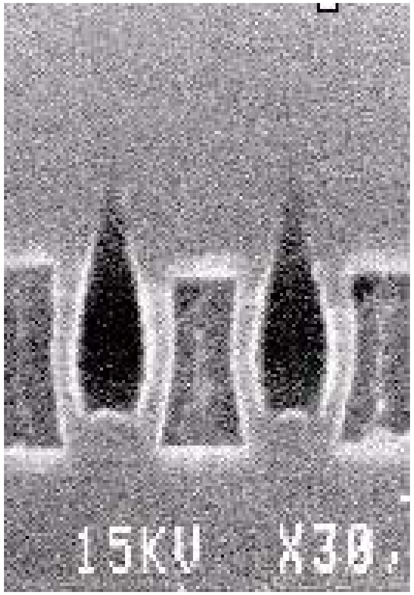
Use of Air-Gaps as a Low-K Dielectric

Benjamin P. Shieh, K.C. Saraswat,
M.D. Deal, and J.P. McVittie
The Center for Integrated Systems, Stanford University

Outline

- Background and Motivation
- Electrical Performance
- Integration Issues
- Thermal Reliability
- Electromigration Reliability
- Summary

Why Air Gaps ?



- Dielectric constant, K, approaching 1.
- Reduces dominating line to line capacitance.
- Interlevel SiO_2 left intact.
- Simple integration.
- Compatible with scaling trends - air gaps easier to form with higher aspect ratios.

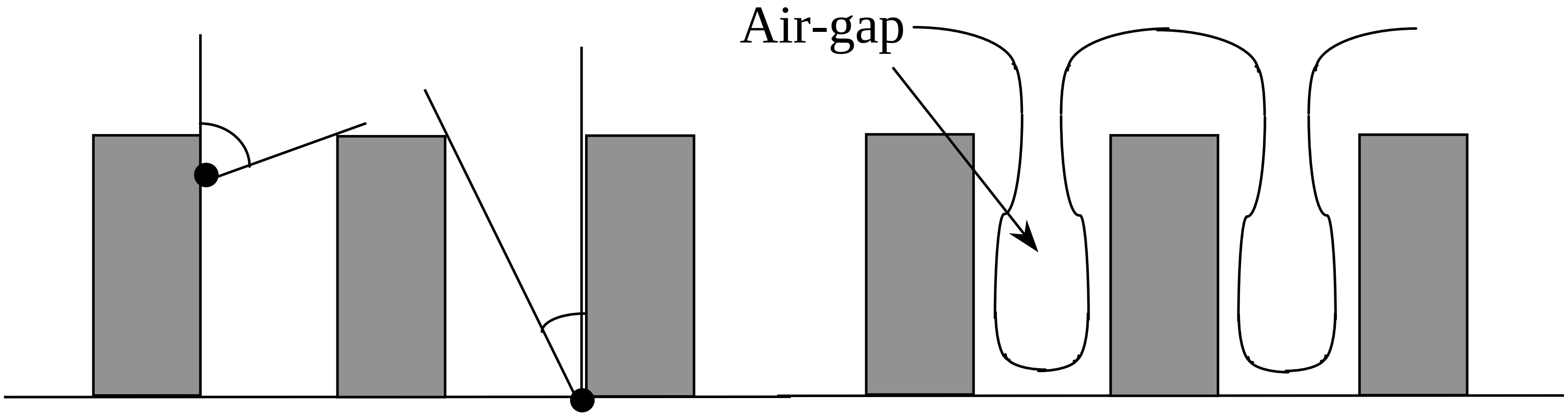
- Good vehicle to study tradeoffs between performance & reliability

Environmental Impact

- No new materials or precursors
  - – SiH_4, O_2, Ar
  - – can use current toolsets (PECVD, HDP-CVD)
  - – do not need new etch or CMP processes
- Known environmental issues
  - – chamber clean: presently worked on by others

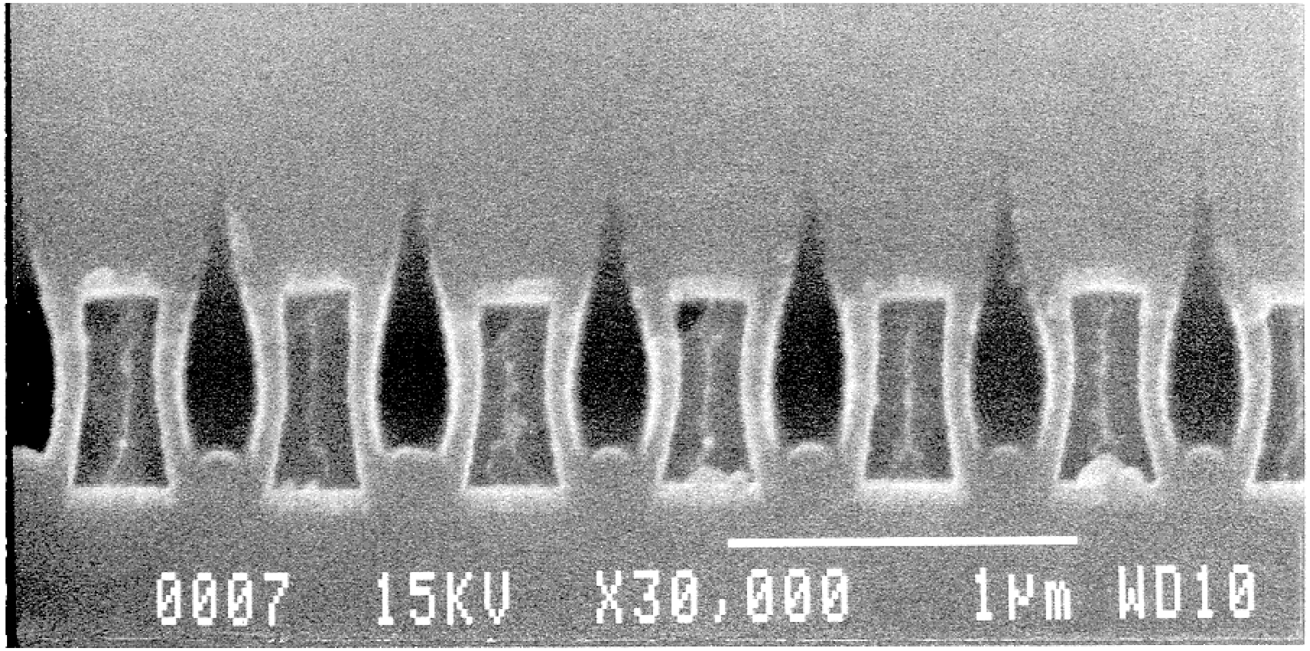
Air-Gap Formation

- Air-gap formed by “breadloafing” due to smaller view angle at bottom of trench.

