Accelerating Electromigration Aging for Fast Failure Detection for Nanometer ICs

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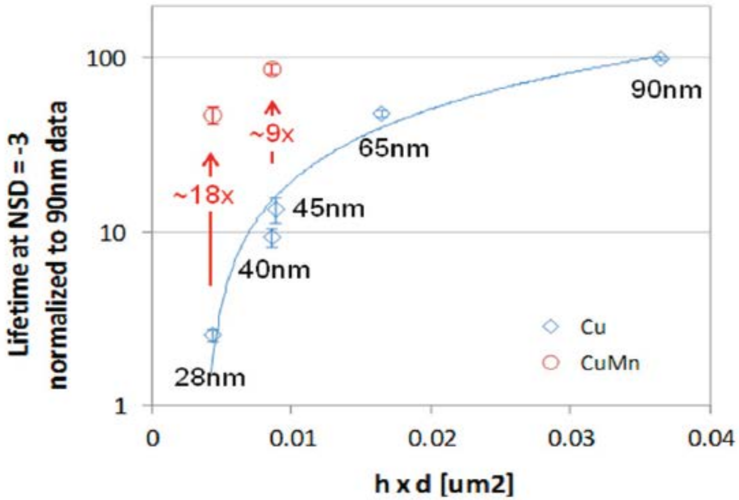
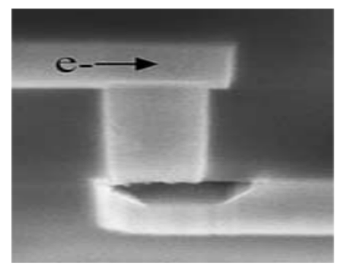
Outline

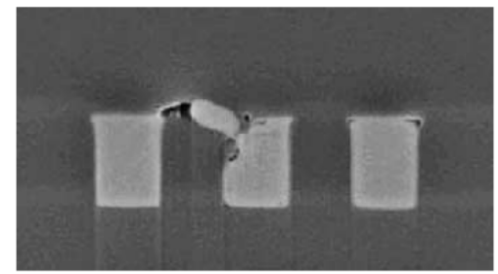
- Introduction
- Review of EM 3-phase stress modeling
  - Review EM physics and stress modeling
  - The recently proposed 3-phase physics-based compact EM model for multi-segment wires
- The new void saturation volume estimation method for general multi-segment wire.
- New configurable reservoir-based EM wearout acceleration
  - Combined temperature and reservoir based EM acceleration study
- Conclusion

The EM crisis predicted for sub-10nm VLSI

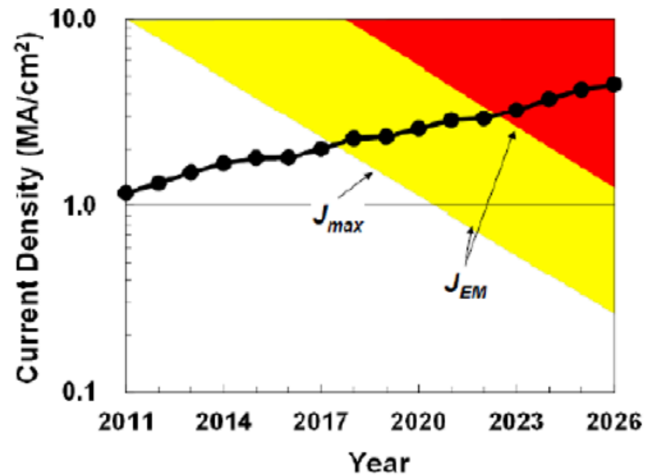


Gall et al, IRPS 2013, EM lifetime at about 0.1% cumulative failure as a function of the product of the line height h and via size d for various technologies.





Both J_{max} and J_{EM} will increase over each generation due decreasing cross section and increased operation Frequencies.

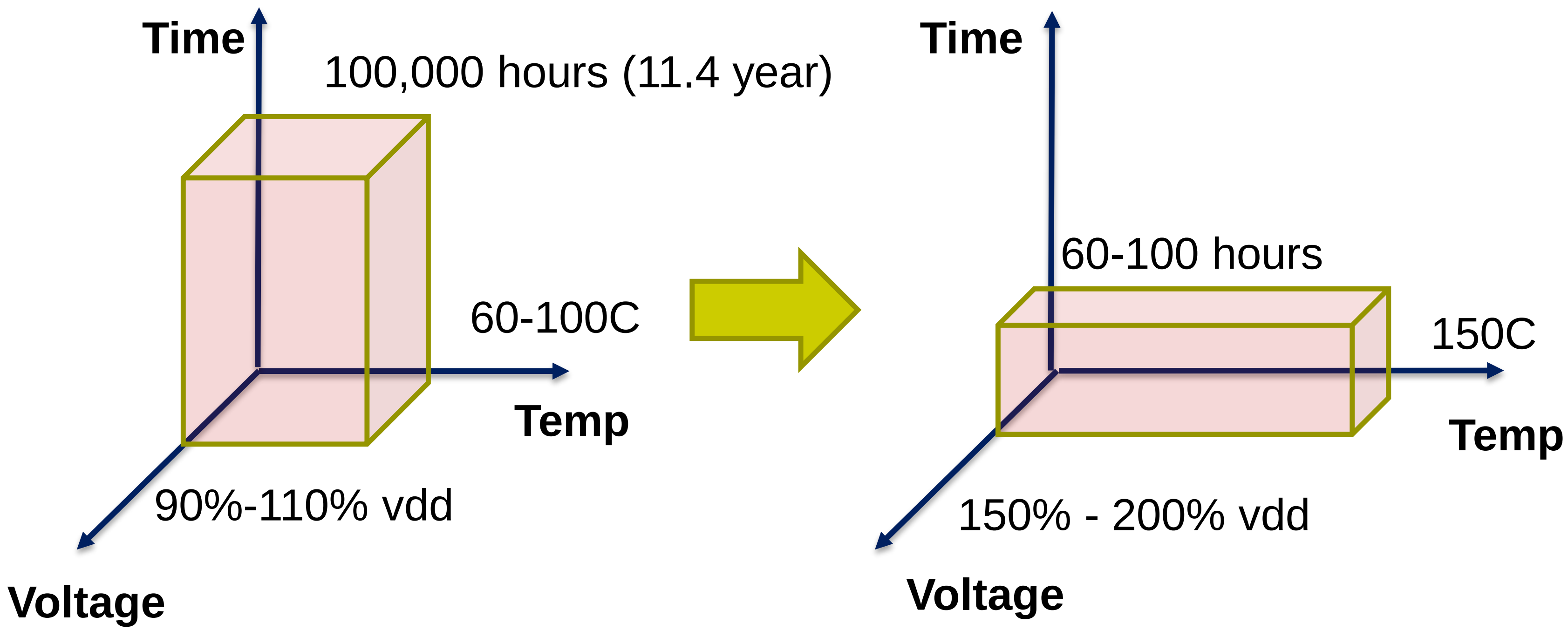


J_{max} is equivalent DC current density
J_{EM} is the maximum current density

Why fast EM wearout acceleration?

- It is important to estimate the EM failure in the accelerated stress conditions for fast EM testing and EM model validation.

How to achieve the 100,000 acceleration so that time to failure is just about 1 hour?



Chip operating space

Stressed conditions

The challenges for fast EM acceleration

- The challenging issue is that how to accelerate the EM failure for a working chip so that other reliabilities such as TDDB, BTI, HCI are still under control.

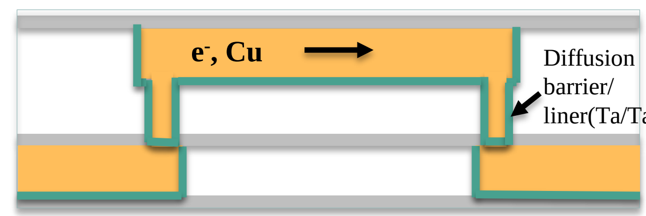
- Need more physics-based EM models for general interconnect wires, which works for wide EM stress conditions.

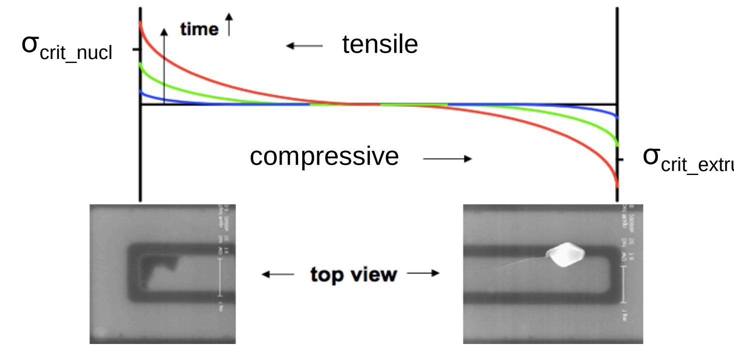
- Recently a number of physics-based EM models have been developed, but no accurate EM models for predict the void saturation volume for a general interconnect tree, which is important for determining the resistance changes in the post-void process.

