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Silicon to Software™

Modeling Material Plastic and Viscous Flow Effects in TSV-middle and Backside TSV-last Processes

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14th International Conference on Reliability and Stress-Related Phenomena in Nanoelectronics – Experiment and Simulation

Agenda

- Introduction
- Material model characterization
- TSV stress effects on performance and reliability
- Summary

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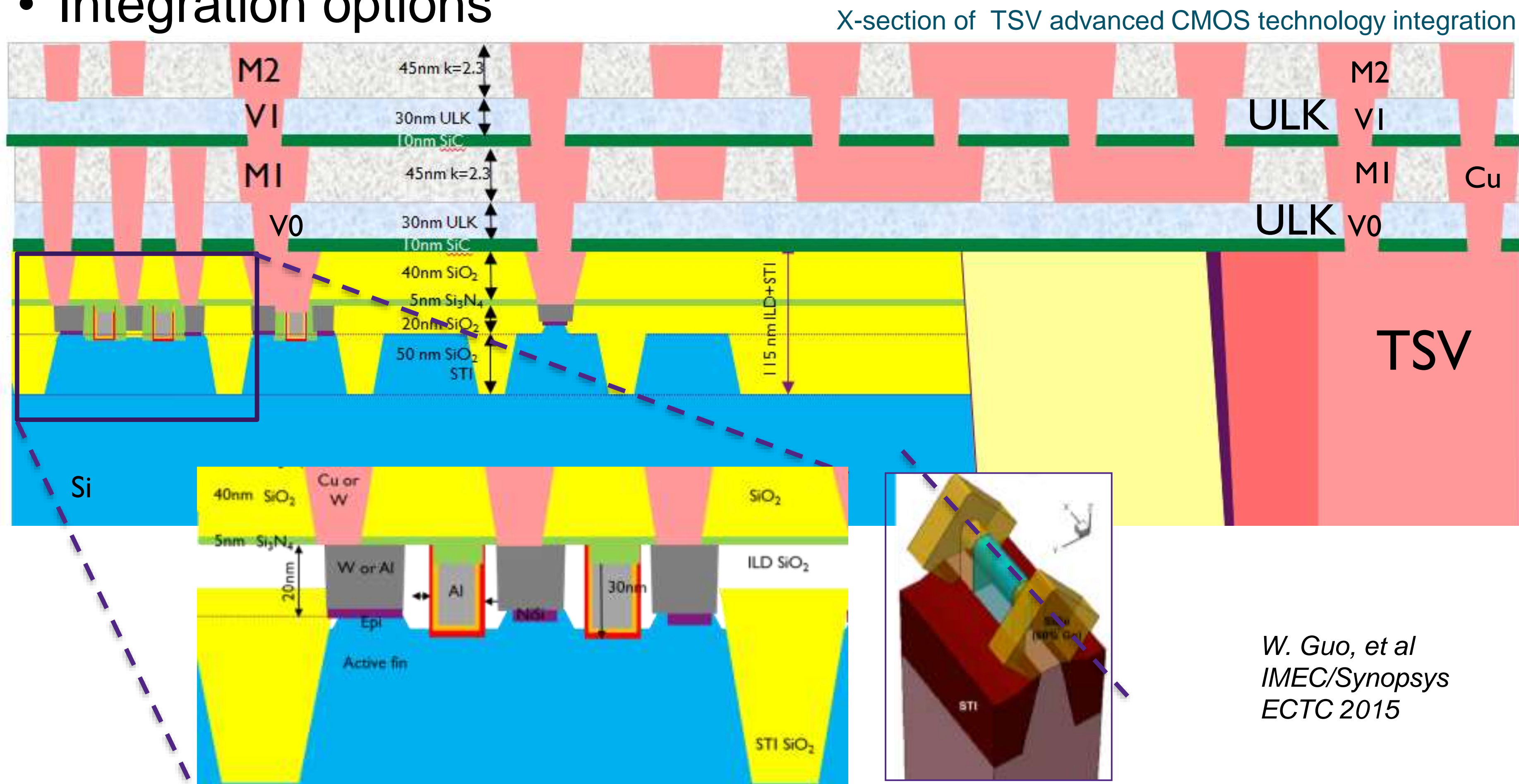
Introduction: TSV integration

- 3D IC with TSV: provides high integration density; allows heterogeneous integration, improves system performance
- Integration options

X-section of TSV advanced CMOS technology integration



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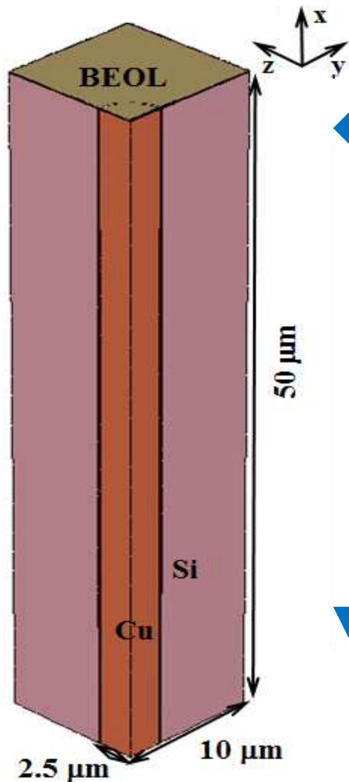
TSV-middle Integration Sample Flow

- TSV-middle: via processed after FEOL and before BEOL
- High thermal budget is expected

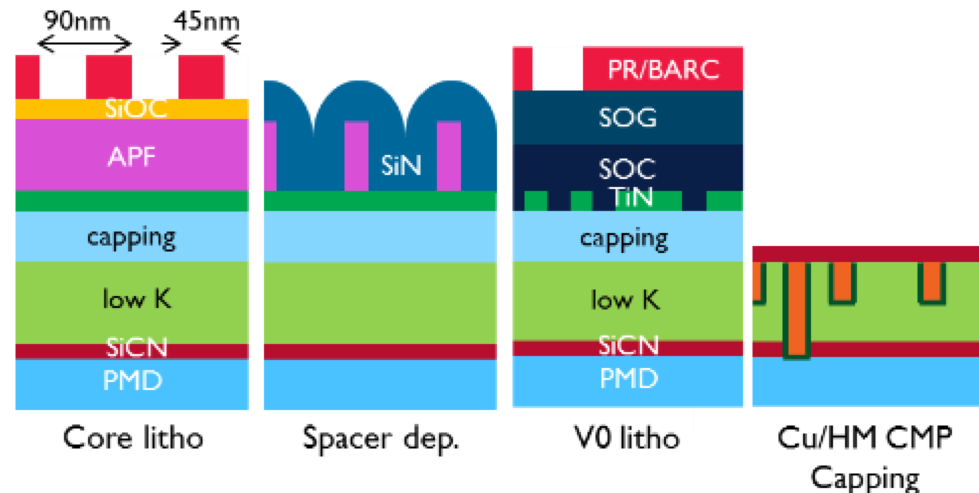


TSV-middle process

FEOL process
TSV etching
TSV liner/Barrier
TSV platting
420°C 1h annealing
TSV CMP
BEOL process
……
Backside process
Stacking

BEOL process

350°C SiCN Dep.
320°C ULK Dep.
400°C UV Cure
400°C APF Dep.
350°C SiOC/DARC Dep.
400°C SiN Dep.
……



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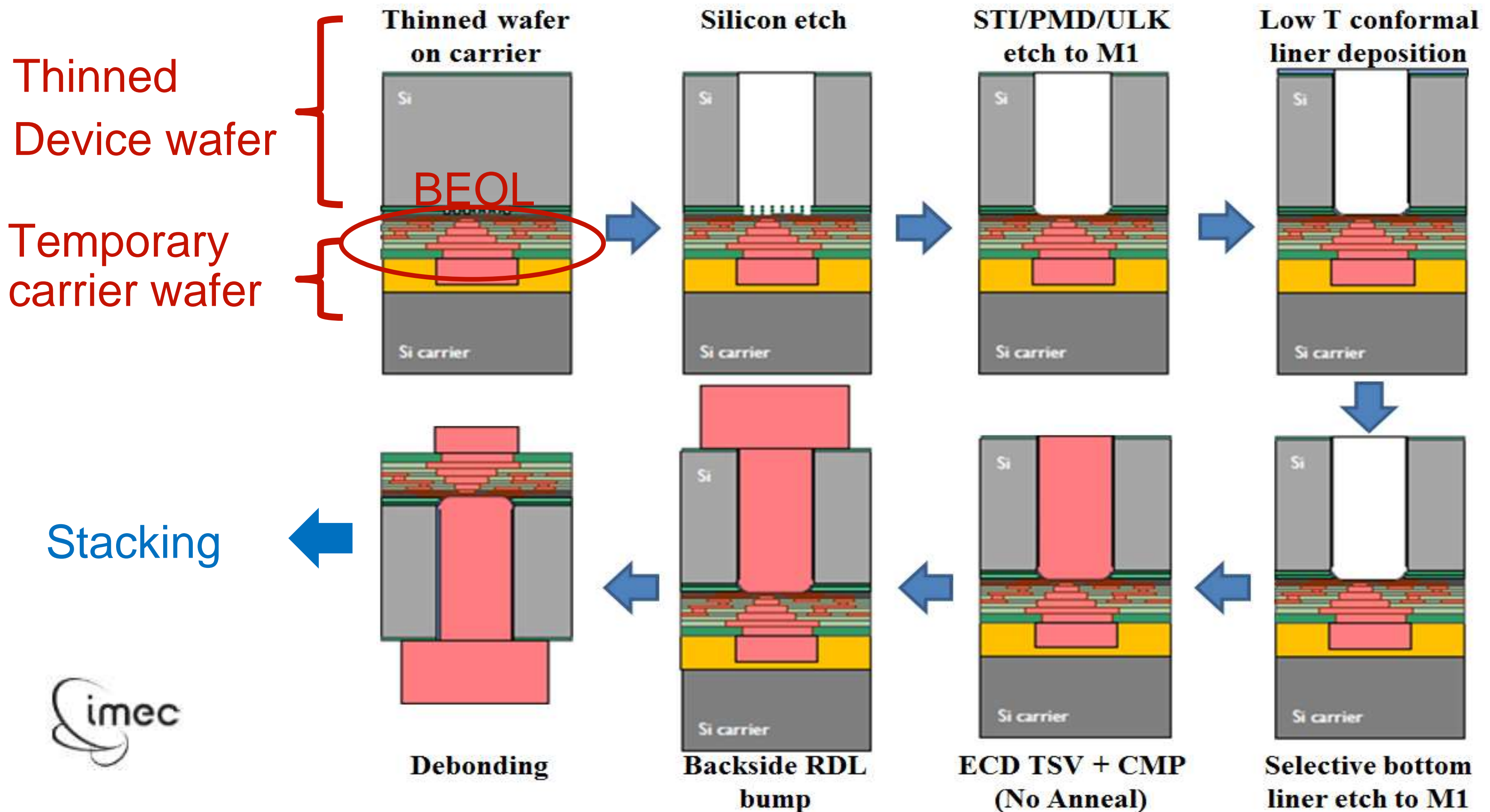
TSV-last Integration Sample Flow

