A Comprehensive Study on Interface Perpendicular MTJ Variability

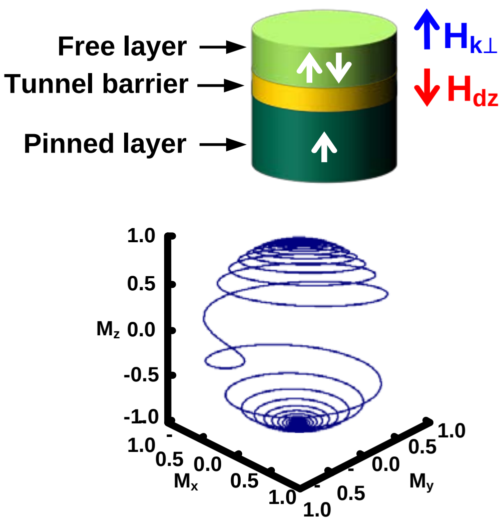
Won Ho Choi, Jongyeon Kim, Ibrahim Ahmed, and Chris H. Kim

University of Minnesota
Dept. of ECE

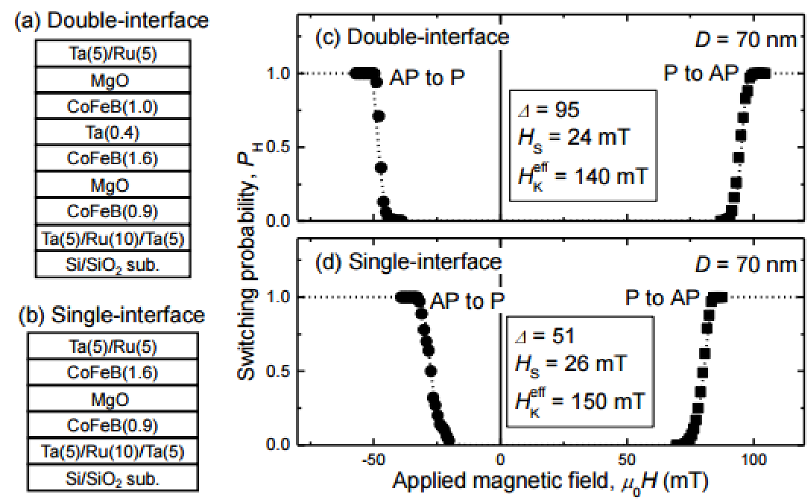
Outline

- Introduction
- Interface Perpendicular MTJ (I-PMTJ)
- Strategy for PMTJ Variability Analysis
- Variation Factors and Material Parameters
- Variability Analysis Results
- Conclusion

Interface Perpendicular Magnetic Tunnel Junction (I-PMTJ)



J. Kim, et al., DRC, 2014.



H. Sato, et al., Journal of Magnetics, 2014.

- **Discovery of interface anisotropy in CoFeB [3]**
- **Perpendicular anisotropy when $t_F < t_c$ (critical thickness, ~1.5nm)**
- **Maturity from CoFeB+MgO but limited thermal stability**
- **Double MgO is used to increase thermal stability [4, 5]**

[3] S. Ikeda, et al., Nature Mater., 2011. [4] H. Sato, et al., APL, 2012. [5] K. Tsunoda, et al., IEDM, 2014.

I-PMTJ Dimensional-Dependent Parameters

$$\Delta = \frac{H_{k\perp eff} \cdot M_s \cdot V}{2k_B T}$$

$$H_{k\perp eff} = (\frac{2}{M_s}) \cdot (\frac{K_i}{t_F}) - 4\pi \cdot N_{dz} \cdot M_s$$