EM 3-phase stress modeling for multi-segment interconnect wires

EM physics in a nut shell

- **Current induced diffusion**
  - ✧ Cu atoms diffuse with electron wind due to momentum transfer
  - ✧ liners block EM through vias
  - ✧ tensile failure (void) at cathode, compressive failure (hillock) at anode





C. V. Thompson, VMIC 2006, Fremont, CA, USA

- **Immortality in 'short' lines**
  - ✧ steady state
    - vanished atomic flux:
    - linear time-invariant stress along the line
  - ✧ failure will not occur if: $F_{EM} = F_{\nabla\sigma}$

$\sigma_{ss} < \sigma_{crit}$ or $(jL) < (jL)_{crit}$ *"Blech limit"*

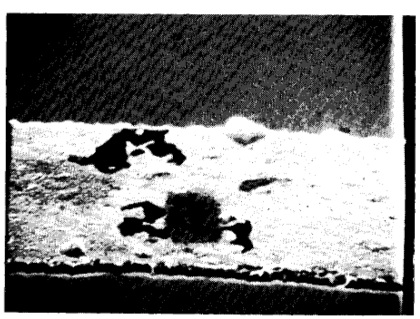
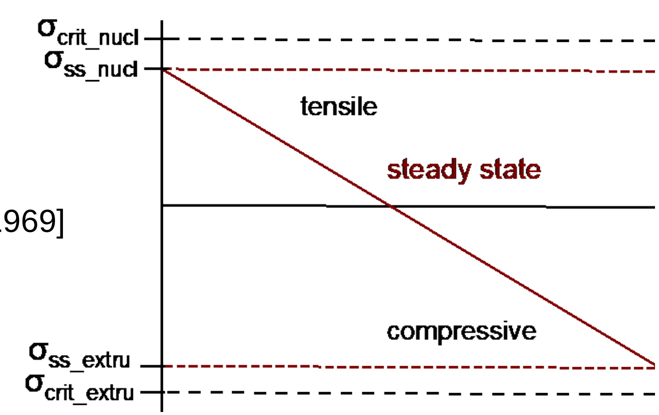


Fig. 3. Voids formed in a ½-mil wide small-grain Al film.

[Black, IEEE Trans Device, 1969]



Traditional EM Assessment

- Mortality check filters out immortal wires using blech limit:

$$(jL)_{imort} \le (jL)_{crit} = \frac{\Omega \sigma_{crit}}{eZ\rho}$$

Ω is the atom volume;
eZ is the effective charge of the migrating atoms;

- MTTF assessment of single mortal wires using Black's equation: $MTTF = \frac{A}{j^n} \exp(\frac{E_a}{kT})$

n is the current density exponent;
E_a is the EM activation energy;

- Shortcomings of traditional method:
  - Does not account for other stress sources, stress contributed by other connected wires, or temperature variations.
  - Overcomes these issues by overestimating EM effect
    - Leads to overdesign which uses more chip area.
    - Can cause longer wire delays making timing signoff difficult.
    - Can lead to further design iterations.

Fundamentals of Physics Based Model [Huang et al. DAC'14].

- The reliability model is built based on stress analysis for void nucleation and void growth .
  - **Nucleation phase:** based on the following dynamic stress

$$\frac{\partial \sigma}{\partial t} = \frac{\partial \sigma}{\partial x}\left[\frac{D_a B\Omega}{kT}\left(\frac{\partial \sigma}{\partial x} + \frac{\rho j e Z}{\Omega}\right)\right]$$

  - **Void growth phase:** The voids continue to accumulate inside the power grids, which leads to the wire resistance change.
- Eventually, the wire resistances of power grid reach a certain amount, causing excessive IR drops and the power grid starts to fail.

Korhonen's Equations

Stress field calculation:

$$PDE: \frac{\partial\sigma}{\partial t} = \kappa\frac{\partial^2\sigma}{\partial x^2} + \kappa\frac{\partial^2\sigma}{\partial y^2}, \qquad at\ 0 < t < t_{nuc}$$

Nucleation Phase Boundary Conditions:

$$BC: \frac{\partial\sigma}{\partial x}(0,t) = G_x, \qquad \frac{\partial\sigma}{\partial y}(0,t) = G_y, \qquad at\ 0 < t < t_{nuc}$$

$$BC: \frac{\partial\sigma}{\partial x}(L,t) = -G_x, \qquad \frac{\partial\sigma}{\partial y}(L,t) = -G_y, \qquad at\ 0 < t < t_{nuc}$$

$$IC: \sigma(0) = [\sigma_1(0), \sigma_2(0), \dots, \sigma_n(0)], \qquad at\ t = 0$$

$$\kappa = D_a B\Omega/kT,\ G_x = \frac{eZ\rho j_x}{\Omega},\ G_y = \frac{eZ\rho j_y}{\Omega}$$

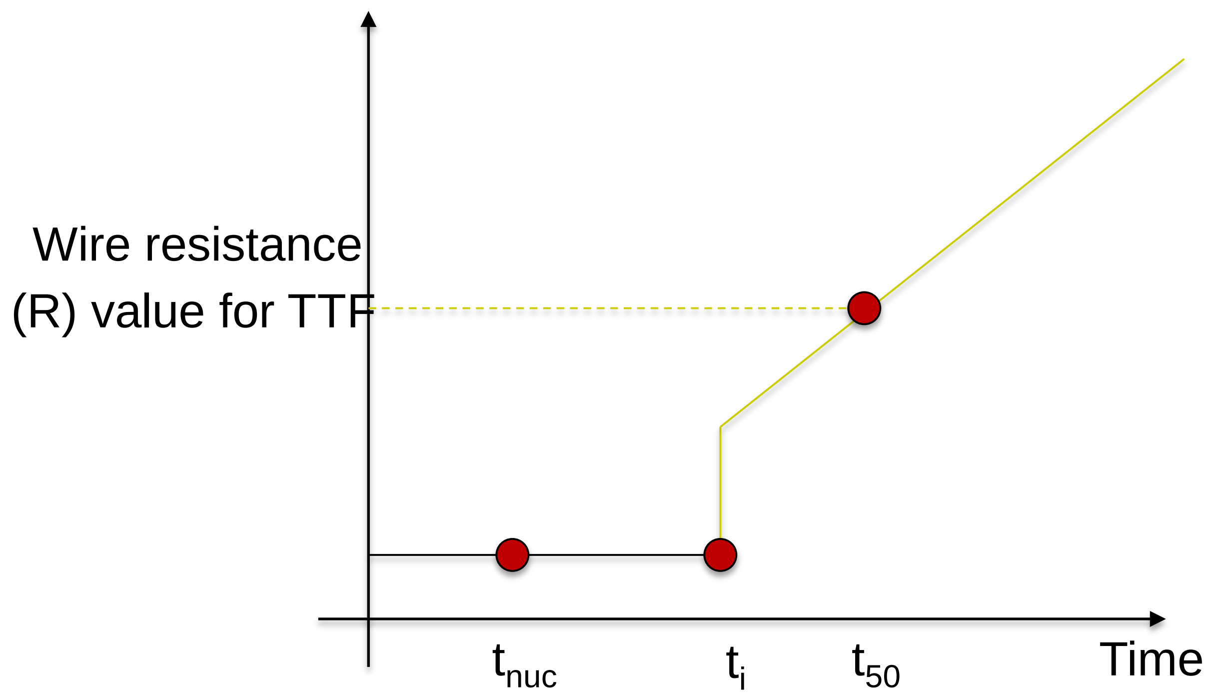
Growth Phase Boundary Condition:

$$BC: \frac{\partial\sigma}{\partial x}(x_{nuc}, t) = \frac{\sigma(x_{nuc}, t)}{\delta}, \qquad at\ t_{nuc} < t < \infty$$

Where: $\boldsymbol{D_a = D_0 e^{Ea/kT}}$: effective atomic diffusivity, $\boldsymbol{E_a}$: activation energy, **T**: absolute temperature, **k**: Boltzmann constant, **B**: effective bulk elastic modulus, $\boldsymbol{\Omega}$: atomic lattice volume, **e**: electron charge, **eZ**: effective charge of migrating atoms, $\boldsymbol{\rho}$: wire electrical resistivity, **j**: current density, **x**: location, **y**: location, **t**: time, δ is width of void interface, which is very small

