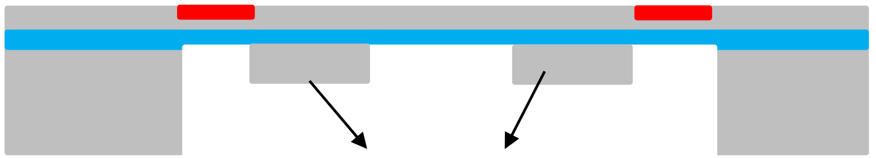
Bulk silicon



Silicon on Insulator



Silicon on Insulator with patterning



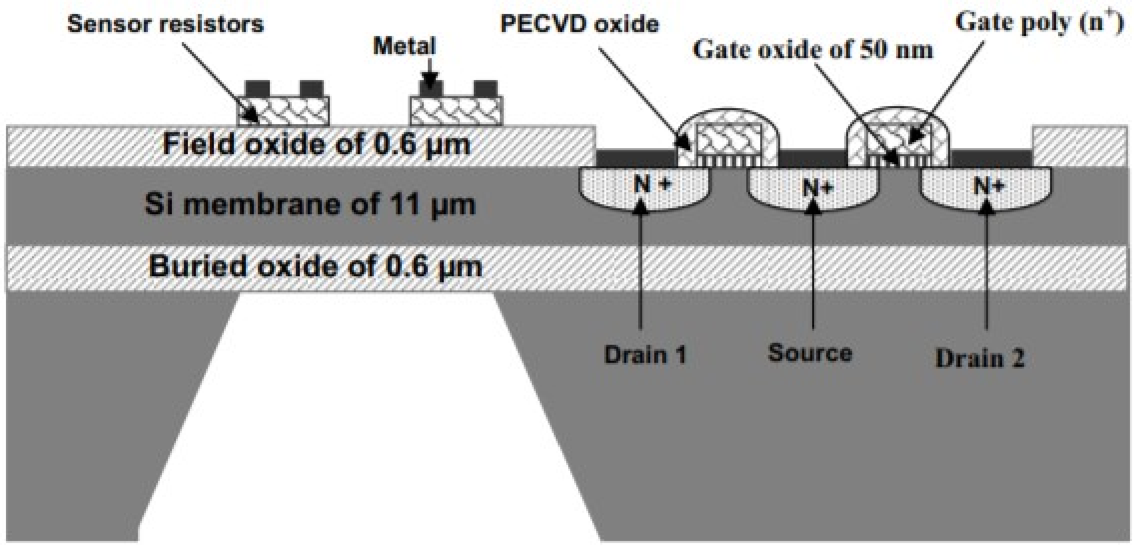
Stress concentrators

<u>SOI :</u>

- Reduced membrane thickness
- High precision membrane patterning

Case studies

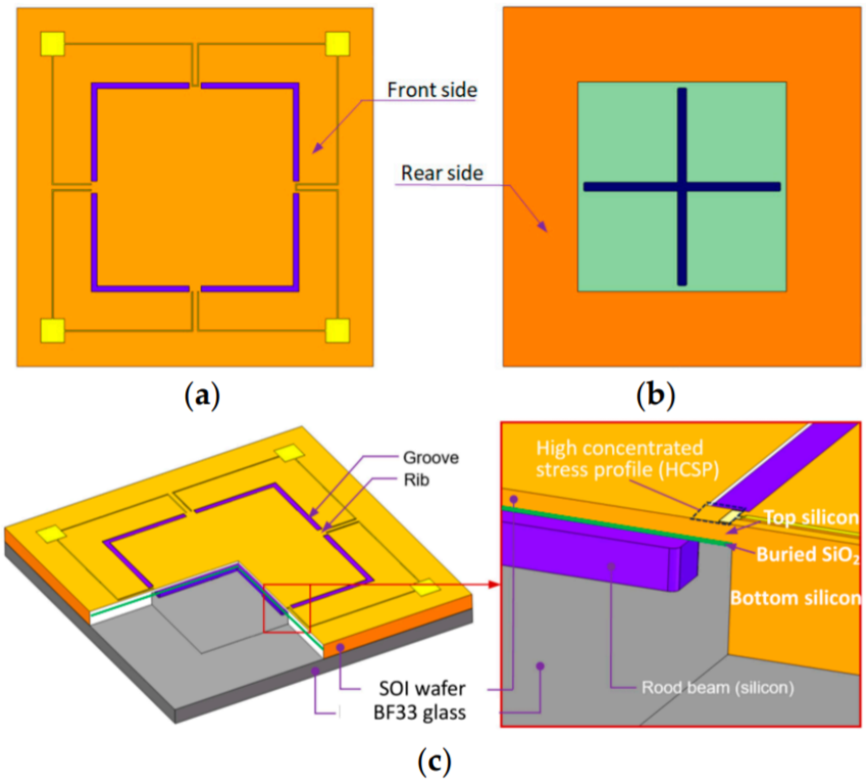
1) Kumar *et al.* (2006) [3]