- TSV-last: via processed after FEOL and BEOL
- No high T budget is expected



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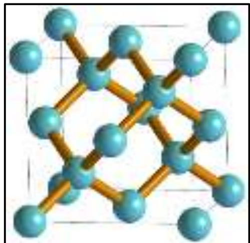
Material Options

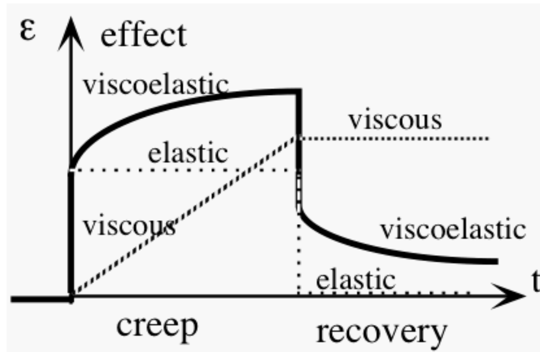
M2
V1
M1
V0
45nm k=2.3
30nm ULK
10nm SiC
45nm k=2.3
30nm ULK
10nm SiC
40nm SiO_2
5nm Si_3N_4
20nm SiO_2
50 nm SiO_2
STI
115 nm ILD+STI
ULK
ULK
M2
V1
M1
V0
TSV

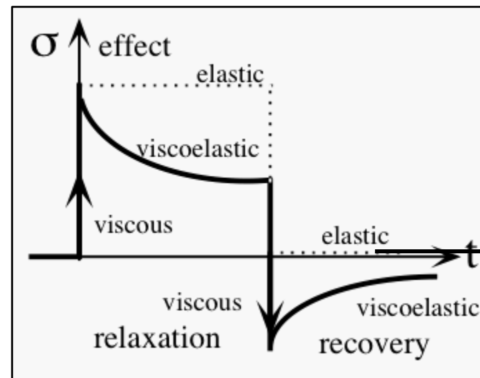
Silicon: anisotropic elasticity

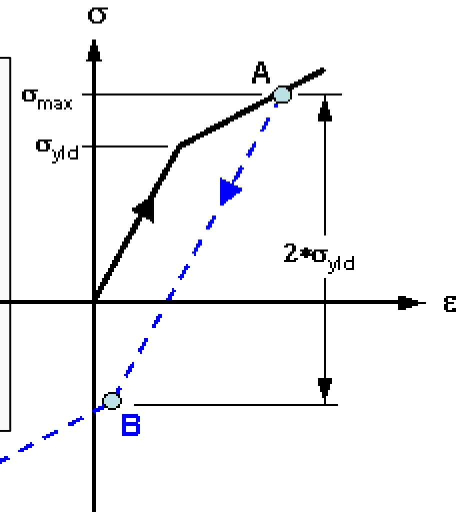
Liner: visco-elasticity

Copper: elastic-plasticity









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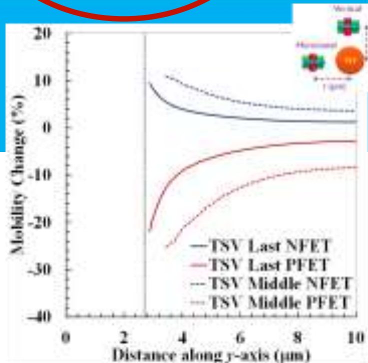
TSV Integration Considerations

M2
V1
M1
V0
45nm k=2.3
30nm ULK
10nm SiC
45nm k=2.3
30nm ULK
10nm SiC
40nm SiO_2
5nm Si_3N_4
20nm SiO_2
50 nm SiO_2
STI
115 nm ILD+STI
ULK
M2
V1
M1
ULK
V0
TSV



FEOL performance

BEOL performance and reliability

Source: GlobalFoundries, ECTC 2015

- How TSV integration process and material options affect FEOL and BEOL
- Capabilities for analysis and optimization

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Agenda

Introduction

Material model characterization

TSV stress effects on performance and reliability

Summary

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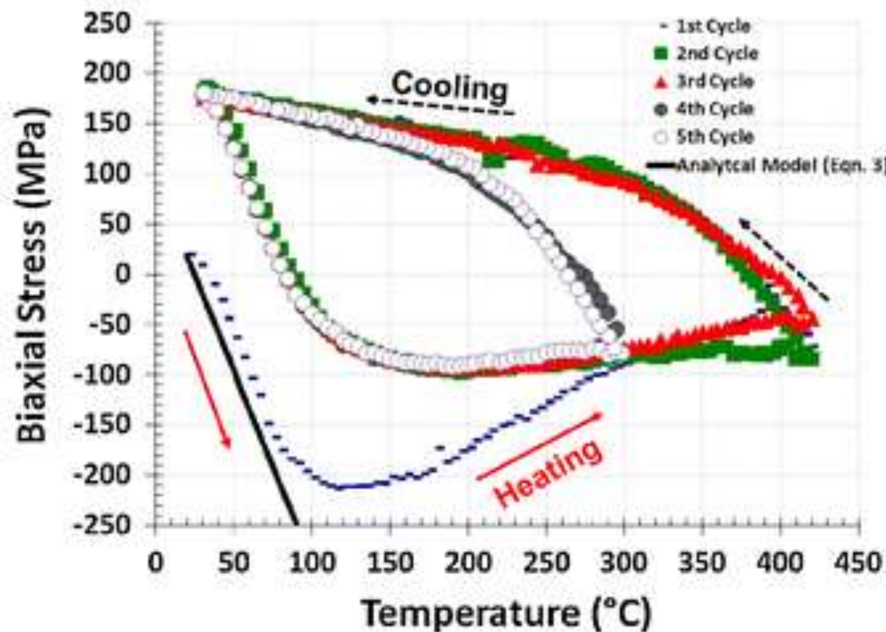
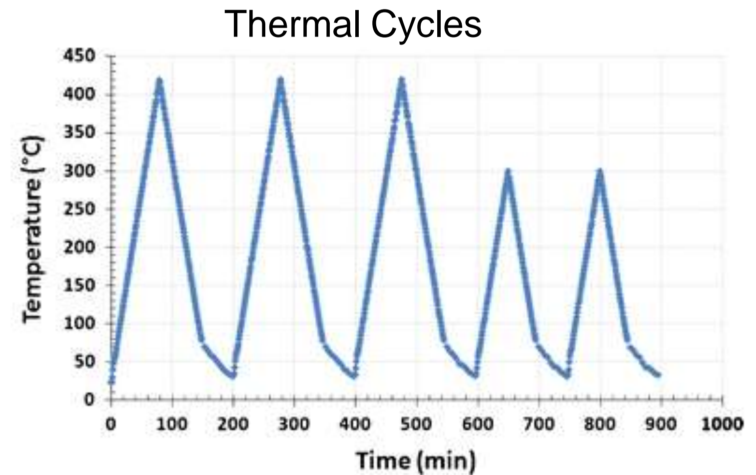
Copper Elastic-Plasticity Behavior

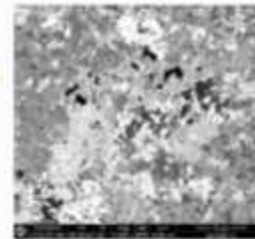
- Experimental Biaxial stress response of Cu film under thermal cycling



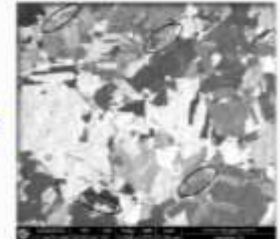


C. Okoro, et al., "Impact of the electrodeposition chemistry used for TSV filling on the microstructural and thermo-mechanical response of Cu," *Journal of Materials Science*, vol. 46, no. 11, pp. 3868 - 3882, June 2011.

As deposited Cu film



After sintering temperature cycling



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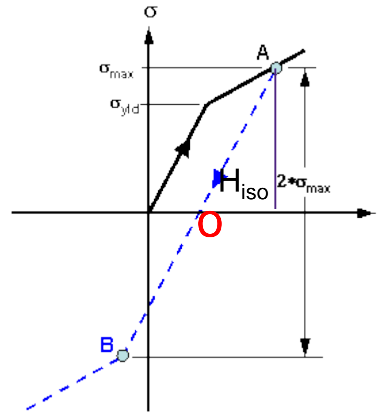
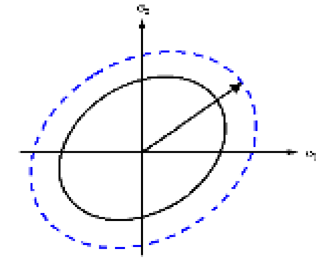
Nonlinear Plasticity with Isotropic and Kinematic Hardening

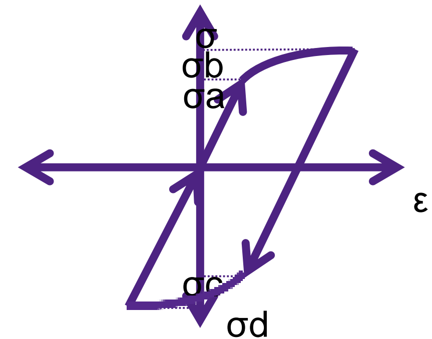
- Isotropic hardening
  - Exponential hardening
  - New yield stress:

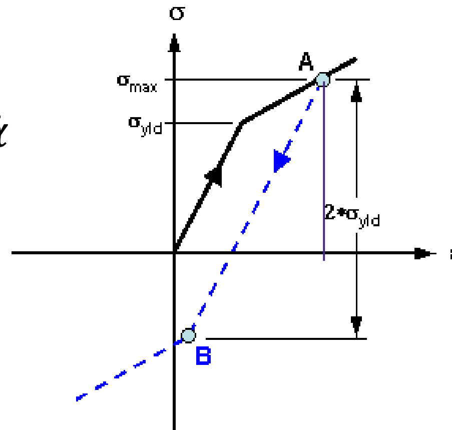
    $$\sigma_y = \sigma_{y0} + R[1 - exp(-b\alpha)]$$
  - Material parameters:
    - Initial yield stress (σ_{y0})
    - R
    - b
- Kinematic hardening
  - Nonlinear hardening
  - Back stress:

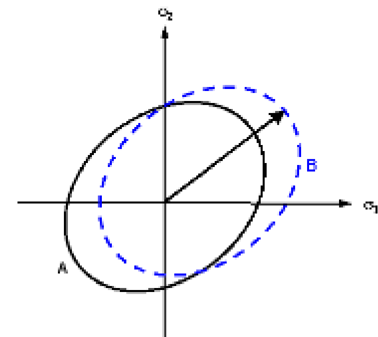
    $$\dot{q}_{ij} = \left(H_{kin} n_{ij} - \sqrt{\frac{2}{3}} H_{kNL} q_{ij} \right) \dot{\alpha}$$
  - Material parameters:
    - Hkin (H_{kin})
    - HNLkin (H_{kNL})











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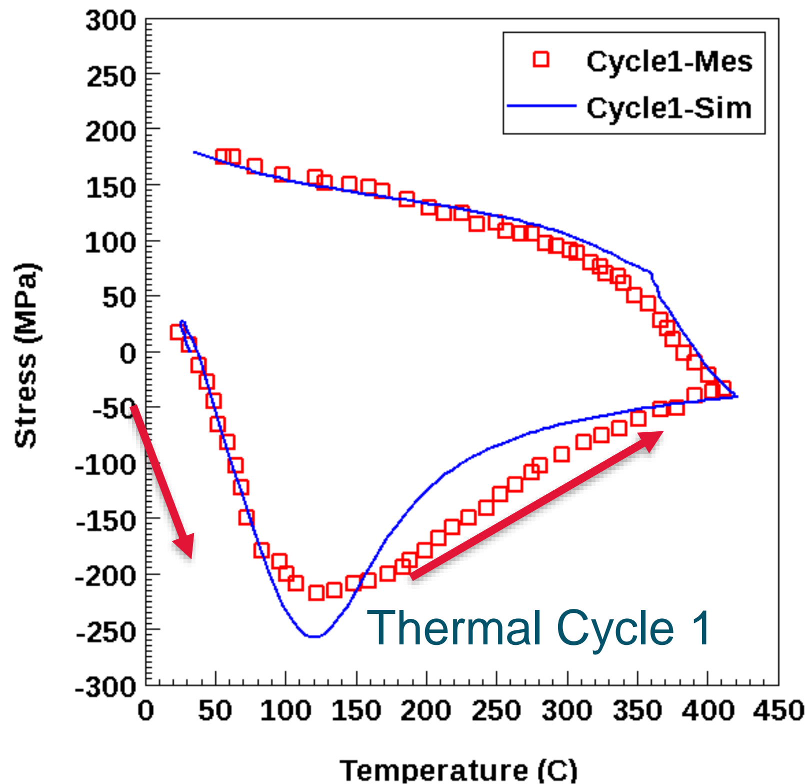
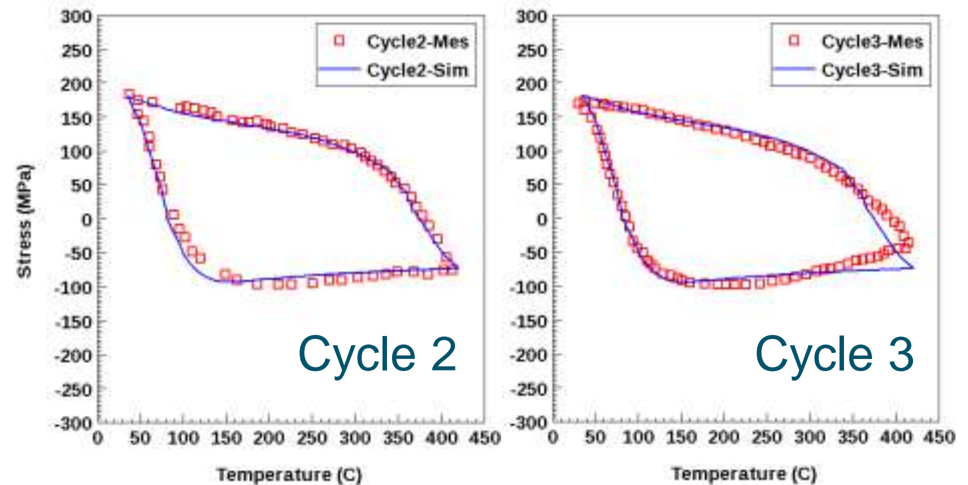
Elastic-Plasticity Model Calibration for Copper

- Incremental plasticity model with nonlinear hardening can match measured data from thermal cycles





Cu stress highly depends on the thermal history of integration flow.

W. Guo, et al, IMEC/Synopsys, ECTC 2015

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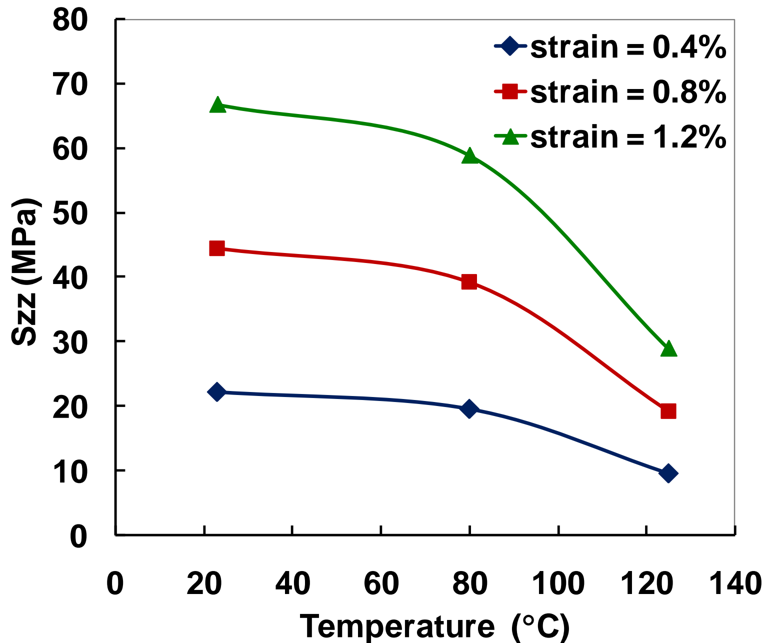
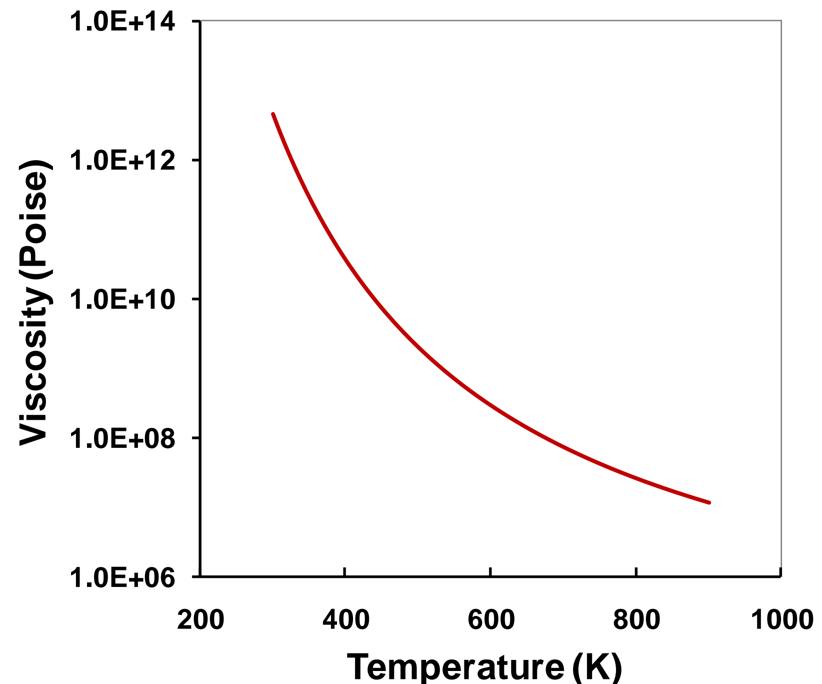
Dieletrics Visco-Elasticity Behavior

- **Stress relaxation at elevated temperatures**





Liner stress highly depends on the thermal history of integration flow.

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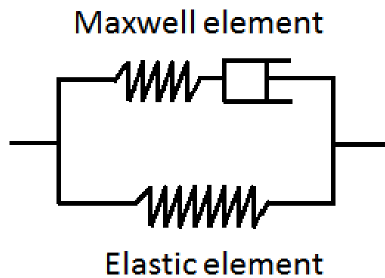
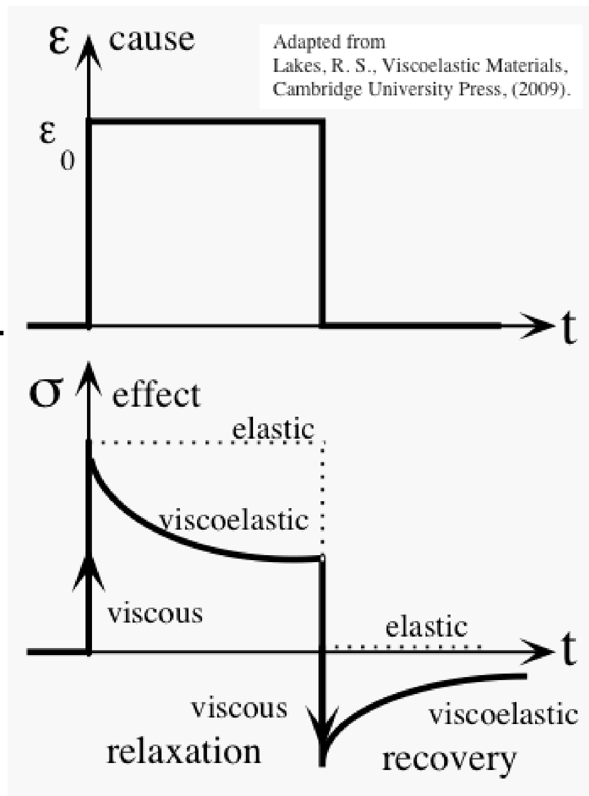
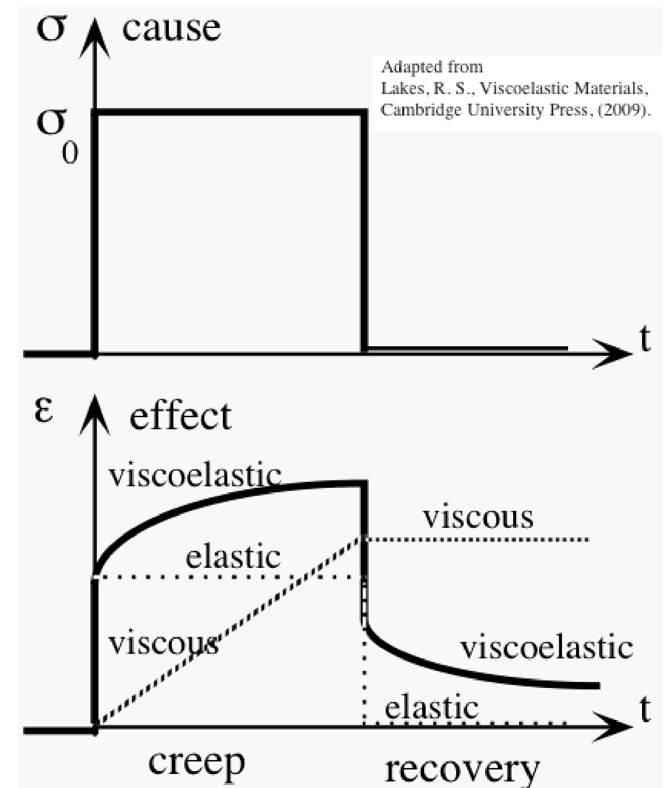
Nonlinear Visco-Elasticity Model with Stress Relaxation and Strain Creep



