Stress phenomena in times of porous low-k dielectrics

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GLOBALFOUNDRIES

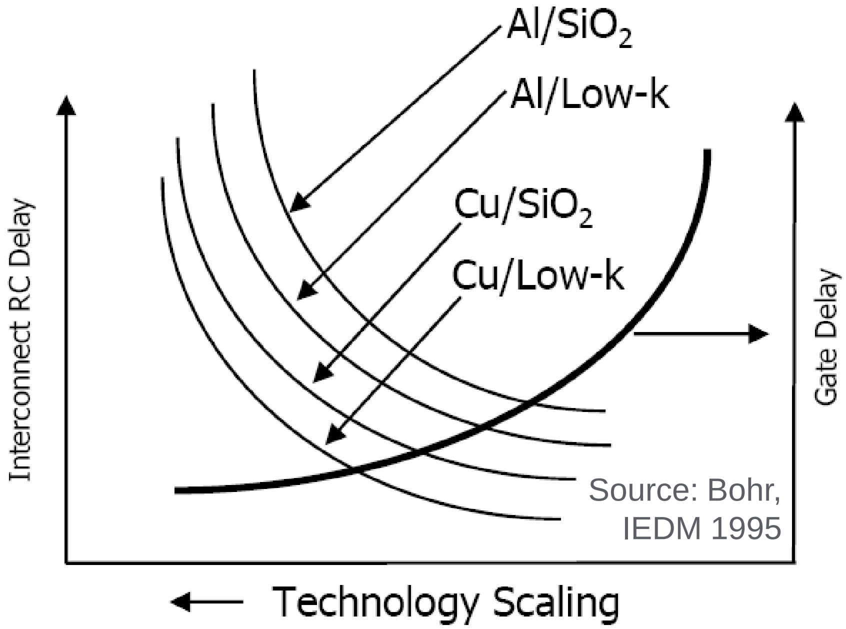
11th international workshop on stress-induced phenomena in metallization

Outline

- Why are we moving to ultra-lower-k (ULK) materials?
- What are the general challenges with ULK?
- What are the challenges for reliability?
- What are improvement options in particular for Stress migration?
- Summary

Why are we moving to ULK materials?

- In advanced technologies not only the transistor is limiting the overall performance anymore
- RC delays are more and more limiting the speed of the system

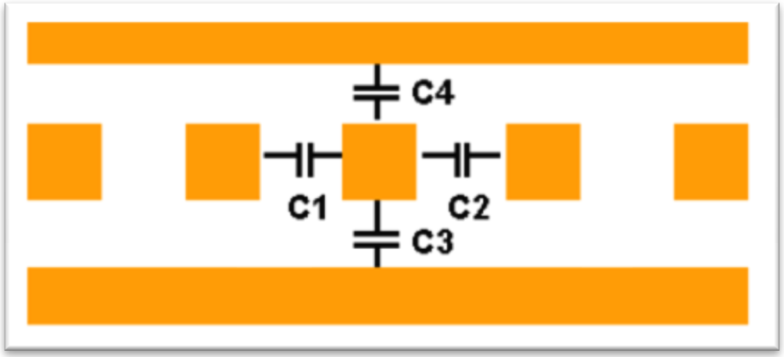


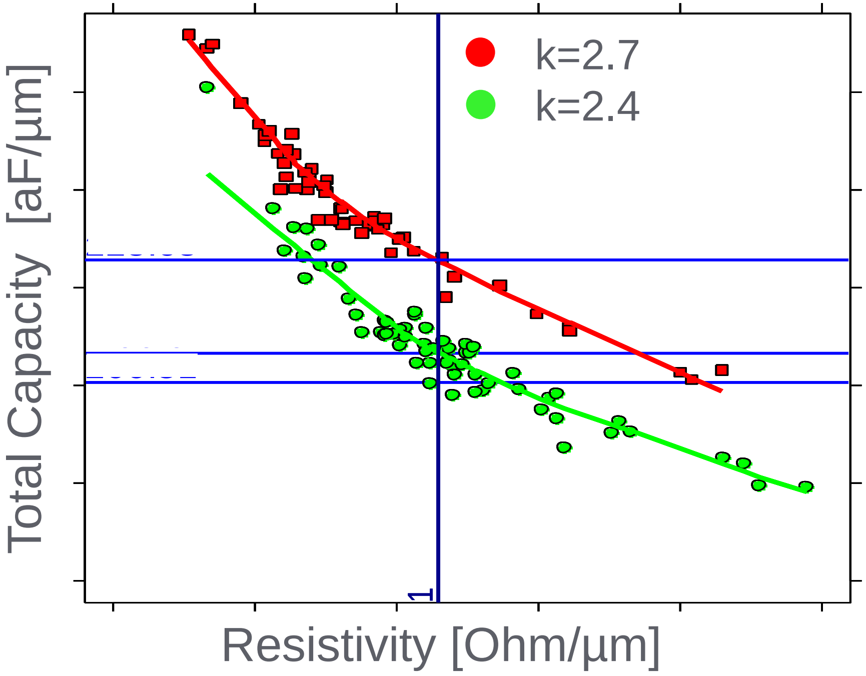
Source: Bohr, IEDM 1995

Why are we moving to ULK materials?

How to reduce RC?

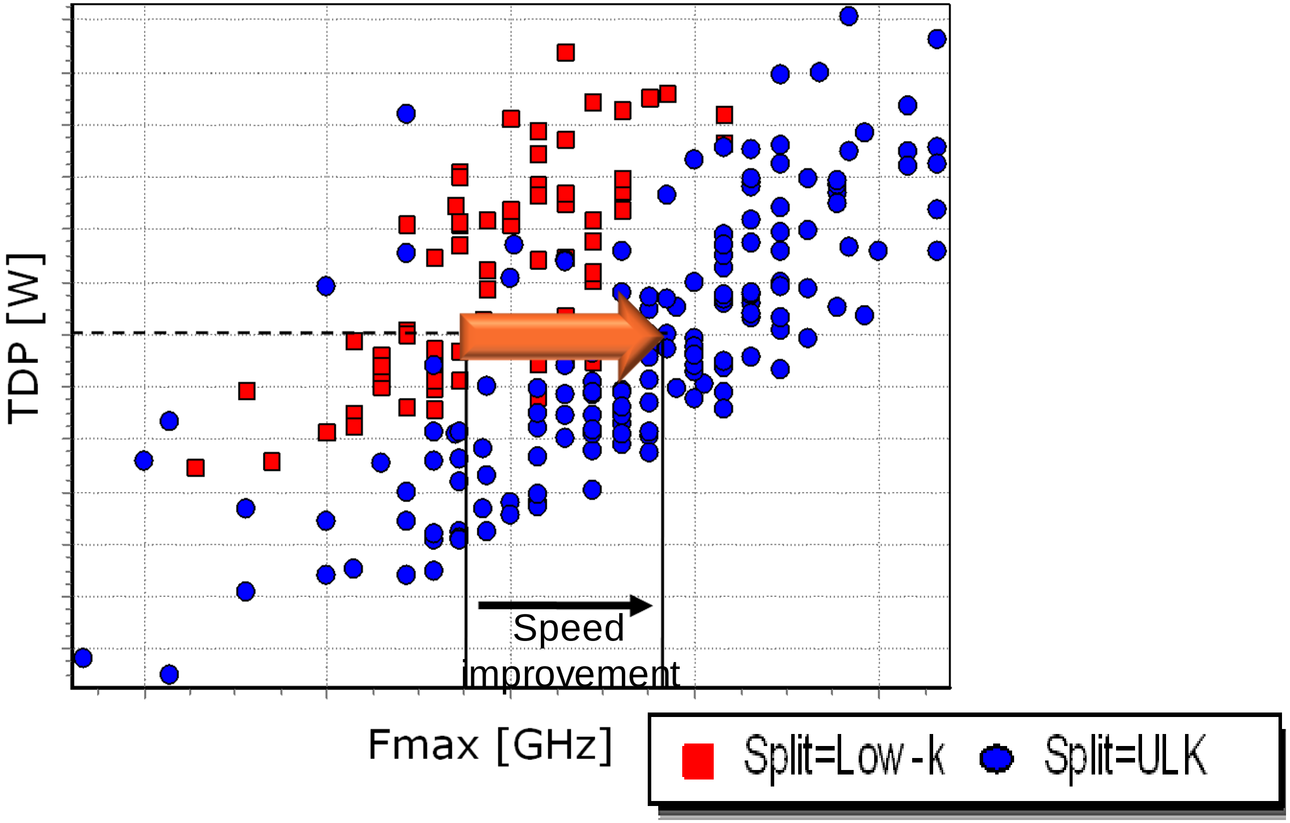
- Limited ways to reduce resistance [thinner barrier and/or deeper trench]
- Ultra Low K (ULK) materials are films with a bulk k-value of <2.6. Between k-values of 2.6 and 3 the ILD is considered a low K (LK) material
- Up-to-date ILDs have k-values of ~2.7, a RC reduction of >10% can be reached by moving to a material with k=2.4 or below