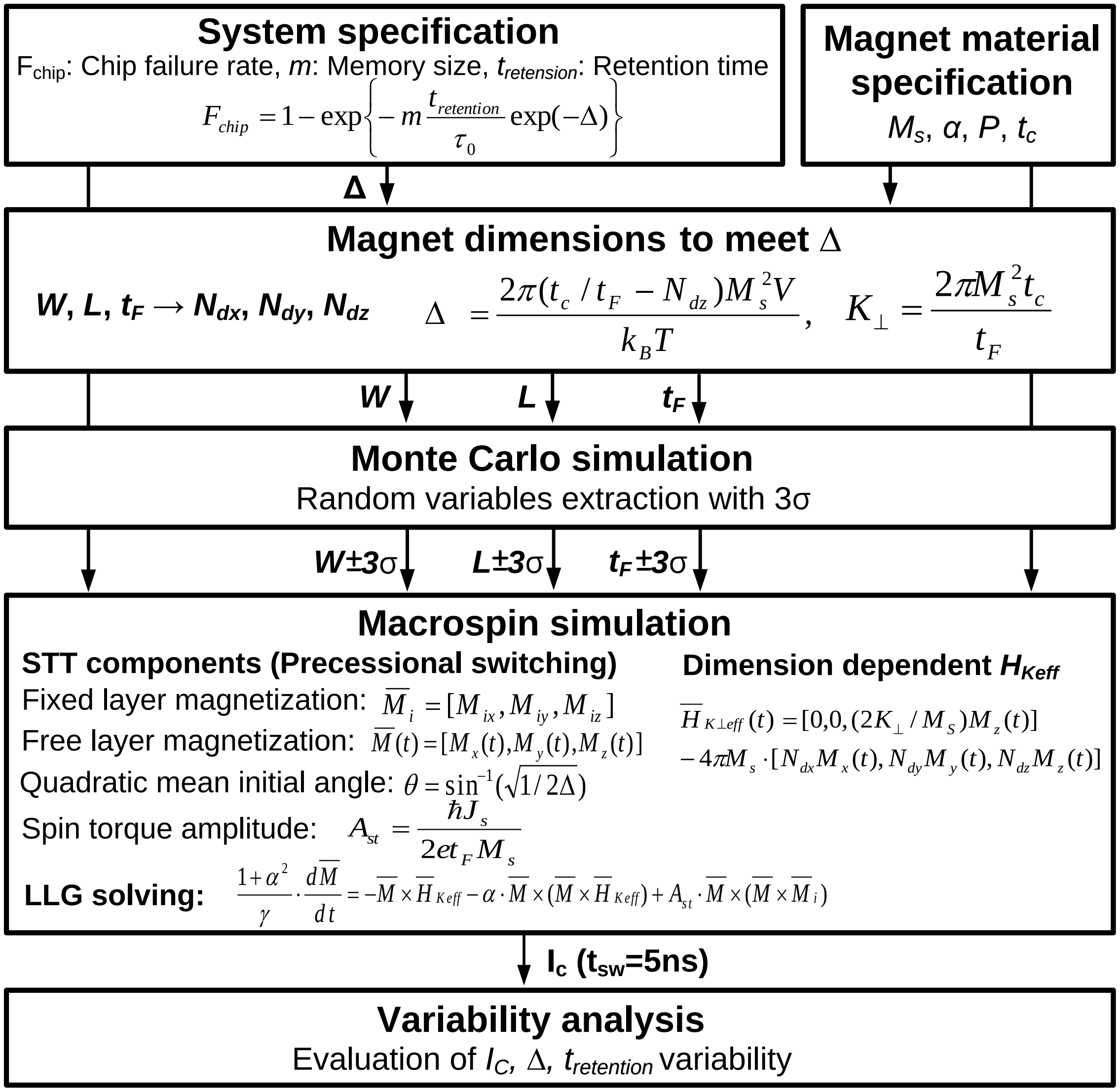
$$I_C = \frac{2e \cdot \alpha \cdot M_S (H_{k\perp eff}) \cdot V}{\hbar \cdot \eta}$$

(grey circle) **: Parameters that depend on I-PMTJ dimensions**

Parameter	Description
Δ	Thermal stability
$H_{k\perp eff}$	Effective perpendicular anisotropy field
I_C	Critical switching current
V	Volume of the magnet
t_F	Thickness of the free layer
K_i	Interface anisotropy energy density
α	Magnetic damping factor
M_s	Saturation magnetization
N_{dz}	Demagnetizing factor in z direction
k_B	Boltzmann constant
T	Absolute temperature
$\hbar$	Reduced Planck's constant
η	Spin transfer efficiency

- **H_k, Δ, and I_C of interface perpendicular magnetic tunnel junction (I-PMTJ) depend on dimension parameters**

Methodology for I-PMTJ Variability Analysis



- **Dedicated MTJ model for variability analysis by incorporating <u>dimension-dependent</u> H_{Keff} into LLG equation**

