Reliability of TSV interconnects in 3D-IC

Electromigration voiding analyzed through 3D-FIB-SEM

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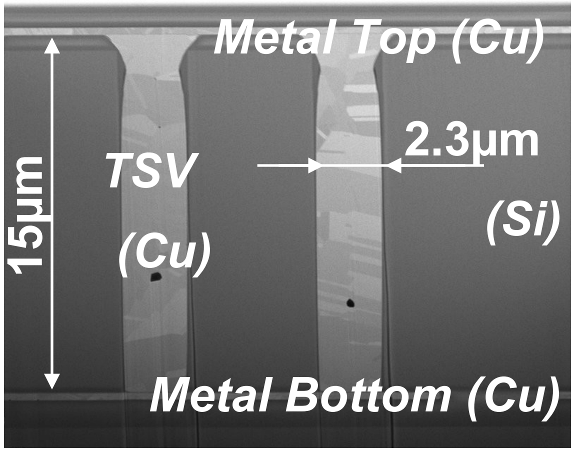
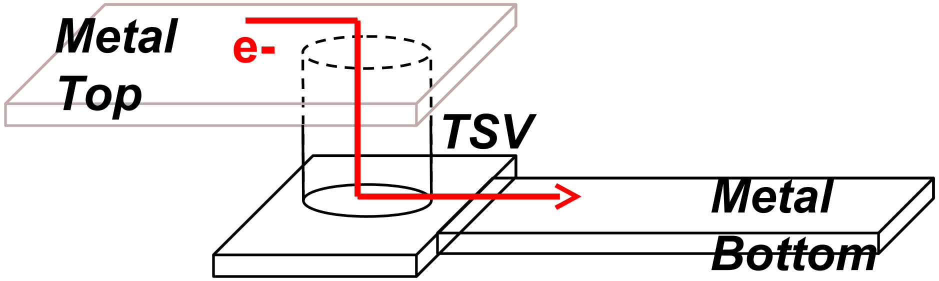
Context & Purpose

- **Reliability of TSV is a major concern**

- **Characterize electromigration of 3D TSV interconnects**





➔Propose a model of electromigration behavior

➔Supported by Failure Analysis

Outline

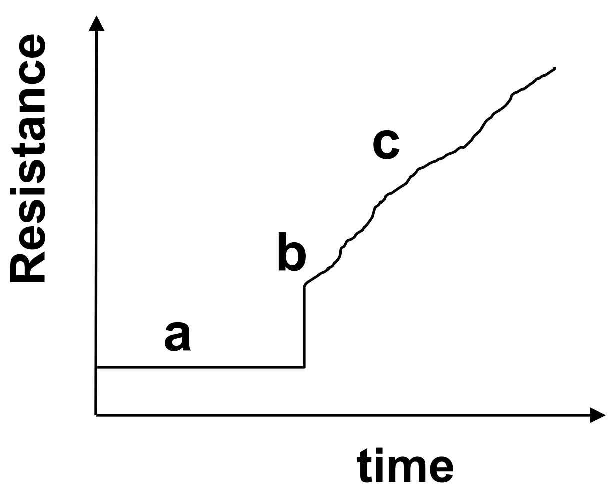
- Introduction
  - Context & Purpose
  - Electromigration in usual Cu BEOL interconnects
- Experimental
  - TSV technology
  - Test structure
  - Resistance increase
  - Failure analyses
- Model of electrical resistance increase
  - Model
  - Parameter extraction
- Discussion
  - Electromigration robustness ⬄ TSV bottom section
- Conclusion

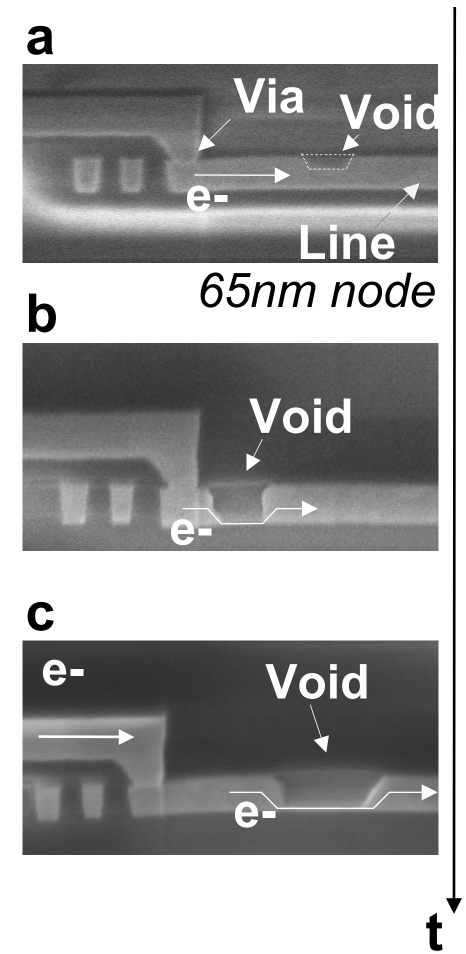
Electromigration in usual interconnects

- Electromigration …
  - Cu migration driven by $j_{[MA/cm^2]}$ & $T_{[°C]}$

    ➔Voids and Hillock formation

- … in usual Cu BEOL Interconnects
  - Via-ended line: ~2MA/cm² & ~300°C
  - Monitoring of $R_{[\Omega]}$ of a via ended line