Why are we moving to ULK materials?

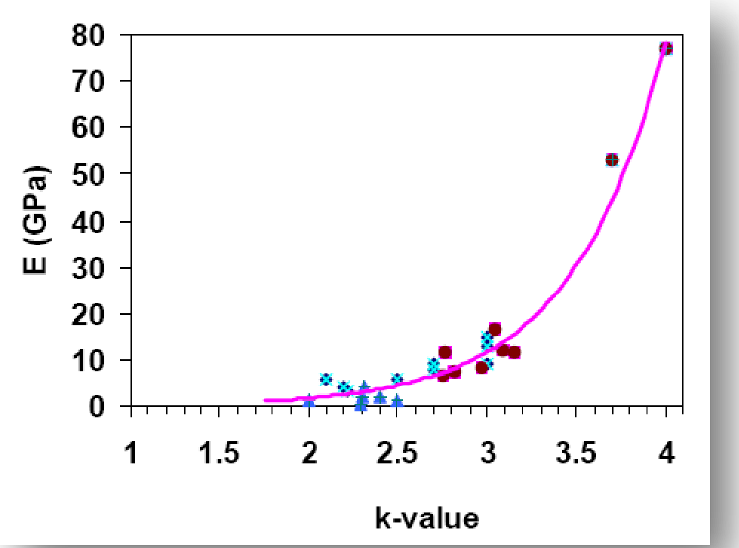
- Does ULK work in integrated circuits?
  - Yes, several 100MHz speed improvement for the same IC can be achieved (non-design optimized)

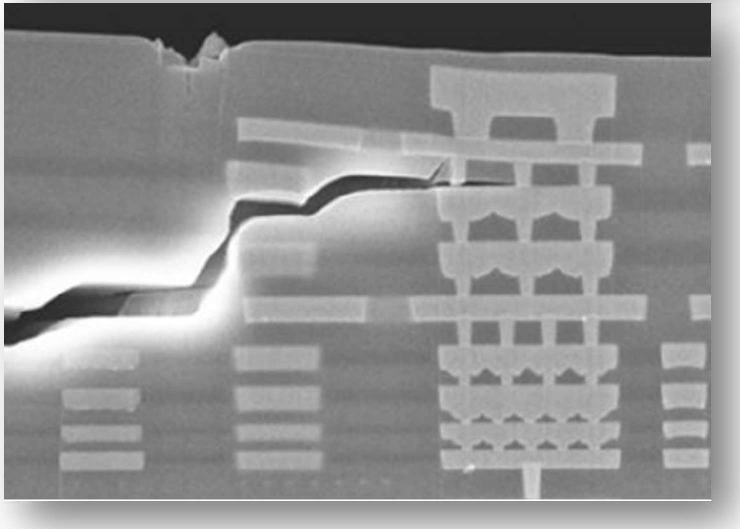


What are the general challenges with ULK?

What are the general challenges with ULK?

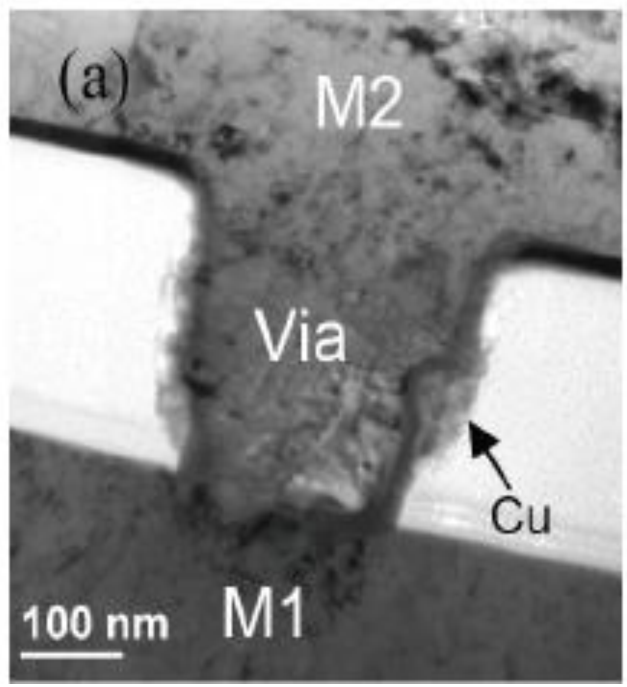
- ULK is a porous material which is mechanically weaker than dense ILDs (and therefore more prone to cracks due to packaging)
- ULK must be integrated using different UNIT processes
- ULK is more sensitive to process damages
- ULK is intrinsically less robust with respect to reliability



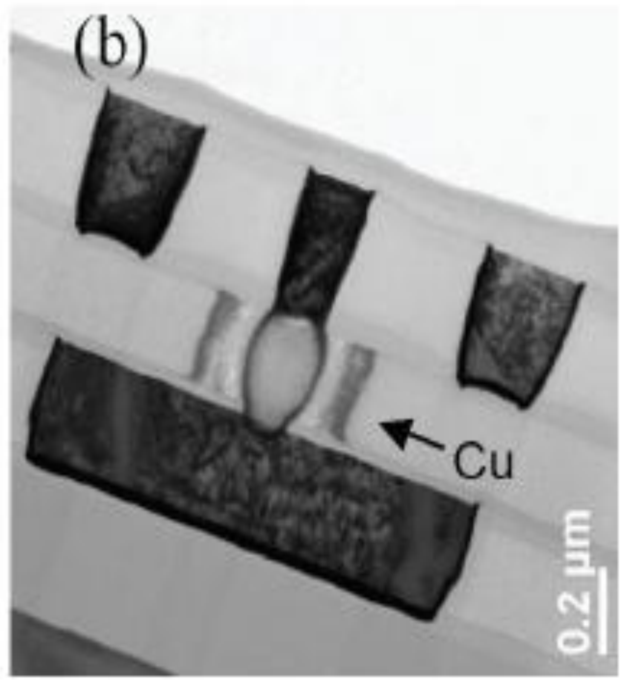


What are the general challenges with ULK?