Relaxation



Creep



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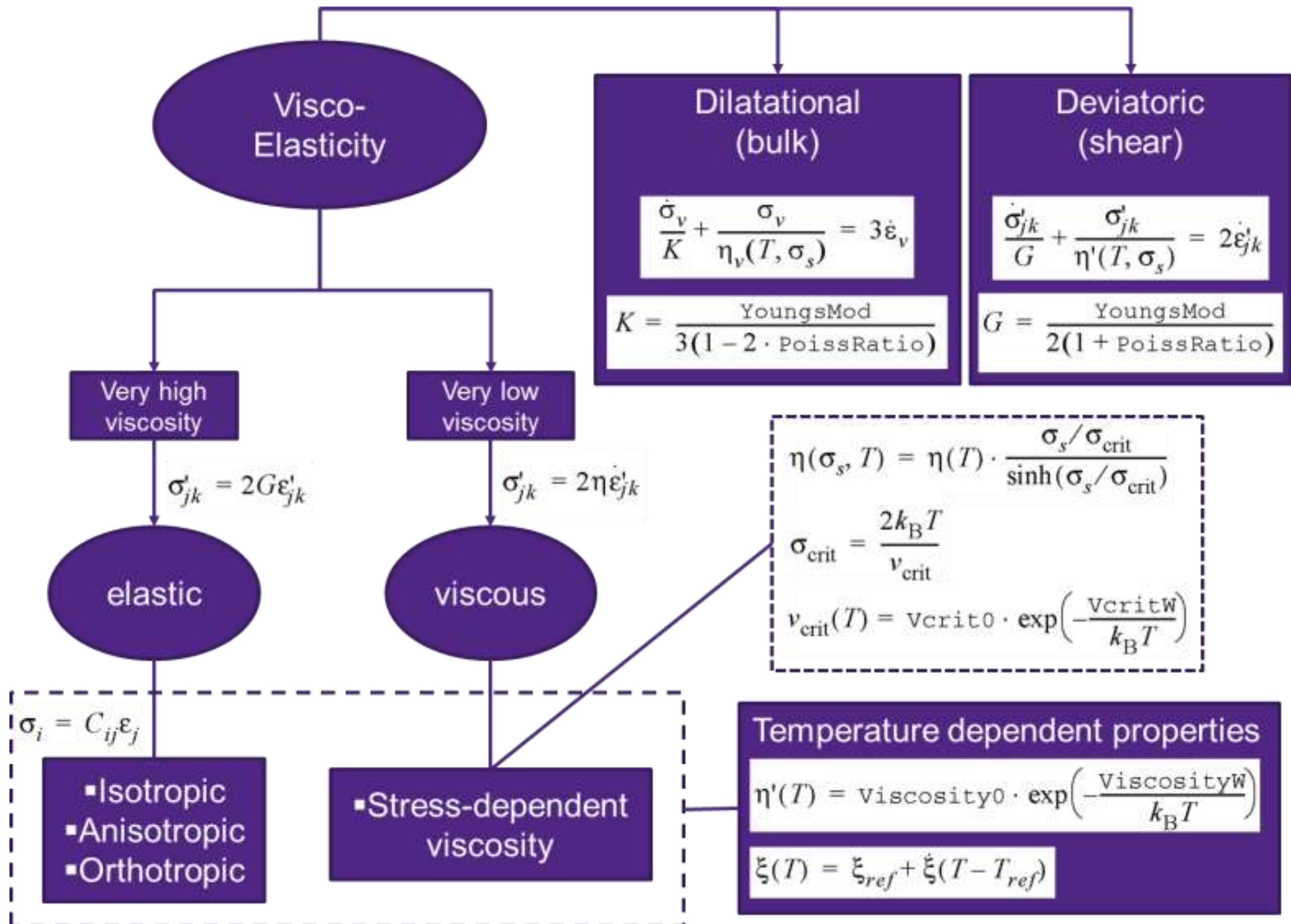
Visco-Elasticity Model Calibration for Liner



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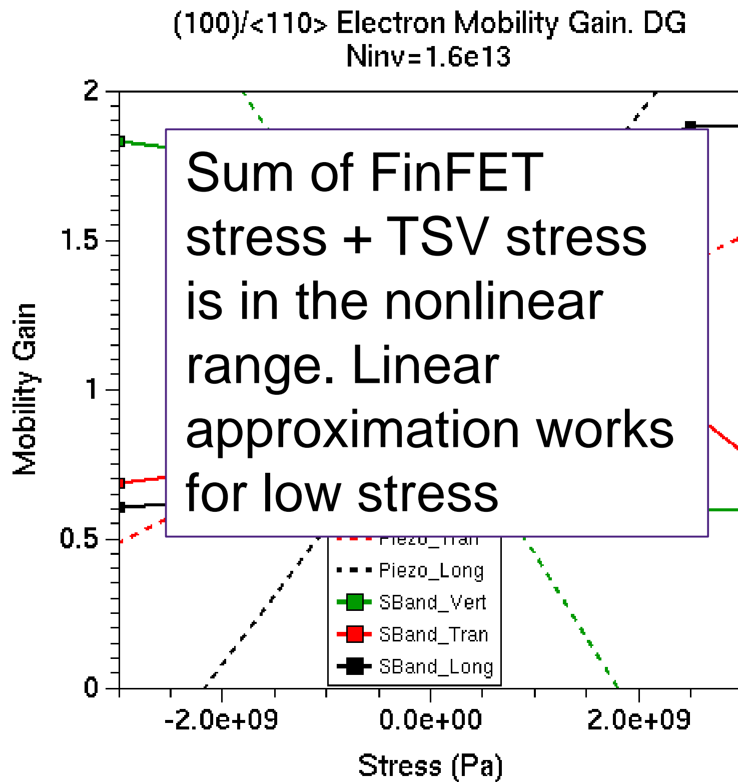
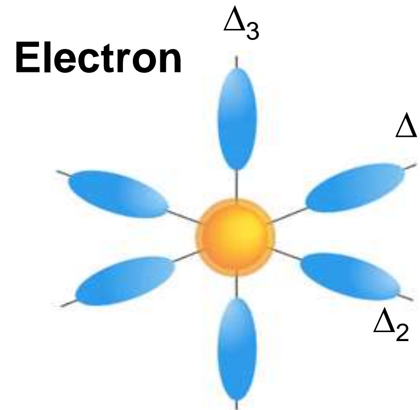
1st and 2nd Order Piezo-Resistance Models

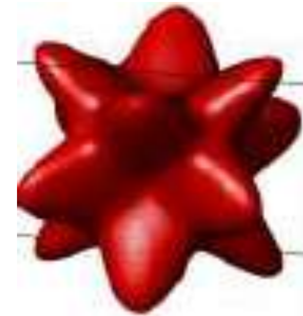


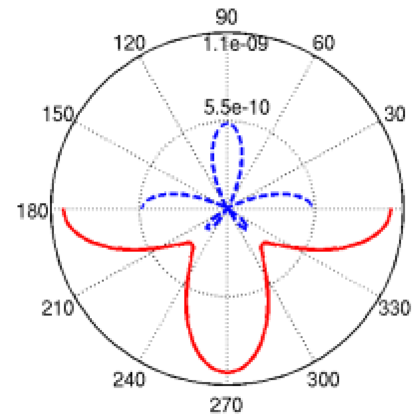
Piezo coefficients depend on crystal orientation, carrier type and stress magnitude

Band structure calculation

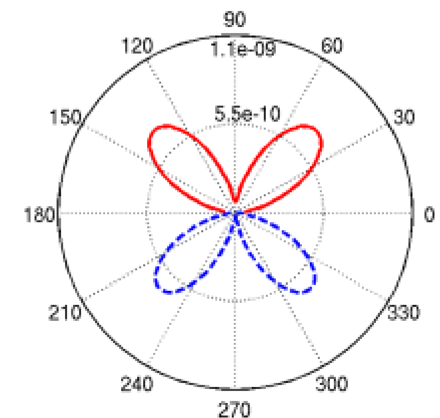


Hole





[001] Surface nMOS



[001] Surface pMOS

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Agenda

Introduction

Material model characterization

TSV stress effects on performance and reliability

Summary

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Test Case Descriptions

- Impact on FEOL performance
  - TSV middle versus TSV last
  - Plastic flow and viscous flow
- Impact on BEOL performance
  - TSV-middle versus TSV-last
  - Plastic flow and viscous flow
- Impact on BEOL Stress in TSV-last
  - M1 at TSV center versus M1 at TSV edge
  - Plastic flow and viscous flow

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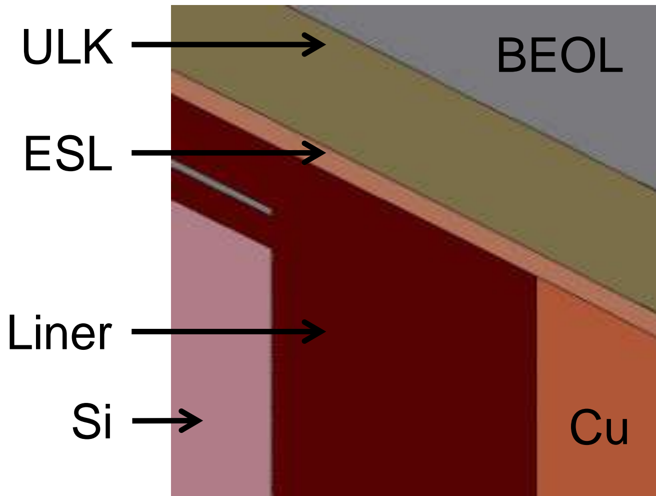
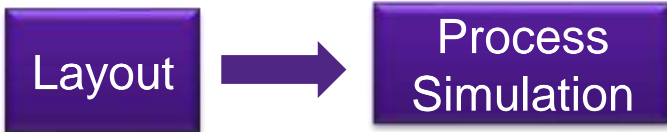
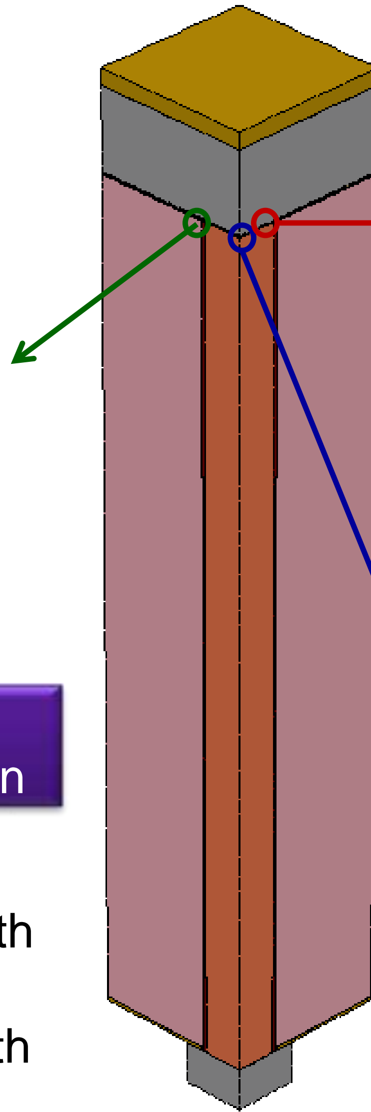
TSV Structures