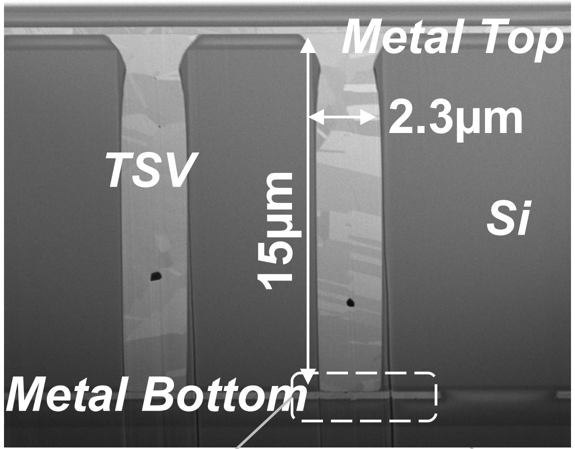


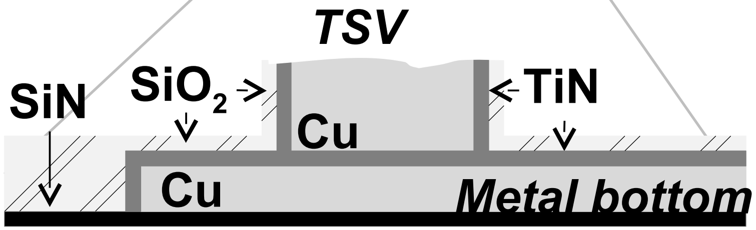


L. Doyen, JAP 2008

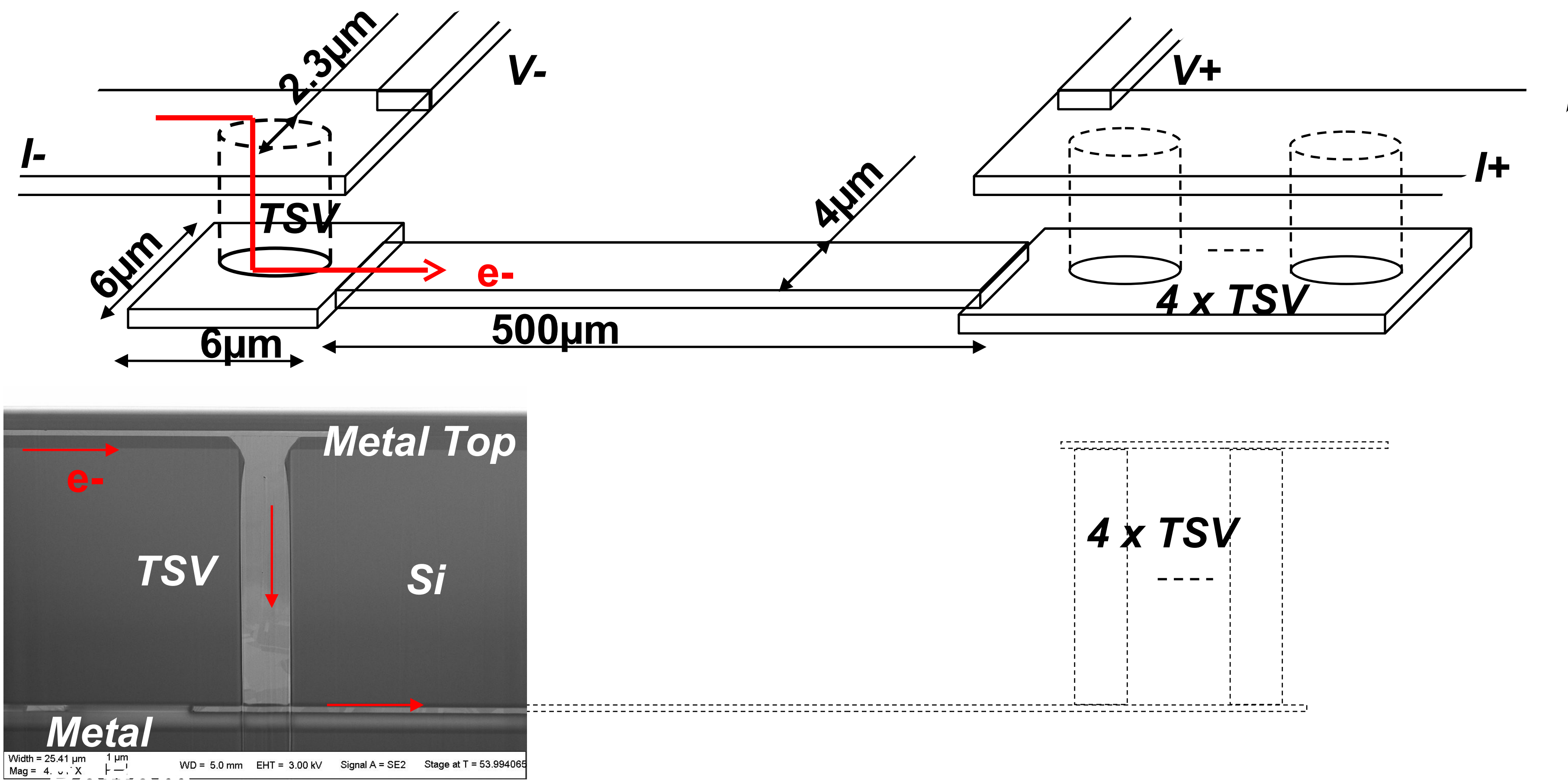
Through Silicon Via technology

- **Stack**
  - 8 inches WoW Direct Bonding
- **TSV**
  - Cu, Via last
  - Height = 15µm
  - Diameter = 2.3µm
  - SiO_2 & TiN integration
- **Interconnects**
  - Cu Damascene
  - SiO_2, SiN, TiN integration
  - Line/TSV interfaces: Cu/TiN/Cu