- Moisture uptake increases the risk of barrier oxidation
- Cu out-diffusion through the barrier was observed resulting in a significant TDDB lifetime decrease



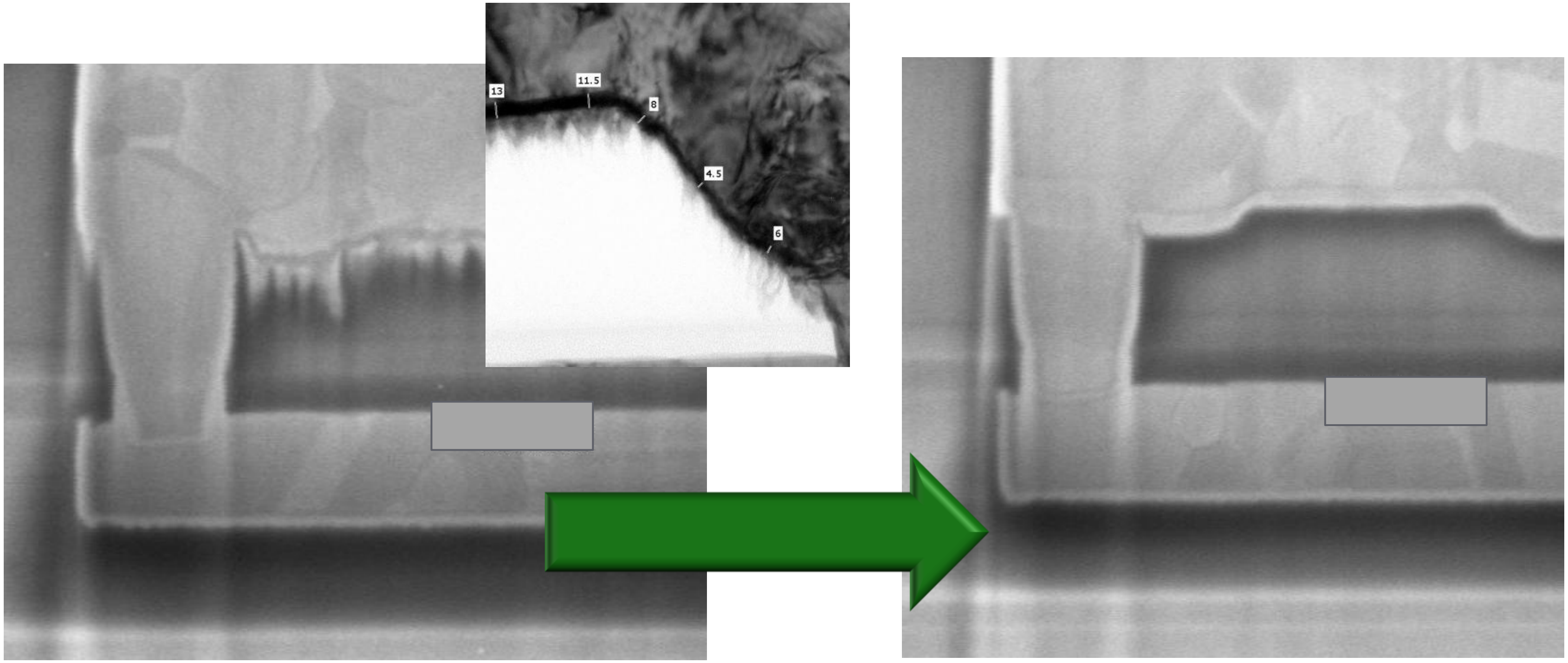
Source: Baek, et al., IRPS, 2006



Source: Michael, et al., APL 83, 2003

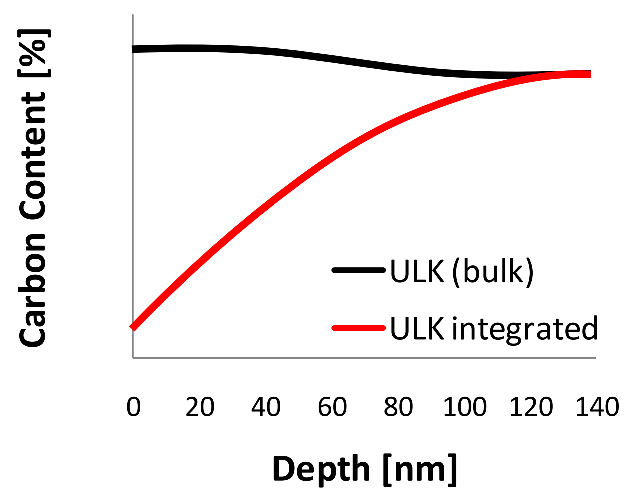
What are the general challenges with ULK?

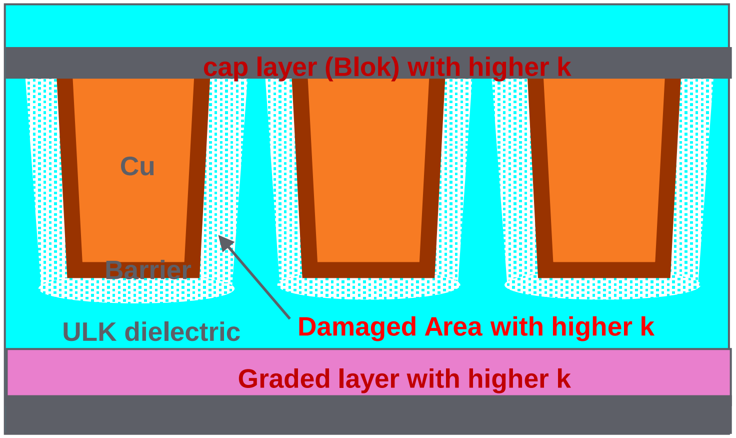
- The ULK is very prone to severe damage due to liner processing
  - Only smooth etch back processes allow reliable ULK integration

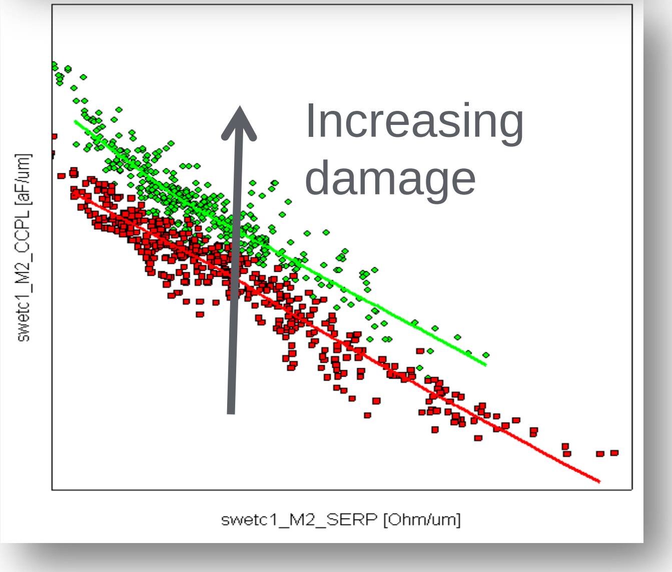


What are the general challenges with ULK?

- Integration of ULK is very challenging:
  - The Etch process is introducing a damage region which increases the effective k-value of the film
  - Damage region is not scaling and will become more and more significant in future







What are the general challenges with ULK?