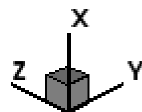
Liner structure near active silicon



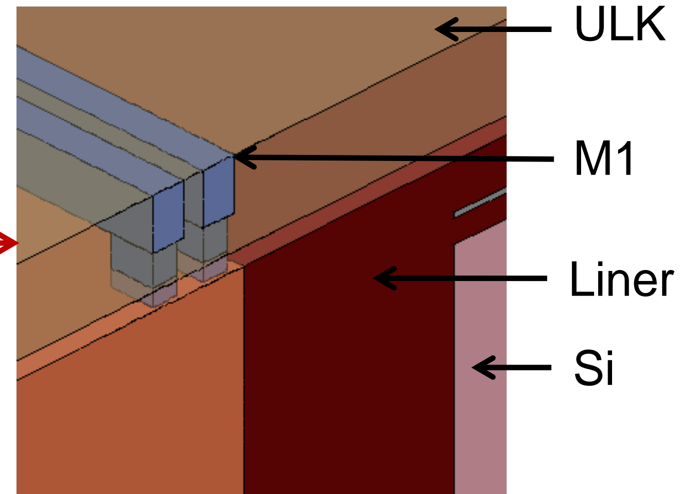


- Liner is modeled with visco-elasticity
- Copper is model with elastic-plasticity

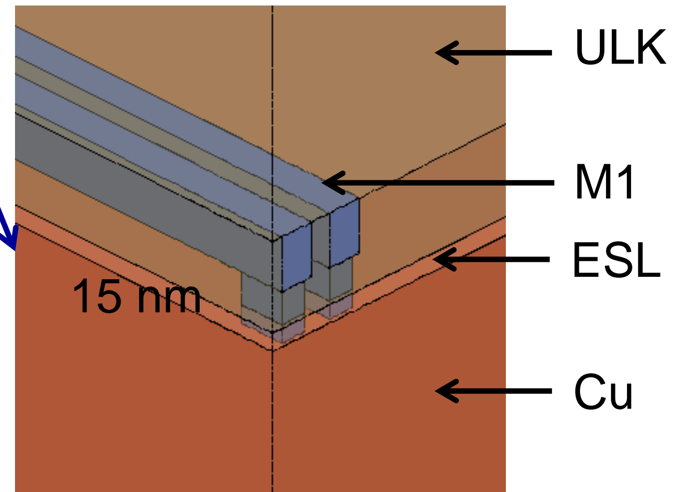




TSV 5x50 um



M1 at the edge of the TSV



M1 at the center of the TSV

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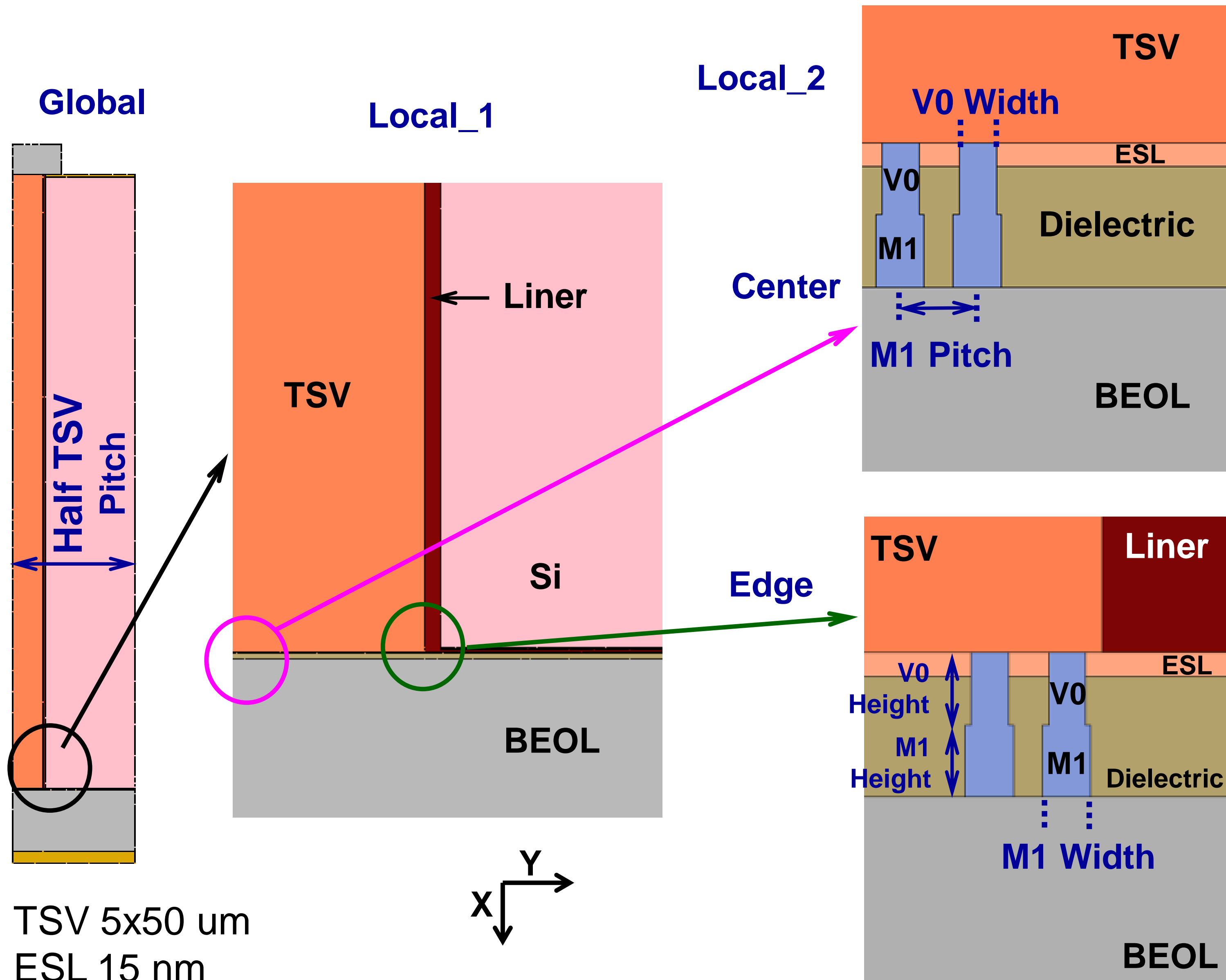
Global and Local Models



TSV 5x50 um
ESL 15 nm

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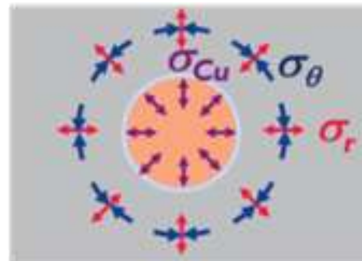
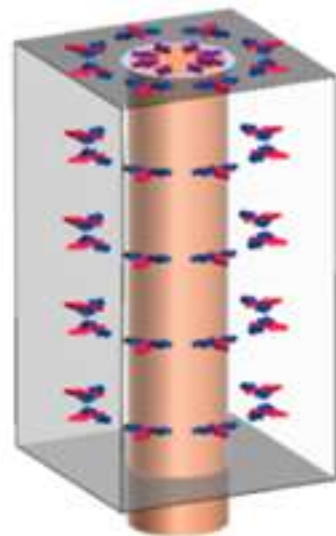
TSV Impact on FEOL:

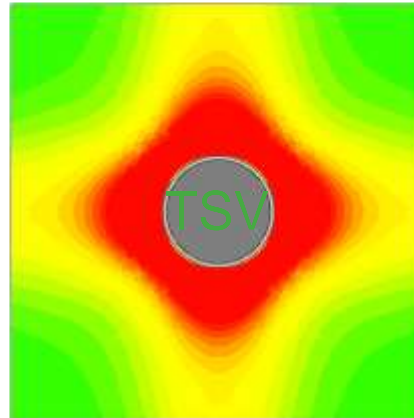
TSV induced in-plane stress

- TSV-last induces lower stress due to lower thermal budget

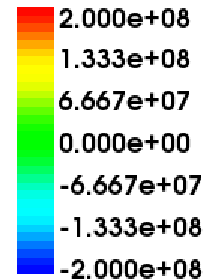




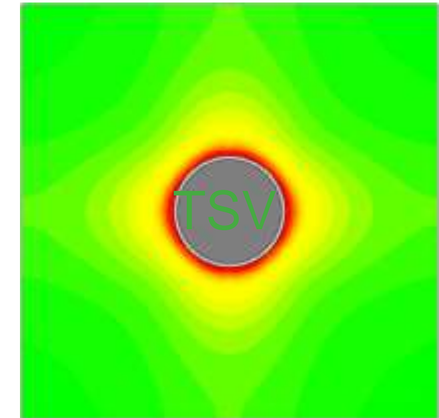
TSV-Middle

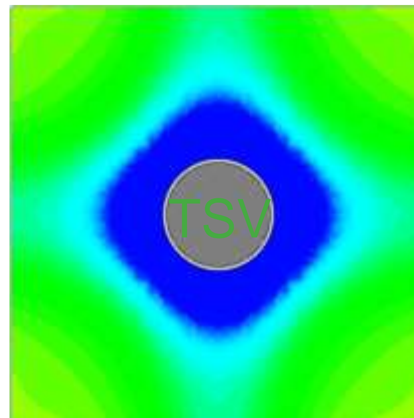


S_{Radial} (Pa)