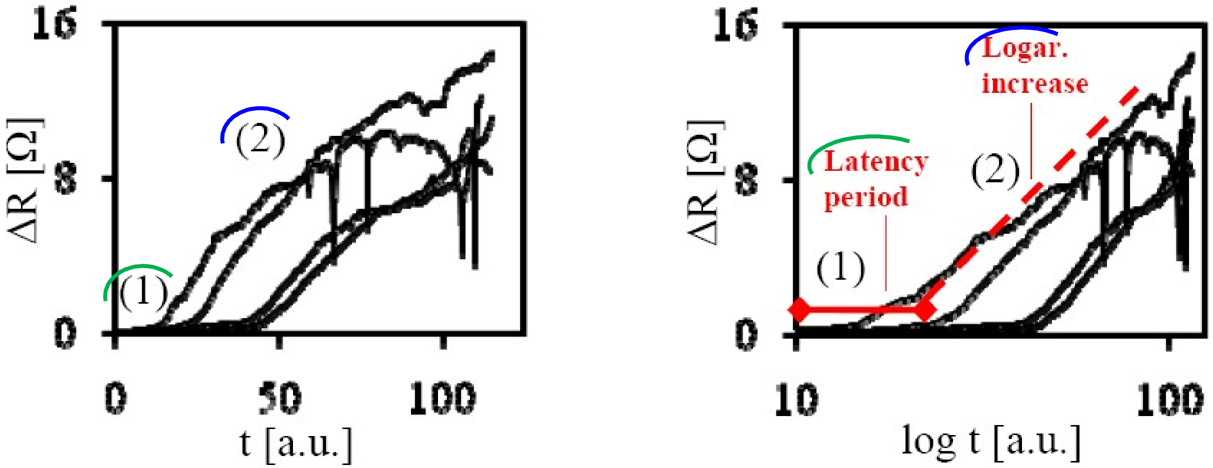


Electromigration test structure



Stress Conditions: **15/25mA & 270/300°C**

Monitored resistance trace



Electrical resistance increase:

- **Latency period at start (1)**
- **Logarithmic increase (2)**
- **No sudden step up**

Different from R(t) of electromigration in usual Cu interconnects

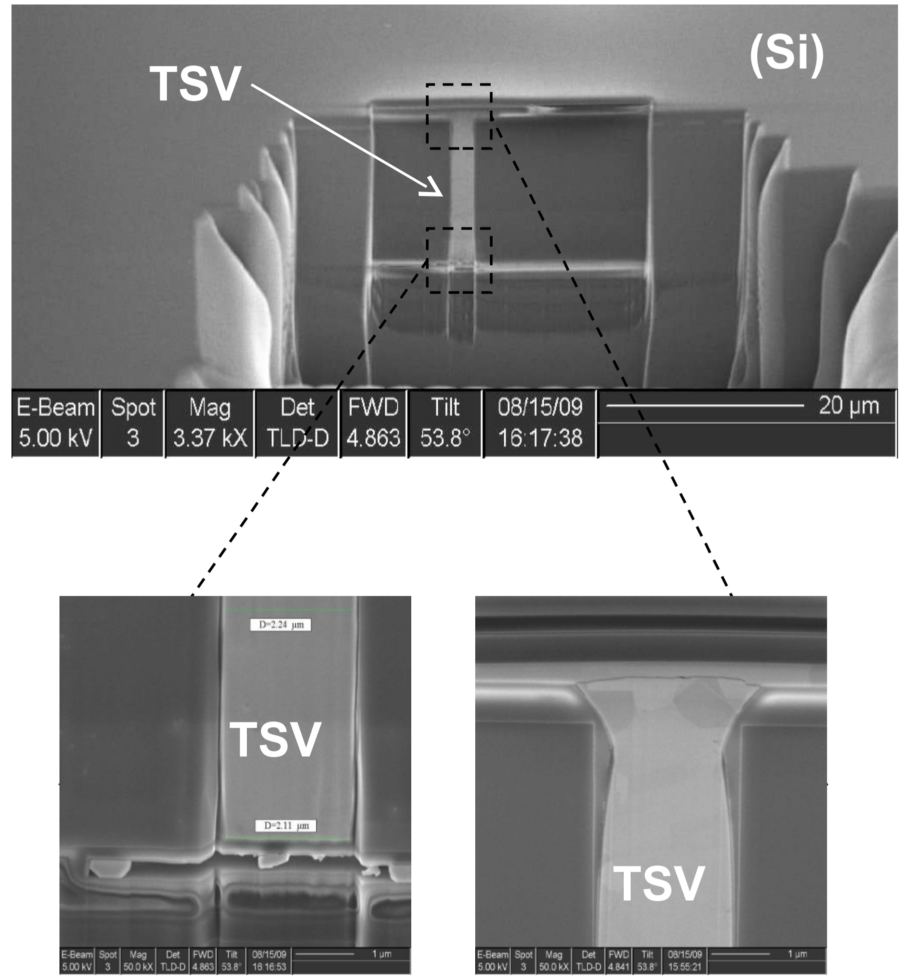
Stress conditions: **15-25MA/cm² & 270-300°C**

Failure Analyses

2D FIB SEM

- **Aggressive TSV form factor (15µm / 2µm)**
  - Large FIB windows
  - Risk of missing structure & failure site
  - Density mismatch of Cu, Si, SiO_2 ➔ relief transfer
  - Time : ~2 hours
  - No automation
  - No void volume data

- **Benefit**
  - Large window
  - TSV top & bottom interfaces
  - Accurate localization of electromigration void