- ULK damage
  - due to liner processes → bad reliability and RC values
  - due to etch damage → bad reliability and RC values
- Moisture uptake → barrier oxidation (and bad TDDB)
- Cracks or delamination due to packaging

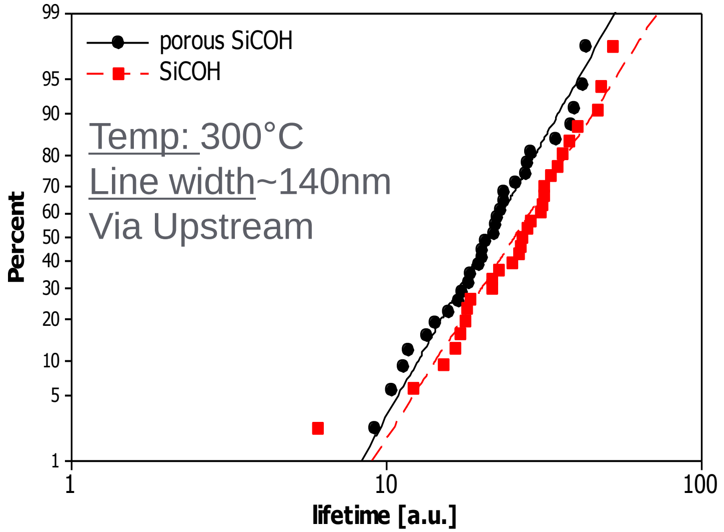
What are the challenges for reliability?

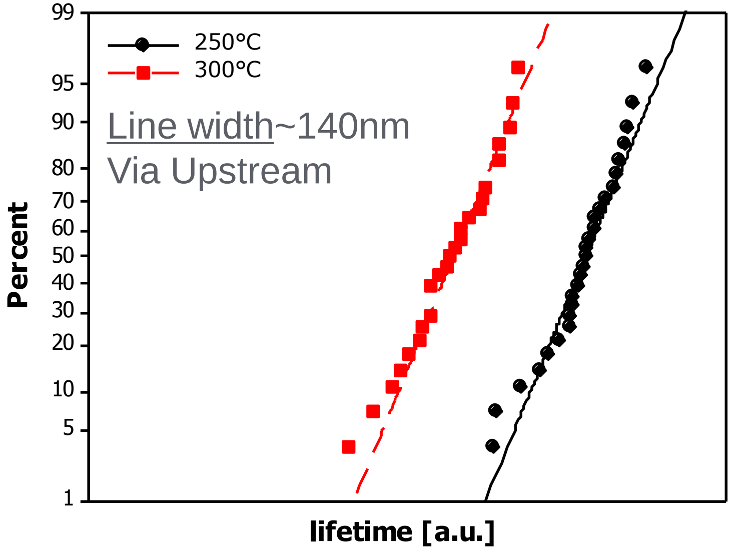
What are the challenges for reliability (EM)?

Intrinsic Reliability Impact!

- Different liner schemes for reduced damage in particular on trench bottom needed
- Comparable EM performance can be reached for ULK compared to dense low-K (k=2.7)
- EM kinetics are comparable
  - For Cu silicidation the E_A value is ~1.0eV
  - For pure Cu the E_A value is ~ 0.9eV

Intrinsic EM reliability robustness is not affected by ULK introduction



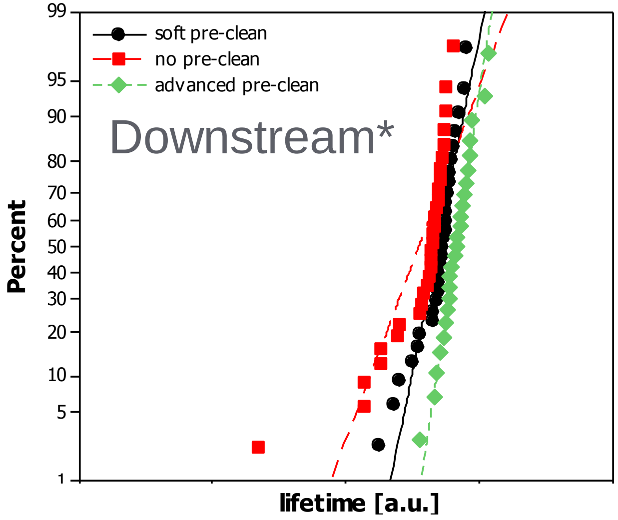


What are the challenges for reliability (EM)?

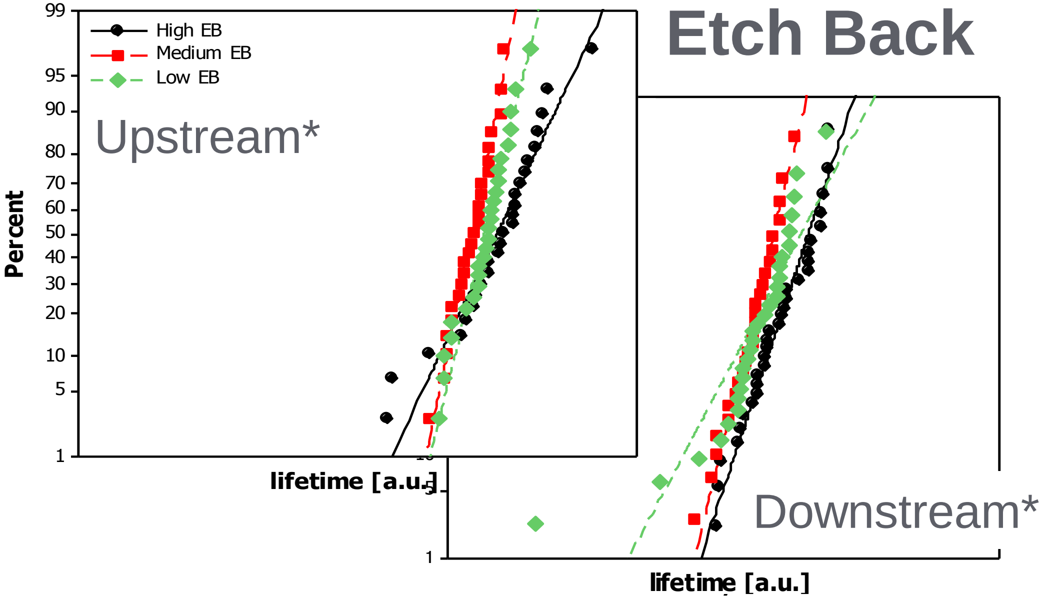
Process Impact on Reliability!

- Significant impact on EM was observed by pre-clean splits after via etch and the barrier schemes (etch back).

Pre-Clean



Etch Back



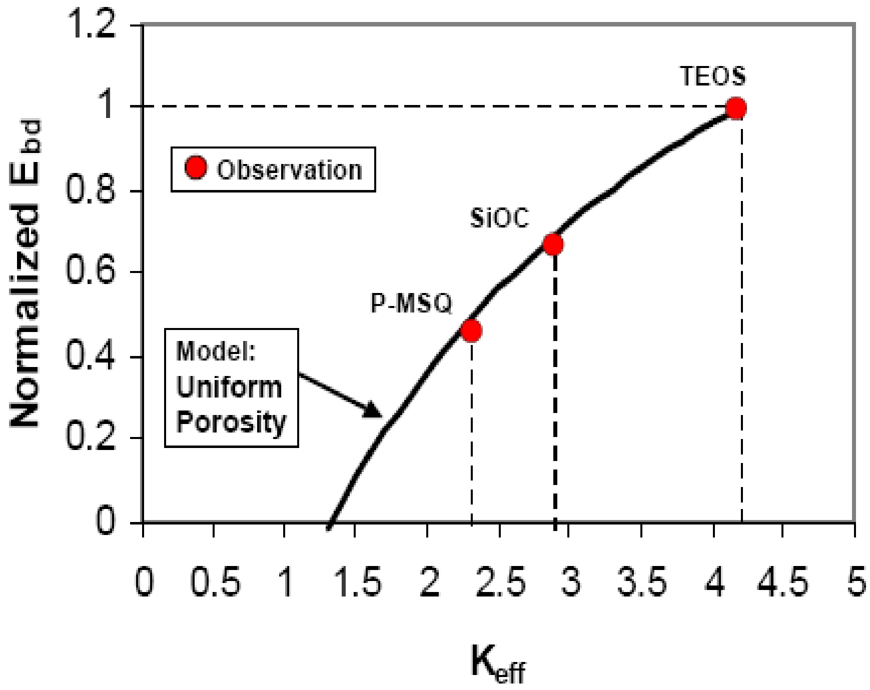
Optimized integration schemes eliminate any process related impact on EM