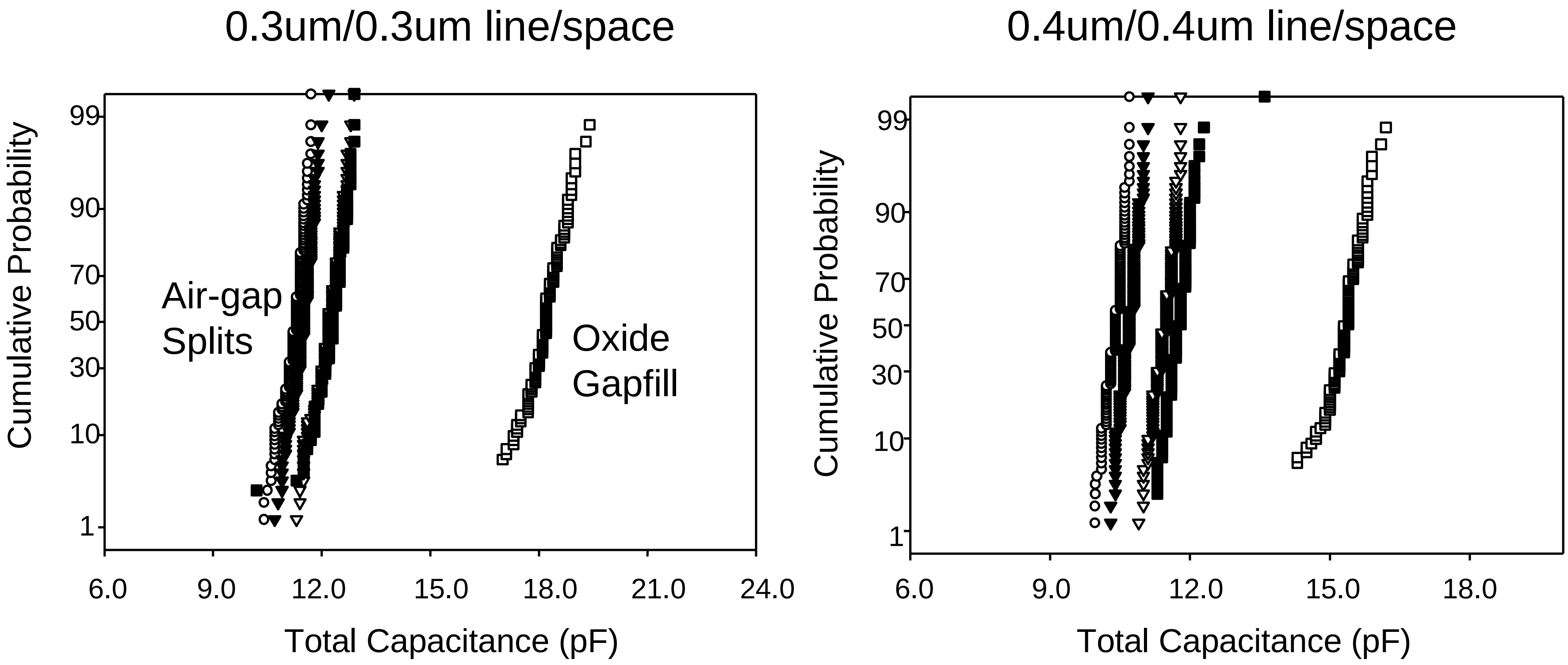


- Greater “breadloafing” → Larger air-gaps

SEM of Experimental Air-Gaps



Experimental Capacitance Data

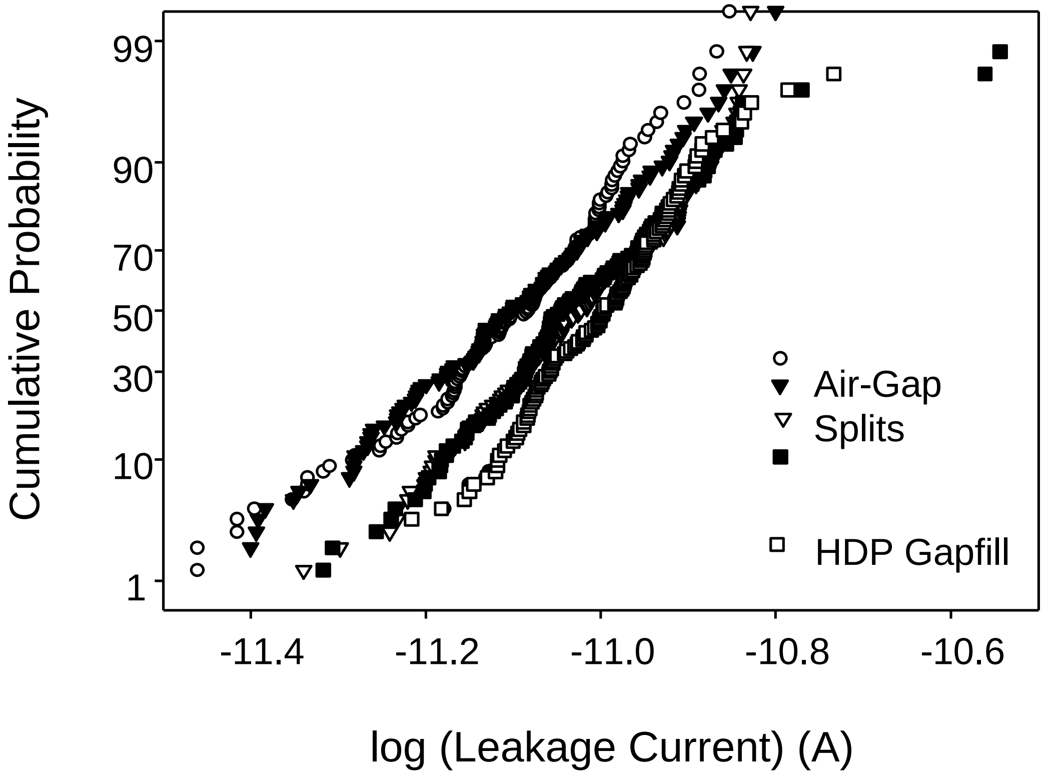


0.3um/0.3um line/space

0.4um/0.4um line/space

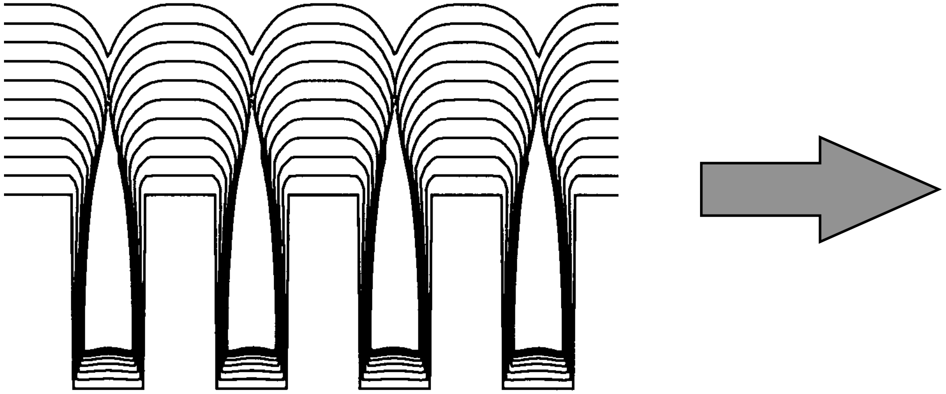
- ~ 33 to 40 % capacitance reduction from HDP oxide gapfill for 0.3µm lines/spaces

Leakage Data

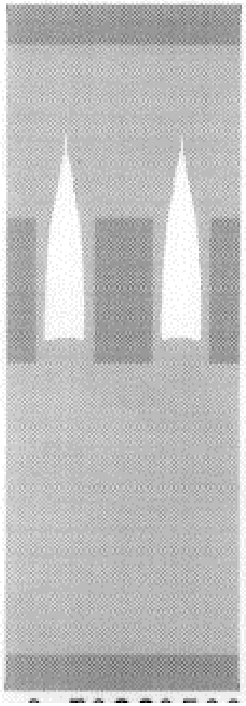


- 0.3um/0.3um line/space, 6.6V applied.