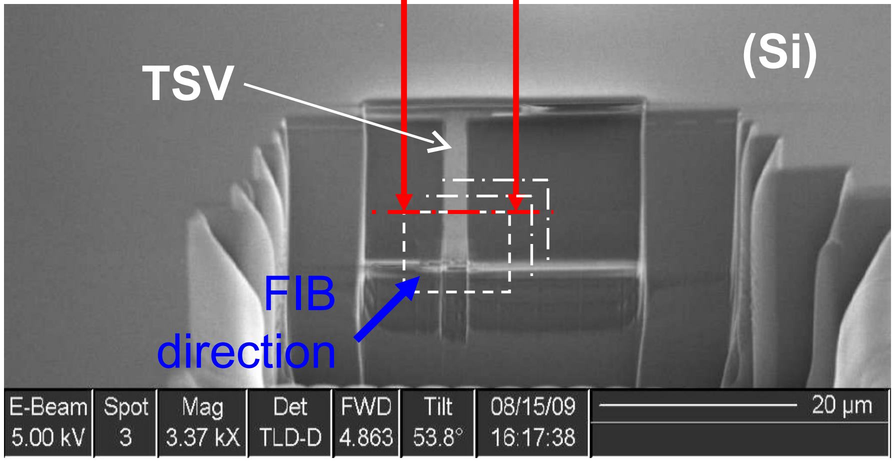
Bottom interface
Top interface

Failure Analyses

3D FIB SEM

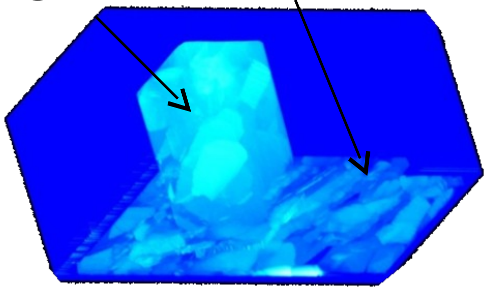
- Aggressive TSV form factor (15µm / 2µm)
  - Sample preparation
  - ➔Reduced window size
  - (need of pre-2D FIBSEM)
  - Time : ~6 hours

Sample preparation
(reduce window size)



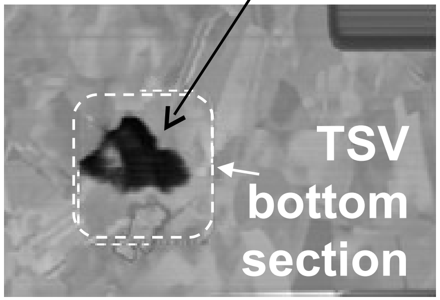
- Benefit
  - No Risk of missing structure & failure site
  - Automated
  - Reconstructed pictures
  - Accurate localization of electromigration void
  - Volume computations