Recently proposed physics-based 3-phase EM failure process [Tan, Integration 2018]

- EM failure kinetics have three distinctive phases



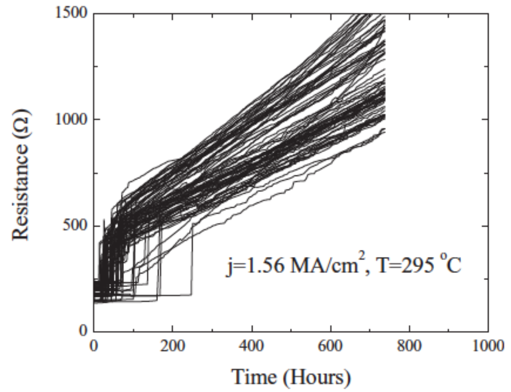


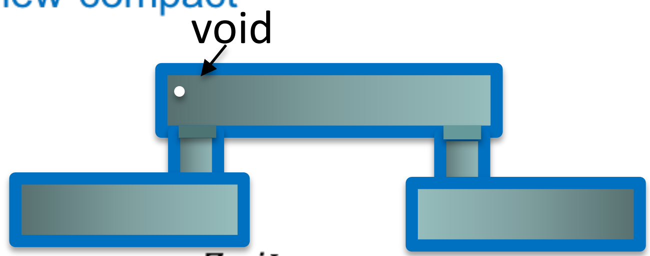
FIG. 3. Resistance vs time for samples stressed at 1.56 MA/cm^2 and 295 °C.

Filippi et al, J. Appl. Phys. 2010.

t_n : nucleation time, time for void to be nucleated
t_i – t_n: the incubation period, time for void to reach the critical void size
t_{50}: the median time to failure, time for failure determined.
The sudden disruptive resistance change typically is due to Joule heating in the liner layer as current flows through liner (so-called liner redundancy)

New scalable physics-based 3-phase EM model [Tan, Integration 2018]

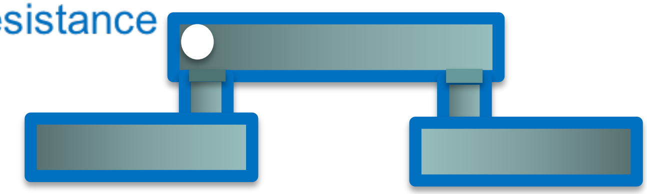
- <u>Nucleation phase</u>: by Korhonen's equation (1) or new compact EM model for nucleation phase (2)



$$\frac{\partial \sigma}{\partial t} = \frac{\partial \sigma}{\partial x}\left\{\frac{D_a B\Omega}{K_B T}\left(\frac{\partial \sigma}{\partial x} + \frac{\rho j e Z}{\Omega}\right)\right\} \quad (1)$$

$$t_n = \frac{L^2}{2D_0}\frac{K_B T}{\Omega B}\exp\left\{\frac{(E_v + E_{VD} - \Omega^* \sigma_{crit})}{K_B T}\right\}\left(\frac{\gamma \alpha^2}{2}\right), \alpha = \frac{\sigma_{crit} - \sigma_T}{\beta}, \beta = \frac{eZ\rho j L}{2\Omega} \quad (2)$$

- <u>Incubation phase</u>: void grow to critical void size, no resistance change.

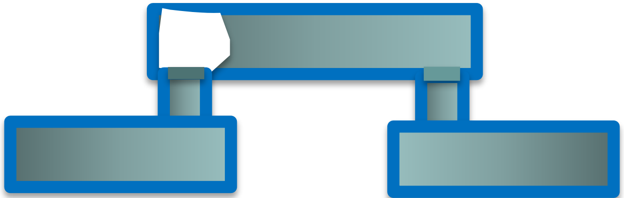


$$t_i - t_n = \frac{\Delta L_{crit}}{v_d}, \quad (3)$$

ΔL_{crit} is the critical void size, which depends on the layout and technology.

$$v_d = \frac{D_{eff}}{K_B T} F_e = \frac{D_{eff}}{K_B T} eZ\rho j = \frac{D_0}{K_B T} e^{\left\{-\frac{E_a}{K_B T}\right\}} eZ\rho j \quad (4)$$

- <u>The growth phase</u>: void growth larger than the cross-section of wire, resistance starts to change.

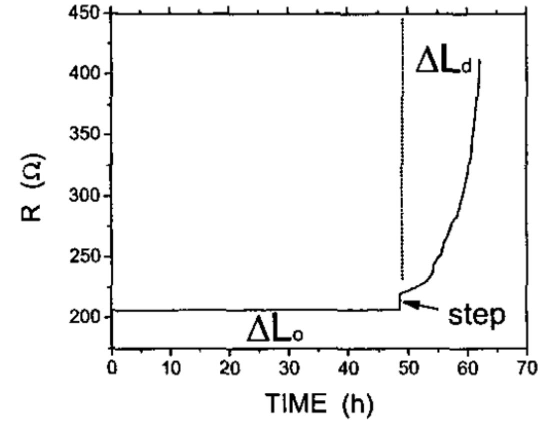


$$\Delta r(t) = v_d (t - t_i)\left\{\frac{\rho_{Ta}}{h_{Ta}}\left(\frac{1}{2H+W}\right) - \frac{\rho_{Cu}}{HW}\right\} \quad (5)$$

But this model mainly focus on singe wire

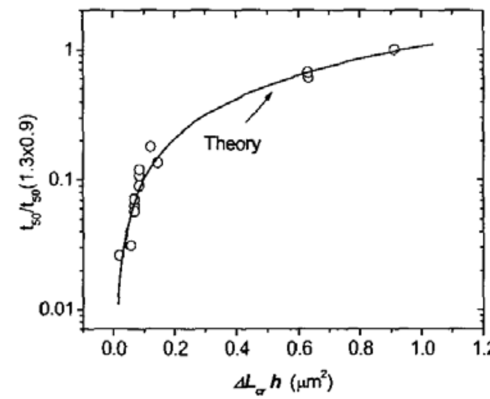
The major differences and highlight of the 3-phase EM model

- The 3-phase model is more close to the EM physics and stress evolution process by considering the practical void growth process.
  - The incubation phase was experimentally observed and reported (C.-K. Hu *et al*, IRPS, 2004 (see the right top figure) and L. Zhang Ph.D. thesis 2010)



C.K. Hu, IRPS 2004

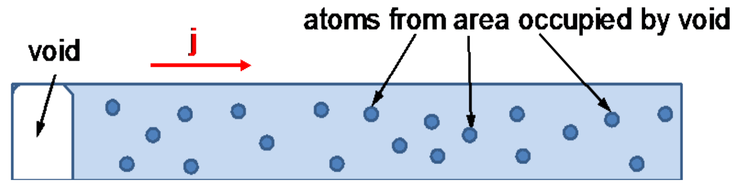
- The new 3-phase model predicts more accurately the wire resistance changes over time (than the 2-phase model) and it also considers joule heating effect, which was ignored by existing models. <u>The model also consistent with the predicted EM lifetime changes over technology generation (see right bottom figure) as **incubation phase** dominates the time to failure in this case.</u>