Import SPEEDIE Air-gap Profile to Raphael

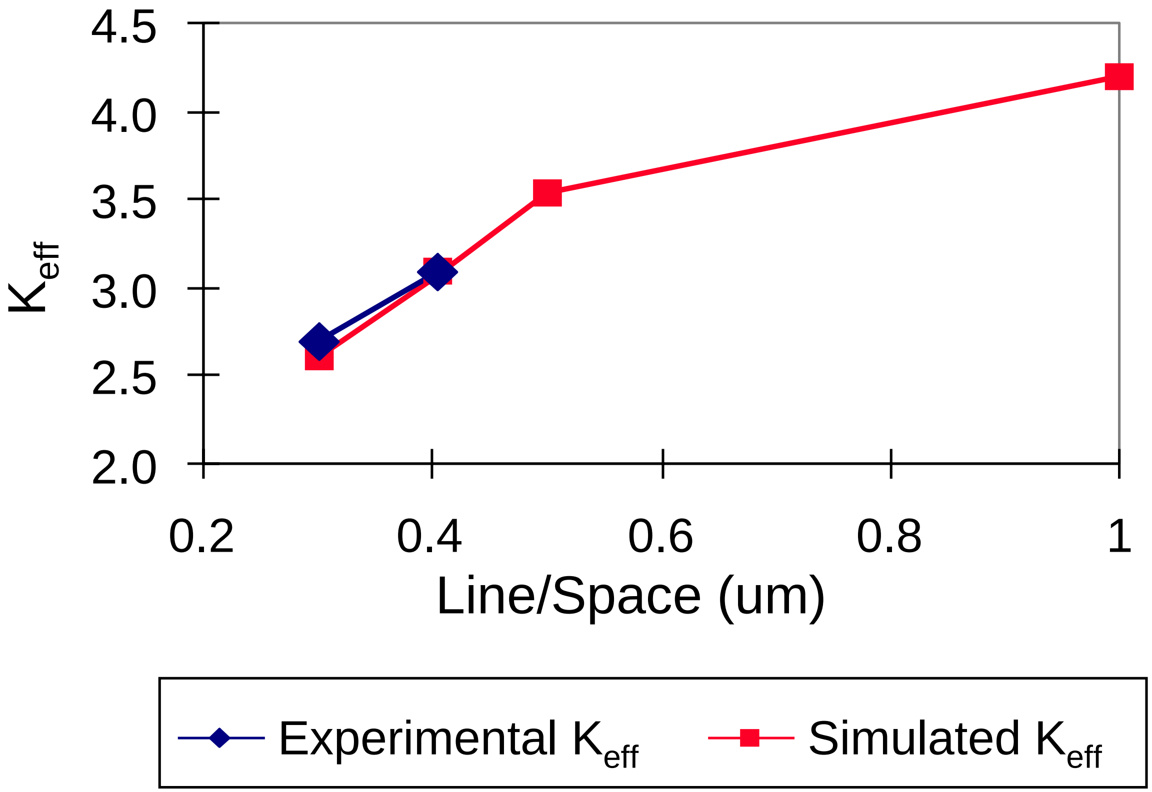


- Deposition simulated using SPEEDIE



- Capacitance extraction using TMA Raphael

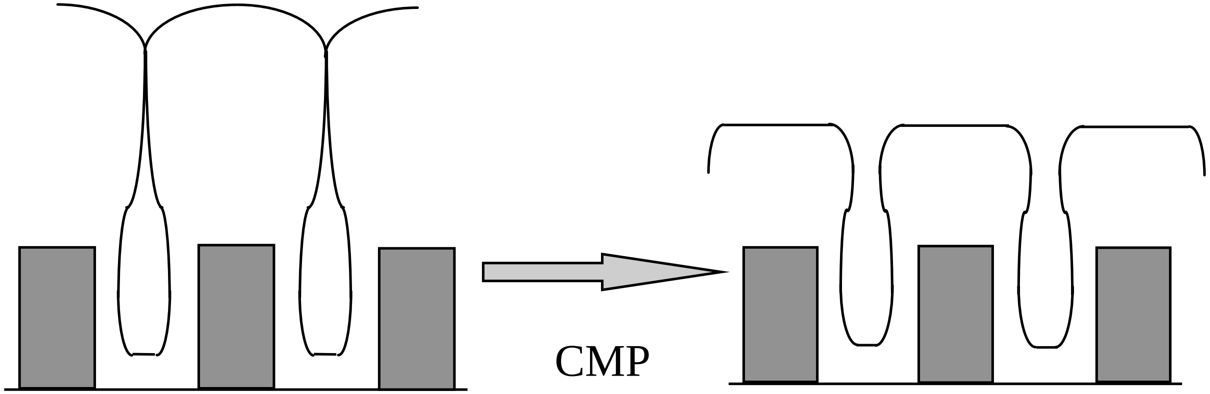
K_{eff} vs. Feature Size



- For small pitches, K_{eff} varies linearly.