Variation Factors and Material Parameters

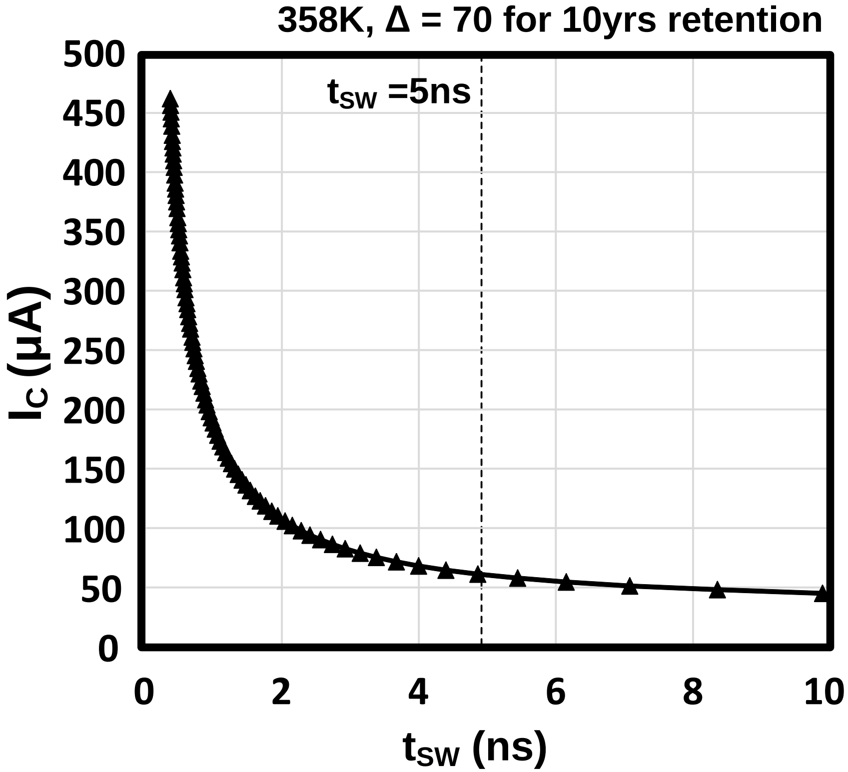
64MB L3 cache memory, Δ = 70 for 10yrs retention

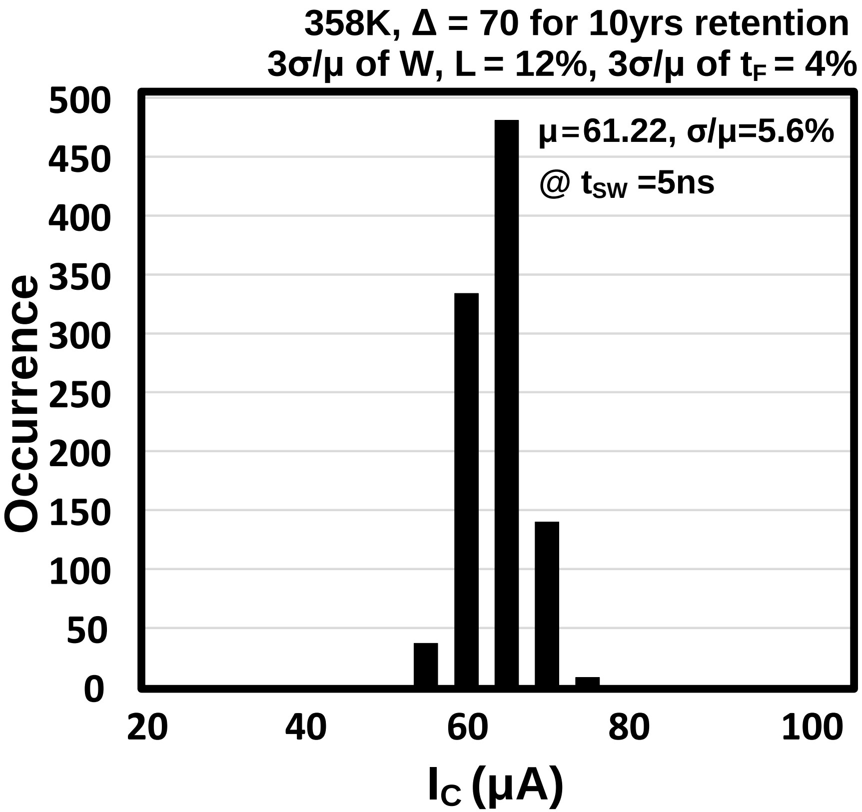
Quantity	PMTJ [3], [5], [6]
Anisotropy source	Interface
Sat. Magnetization, M_S (10^3A/m)	1077
Polarization factor, P	0.6
Effective critical thickness, t_C (nm)	3 (1.5 x 2, double MgO interface*)
Gilbert Damping, α	t_F dependent**
Length, width of free layer, L, W (nm)	μ=22, μ=22 (3σ/μ=12%***)
Thickness of free layer, t_F (nm)	μ=2.78 (3σ/μ=4***~9%)