- SOI substrate
- Membrane released by wet etching

Case studies

2) Li *et al.* (2018) [4]



- SOI substrate
- Membrane released by dry etching

Piezoresistive pressure sensor: Bottom-Up Life-Cycle Assessment

LCA : objectives

Quantifiying :

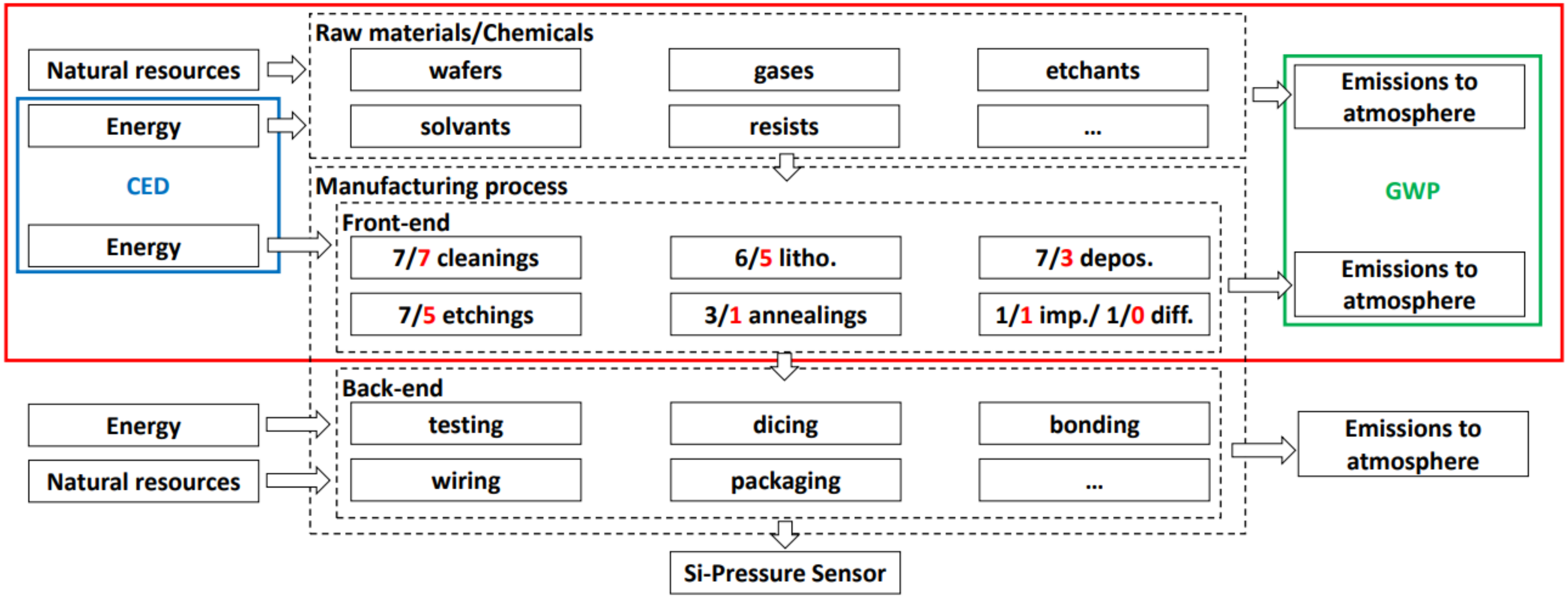
- Cumulated primary Energy Demand (CED): Energy needed during the MEMS pressure sensors manufacturing.