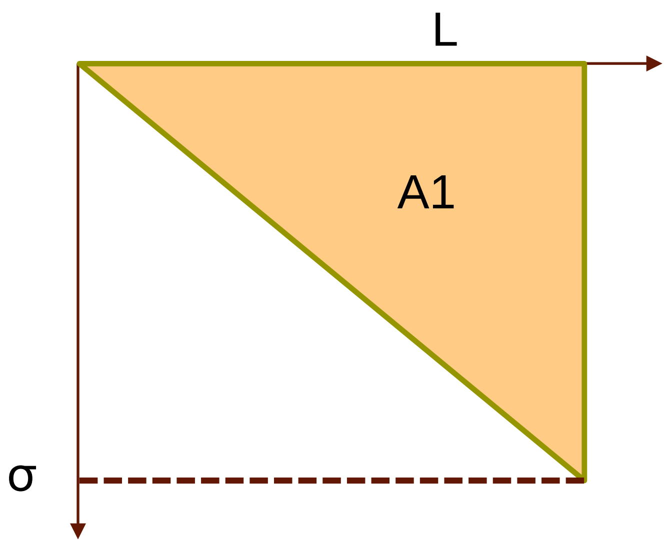


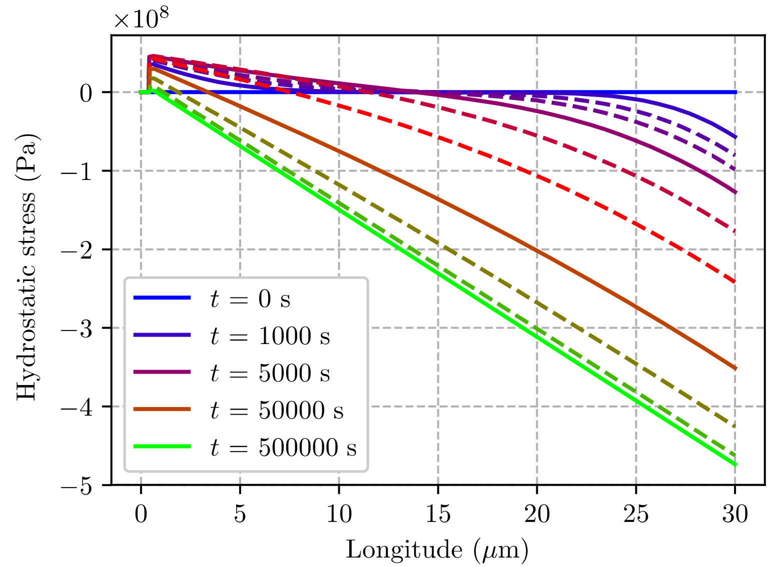
C.-K. Hu, IRPS, 2004. The predicted normalized lifetime vs. experimental data for Cu interconnect

- The new 3-phase model gives more accurate current exponent (n) values for three phases, which is consistent with experimentally observed results and <u>is more scalable over wide stress conditions</u>. The 2-phase model by X. Huang gives incorrect *n* values as we show.

Saturation volume in the post-voiding process







$$V_{sat} = A\left(\frac{\sigma_{init}L}{B} + \frac{j\rho e Z^{*} L^{2}}{2\Omega B}\right)$$

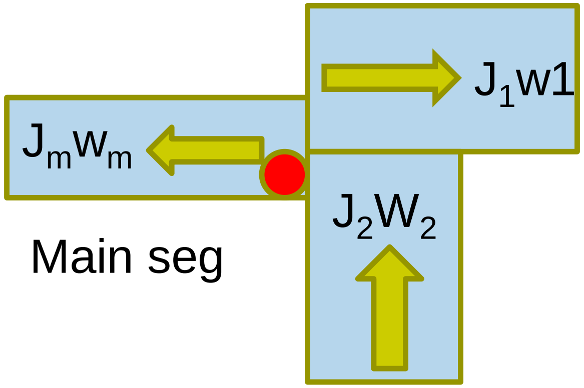
Void grows will saturate when steady-state is reached

But this formula only works for one single wire

Proposed Incubation phase for multi-segment wires

- Electron wind at each segment can accelerate or slow down the void growth based on their directions.

- A equation to calculate v_d for multi-segment tree is developed in this work



$$v_d = \Omega J_m^* = \Omega \frac{1}{W_m} \sum_i J_i W_i = \frac{D_a e Z \rho}{kTW_m} \sum_i j_i W_i$$

Essentially we compute the averaged flux for the main segment

- Here j_i and W_i are current density and width of i_{th} segment. W_m is the width of the main segment where void is formed. J_m is the total flux impact on the main segment. Here, we use $J_m^* = \frac{1}{W_m} \sum_i J_i W_i$ to compute the effective atomic flux J_m on the main segment

When one segment case, we get the same equation as before

$$v_d = \frac{D_a e Z \rho j}{kT}$$

The growth phase for multi-segment wire

- Growth phase start when stress reach critical level.
- Resistance start change in that phase.
- Time of growth phase can be calculated as

$$t_{50} - t_i = \frac{\Delta R(t)}{v_d[\frac{\rho T_a}{h_{Ta}(2H + W_m)} - \frac{\rho C_u}{H W_m}]}$$

  - ρ_{Ta} and ρ_{Cu} are the resistivity's of the (barrier) liner material (Ta, for instance) and copper respectively, W_m is the line width of the segment void is formed, H is the copper thickness, and h_T a is the liner layer thickness, ΔR(t) is the given resistance change criteria

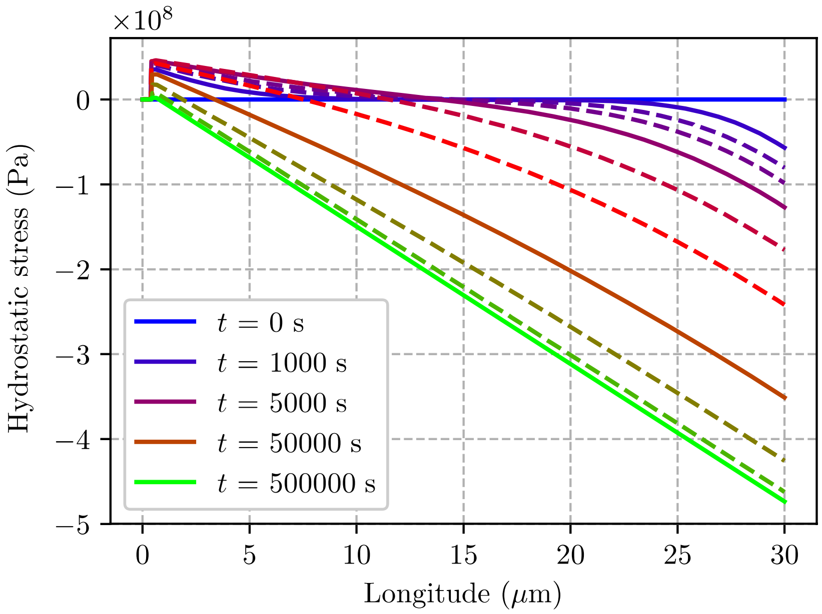
The new void saturation volume estimation for general multi-segment wire

Overview of saturation volume

- Saturation void volume in the steady state is critical for the immortality check of a wire.
- Void volume satisfies atom conservation equation.

$$V_v(t) = A \int_{\Omega_L} \frac{\sigma(V,t)}{B} dV$$

  - Ω_L is the volume of the remaining interconnect. For one dimensional and single segment case with wire length L.

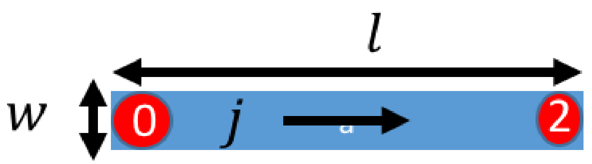


The typical stress evolution on a 30 μm copper wire computed by finite element analysis.

Saturation length for single wire

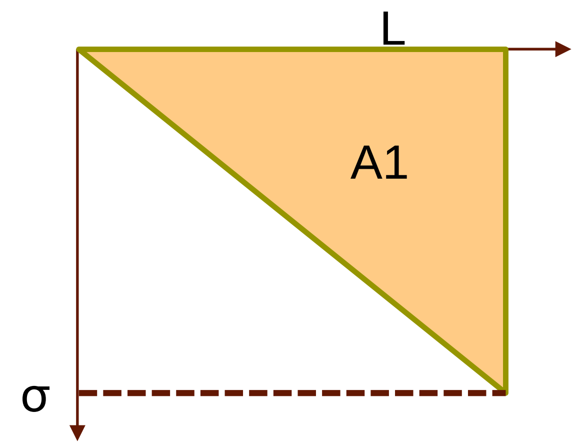
- In the steady-state, in 1D case, the saturation length of the void is:

$$L_{sat} = A\int_0^L \frac{\sigma(x)}{B}dx = \frac{A\sigma_{max}L}{2B}$$



- Maximum stress can be expressed as :

$$\sigma_{max} = \frac{j\rho eZ^*L^2}{2\Omega} = \frac{VeZ^*L}{2\Omega}$$



- Initial length can be expressed with initial stress:

$$L_{init} = \frac{A\sigma_{init}L}{B}$$

- Combine these equations, saturation length can be updated as :

$$L_{sat} = A\left(\frac{\sigma_{init}L}{B} + \frac{j\rho eZ^*L^2}{2\Omega B}\right) = A\left(\frac{\sigma_{init}L}{B} + \frac{VeZ^*L}{2\Omega B}\right)$$

V is the segment voltage for the wire segment

Saturation area estimation for one segment in a multi-segment wire

- Stress between cathode and anode can be expressed as:

$$\sigma_c - \sigma_a = \frac{(V_a - V_c)eZ}{\Omega} = \frac{jL\rho eZ}{\Omega}$$

- We consider the area of the void, A_i, For each segment the saturation area can be calculated by the stress and length of the segment.