TSV
Metal level



Reconstructed 3D view

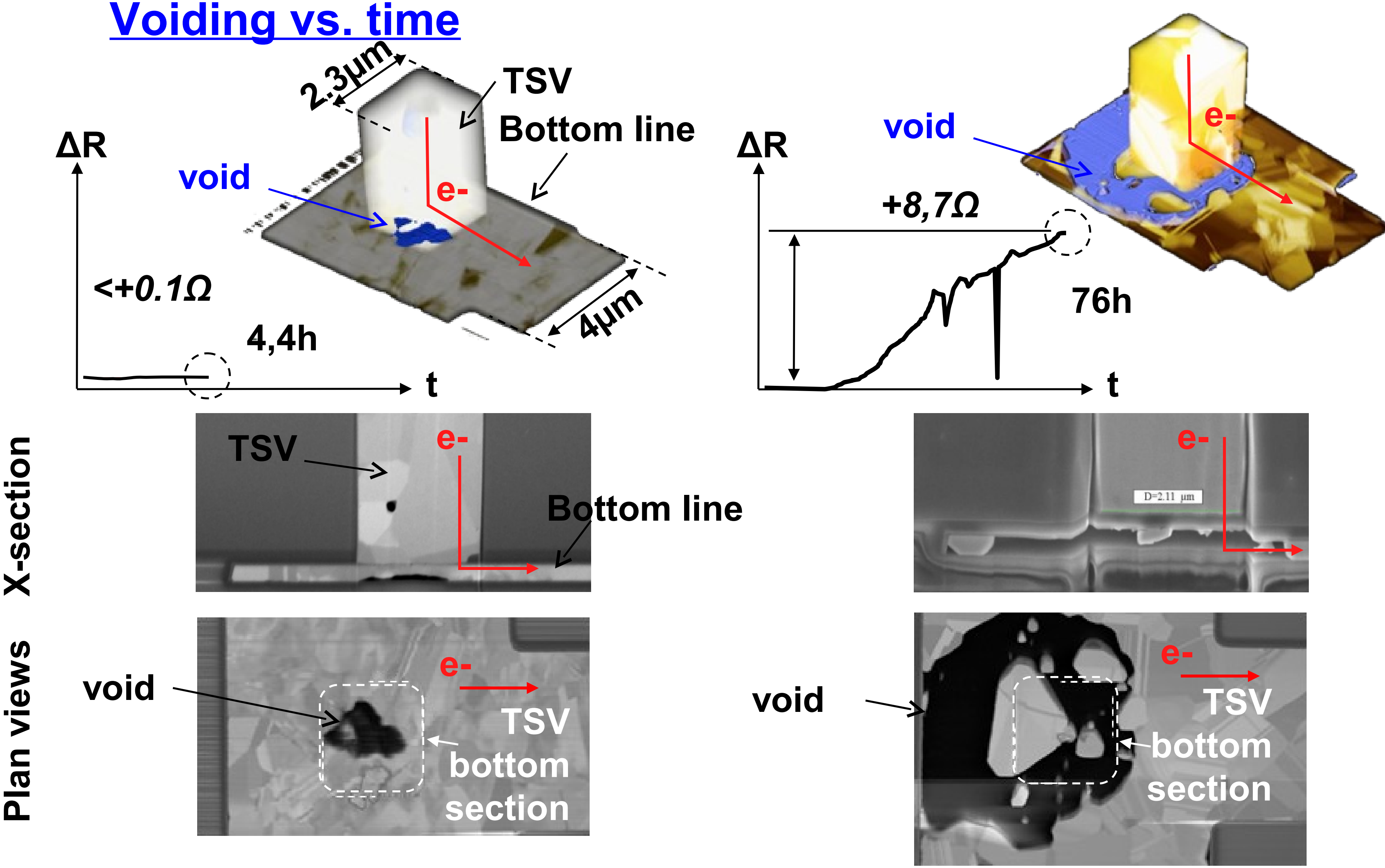
void



Reconstructed Plan view

Failure Analyses

Voiding vs. time



Model of resistance increase

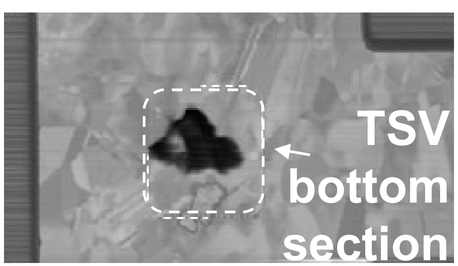
FIB SEM failure analyses

Electromigration physics

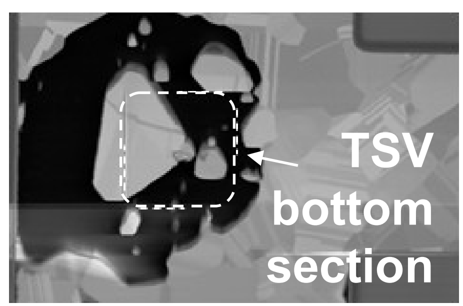
Model of:

$$\Delta R_{[\Omega]} = f(time)$$

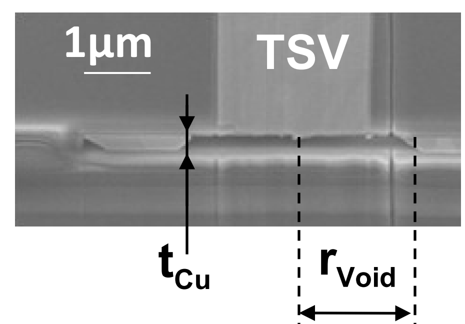
- Void grows right under the TSV
- Radial void growth
- Void spans over whole line thickness



Plan view



Plan view



Cross section view

Model of resistance increase

Model of resistance increase:

$$\begin{cases} R(t) - R_0 = A \cdot \ln(\frac{t}{t_0}), & t > t_0 \\ R(t) - R_0 = 0, & t \le t_0 \end{cases}$$

Barrier resistivity

$$A = \frac{\rho_B}{4 \cdot \pi \cdot t_B}$$

Barrier thickness

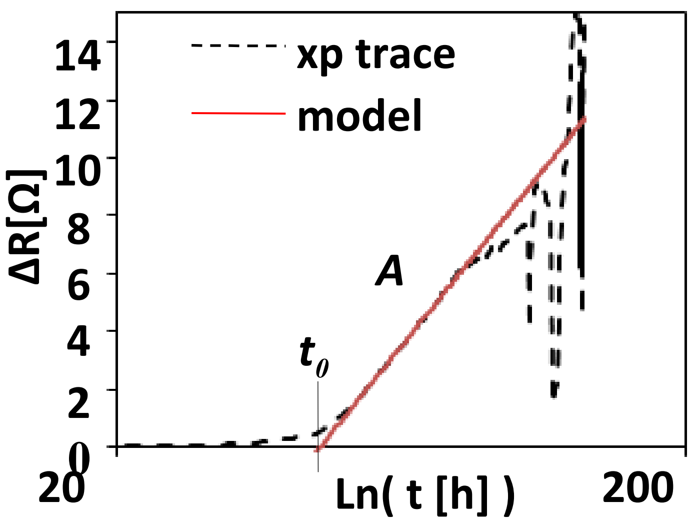
Cu line thickness

TSV radius

$$t_0 = \frac{t_{Cu} \cdot \pi \cdot r_{TSV}^{\ 2}}{\alpha \cdot F}$$

Proportional constant

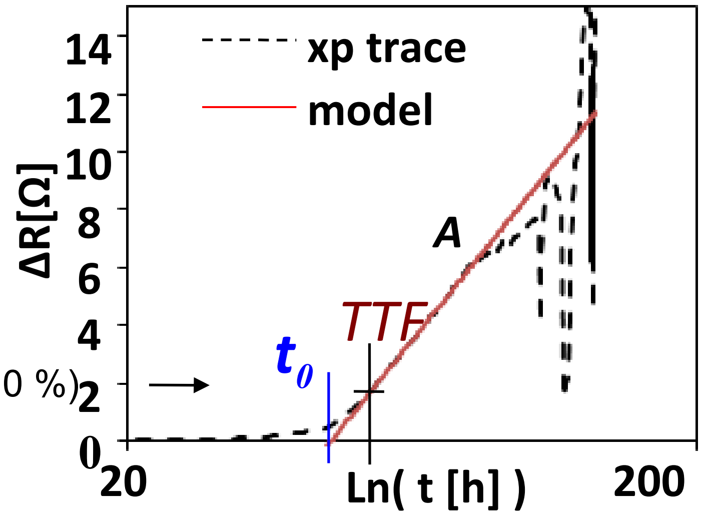
Electromigration Cu flow



Model is fitted for each sample, and (*A*, *t_0*) are extracted

Model fits on 89 out of 128 tested samples

Parameter extraction



$$R(t) - R_0 = A \cdot \ln\left(\frac{t}{t_0}\right)$$

$$t_0 = \frac{t_{Cu} \cdot \pi \cdot r_{TSV}^2}{\alpha \cdot F}$$

Electromigration Cu flow

Compare

Current expon.