Process Integration Issues

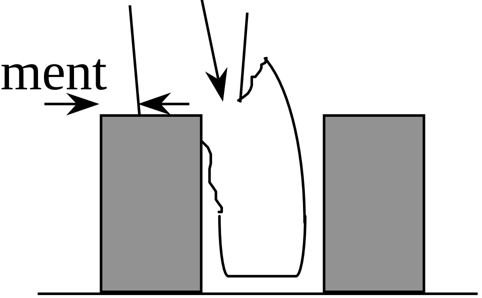
- CMP Reliability



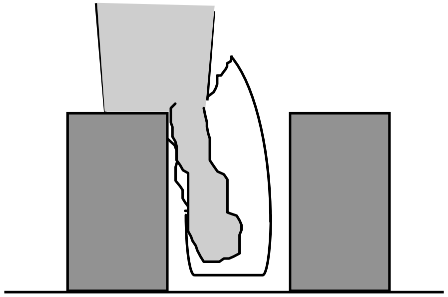
- Via Reliability

Via etch into air-gap

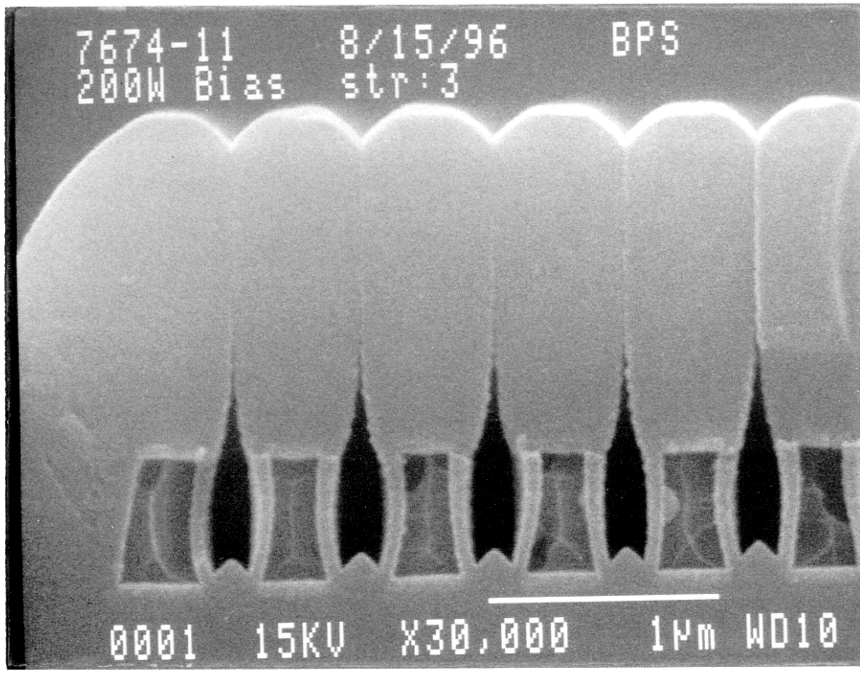
Litho mis-alignment



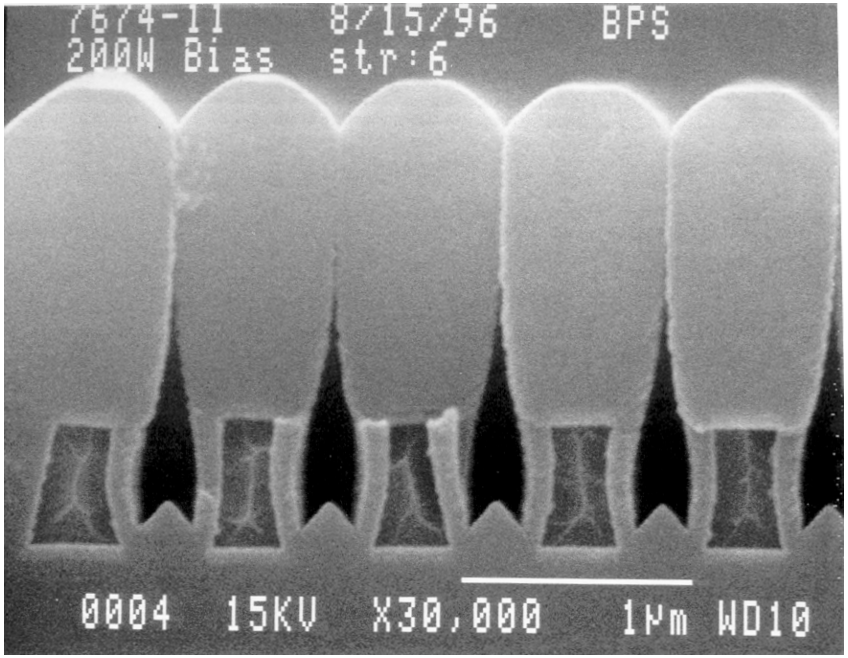
Via metal fills air-gap



SEM Images of Seam and Void Extension



Line/Space = 0.3μm/0.3μm

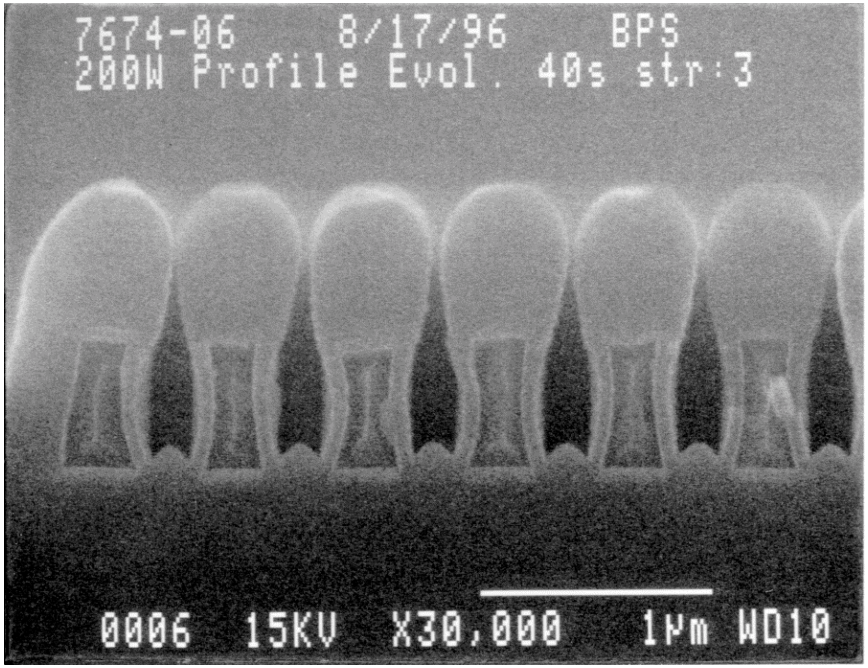


Line/Space = 0.4μm/0.4μm

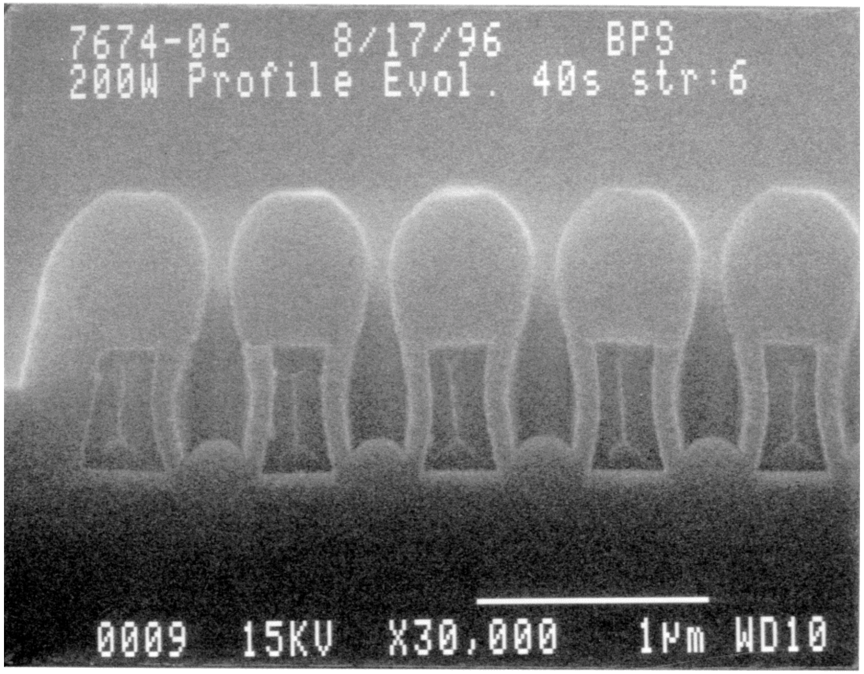
Proposed Solution:
Two Step HDP CVD Process

- First step : High deposition to sputter etch (D/S) ratio conditions to form initial void
  - High Gas Flows, Low Substrate Bias
- Second step : Decrease D/S ratio to prevent seam from forming, limit extent of void above metal lines, and provide local planarization
  - Low Gas Flows, High Substrate Bias