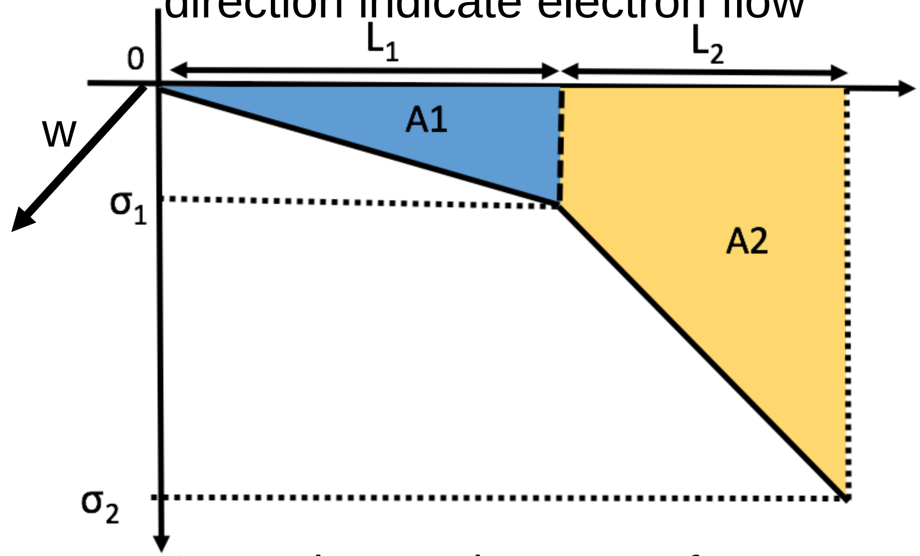
A two-segment wire and the direction indicate electron flow

- Saturation area of each segment can be calculated as:

$$A_{sat,i} = \left(\left(-\sigma_{c,i}\right) + \left(-\sigma_{a,i}\right)\right) \times \frac{L_i W_i}{2B}$$

$$= \left(-2\sigma_{c,i} + \frac{V_i eZ}{\Omega}\right) \times \frac{L_i W_i}{2B}$$

$$= \left(-2\sigma_{c,i} + \frac{j_i L_i eZ}{\Omega}\right) \times \frac{L_i W_i}{2B}$$



Stress integration area of a two-segment wire

Saturation volume for a multi-segment wire

- For a general multi-segment wire, assume that void is formed in the cathode node of one segment and all the initial stress are zero, then the saturation volume of the void V_{sat} can be computed as:

$$A_{sat} = \sum_i A_{sat,i} = \sum_i \left(-2\sigma_{c,i} + \frac{V_i eZ}{\Omega}\right) \times \frac{L_i W_i}{2B}$$

$$= \sum_i \left(-2\sigma_{c,i} + \frac{j_i L_i eZ}{\Omega}\right) \times \frac{L_i W_i}{2B}$$

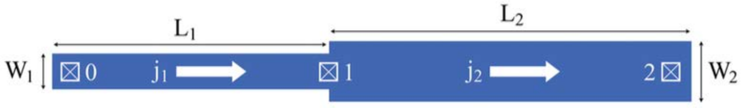
- Here $A_{sat,i}$, $\sigma_{c,i}$, j_i , L_i and W_i are void area, stress at cathode current density, length and width for the ith segment. If A_{sat} is smaller than the area of via, resistance will never increase. The interconnect tree can be considered as immortal in this case.

Two segment wire example

- For a two segment wire stress at node 1 and 2 are:

$$\sigma_1 = 0 - \frac{(V_1 - 0)eZ}{\Omega} = -\frac{j_1 L_1 \rho eZ}{\Omega}$$

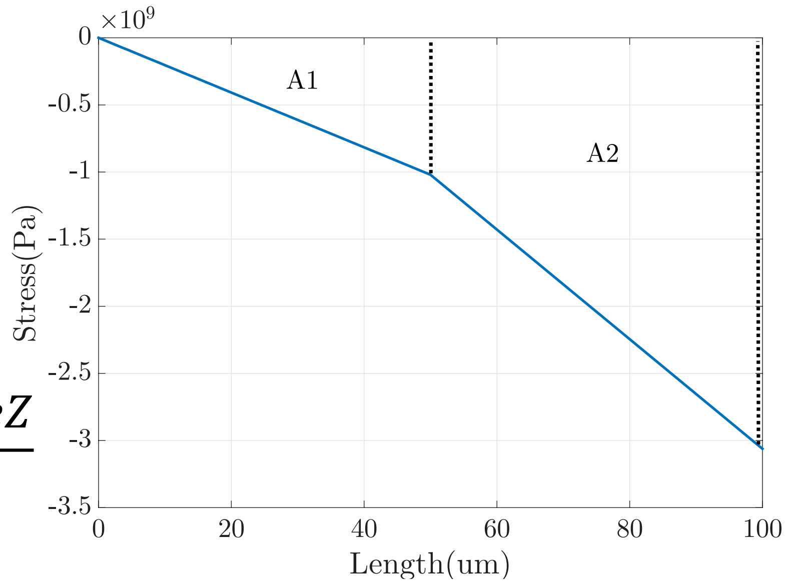
$$\sigma_2 = \sigma_1 - \frac{(V_2 - V_1)eZ}{\Omega} = -\frac{(j_1 L_1 + j_2 L_2)\rho eZ}{\Omega}$$



- The saturation volume is:

$$A_{sat,2seg} = \frac{-\sigma_1 L_1 W_1 + (-\sigma_1 - \sigma_2) W_2 L_2}{2B}$$

$$= \frac{j_1 L_1^2 W_1 \rho eZ}{2B\Omega} + \frac{(2j_1 L_1 + j_2 L_2) L_2 W_2 \rho eZ}{2B\Omega}$$



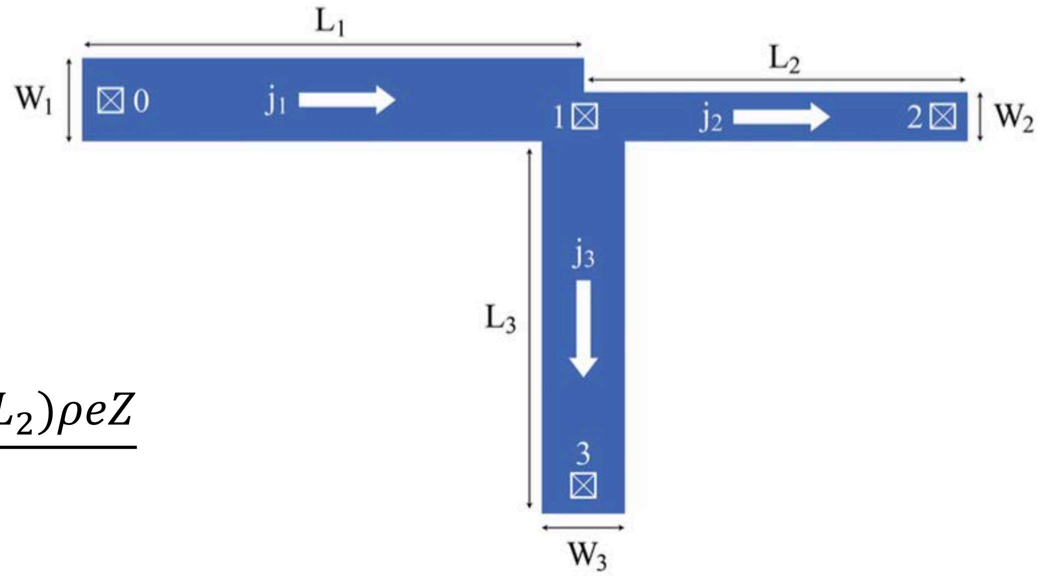
Three segment wire example

- For a T-shape three segment wire stress at all nodes are:

$$\sigma_1 = -\frac{V_1 eZ}{\Omega} = -\frac{j_1 L_1 \rho eZ}{\Omega}$$

$$\sigma_2 = \sigma_1 - \frac{(V_2 - V_1)eZ}{\Omega} = -\frac{(j_1 L_1 + j_2 L_2)\rho eZ}{\Omega}$$

$$\sigma_3 = \sigma_1 - \frac{(V_3 - V_1)eZ}{\Omega} = -\frac{(j_1 L_1 + j_3 L_3)\rho eZ}{\Omega}$$