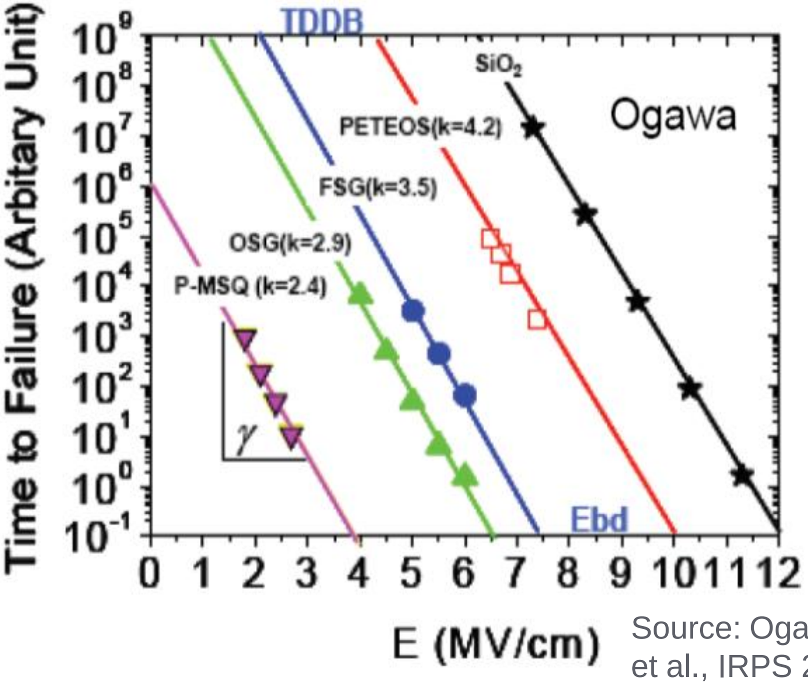
*Line width~140nm

What are the challenges for reliability (TDDB)?

Intrinsic Reliability Impact!

- Porous materials have about 30% less breakdown strength than dense materials





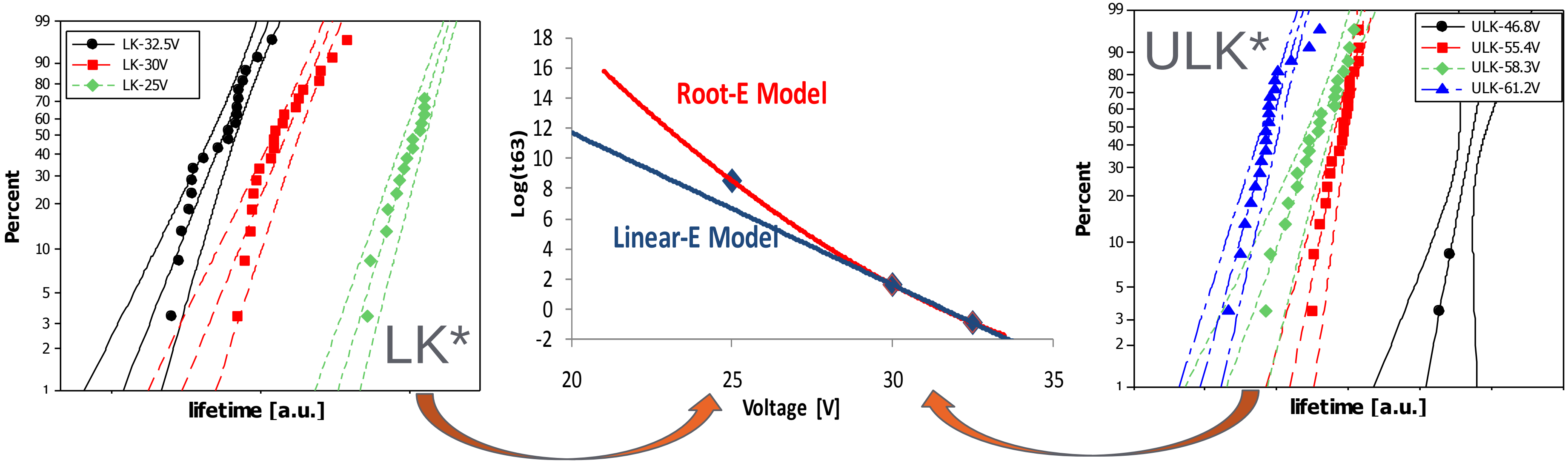
Source: Ogawa, et al., IRPS 2003

Intrinsic TDDB reliability suffers from ULK introduction

What are the challenges for reliability (TDDB)?

Intrinsic Reliability Impact!

- IMD-TDDB measurements are indicating that the physical mechanisms are not changing between the different ILDs



TDDB lifetime extrapolation stays the same (root-E model valid for ULK)

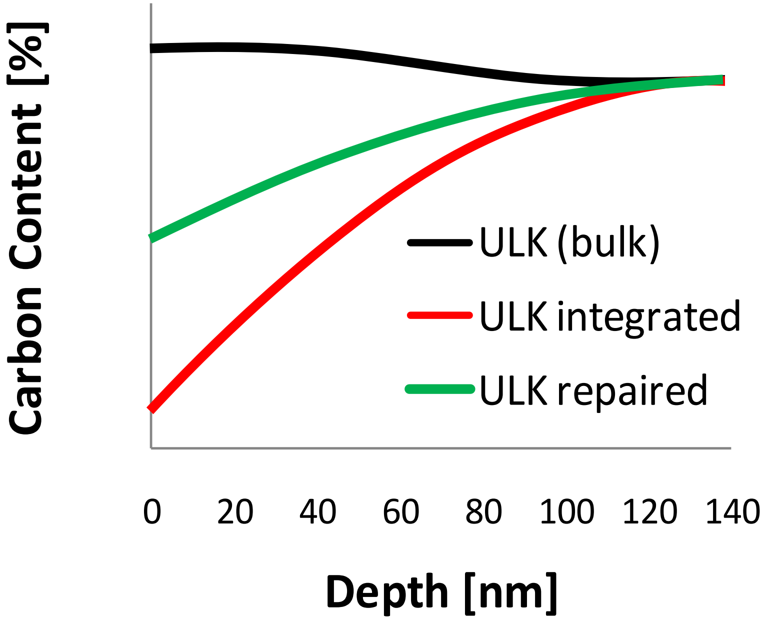
*Tested on via-combs (~50k vias)

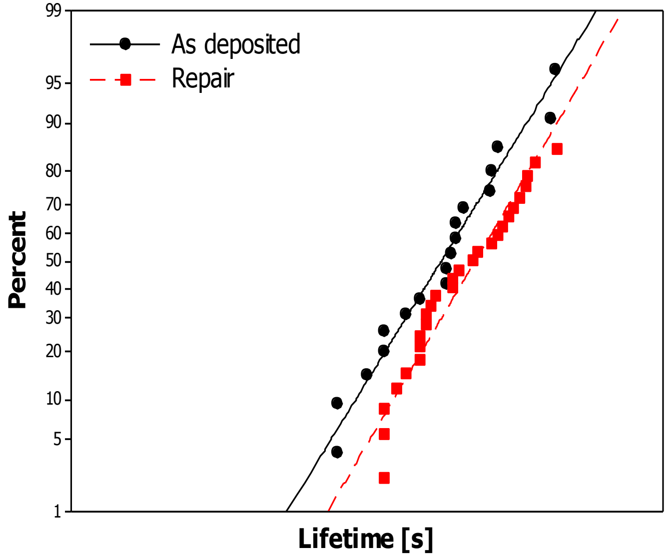
What are the challenges for reliability (TDDB)?