*** To increase the Δ for 10yrs retention, double MgO interface is used [5]**
**** t_F dependent α is used [3], *** ITRS roadmap**

[3] S. Ikeda, et al., Nature Mater., 2011. [5] K. Tsunoda, et al., IEDM, 2014. [6] J. Hayakawa, et al., Jpn. JAP, 2005.

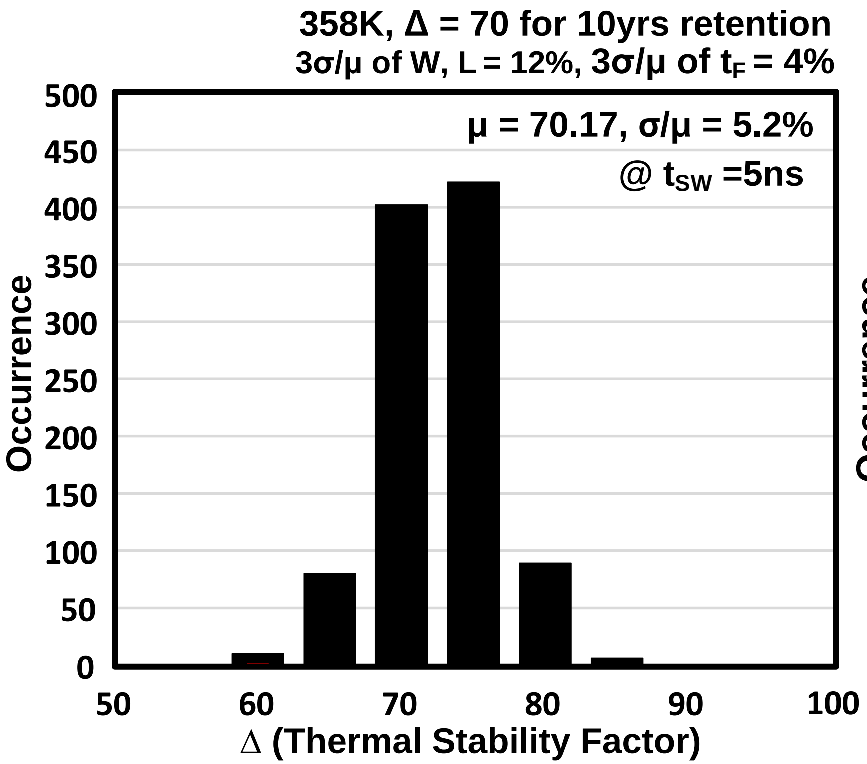