Activation energy

$$MTF = A \cdot j^{-n} \cdot \exp\left(\frac{E_A}{k_B T}\right)$$

Current density

Temperature

Black's law: *MTF* ⇔ *n*, *E*$_A$

MTF: Mean Time To Failure
TTF: Time To Failure

$$t_0 \propto j^{-n} \cdot \exp\left(\frac{E_A}{k_B T}\right)$$

0 ⇔ ***F***

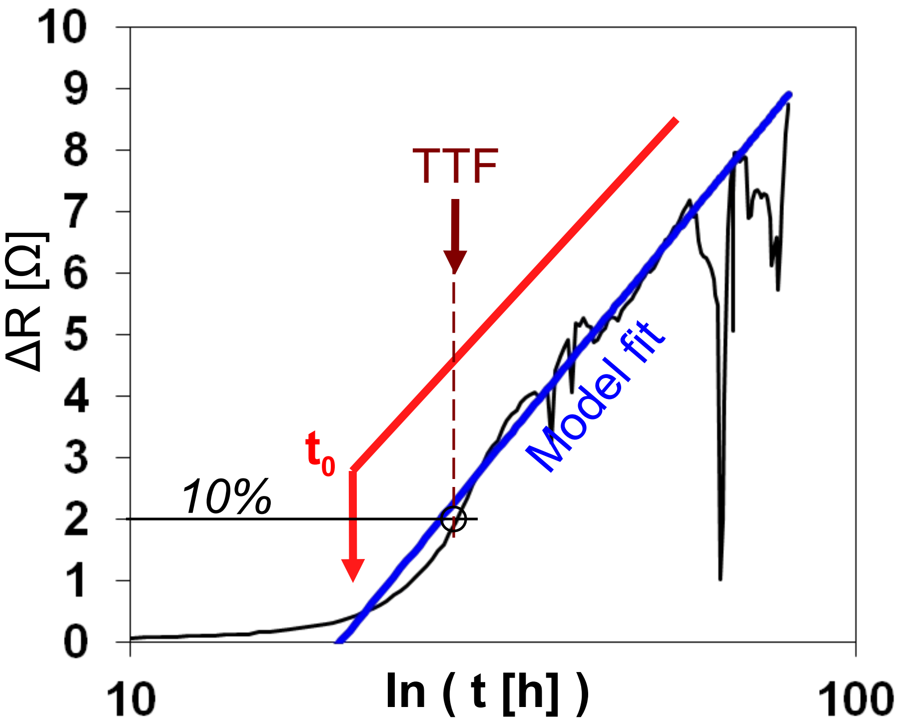
(current exponent),

⇔ ***E*$_A$(activation energy).**

Parameter extraction

Compare $(n;E_A)_{t0}$ vs. $(n;E_A)_{TTF}$

➔ **But t_0 and *TTF* extractions have to be independent**



Time To Failure (TTF):
Failure Criterion:10%

Point of resistance trace.

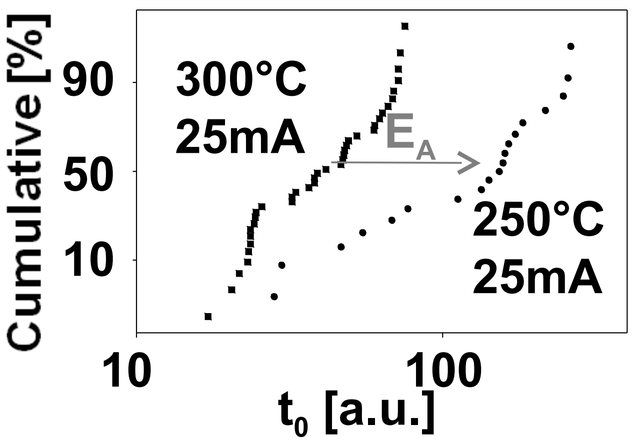
t_0 :

Evolution of resistance increase.

Parameter extraction

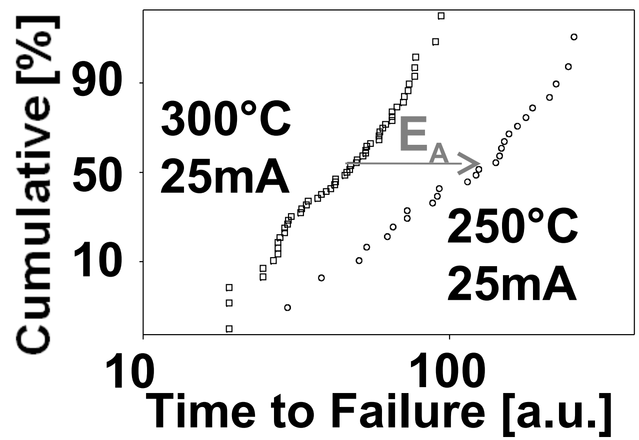
ctivation Energy (E_A):

Model's t_0 extraction



E_{A,t_0} = 0.9 ±0.2 eV.

Black's Law (TTF)

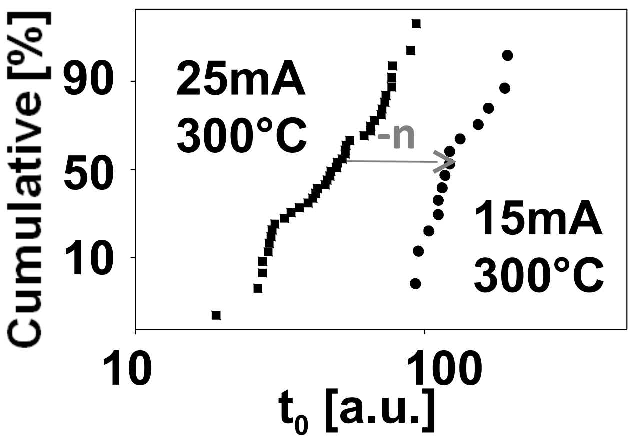


$E_{A,TTF}$ = 0.9 ±0.1 eV.