- Global Warming Potential (GWP): Global Warming Potential of the greenhouse gases emitted during the MEMS pressure sensors manufacturing.

LCA : Method

Perimeter of the study

From cradle to front-end process



UCLouvain icteam

LCA : Method

Inventory model [5]

- For CED:

Raw material flows [kg]

Chemical flows [kg]

Energy associated with electricity use [kWh]

$$CED = CED_{mat} + CED_{proc} = \sum [m_{mat} \times e] + \sum [(m_{chem} \times e) + e_{proc}]$$

Raw material energy intensities [kWh/kg]

Chemicals energy intensities [kWh/kg]

- Idem for GWP

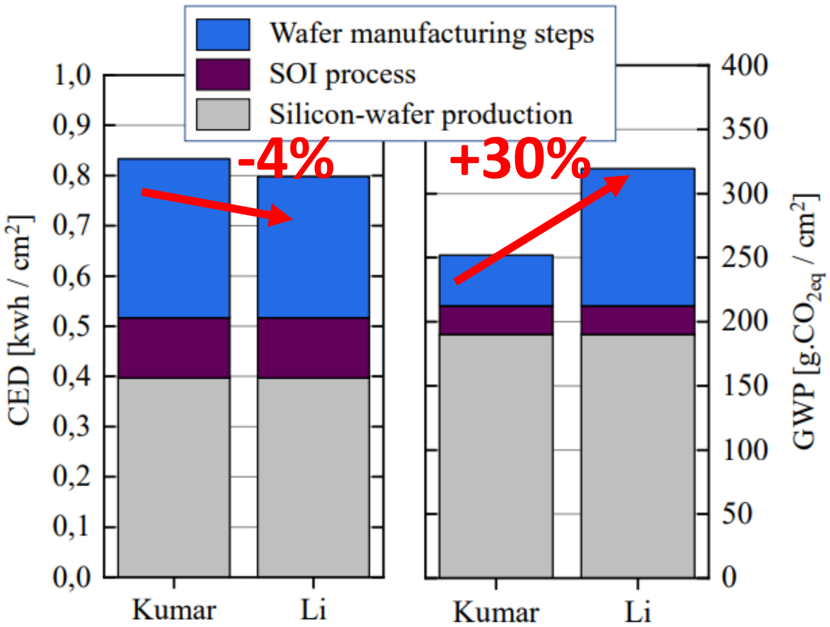
Data come from previously generated life-cycle inventories for CMOS processes [2,6-7]

LCA : Main results

- Major contribution in CED and GWP is coming from the silicon wafer production
- Impact of SOI versus bulk silicon:

  ~20% CED increase

  ~10% GWP increase (only for the wafer)