Profile After First Step

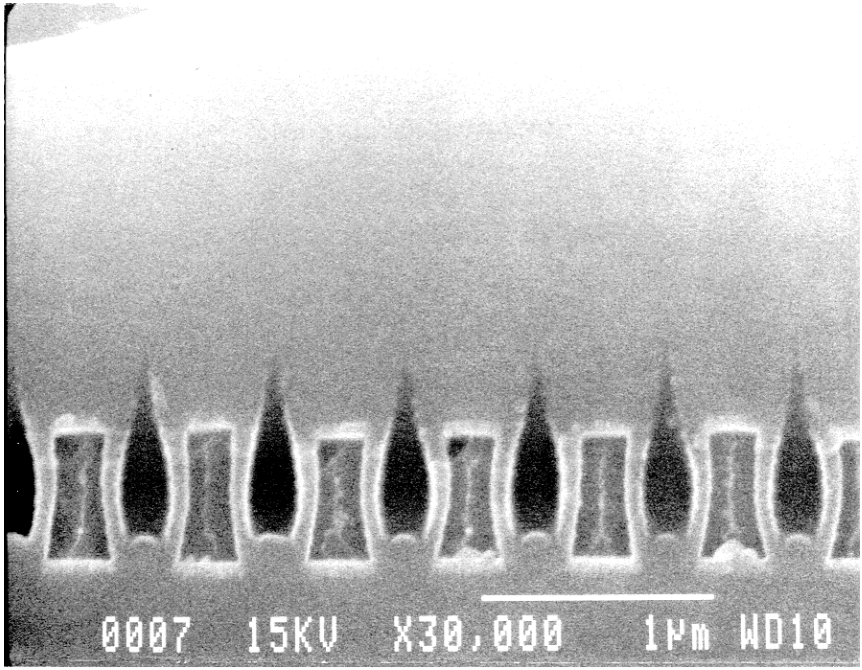


Line/Space = 0.3µm/0.3µm

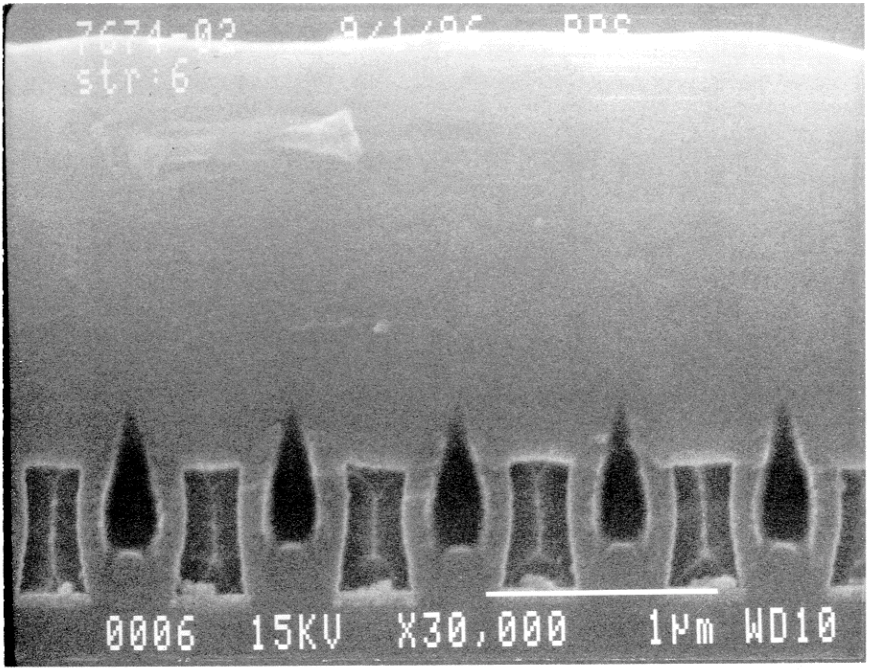


Line/Space = 0.4µm/0.4µm

Profile After Second Step

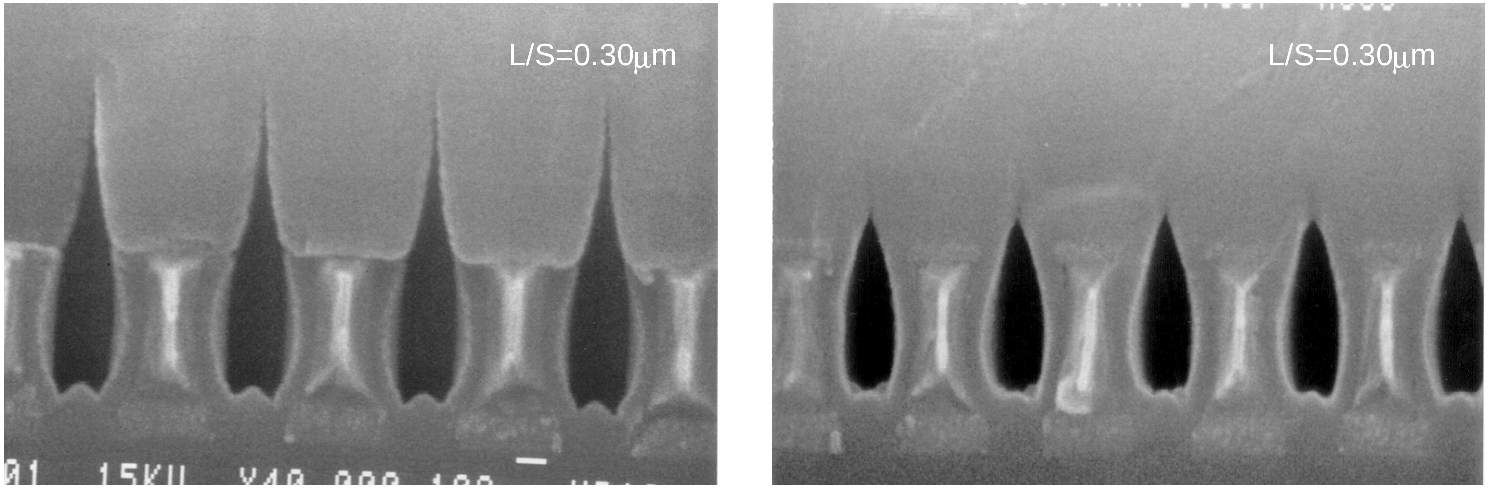


Line/Space = 0.3µm/0.3µm



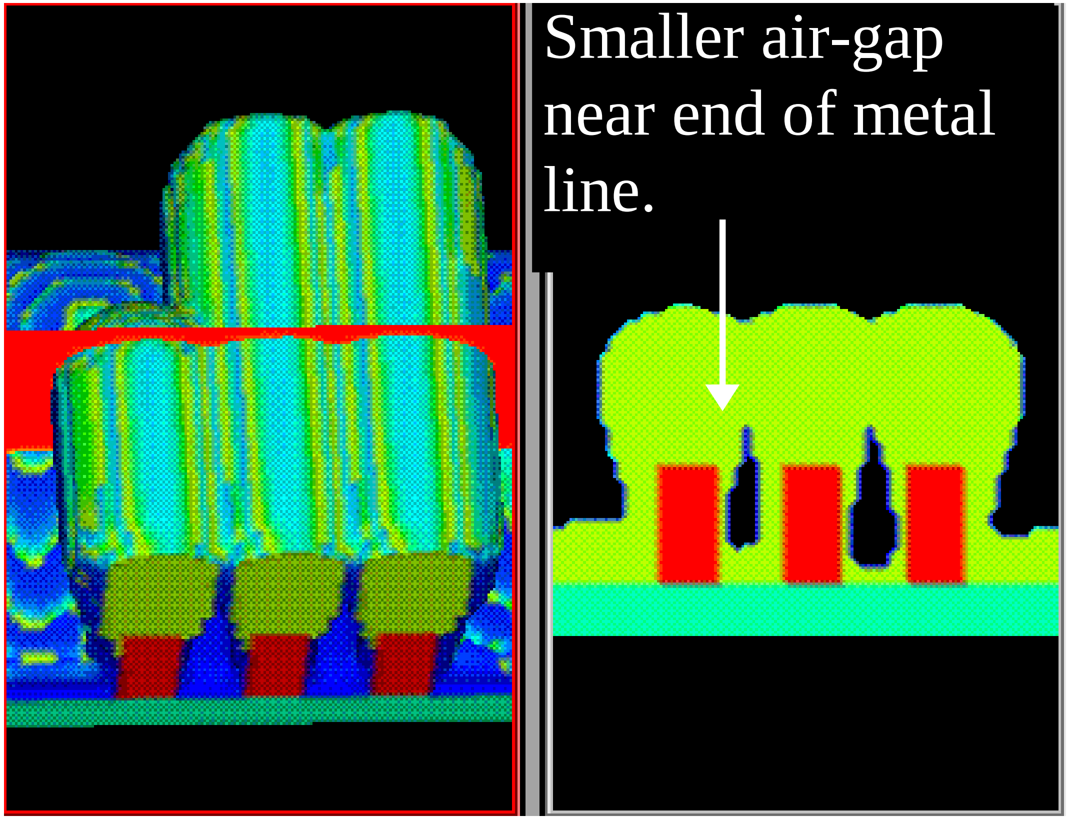
Line/Space = 0.4µm/0.4µm

Control of Air-Gap Size and Shape



- Air-gap size and extension above metal lines can be controlled by varying deposition conditions.
- Samples shown held up to CMP

Layout Dependence of Air-Gaps

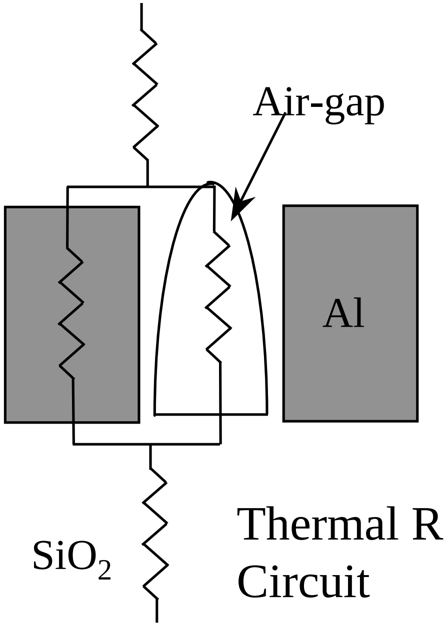