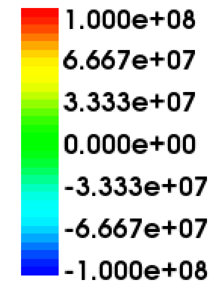


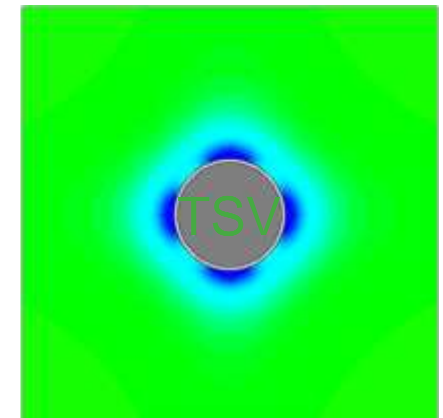
TSV-Last





S_{Hoop} (Pa)





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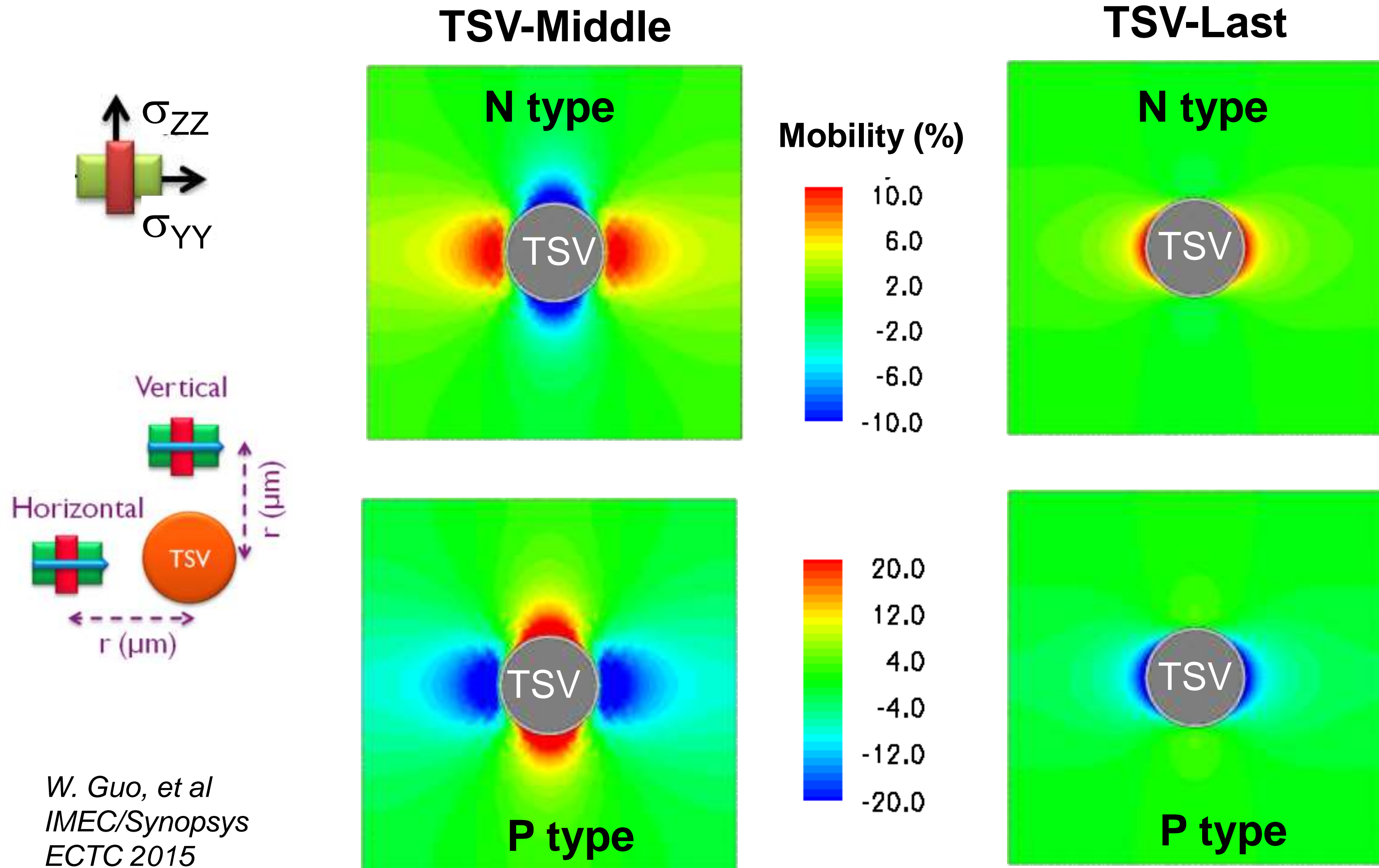
Impact on FEOL:
Stress induced mobility change

- Device mobility change calculated for (100)/<110>



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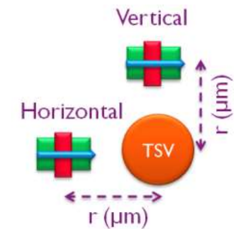
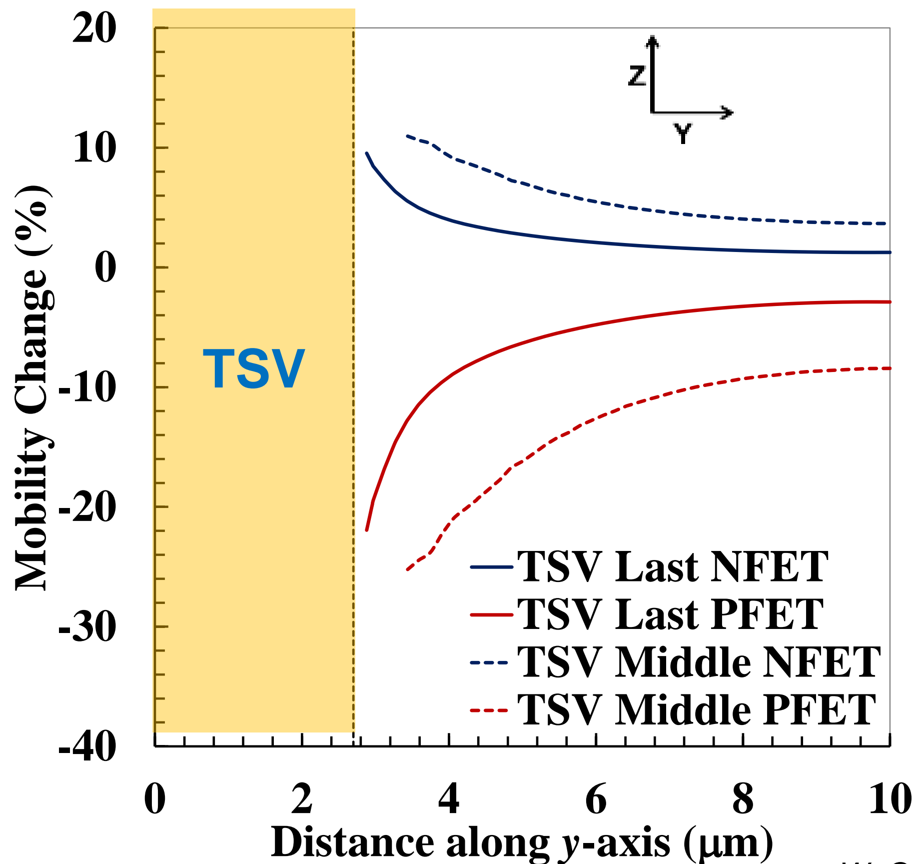
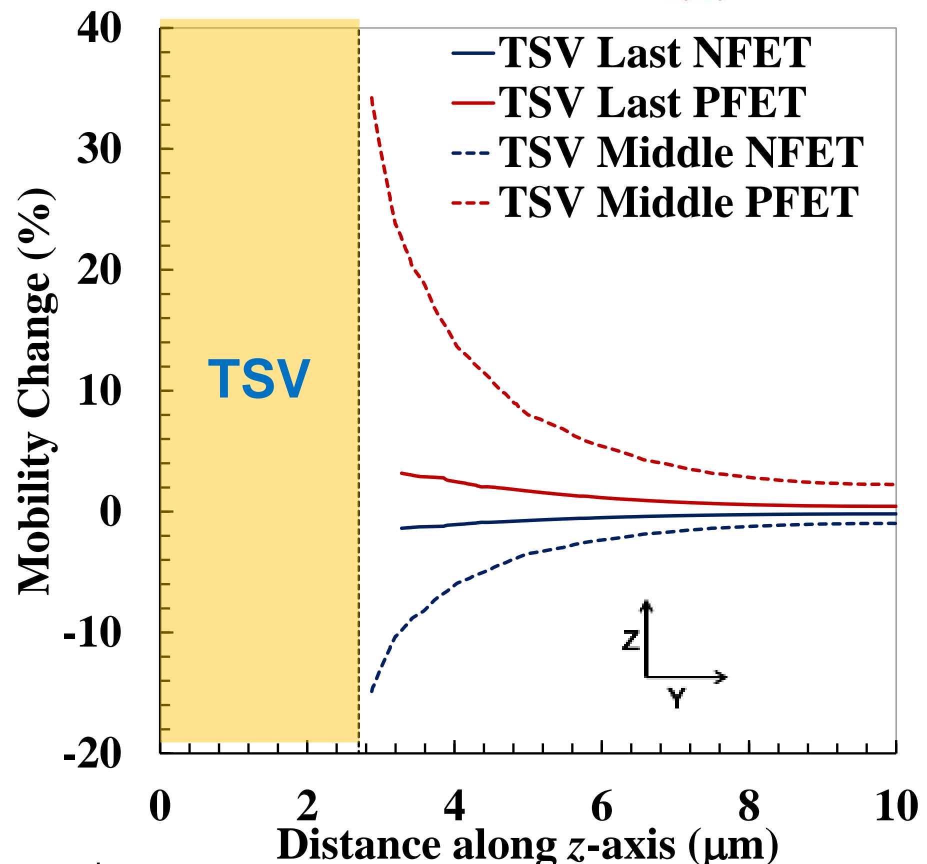
Impact on FEOL

Stress induced mobility change

- Lower via-last stress affects less on mobility
- Impact on NFET is smaller compare to PFET