Simulated I_C and Its Variation

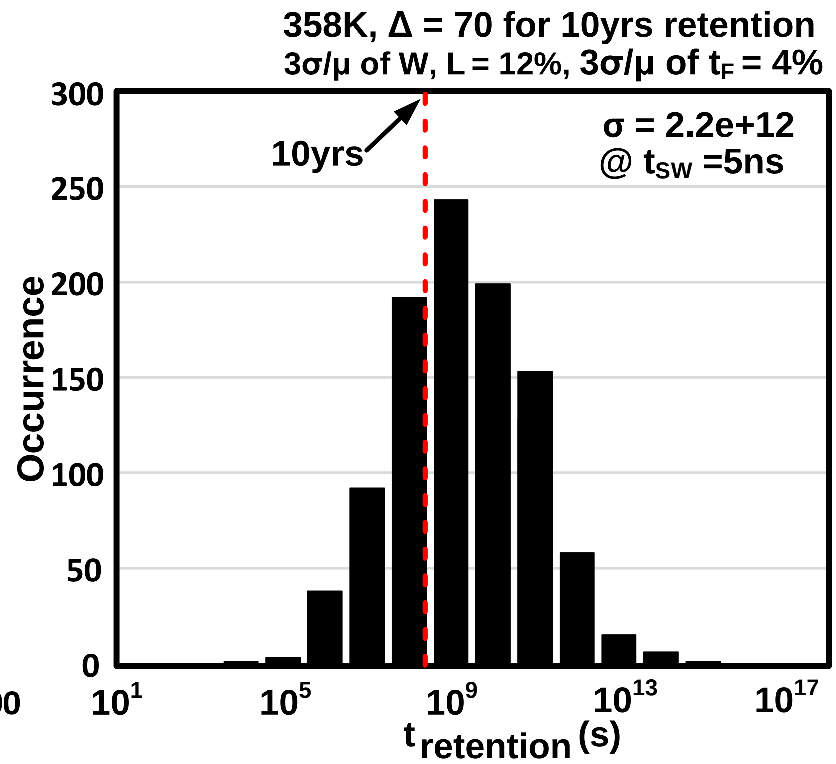




- A constant switching time t_{sw} of 5ns was chosen for all variability simulations
- I_C roughly follows a Gaussian distribution

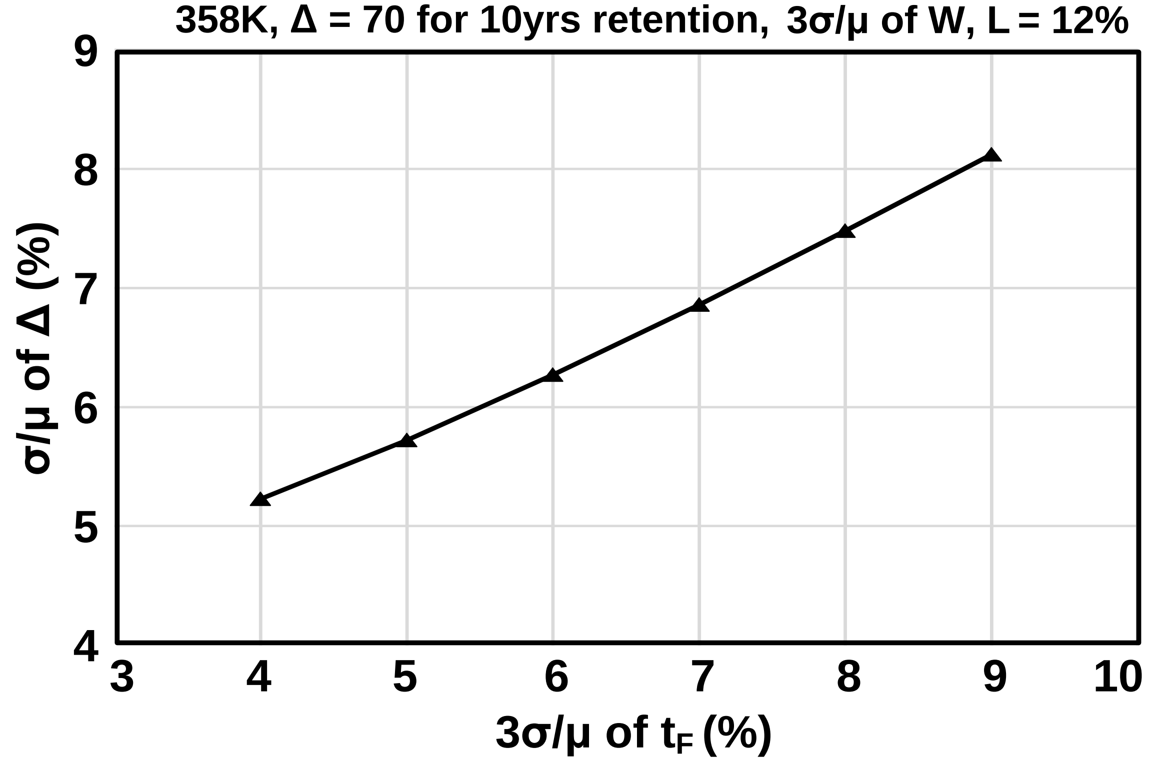
Δ (Thermal Stability Factor) and $t_{retention}$ Variations