Smaller air-gap near end of metal line.

- Additional deposition flux at end of metal lines results in smaller air-gaps which may help via reliability.

Simulated Joule Heating and Thermal Reliability

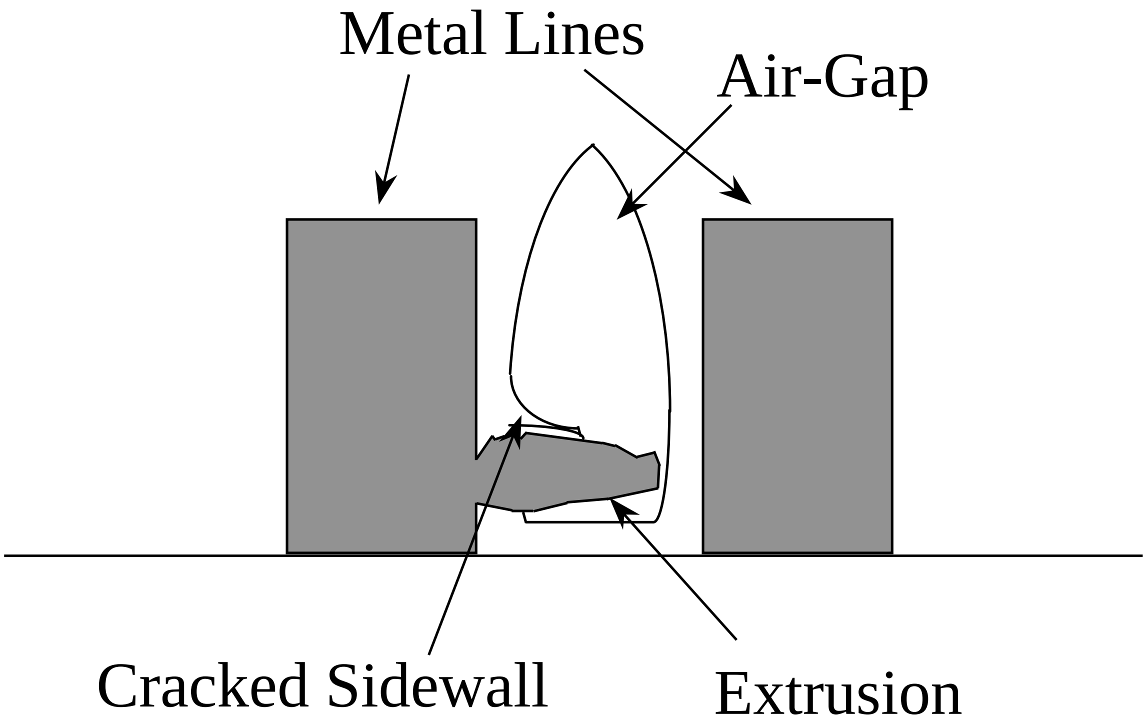
Material	ΔT above $T_{substrate}$
Homogeneous SiO_2	4.9 K
Homogeneous low-K	76.7 K
Air-gaps w/ SiO_2 ILD	5.2 K



Thermal Resistance Circuit

- Heat conduction to substrate limited by interlevel dielectric
- Interconnects with air-gaps show comparable thermal performance to conventional SiO_2.