Process Impact on Reliability!

- Two ways to improve TDDB performance
  - Avoid damage (ACP)
  - Repair damage (ULK repair)
  - Both are improving lifetime and V_{acc}

Optimized integration schemes reduce process related impact on TDDB

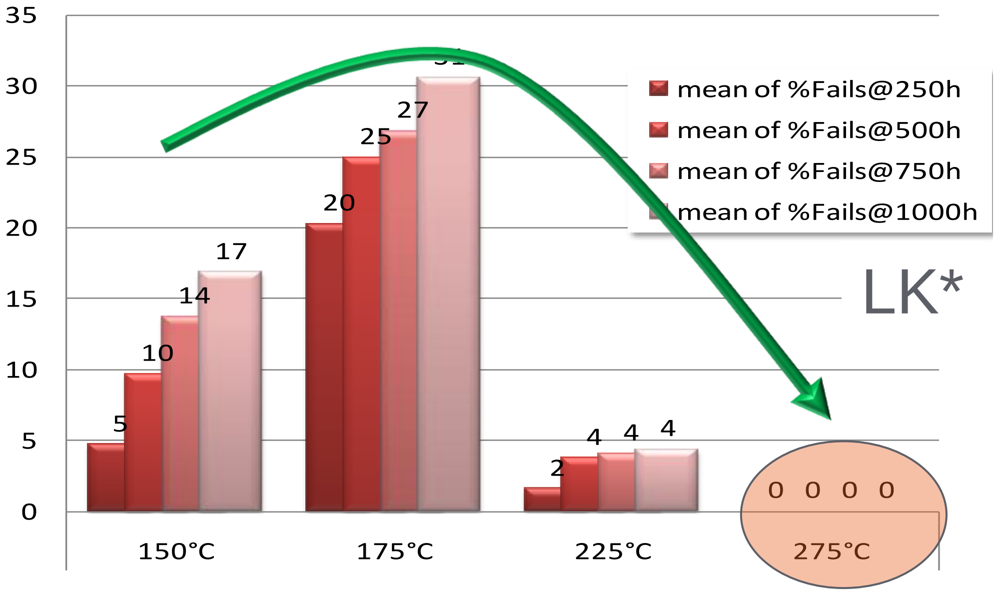


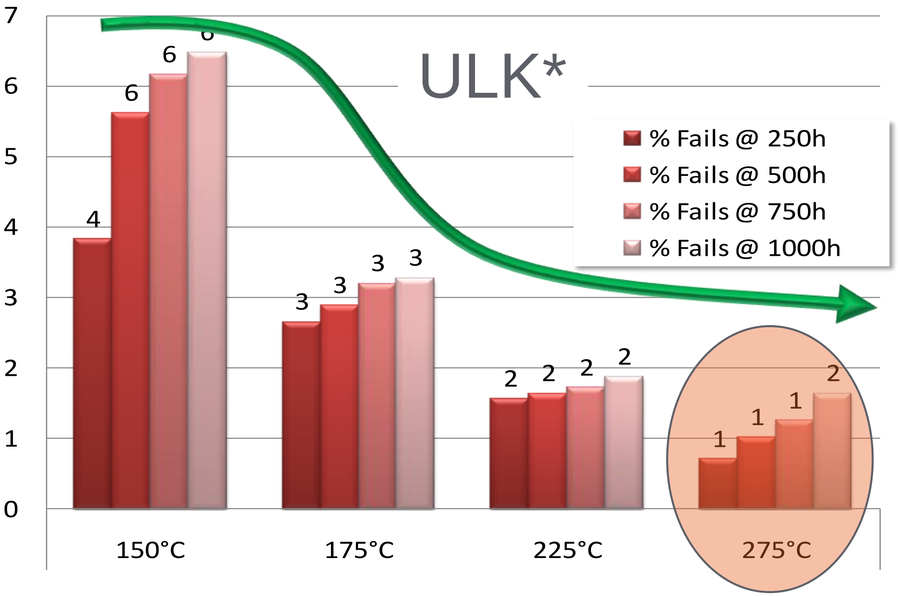


What are the challenges for reliability (SM)?

Intrinsic Reliability Impact!

- SM peak temperature seem to move to 150°C
- High temperature behavior has changed





Intrinsic SM reliability behavior may change due to ULK introduction

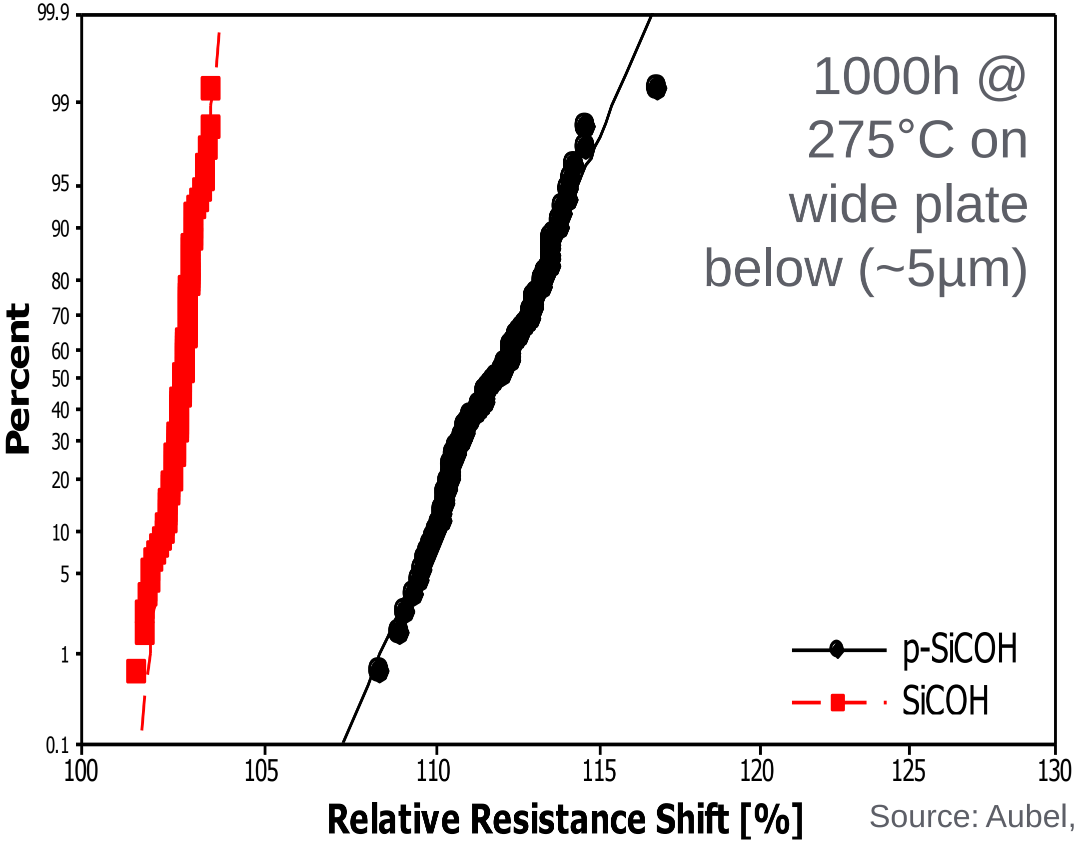
*Wide plate below (~5µm)

What are the challenges for reliability (SM)?

Intrinsic Reliability Impact!