Parameter extraction

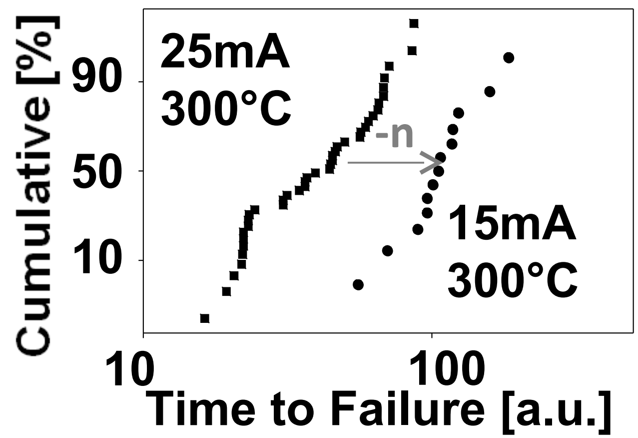
urrent Exponent (*n*):

Model's t_0 extraction



n_{t_0} = 1.8 ±0.2

Black's Law (TTF)



n_{TTF} = 2.0 ±0.1

➔ ***n & E_A extracted values are relevant regarding values calculated from Black's equation using Time To Failure***

Parameter extraction

- **Summary:**
  - Extracted values of current exponent and activation energy match independent experimental values

Model of resistance increase matches experimental data

Extract guidelines to increase robustness of TSV ended interconnect

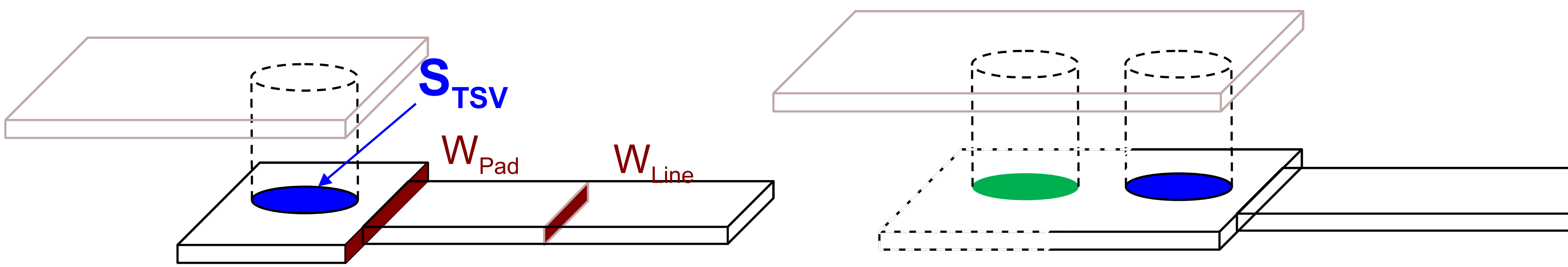
Electromigration robustness ⬄ TSV bottom section

- **The instant the resistance starts to increase depends**

$$t_0 = \frac{t_{Cu}\pi r_{TSV}^{2} k_B T}{\alpha N_i D_{eff_0} Z^* \rho_{Cu}} \cdot i^{-n} \cdot \exp\left(\frac{E_A}{k_B T}\right)$$

(πr_{TSV}^2 = S_{TSV})

- **To increase robustness :**
  - **Increase TSV section [*Process / Technology*]**
  - **No benefits from pad or line width increase [*Design*]**
  - **Possibility to add redundant TSV [*Design*]**



Conclusion & Question

- **Propose a model of electromigration in a TSV ended line**
  - **Experimental observations**
    - **Electrical resistance increases under $T_{[°C]}$ and $i_{[mA]}$ stress**
    - **FIB SEM analyses reveal void grows in bottom line under TSV**
  - **A model is proposed for the resistance increase**
    - **Radial growth of void under TSV**
    - **Model enables extraction of aging parameters (E_A and n)**
    - **Propose solutions to increase robustness**
  - **Workshop Question**
    - **Failure analyses are essential for 3D-IC reliability studies**
    - **FIB SEM analyses are limited by the TSV dimensions**

    ➔ Possible to use non destructive analyses?

Thank You for your attention

Annex

Model of resistance trace

- **Purpose: ➔ Give an expression of:**

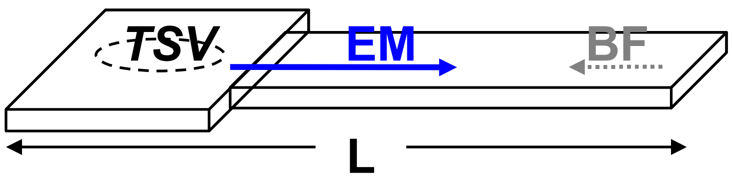
$$\Delta \boldsymbol{R}_{[\Omega]} = \boldsymbol{f}(\boldsymbol{t})$$

- **Based on void growth kinetic**
  - **Assumption 1: No Matter Back-Flow**
  - **Assumption 2: Radial void growth**
  - **Assumption 3: TSV bottom section approximated to a circle**

Hypotheses of the model

Assumption 1: No Matter Back-Flow

Total matter Flow: $$F = F_{EM} + F_{BF}(t)$$

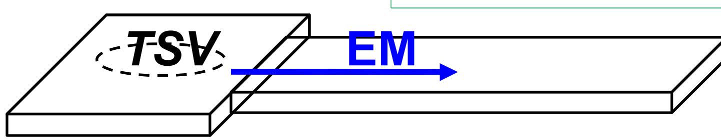


F_{EM}: Electromigration matter flow

F_{BF}: Backflow induced by gradient of matter concentration

V_M: Depleted matter volume

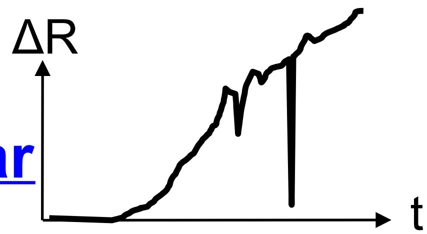
$$\begin{cases} L >> 1 \\ j_{stress} >> 1 \end{cases} \Rightarrow F_{BF}(t) << F_{EM}$$