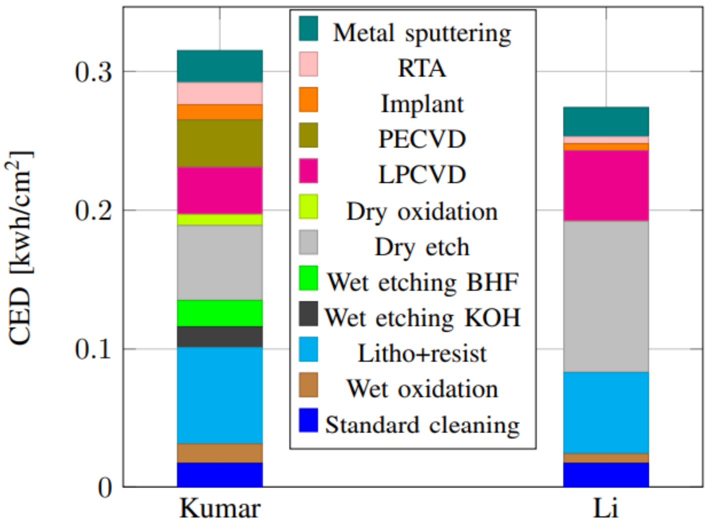


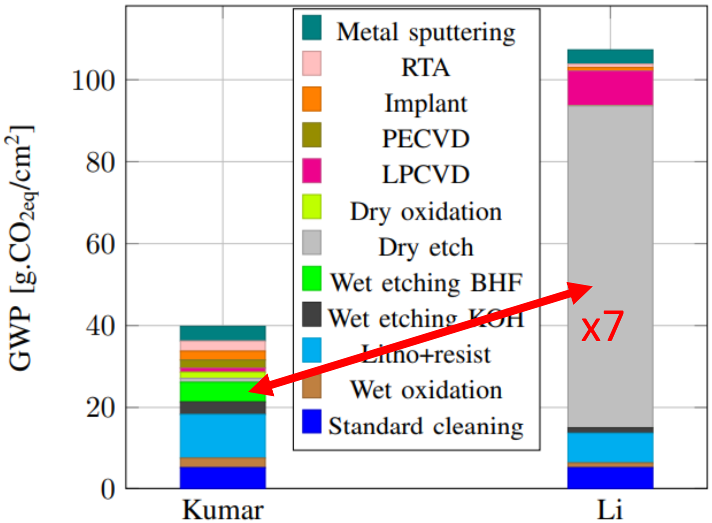
LCA : Main results

- About process steps : dry etchings have a huge amount of GWP

- Impact of dry etching versus wet etching:

  ~ GWP multiplied by 7 for membrane release step, mainly due to SF_6 released in the atmosphere (90% abatement)



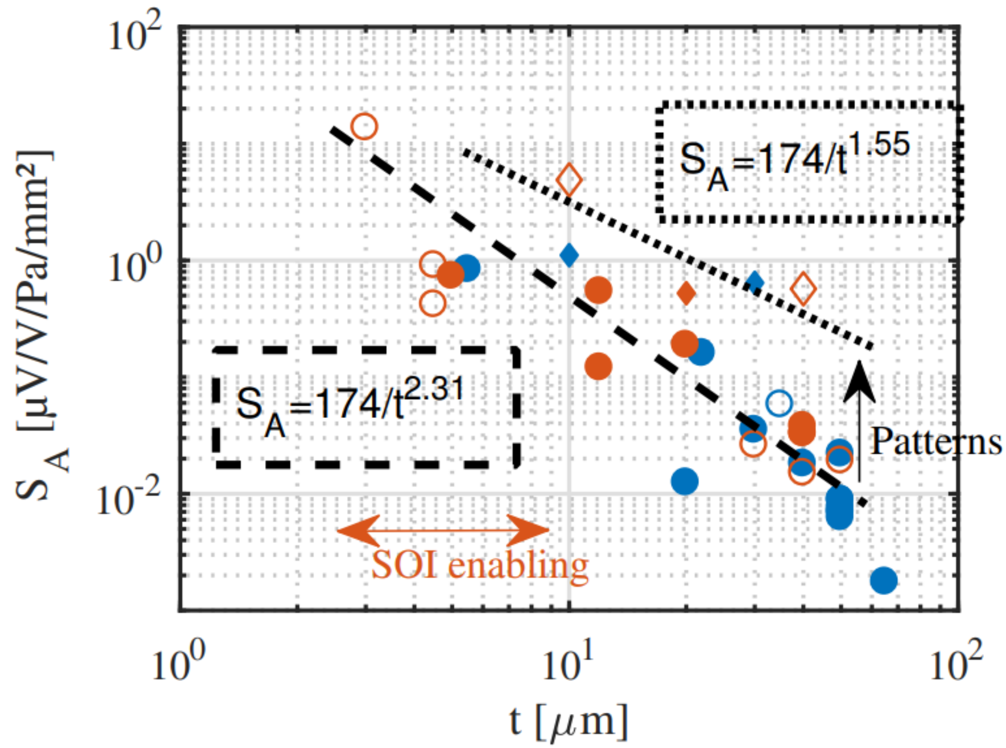


MEMS Piezoresistive pressure sensor: Impacts versus Performances

Mechnical figure of merit (FoM): S_A

S_A = Sensitivity divided by membrane area [8]