- Since ULK is porous and therefore much more sensitive to oxygen diffusion

- The barrier oxidation (BIT) is much more pronounced compared to LK



1000h @ 275°C on wide plate below (~5µm)

Source: Aubel, et al., IRW 2009

Intrinsic high temperature SM behavior changes due to ULK introduction

What are the challenges for reliability (SM)?

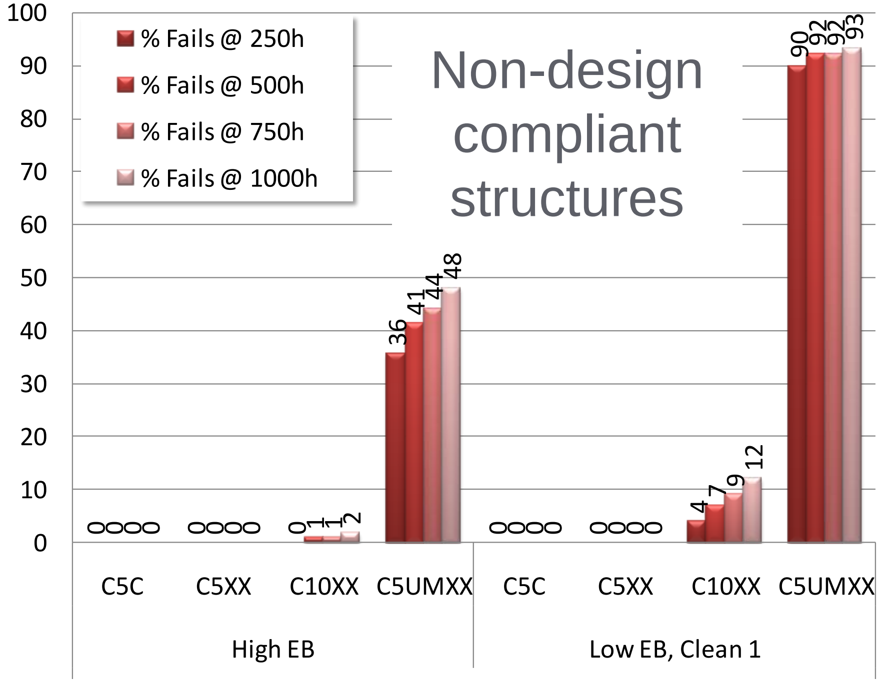
Intrinsic Reliability Impact!

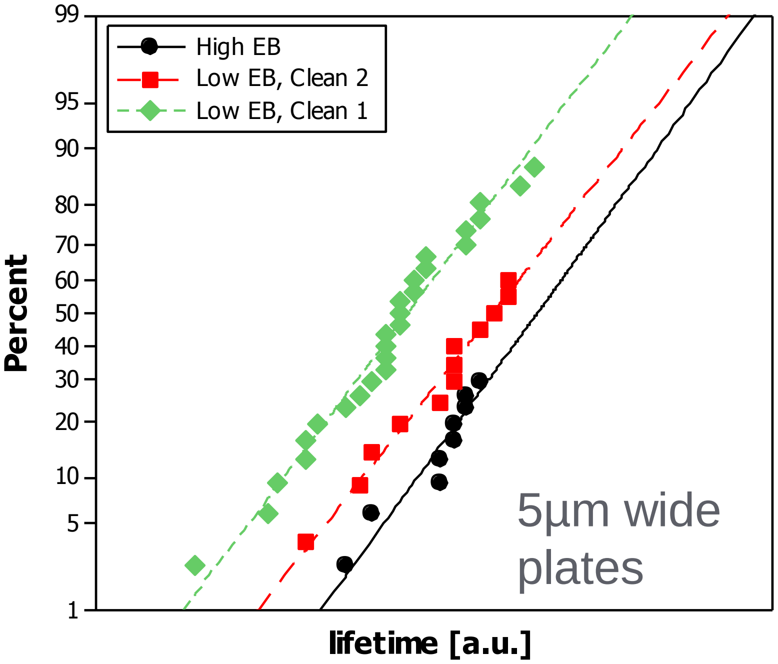
- Intrinsic SM reliability physics may change due to ULK introduction
    - “peak” SM temperature seems to decrease down to 150°C or below
    - High temperature behavior (Barrier Integrity)
- Possible root causes:
    - Low temperature:
        - ULK deposition temperature is well below the deposition temperature from LK, but measured stress (as deposited) = 45GPa is identical to LK
        - CTE_{ULK} is 14ppm/K compared to CTE_{LK} is 11ppm/K
    - High temperature:
        - Moisture sensitivity, higher diffusivity for oxygen, ULK serving as oxygen source

What are the challenges for reliability (SM)?

Process Impact on Reliability!

- SM is very sensitive to barrier schemes
  - comparable to EM: smooth barrier has reduces SM margin but can be compensated by pre-clean processes
  - Still some margin for meeting targets





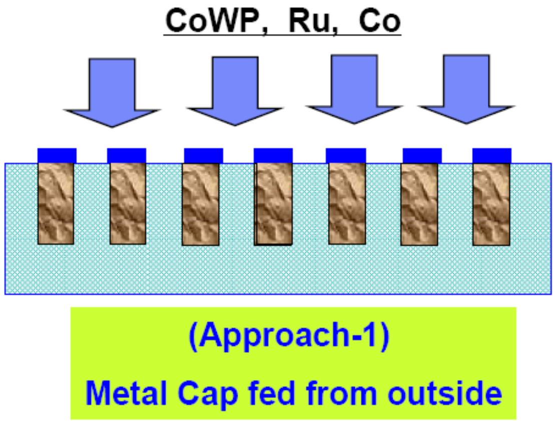
What are the challenges for reliability (Status)?

Mechanism	Comment	Status
EM	• No impact on **intrinsic EM reliability** robustness • LK Performance can be met by optimized process (not **process impact on EM** performance)	🟩
TDDB	• Very critical due to **“intrinsic” material degradation** (lower V_{acc} and lower V_{BD}) • No change in extrapolation methodology observed • Lifetime margin is reduced compared to LK • Process impact can be reduced by optimized process	🟨
SM	• **Intrinsic SM reliability behavior** changes due to ULK introduction • Peak stress temperature is changing • Barrier integrity performance is challenging	🟨🟩

What are improvement options in particular for Stress migration?

Using the toolbox of EM enhancement options

1. CoWP cap layer
    - Max. EM improvement
    - **Max. SM improvement**
    - TDDB challenging
2. Cu-Silicidation
    - Some EM improvement
    - **Some SM improvement**
    - TDDB improvement
    - RC challenging
3. Alloy
    - Some EM improvement
    - **Some SM improvement**
    - RC challenging



CoWP, Ru, Co

(Approach-1)

Metal Cap fed from outside

alloy

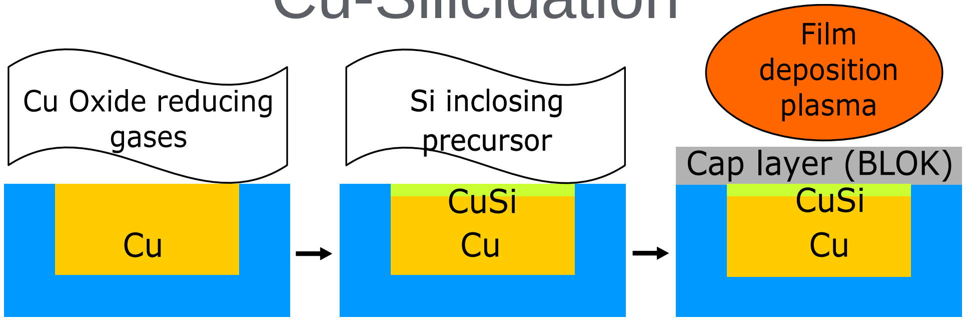
Alloy

(Approach-2)