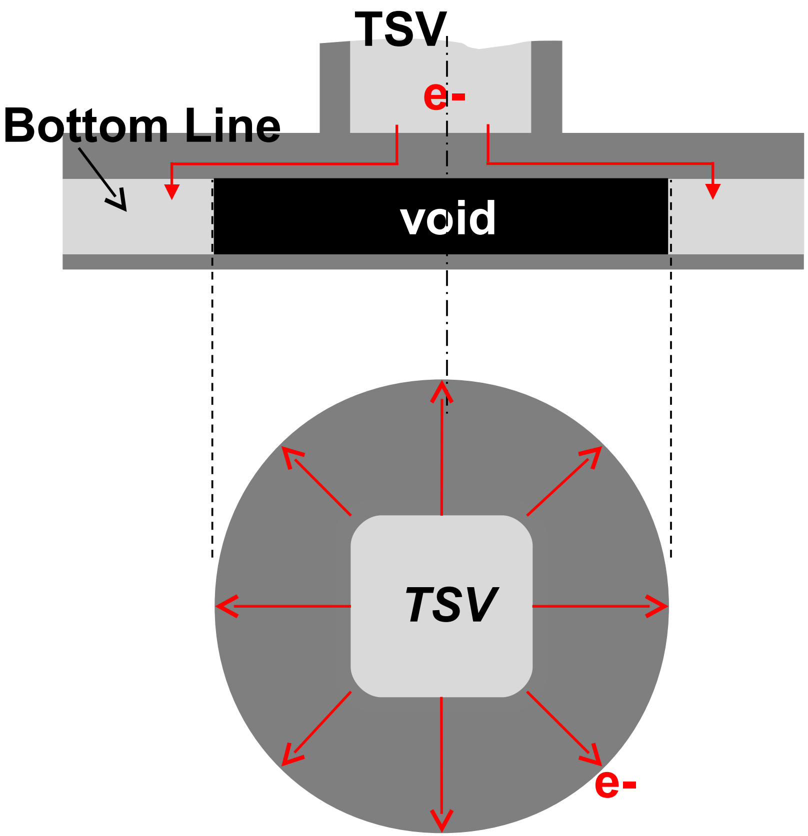
➔ **Constant Flow during test :** $$F = F_{EM}$$

$$V_M(t) = \int_0^t F \cdot dt \quad \Rightarrow \quad V_M(t) = F \cdot t$$

Hypotheses of the model



Assumption 3: TSV bottom section is circular

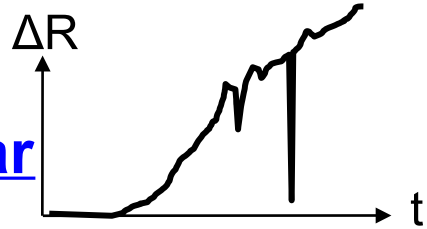


Void larger than TSV bottom section:

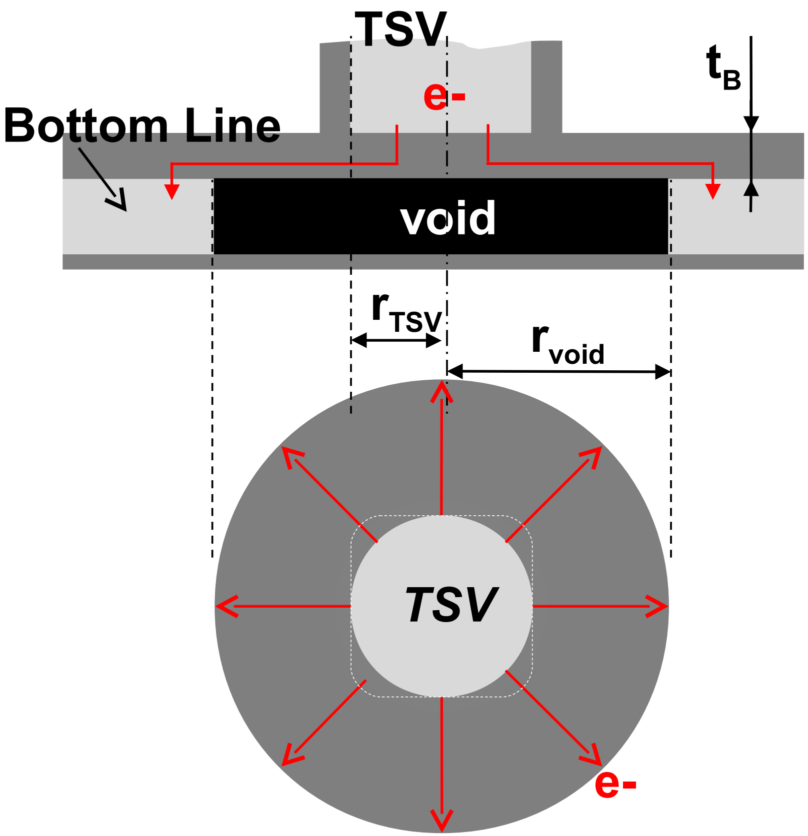
➔ Electrons have to flow through the barrier

$$\Rightarrow \Delta R(r_{Void}) > 0$$

Hypotheses of the model



Assumption 3: TSV bottom section is circular



Void larger than TSV bottom section:

➔ Electrons have to flow through the barrier

Approximation of the circular TSV bottom section enables direct expression of $R_{[\Omega]}$ increase

$$\Rightarrow \Delta R(r_{Void}) = \frac{\rho_B}{2 \cdot \pi \cdot t_B} \cdot \ln\left(\frac{r_{Void}}{r_{TSV}}\right)$$

ΔR: Resistance increase

r_{TSV}: TSV radius

r_{Void}: Void radius radius

t_B: Barrier thickness

ρ_B: Barrier resistiviy