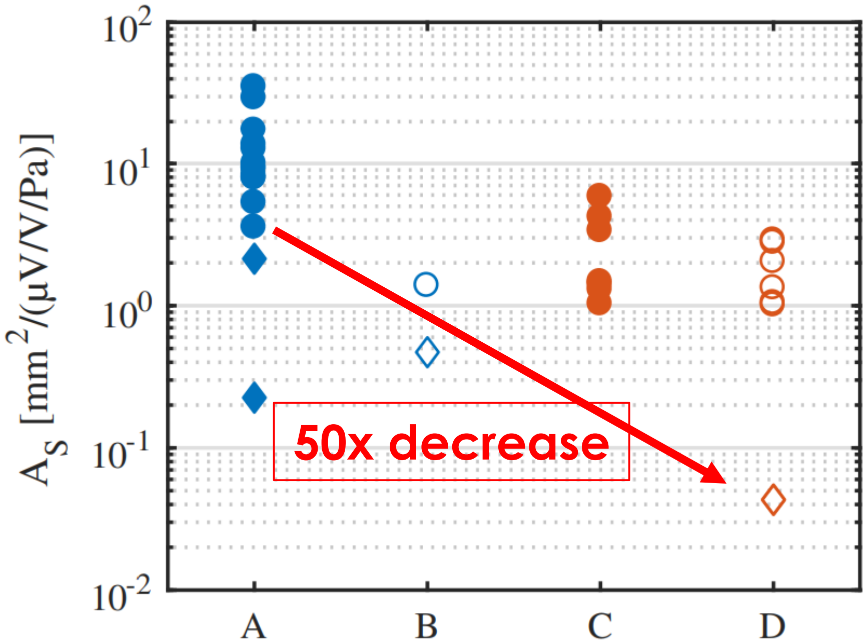
- SOI + dry etching (empty symbols) allow for reaching finner membranes (down to 3 µm)
- Membrane patterning allows a 6-fold increase of the Mechanical FoM at 10µm



Area needed versus Sensitivity

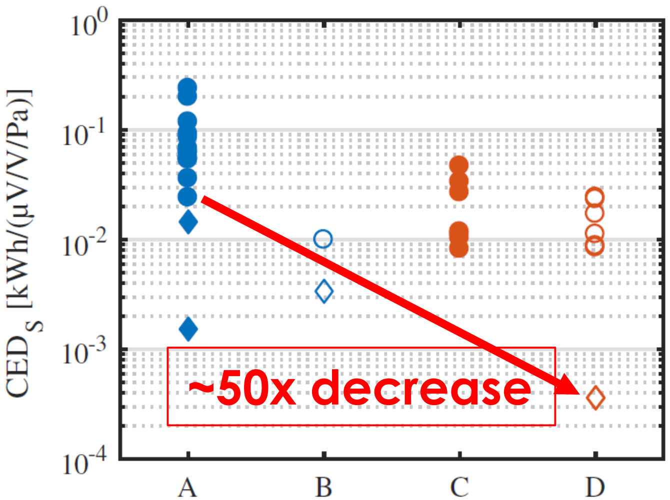
- By normalization regarding to the membrane thickness, we found the best performances achievable depending on technology mix.