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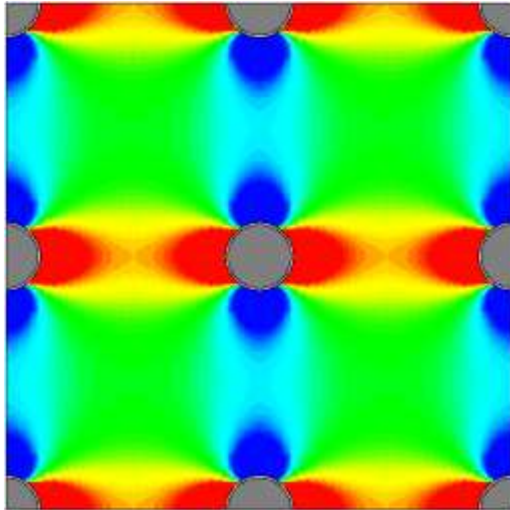
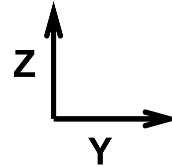
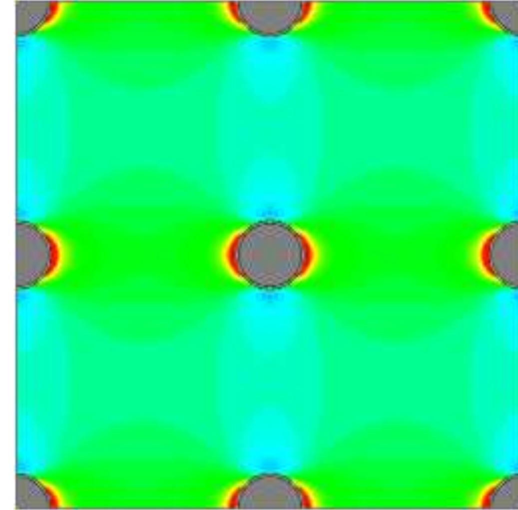
Syy with Plastic or Plastic+Viscous Flow

Plastic + viscous flow, TSV Middle

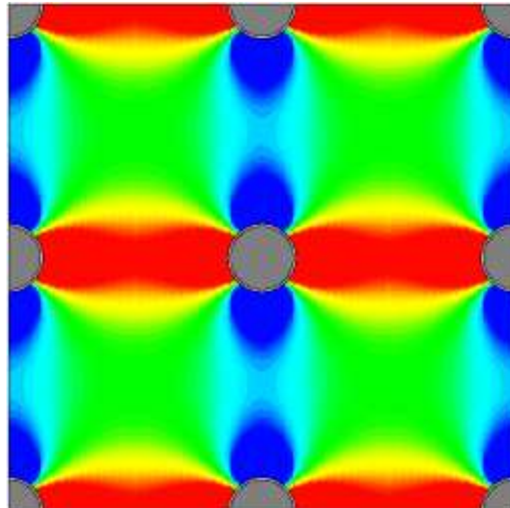


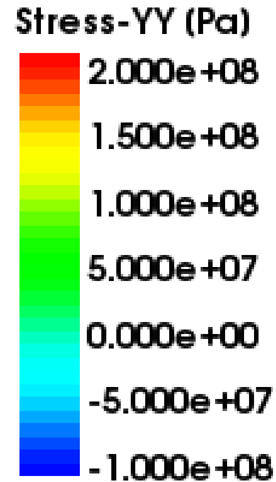


Plastic + viscous flow, TSV Last

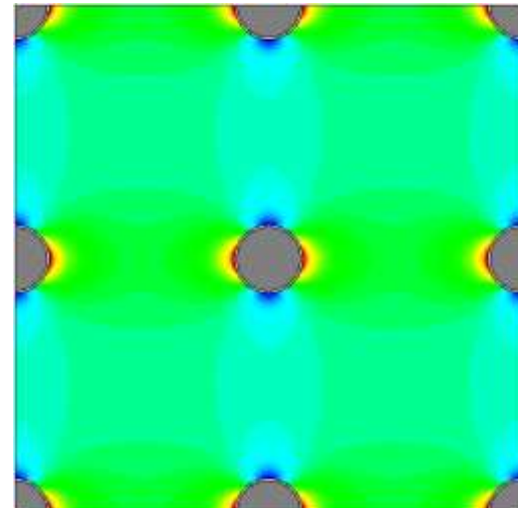


Plastic flow, TSV Middle





Plastic flow, TSV Last



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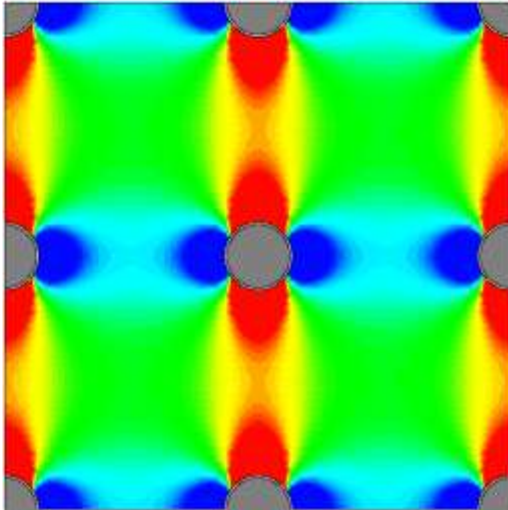
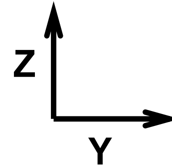
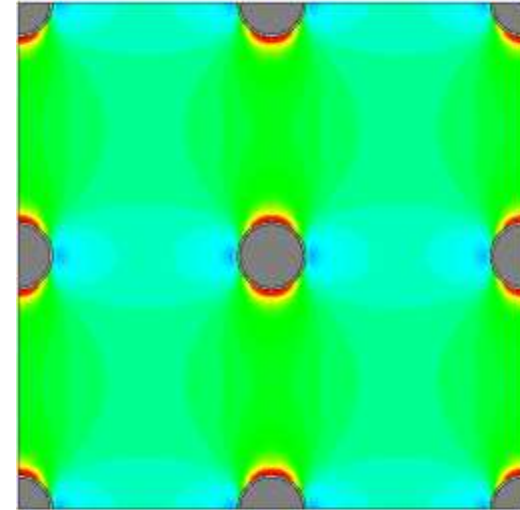
Szz with Plastic or Plastic+Viscous Flow

Plastic + viscous flow, TSV Middle

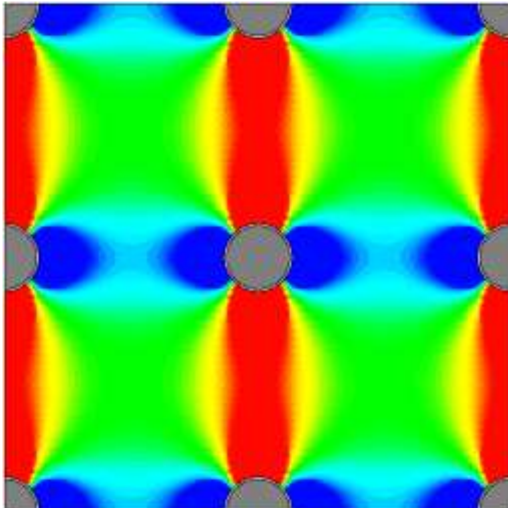


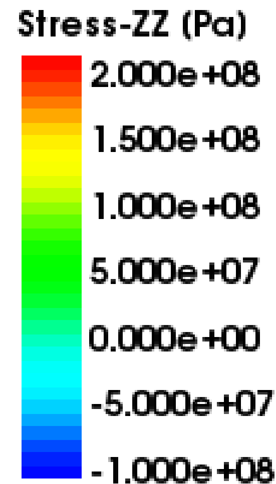


Plastic + viscous flow, TSV Last

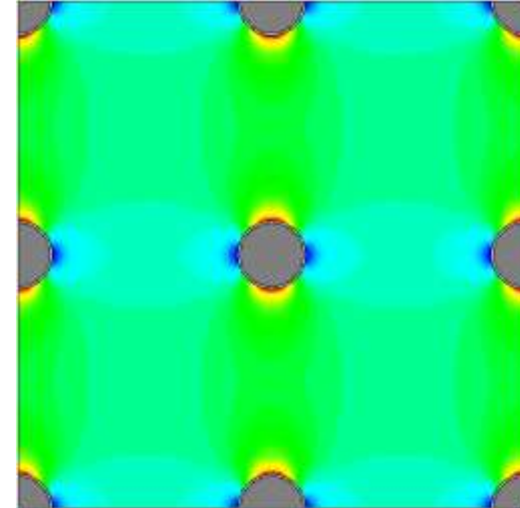


Plastic flow, TSV Middle





Plastic flow, TSV Last



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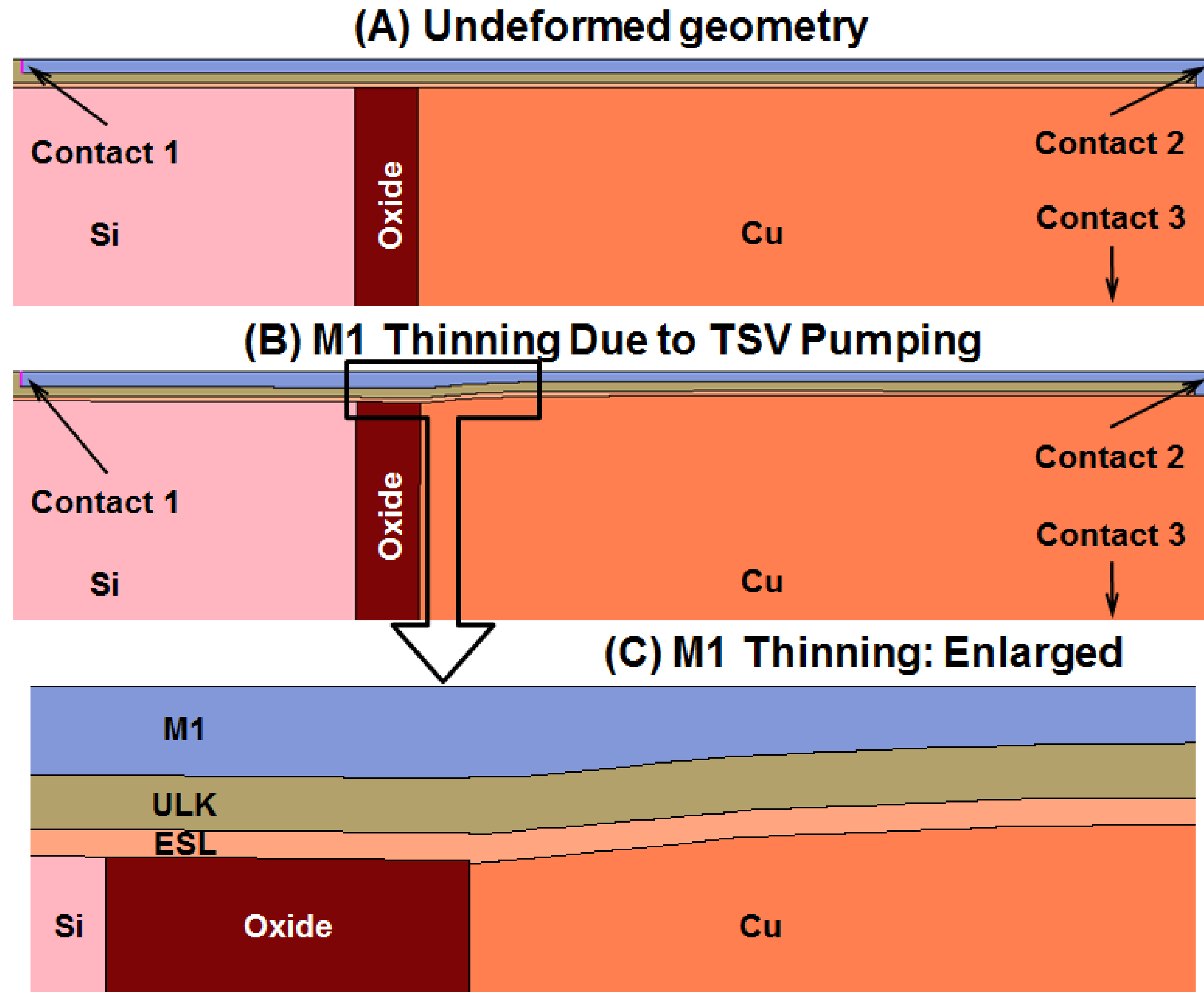
Test Case Descriptions