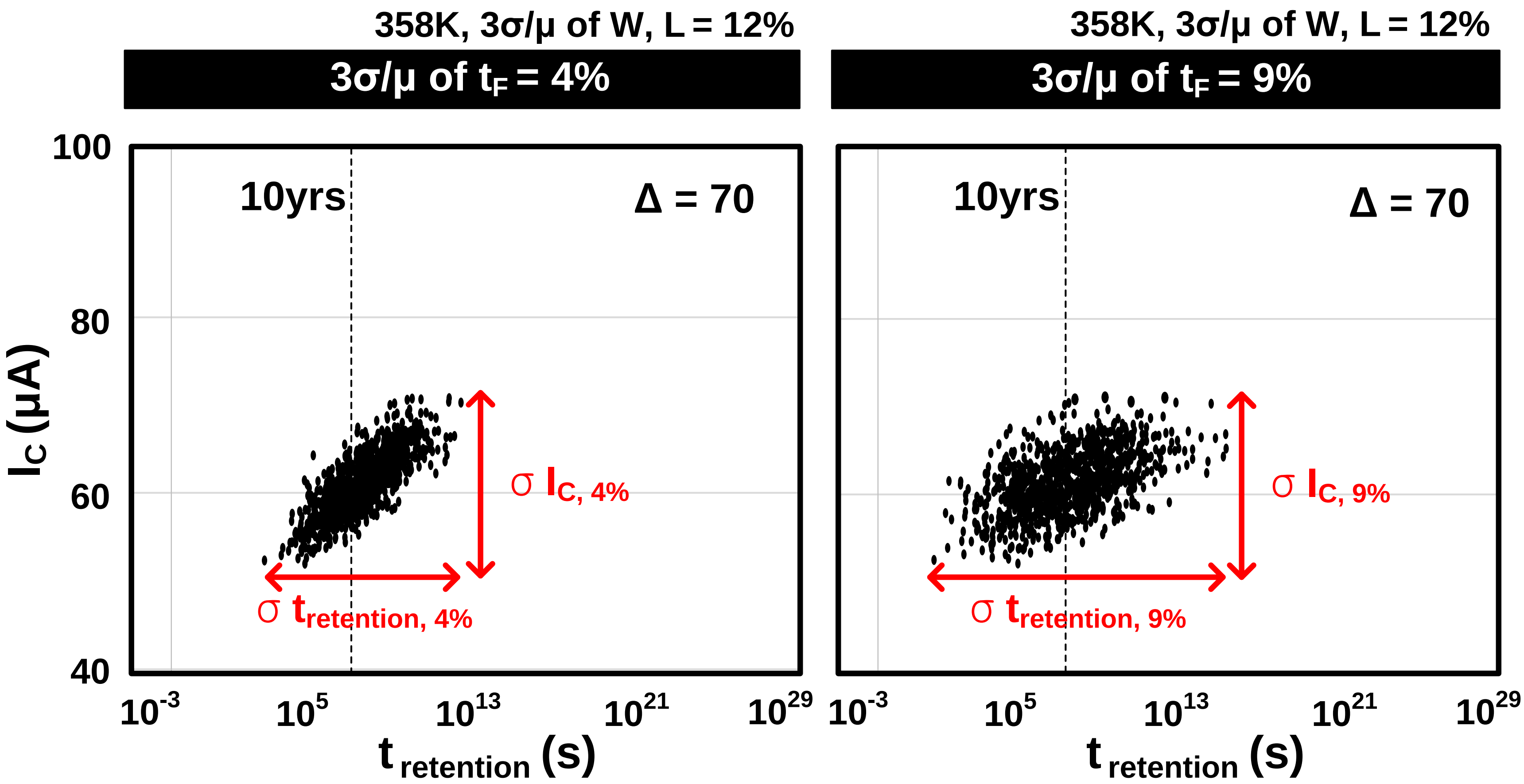
- **Δ and log($t_{retention}$) roughly follow Gaussian distributions**
- **Over 40% of the MTJs fail to meet the 10 year retention time target**