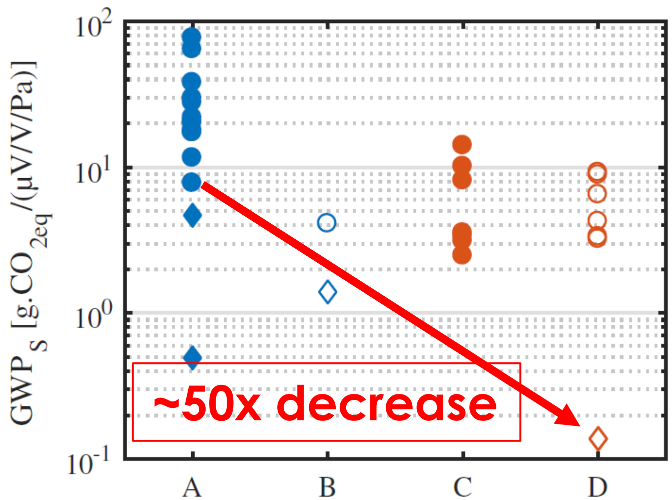
- Going from bulk-silicon, with membrane release by wet etching, to SOI with membrane released by dry etching with patterning allows for a 50-fold reduction of area needed per sensitivity units.



CED and GWP versus Sensitivity

- Improvement of S_A thanks to SOI, dry etching and membrane patterning is way bigger than the increase in CED and GWP, that become marginal.





Conclusions (1)

- IMPACTS:
  - Major impacts in CED and GWP are coming from the substrate
  - Increase of 20% and 10% of the substrate CED and GWP due to SOI substrate.
  - Multiplication by 7 of the release step GWP due to dry etching.
- IMPACTS vs PERFOMANCES:
  - A 50-fold reduction of area needed per sensitivity units, thanks to SOI susbtrate, dry etching and membrane patterning.
  - Perfomances improvement supplants by far impacts increases.

Conclusions (2)

- Imrovement tracks:
  - Investigation about an low-GWP alternative to SF_6 for silicon dry etching to reduce release step GWP.
  - Analysis of Yield reduction versus wafer thickness reduction to reduce substrate impacts.

Acknowledgements

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References

[1] C. Troadec, “MEMS, Sensors and Actuators Industry trends,” Kaoshiung, Taiwan, Jun. 2017. [Online].

[2] M. Garcia Bardon, P Wuytens, L-˚A Ragnarsson, G Mirabelli, D Jang, G Willems, A Mallik, A Spessot, J Ryckaert and B Parvais, ”DTCO including Sustainability: Power-Performance-Area-Cost-Environmental score (PPACE) Analysis for Logic Technologies”, IEDM, 2020.

[3] V. V. Kumar et al., ”Process optimization for monolithic integration of piezoresistive pressure sensor and MOSFET amplifier with SOI approach”, J. Phys. Conf. Ser., vol. 34, no. 1, pp. 210, Apr. 2006.

[4] C. Li, J. Xie, F. Cordovilla, J. Zhou, R. Jagdheesh and J. L. Ocãna, ”Design fabrication and characterization of an annularly grooved membrane combined with rood beam piezoresistive pressure sensor for low pressure measurements”, Sens. Actuators A Phys., vol. 279, pp. 525-536, Aug. 2018.

[5] G. Le Brun and J.-P. Raskin, ”Material and manufacturing process selection for electronics eco-design: Case study on paper-based water quality sensors,” Procedia CIRP, vol. 90, pp. 344-349, 2020.

[6] S. Boyd, ”Life-Cycle Assessment of Semiconductors,” New York:Springer, 2011.

[7] N. Krishnan, S. Boyd, A. Somani, S. Raoux, D. Clark and D. Dornfeld, ”A hybrid life cycle inventory of nano-scale semiconductor manufacturing”, Environ. Sci. Technol., vol. 42, no. 8, pp. 3069-3075, Apr. 2008.

[8] T. P. Delhaye, N. Andr´e, L. A. Francis and D. Flandre, ”New Universal Figure of Merit for Embedded Si Piezoresistive Pressure Sensors,” in IEEE Sensors Journal, vol. 21, no. 1, pp. 213-221, 1 Jan.1, 2021, doi:10.1109/JSEN.2020.3013017.