- Impact on FEOL performance
  - TSV middle versus TSV last
  - Plastic flow and viscous flow
- Impact on BEOL performance
  - TSV-middle versus TSV-last
  - Plastic flow and viscous flow
- Impact on BEOL Stress in TSV-last
  - M1 at TSV center versus M1 at TSV edge
  - Plastic flow and viscous flow

TSV Pumping: TSV-middle vs TSV-last

M1 resistance change for TSV-middle process

- TSV pumping for TSV-middle due to high T BEOL
- 33% M1 resistance increases due to TSV plastic flow
- Additional 12% M1 resistance increase due to viscous flow
- No TSV pumping for TSV-last due to lower T budget



W. Guo, et al IMEC/Synopsys, ECTC 2015

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Test Case Descriptions

- Impact on FEOL performance
  - TSV middle versus TSV last
  - Plastic flow and viscous flow
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  - TSV-middle versus TSV-last
  - Plastic flow and viscous flow
- Impact on BEOL Stress in TSV-last
  - M1 at TSV center versus M1 at TSV edge
  - Plastic and viscous flow versus no flow

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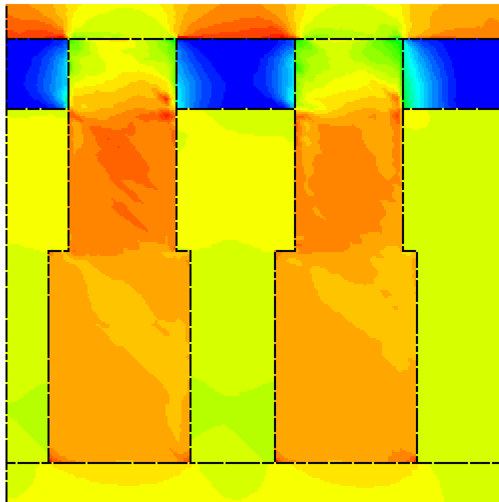
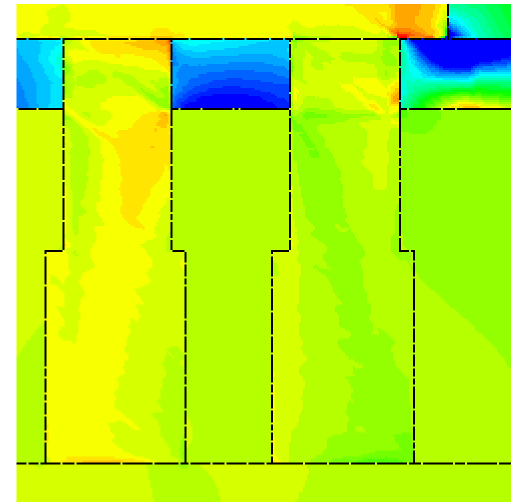
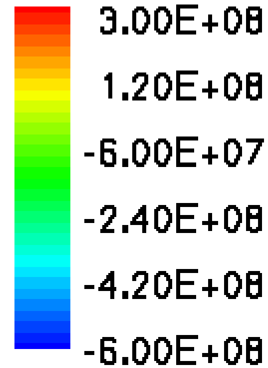
BEOL Hydrostatic Stress in TSV-last

Plastic + viscous flow, Center

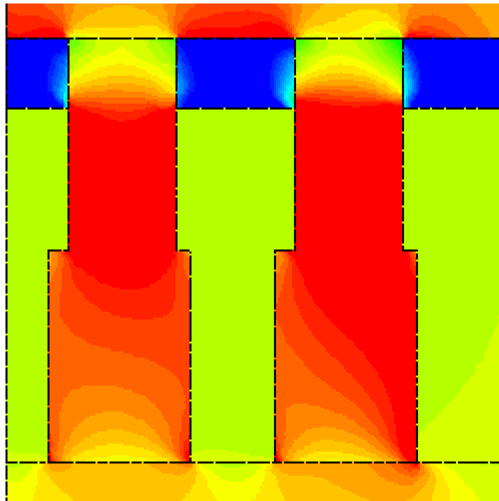


Plastic + viscous flow, Edge

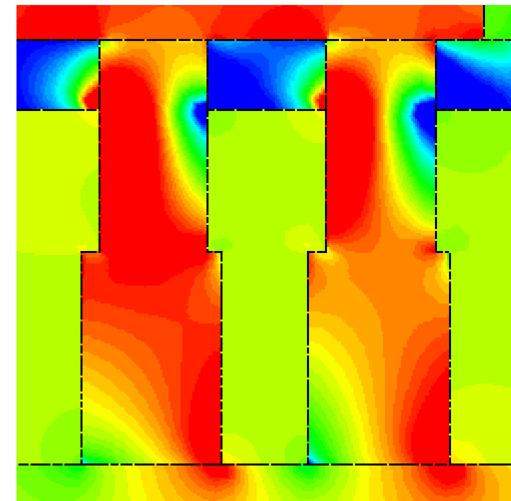


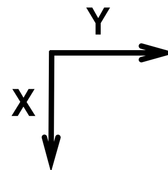


No flow, Center



No flow, Edge





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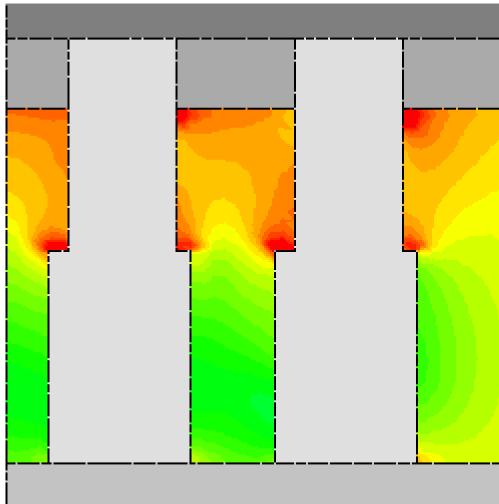
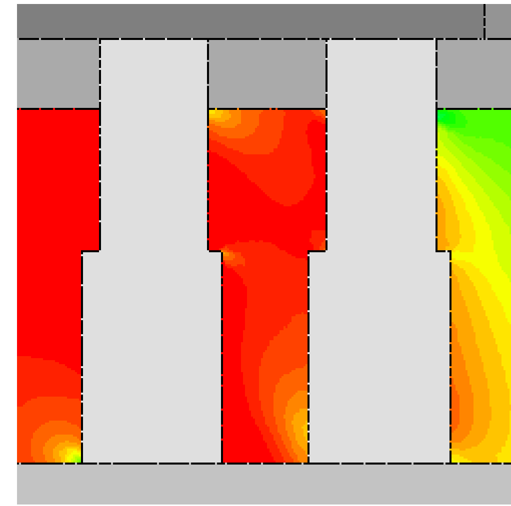
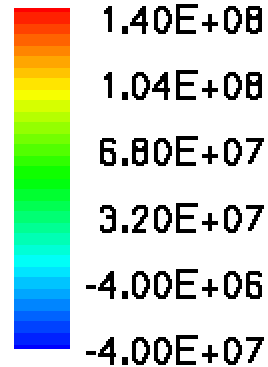
Dielectric 1st Principal Stress in TSV-last

Plastic + viscous flow, Center

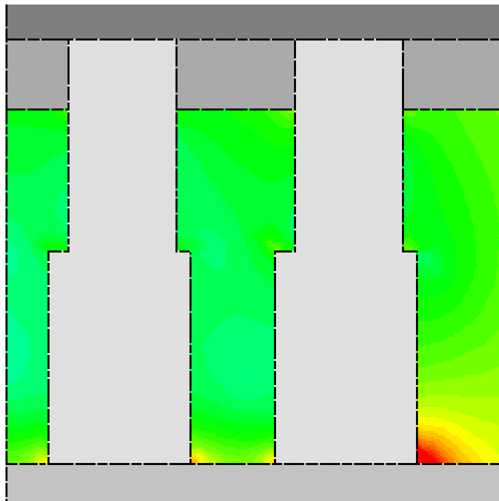


Plastic + viscous flow, Edge

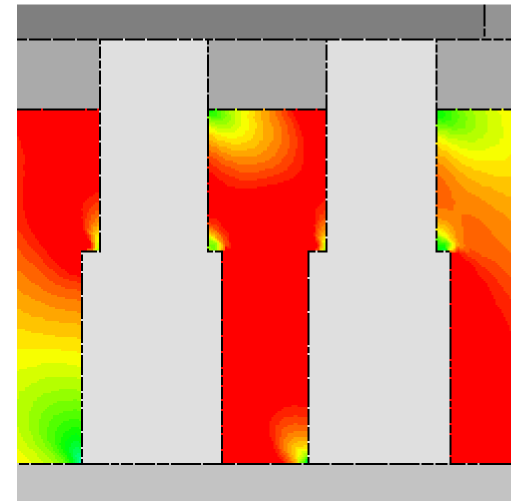


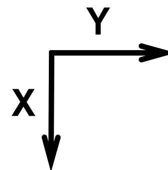


No flow, Center



No flow, Edge





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Summary

- Impact on FEOL performance
  - TSV-middle integration introduces larger residual stresses in active silicon compared to the TSV-last flow integration.
  - Plastic and viscous flow reduce silicon stress
- Impact on BEOL performance
  - TSV-middle integration results in M1 metal resistance increase due to copper pumping
  - Plastic and viscous flow increase TSV pumping
- Impact on BEOL stress
  - Residual stress profiles in BEOL structures are different for TSV middle and TSV last flows
- Ongoing work
  - TSV-last long term stability and reliability

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