Metal Cap fed from inside

CuMn Seed Layer

Cu-Silicidation



Cu Oxide reducing gases

Cu

Si inclosing precursor

CuSi

Cu

Film deposition plasma

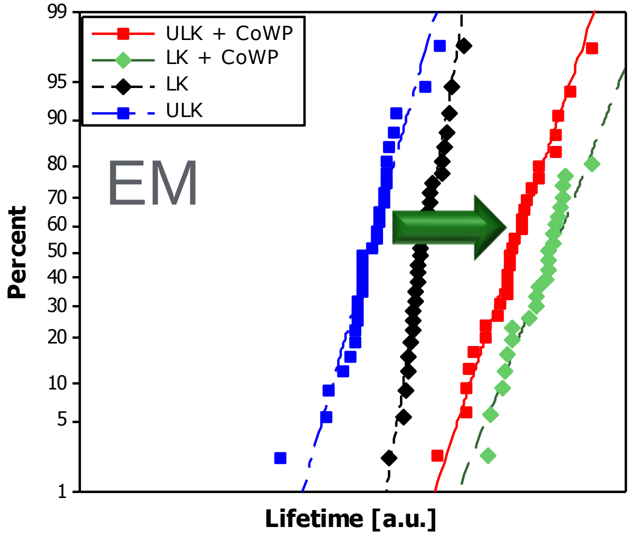
Cap layer (BLOK)

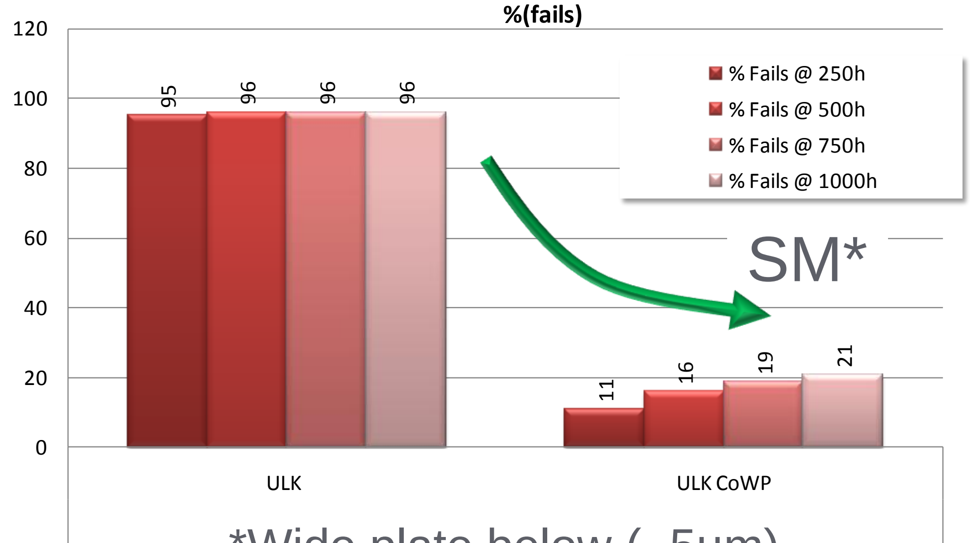
CuSi

Cu

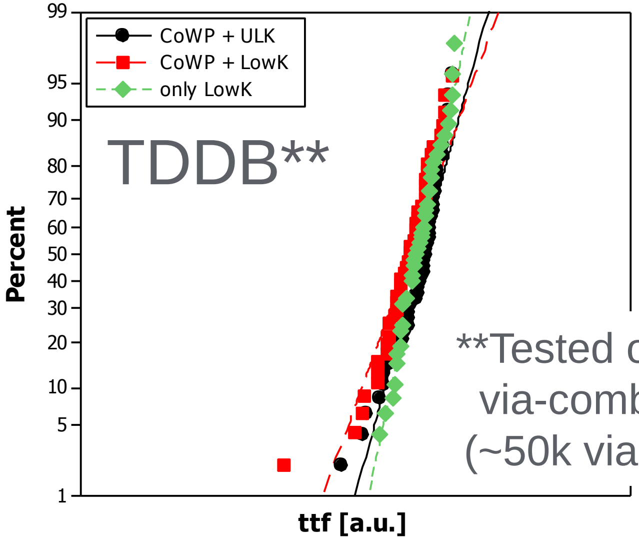
How to solve these problems in SM?
→ CoWP on ULK

- During early process development CoWP was investigated for EM/SM improvements and TDDB impact
  - EM and SM improvement is significant (for EM >> t50 improvement)
  - No impact on TDDB has been observed





*Wide plate below (~5µm)

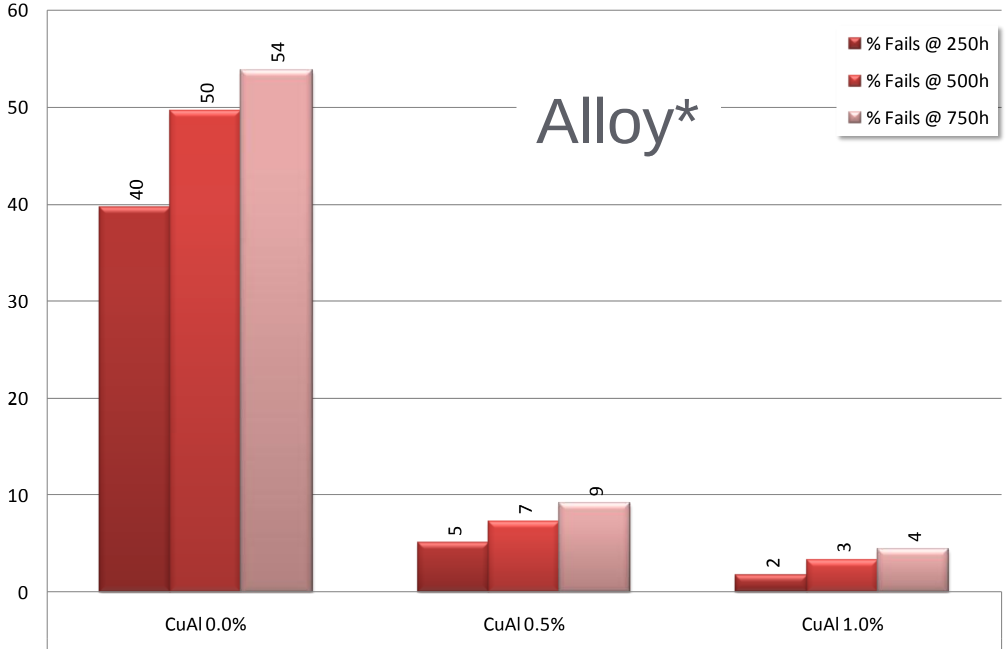


**Tested on via-combs (~50k vias)

How to solve these problems in SM?

→ Alloy and Silicidation

- The electromigration enhancement options work for stress migration accordingly
  - Cu seed alloy with e.g. Al significantly improves SM performance for wide plates (>5µm)
  - Cu surface silicidation significantly reduces stress migration failures in wide plates



*Wide plate below (~5µm)

Summary and Conclusions

Summary

- The introduction of porous ULK material is very challenging for the integration as well as for the reliability
  - Barrier – seed depositions techniques will need to be reevaluated to reduced the damage for the underlying ILD
  - Electromigration in down flow direction is suffering from the adopted barrier –seed process but can be adjusted by advanced pre-clean processes
  - TDDB is significantly degraded due to the change of material properties as well as the ULK damage of the process. ULK repair techniques can help to reduce the process influence.
  - The physics of stress migration behavior seem to change with respect to high temperature and <u>low temperature regime which can be compensated by EM enhancement options</u>.

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