Electromigration Reliability


Metal Lines

Air-Gap

Cracked Sidewall

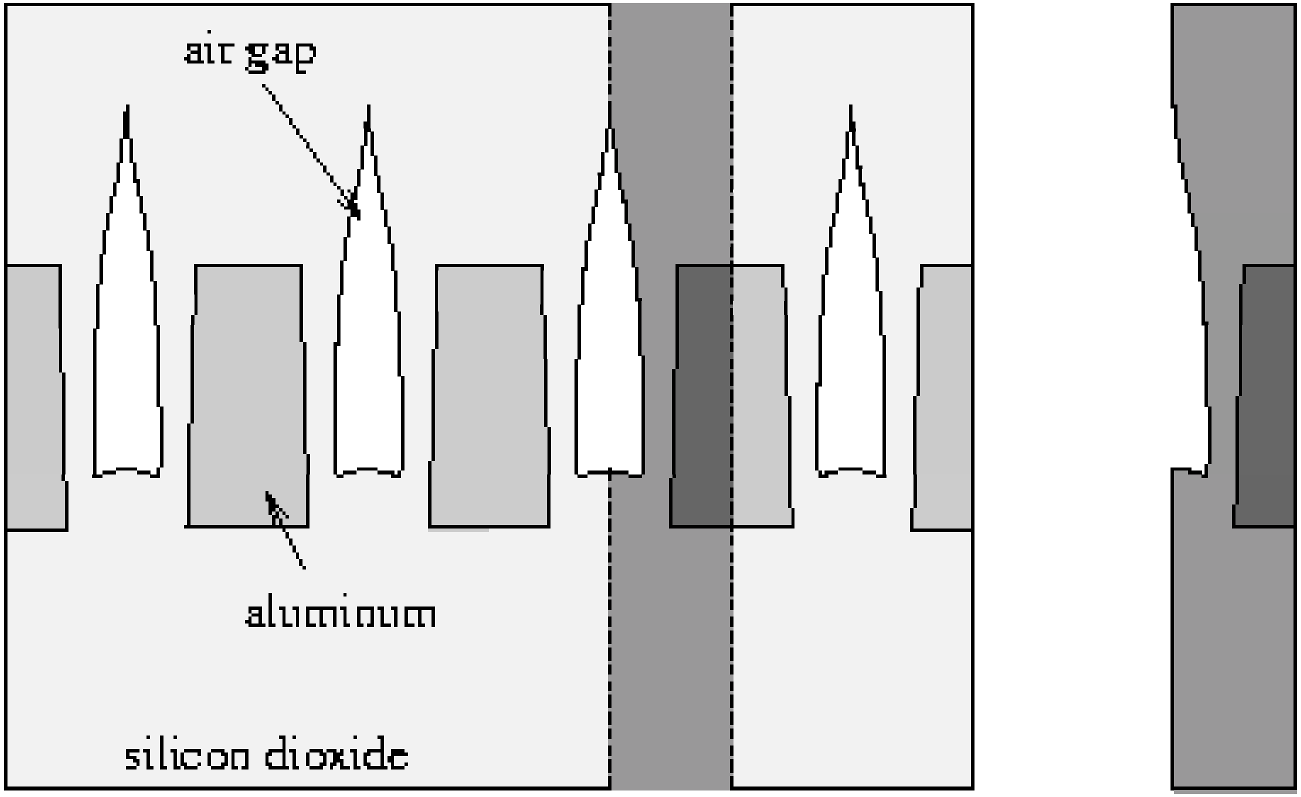
Extrusion

- Thin SiO_2 sidewall may lead to shorter electromigration lifetimes.

Simulation Methodology to Assess Electromigration Reliability

1) Assume fracture stress for dielectric material
2) Solve for stress distributions in interconnect geometry as function of loading
3) Calculate hydrostatic stress in the metal which occurs simultaneously with dielectric failure
4) Use hydrostatic stress to determine MTTF using MIT reliability models by Thompson, et al.

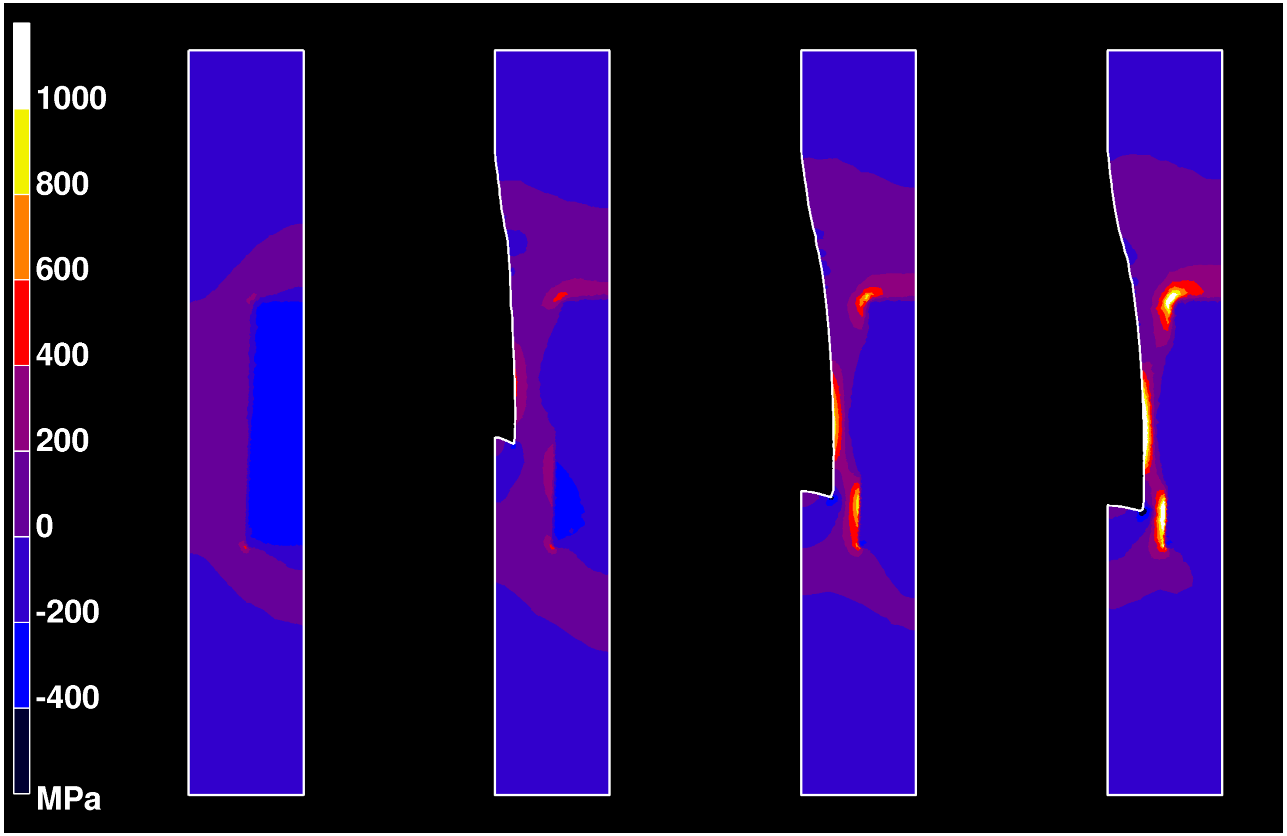
Import SPEEDIE Air-gap Profile to MARC for Electromigration Induced Stress Analysis