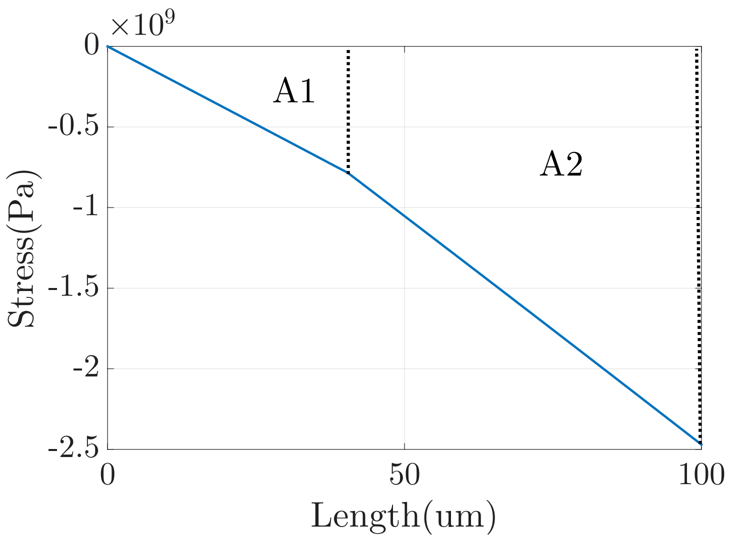
T-shape structure

Three segment wire example (cont'd)

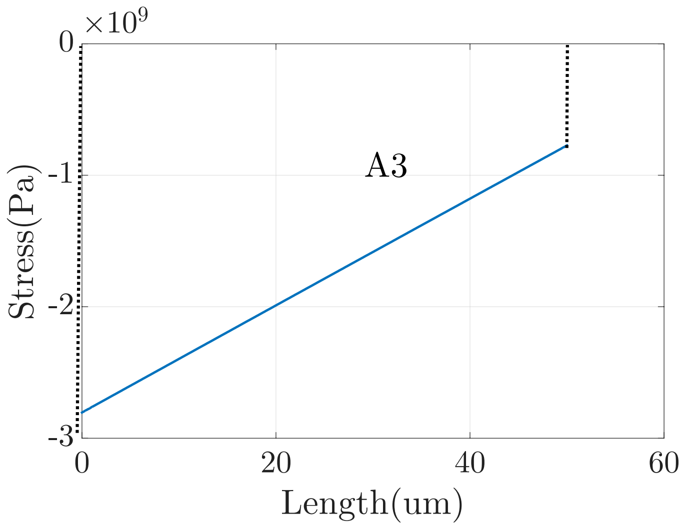
- Saturation volume can be calculated as:

$$A_{sat,2seg} = \frac{-\sigma_1 L_1 W_1 + (-\sigma_1 - \sigma_2) L_2 W_2 + (-\sigma_1 - \sigma_3) L_3 W_3}{2B}$$

$$= \frac{j_1 L_1^2 W_1 \rho e Z}{2B\Omega} + \frac{(2j_1 L_1 + j_2 L_2) L_2 W_2 \rho e Z}{2B\Omega} + \frac{(2j_1 L_1 + j_3 L_3) L_3 W_3 \rho e Z}{2B\Omega}$$



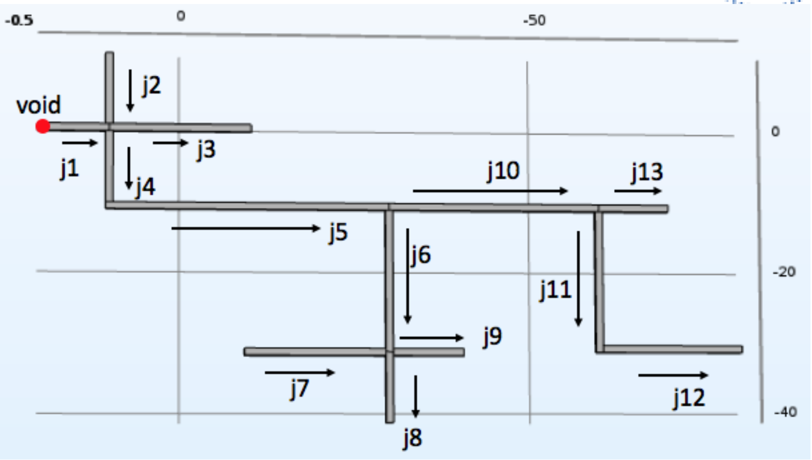
Stress on horizontal segment 0-2



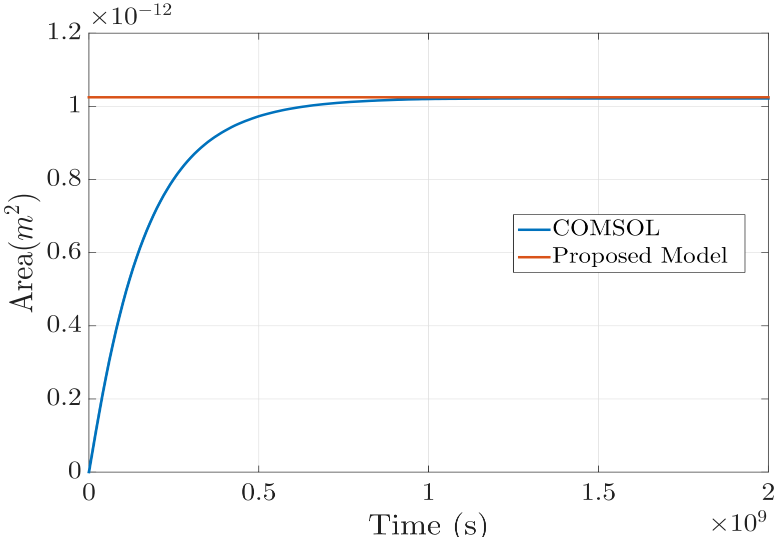
Stress on vertical segment 1-3

Multi-segment wire example

- Apply proposed method to a complex structure.
- There is only 1.3% error with proposed method.



Complex multi-segment structure.



Compare saturation volume with COMSOL result for 13-segment wire

Acceleration for structure with reservoir

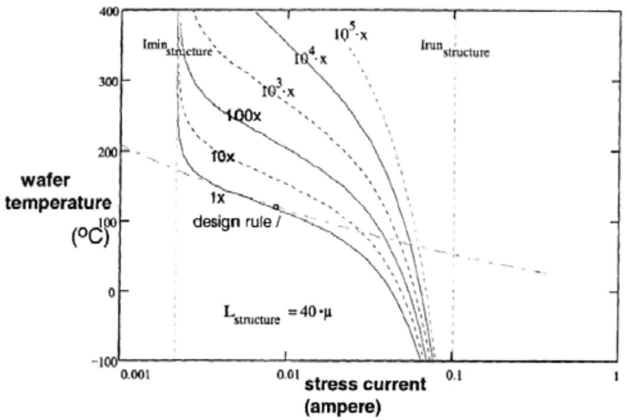
EM Wearout acceleration

- In general, VLSI chips are designed for a lifetime of 10 years or more
- However, it is not practical to wait for 10 years to test EM effects on these chips.
- Accelerated testing and stressing are require such that the testing process can be completed within an hour or few hours.
- 10^5X acceleration is required to reduce lifetime from 10 years to 1 hour.
- Note, the stressing conditions should be designed such that the chips only fails under EM, not other reliability effects.

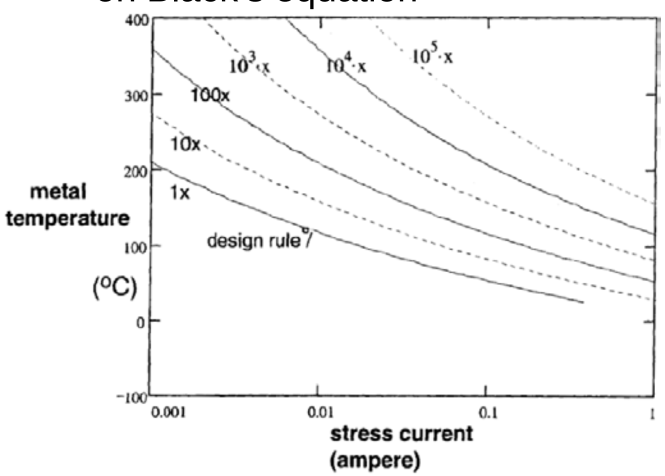
Traditional EM Acceleration techniques

- Two ways of accelerating EM effects.
  - Apply high current density
  - Apple high temperature
- However there are limitations for both high current density and high temperature
  - High current density can lead to thermal runaway
  - High temperature will lead to other failure effects such as TDDB and chemical reaction such as oxidation of copper.
- Our solution is a hybrid of the two techniques that guarantees failure due to EM while staying within the thermal and current restrictions.

W.K. Meyer, Ph.D. Thesis, 2004.
The measured iso-acceleration curve

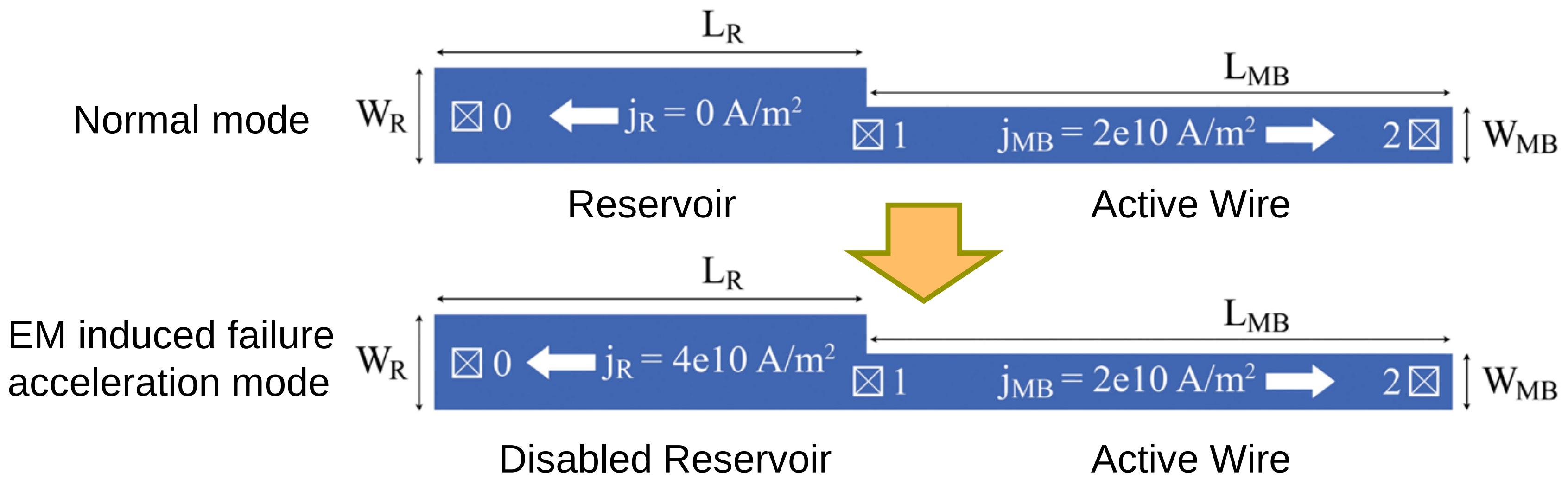


The predicted acceleration factors based on Black's equation

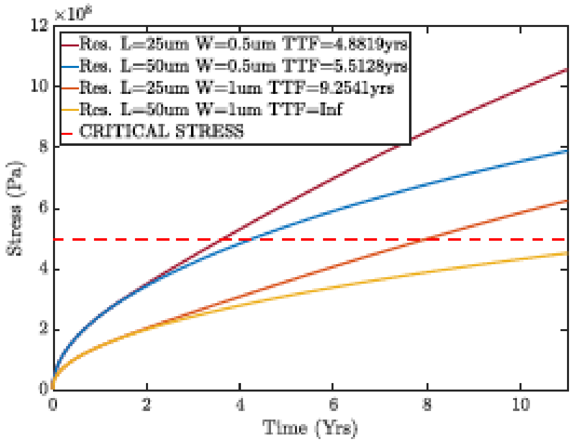


Reservoir-based acceleration

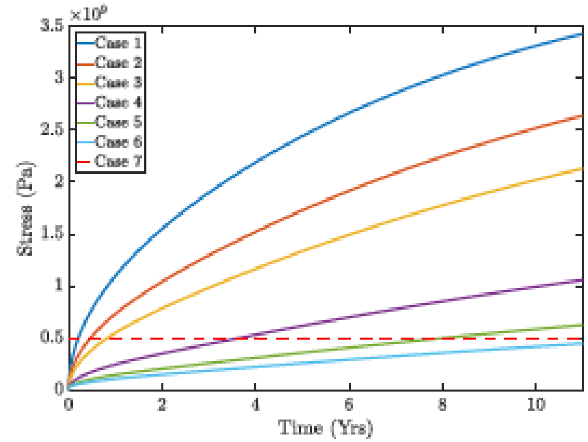
- Adding reservoirs to the cathode end of an interconnect segment extends its EM lifetime.
- If a reservoir can be disabled, the stress at the cathode will increase significantly, thus accelerating nucleation time.
- Additionally, the new atom flux generated from the reservoir segment will also contribute to accelerating void growth time.



Reservoir width and length impacts



(a) Length impact on TTF



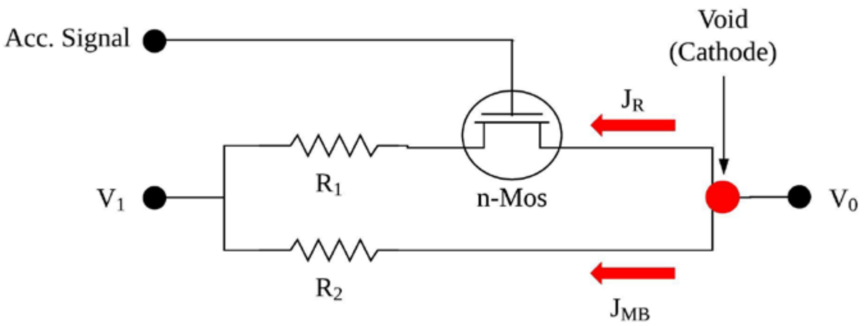
(b) Width impact on TTF

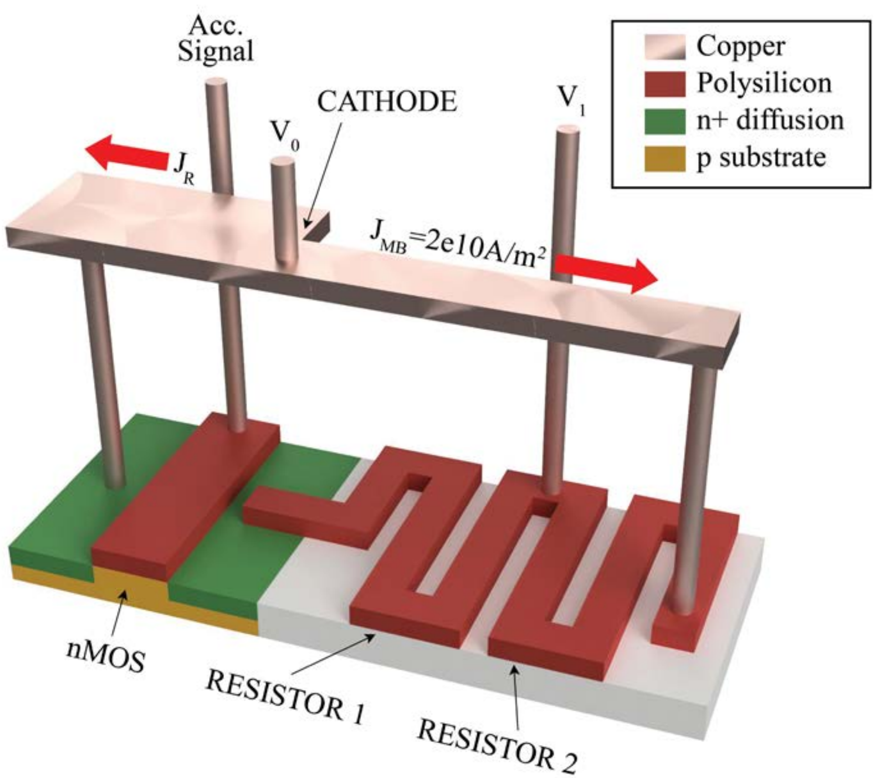
Case	L_R (um)	W_R (um)	TTF (hrs.)
1	0	0	1.26×10^4
2	25	0.07	1.49×10^4
3	25	0.14	1.81×10^4
4	25	0.5	4.28×10^4
5	25	1	8.11×10^4
6	25	1.5	$9.64 \times 10^4+$
7	CRITICAL STRESS		

(a) Reservoir length impact on TTF, (b) Reservoir width impact on TTF

The proposed reconfigurable reservoir-based EM acceleration technique

- We propose a novel EM acceleration structure consisting of a two segment wire, one MOSFET device and two resistors to configure the currents in the wires.
- One of the wire segments acts as a reservoir during normal operation until it is disabled when an acceleration signal activates the NMOS device.
- Once acceleration is triggered, the reservoir becomes an active wire, accelerating void nucleation at the cathode.





Acceleration results

- The desired accelerated TTF can be achieved by configuring the dimensions and current density of the reservoir segment.
- Using the proposed structure can be configured for an EM lifetime of 10+ years but, at the same time, be made to fail within few days by triggering the acceleration signal.

NORMAL VERSUS ACCELERATED TTF UNDER DIFFERENT CONFIGURATION

L_R (um)	W_R (um)	TTF (Yrs.)	Acc. TTF (Yrs.)	Acc.
25	0.7	6.57	0.18	37.52X
25	0.8	7.46	0.16	46.91X
25	0.9	8.36	0.15	56.09X
25	1	9.25	0.14	65.63X
25	1.5	11+	0.11	98.21X+
25	2	11+	0.10	111.11X+
50	0.7	8.58	0.175	49.02X
50	0.8	10.46	0.159	65.76X
50	0.9	11+	0.15	73.83X+
50	1	11+	0.14	78.01X+
50	1.5	11+	0.11	98.21X+
50	2	11+	0.10	111.11X+

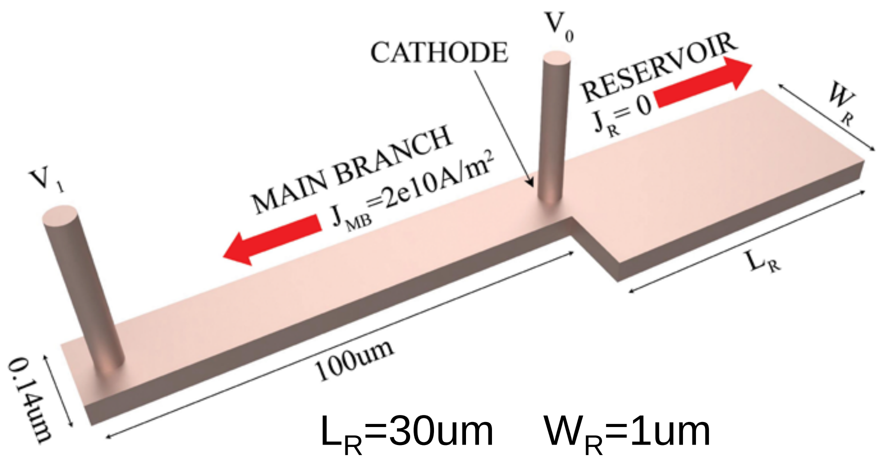
IMPACT OF j_R ON EM FAILURE ACCELERATION

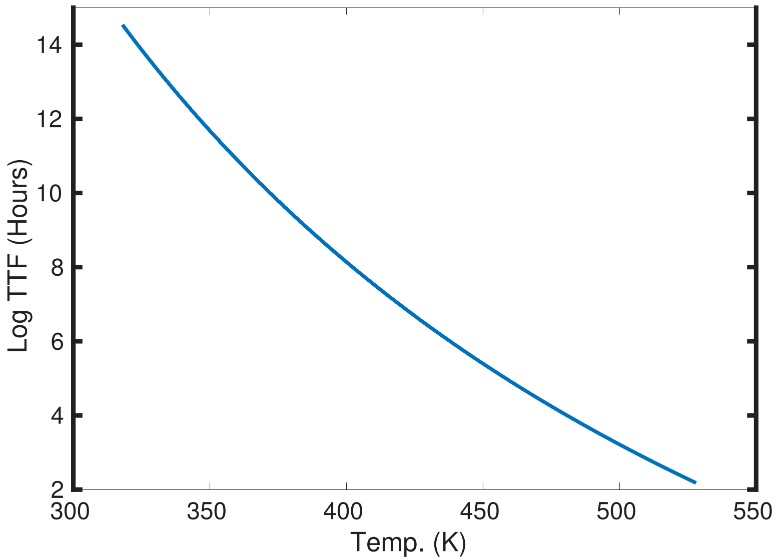
$j_R(A/m^2)$	Acc. TTF (Yrs.)	Acc.
0	9.25	baseline
0.5e10	3.69	3.5X
1.0e10	0.99	9.4X
1.5e10	0.54	17.3X
2.0e10	0.36	25.7X
2.5e10	0.27	34.7X
3e10	0.21	44.8X
3.5e10	0.17	55.3X
4.0e10	0.14	65.7X

Temperature-based acceleration

- Increasing temperature has a significant impact on EM acceleration.
- Based on our 3-phase EM model, 10% increase in temperature yields 10X decrease in EM lifetime (exponential relationship).
- However, we need to operate within the temperature limitations of VLSI chips to ensure the failure happens because of EM, not other reliability effects.
- For instance, for typical CMOS circuits, if the maximum temperature is about 150C and normal use temperature is 60C (Celsius), the maximum acceleration one can achieve is about 323X by rising temperature only.

Temperature-based acceleration



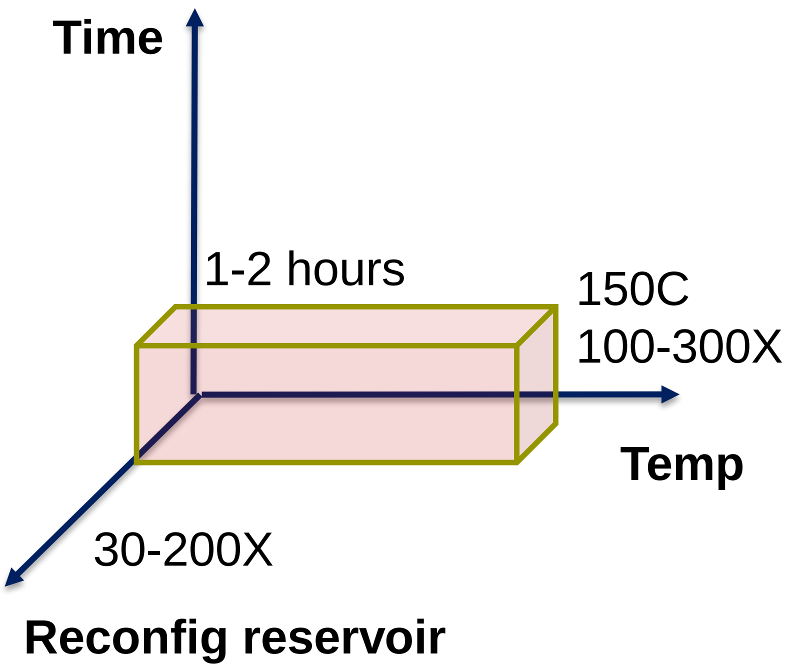


Temp. (K)/(C)	TTF (Hours)	Temp. (K)/(C)	TTF (Hours)
318K / 44.9C	2.06e6	423.2K / 150.1C	880.5
349.8K / 76.7C	1.19e5	465.6K / 192.5C	101.3
384.8K / 111.7C	9038	512.2K / 239.1	15.6

Similar to the reservoir-based method, this method also yields an acceleration from 10+ years to a few days within the 150C limit

Combined reservoir-based and temperature-based acceleration

- By combining the two techniques, it is possible to accelerate EM induced failure from 10+ years (normal case) to within a few hours (accelerated case).



Stressed conditions

TOTAL ACCELERATION BY COMBINED RESERVOIR-BASED AND TEMPERATURE-BASED ACCELERATION

$j_R(A/m^2)$	Temp. (K/C)	TTF (hrs)	Acc.
0	353.00K/79.85C	9.63×10^4	baseline
7e10	367.03K/93.88C	126.62	761.02X
8e10	381.16K/108.01C	38.79	2484.15X
9e10	395.09K/121.94C	13.14	7333.33X
10e10	409.12K/135.97C	4.83	19950.31X
11e10	423.15K/150.00C	1.92	50187.50X

Configuration

L_{MB}=100um W_{MB}=0.14um J_{MB}=2x10^4A/m^2

L_R=50um W_R=2um

Conclusion

- Proposed a novel 3 phase EM model for general interconnect wires
  - Proposed a new a new equivalent void edge velocity computation method for incubation and growth phase for general multi-segment wire
  - Proposed a new saturation volume/area model for general multi-segment wire
- Proposed a new and novel reconfigurable reservoir based EM acceleration techniques
  - Less sensitive to the stress conditions
  - Acceleration is highly tunable via structure and current density parameters
  - Combined temperature and reservoir-based EM condition can lead to 10^5 acceleration

Questions???