t_F Variation versus Δ Variation



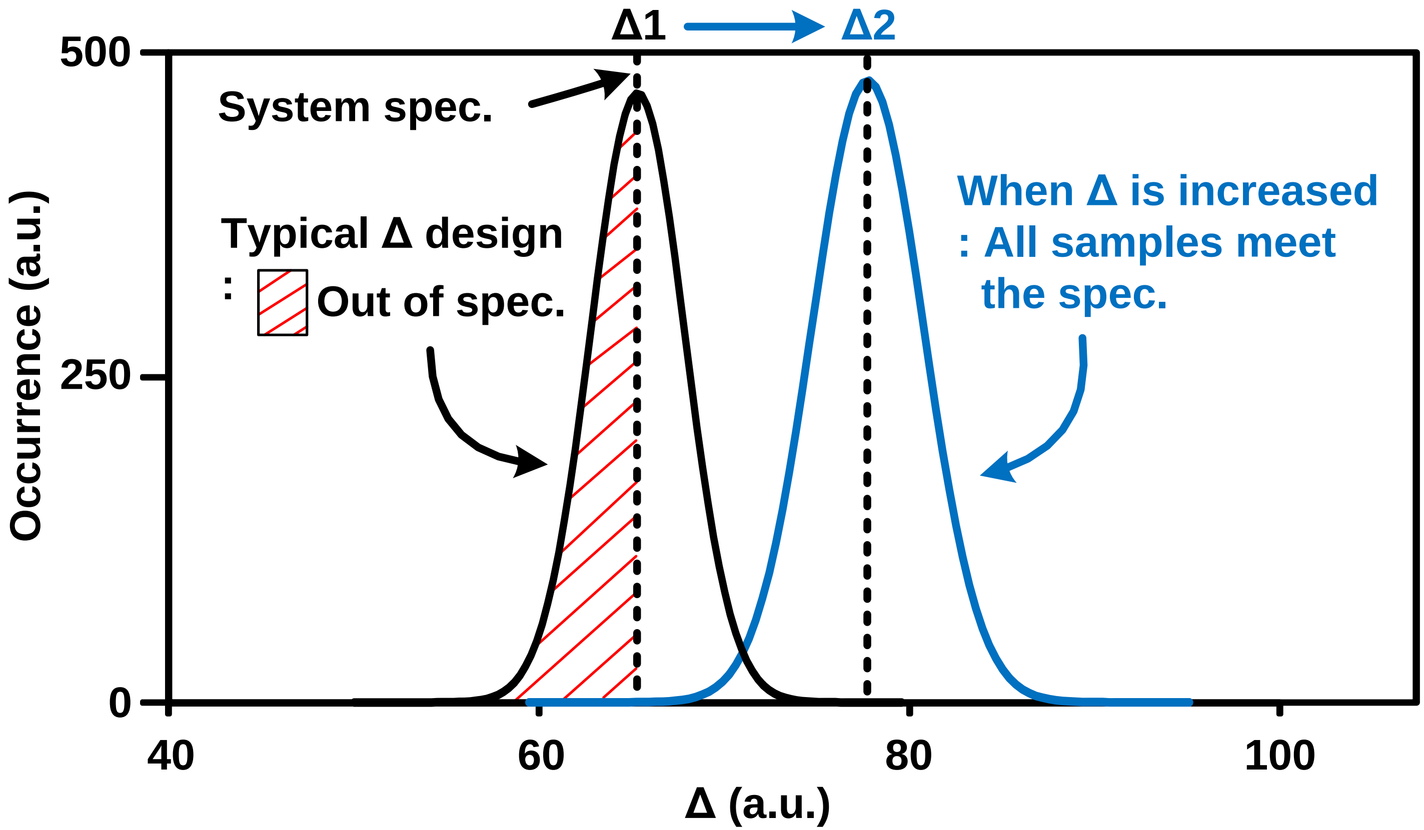
- Δ variation depends strongly on t_F variation
- Retention time variation estimated from Δ variation

$t_{retention}$ versus I_C Variation Plots



- $t_{retention}$ variability has a stronger dependency on t_F variation compared to I_C variability