constants used:
Aluminum
E = 70 GPa
$\nu = 0.34$
$\sigma_{yield} = 200$ MPa

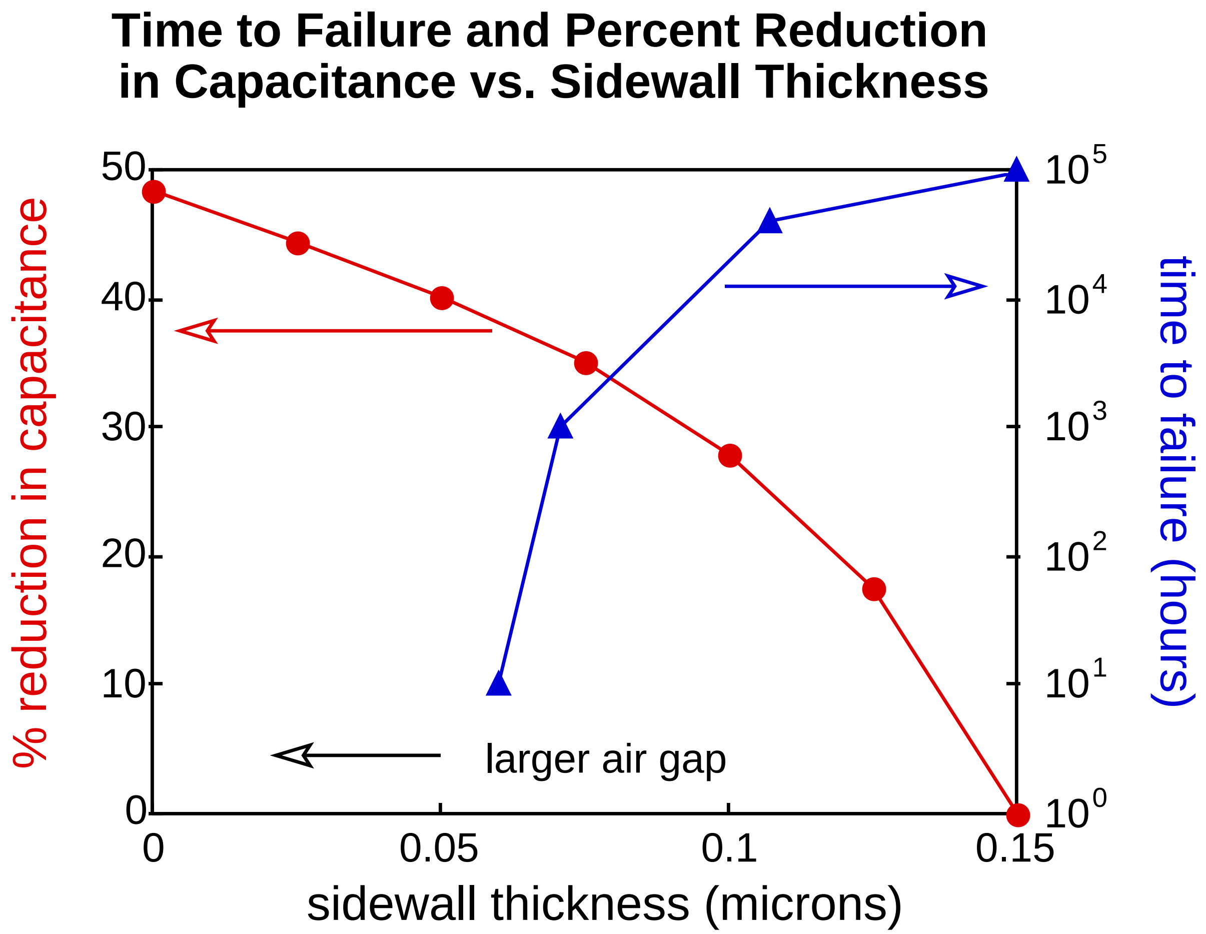
Silicon Dioxide
E = 83 GPa
$\nu = 0.20$

Contour Plots of Maximum Principal Stress



- All structures are shown with the same average hydrostatic stress in the Al (300 MPa)

Simulated Reliability/Performance Tradeoff



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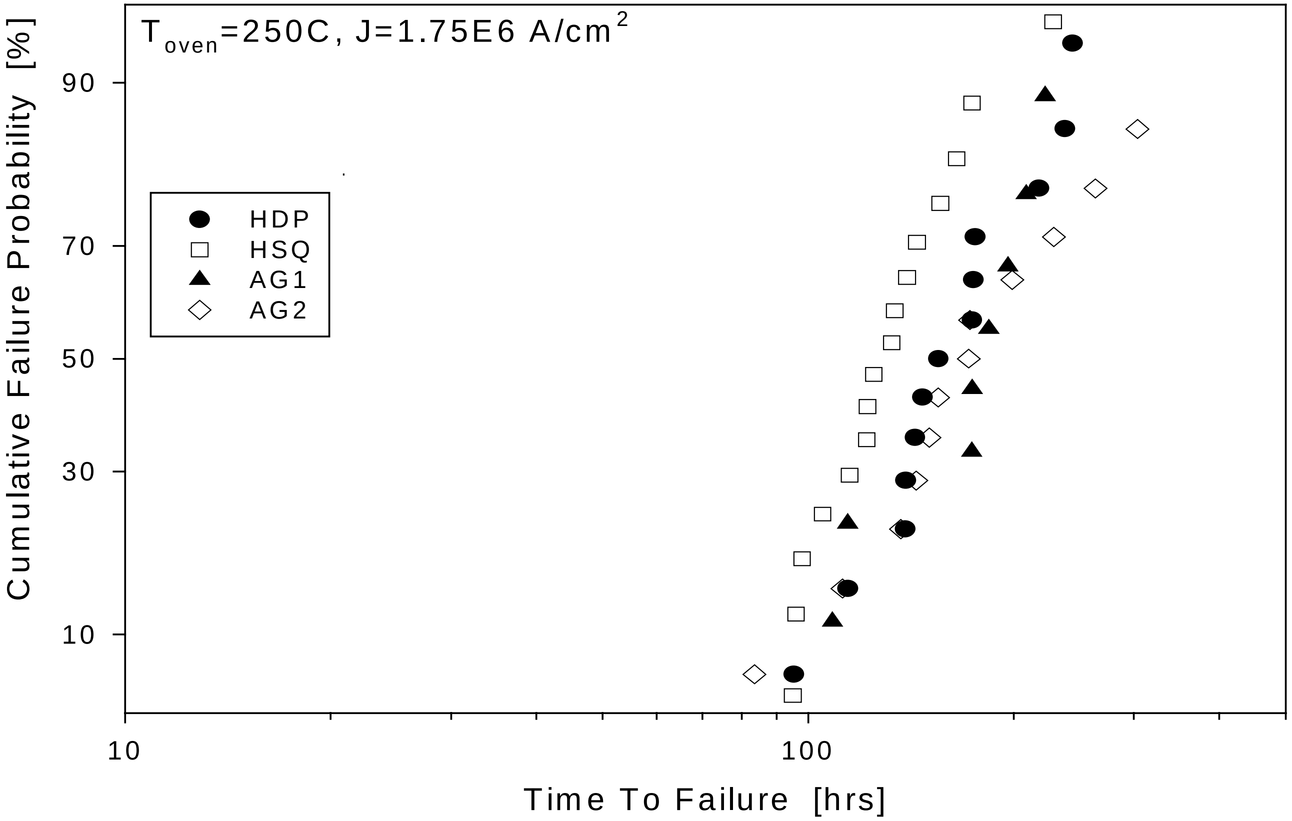
Preliminary Electromigration Data



Summary and Conclusions

- Developed methodology for assessing tradeoffs between reliability and performance for IC interconnects.
- Capacitance reduction using air-gaps comparable to most low-K materials under investigation.
- Air-gap size and shape can be controlled to address CMP and via reliability issues.
- Thermal performance of air-gaps comparable to homogeneous SiO_2.
- Preliminary electromigration data show no difference between air-gaps and homogeneous SiO_2.

Future Work

- Further integration and reliability studies
- Integration of Air-Gaps with Dual Damascene Copper.
- Extension of air as dielectric to "Air-Bridges".

Acknowledgements

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