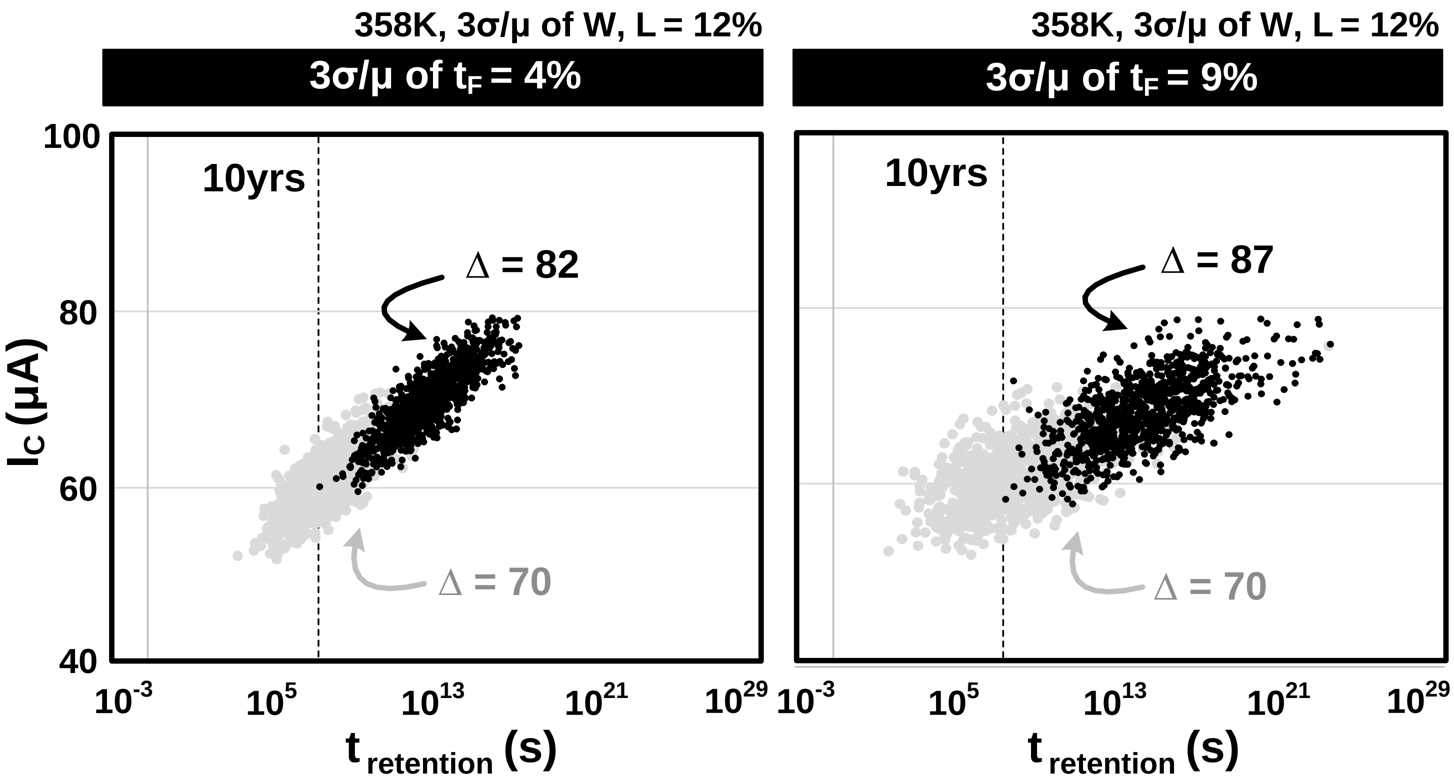
Variability-Considered Δ Overdesign [10]



- **Δ will have to be overdesigned (Δ1 → Δ2) to ensure that all MTJs meet the target retention time**

[10] K. Hofmann, et al., VLSI Tech. Symp. 2014.

Re-plotted Correlation Maps after Increasing Δ



- **I_C increases when overdesigning Δ**
- **Tighter t_F control (9%→4%) results in lower Δ (87→82) and I_C (10.72μA→6.89μA) for achieving a worst case retention time of 10 years**

Conclusion

- **A comprehensive study on I-PMTJ variability was performed with realistic parameters using a physics-based model**
- **Variability of Δ and $t_{retention}$ is more sensitive to t_F variation compared to I_C variability**
  → Tighter t_F control allows a smaller increase in Δ and I_C to ensure all MTJ's meet a 10 year retention time

Acknowledgement

- This work was supported in part by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA