Analyzing Static Noise Margin for Sub-threshold SRAM in 65nm CMOS

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presented at

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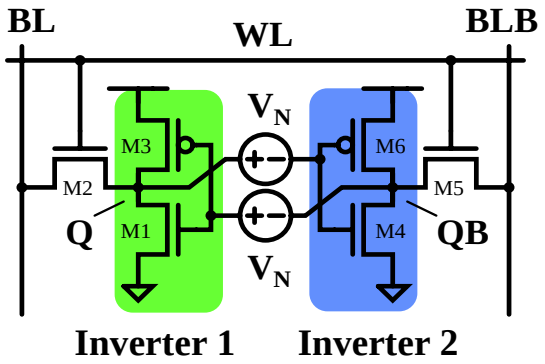
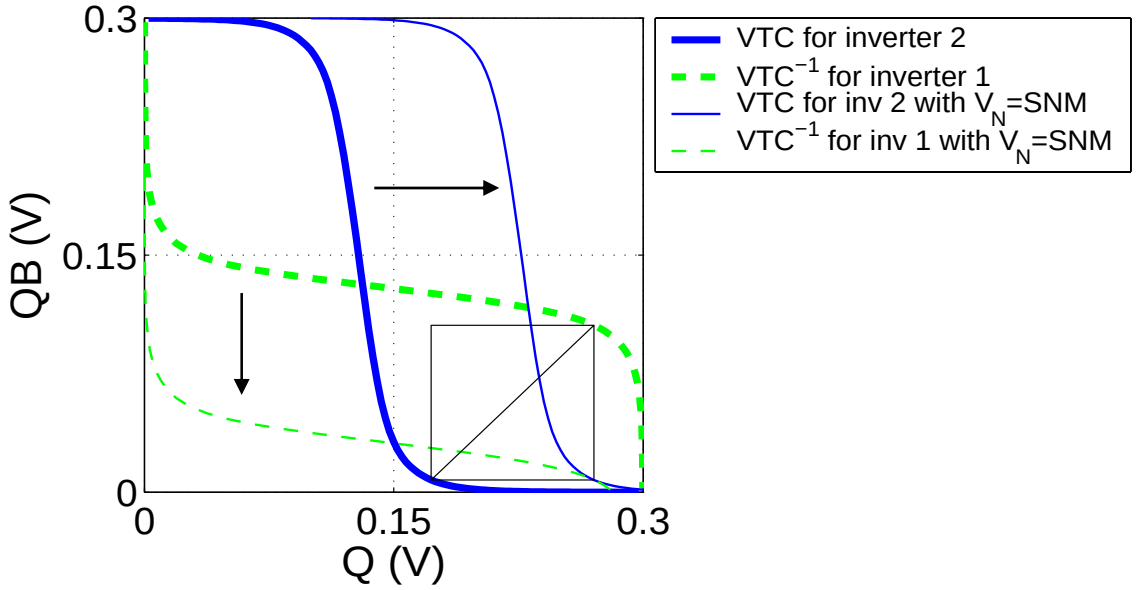
Outline

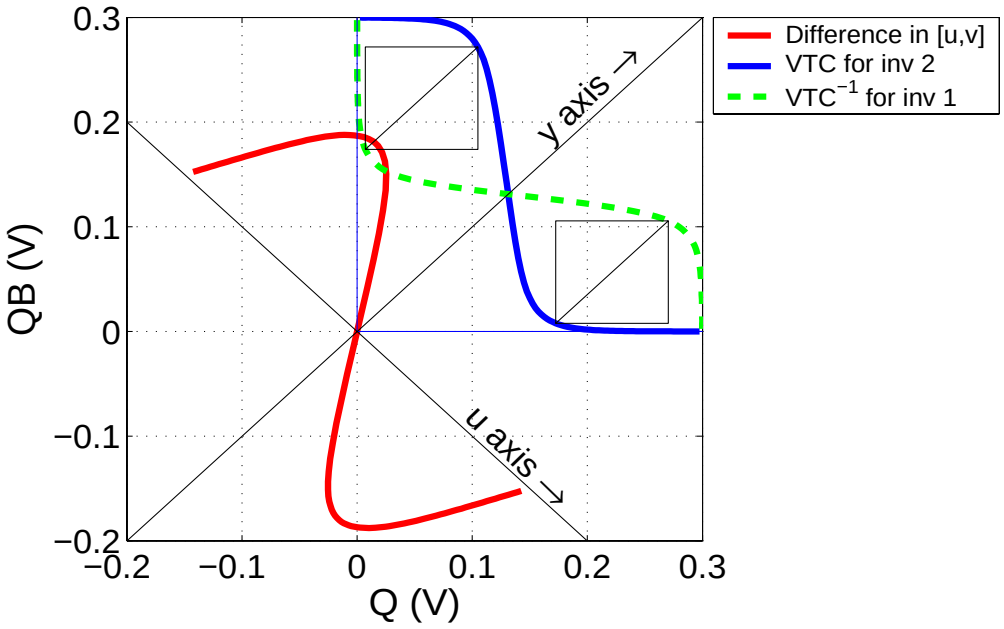
- Introduction to Static Noise Margin (SNM)
- Modeling SNM
- Dependencies of SNM
- Impact of Variation on SNM
- Conclusions

Graphical Method for Finding SNM



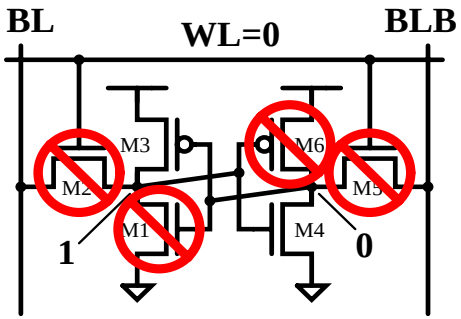
SNM is length of side of the largest embedded square on the butterfly curve

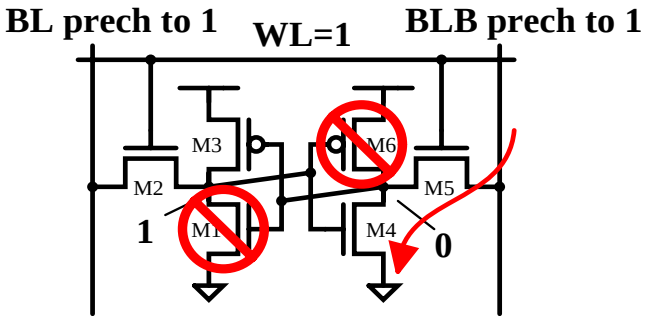


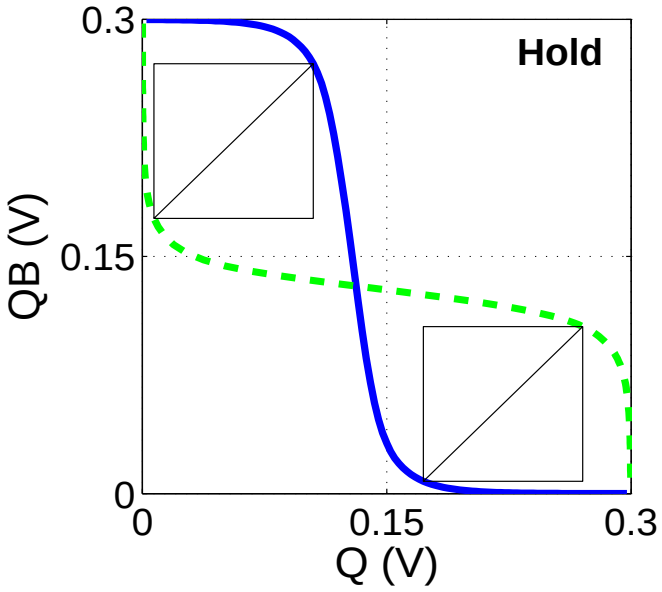


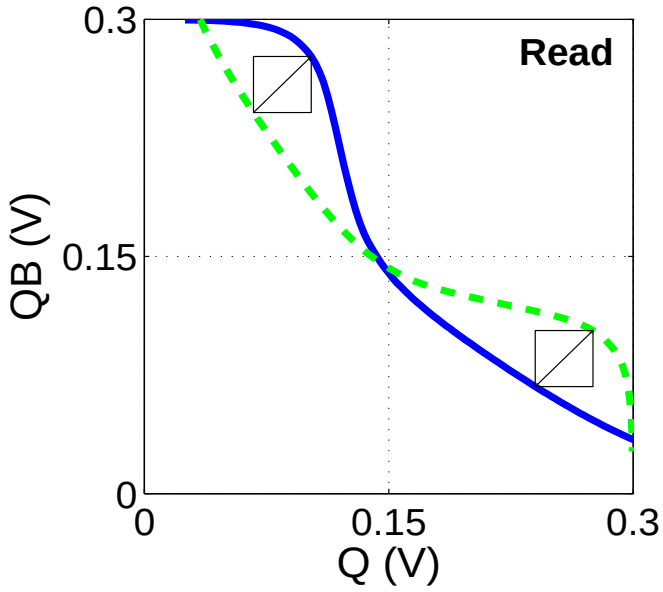
E. Seevinck, F. List, J. Lohstroh, "Static-Noise Margin Analysis of MOS SRAM Cells" JSSC, Oct '87.

SNM during Hold and Read









Read SNM is worst-case

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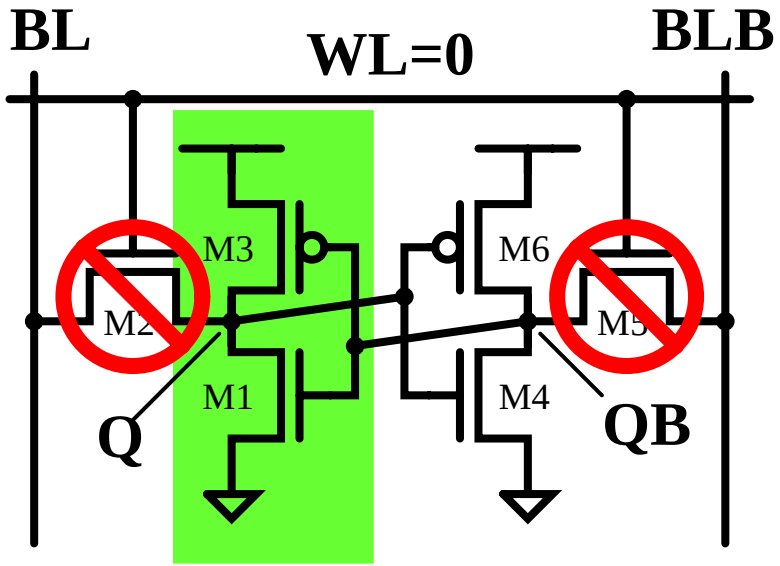
Modeling SNM Hold



In Sub-threshold:

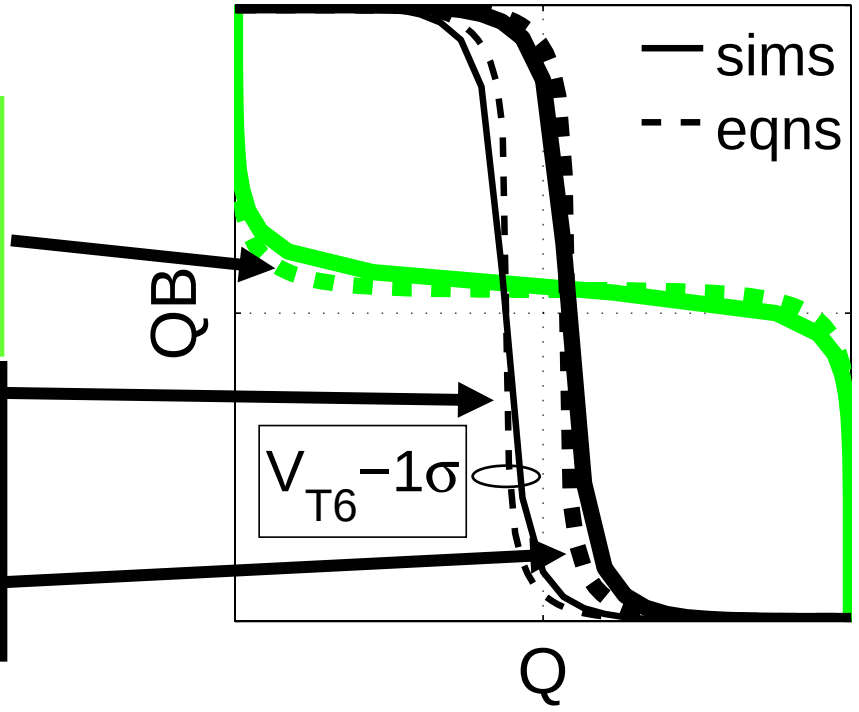
$$I_D = I_S \exp\left(\frac{V_{GS} - V_T}{nV_{th}}\right)\left(1 - \exp\left(\frac{-V_{DS}}{V_{th}}\right)\right)$$

Assumptions:
- $I_{M3} = I_{M1}$
- $I_{M6} = I_{M4}$

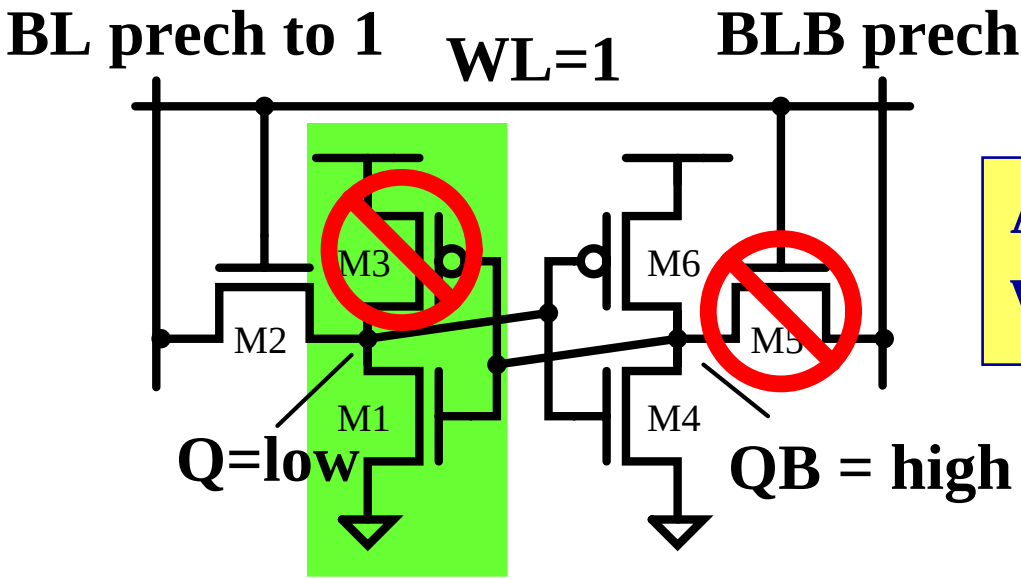
$$QB = V_{th}\frac{n_1 n_3}{n_1 + n_3}\left(\ln\frac{I_{S3}}{I_{S1}} + \ln\left(\frac{1 - \exp((-V_{DD} + Q)/V_{th})}{1 - \exp(-Q/V_{th})}\right)\right) + \frac{n_1 V_{DD}}{n_1 + n_3} + \frac{n_1 n_3}{n_1 + n_3}\left(\frac{V_{T1}}{n_1} - \frac{V_{T3}}{n_3}\right)$$

$$QB = V_{DD} + V_{th}\ln\left(0.5 * \left(1 - G + \sqrt{(G-1)^2 + 4e^{\frac{-V_{DD}}{V_{th}}} G}\right)\right),$$

$$G = \exp\left(\frac{n_4 + n_6}{n_4 n_6 V_{th}} Q - \ln\frac{I_{S6}}{I_{S4}} - \frac{V_{DD}}{n_6 V_{th}} - \frac{1}{V_{th}}\left(\frac{V_{T4}}{n_4} - \frac{V_{T6}}{n_6}\right)\right)$$

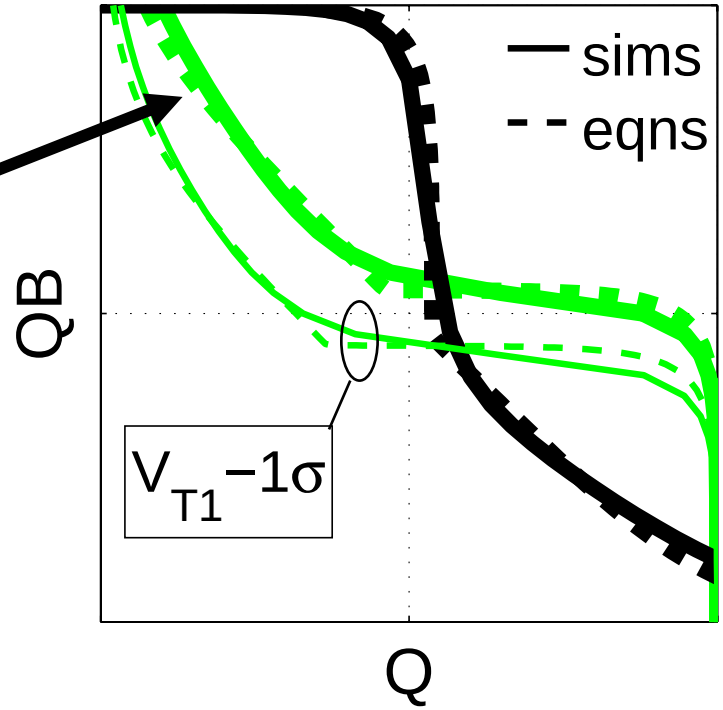


Modeling SNM Read



Assumptions when Q is low:
- $I_{M2}=I_{M1}$
- $I_{M6}=I_{M4}$

$$QB = n_1 V_{th} \ln\frac{I_{S2}}{I_{S1}} + n_1 V_{th} \ln\left(\frac{1-\exp((-V_{DD}+Q)/V_{th})}{1-\exp(-Q/V_{th})}\right) + V_{T1} + \frac{n_1}{n_2}\left(V_{DD} - V_{T2} - Q\right)$$



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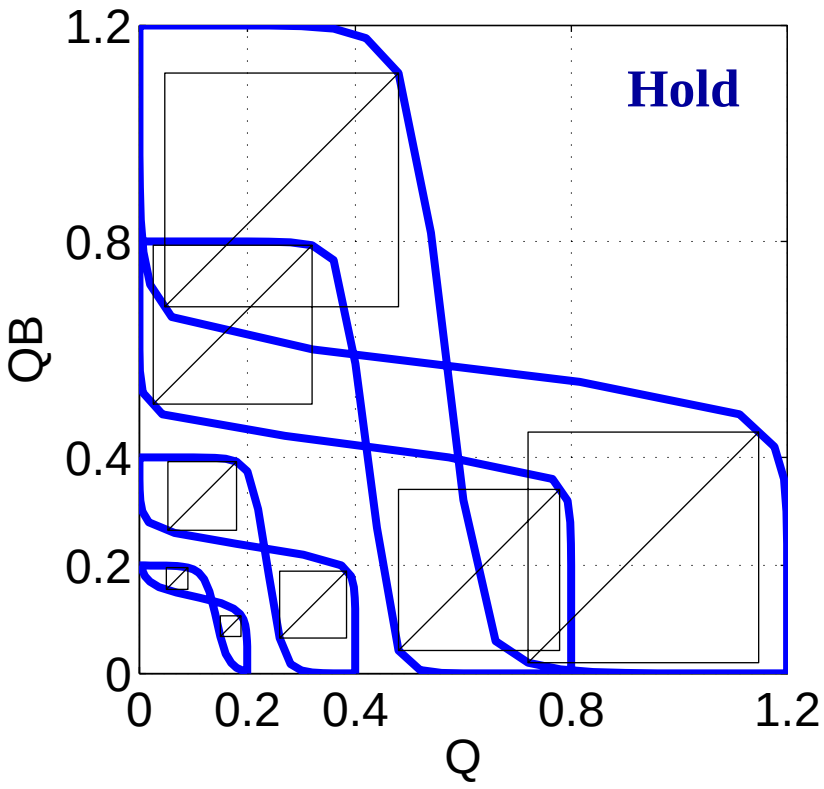
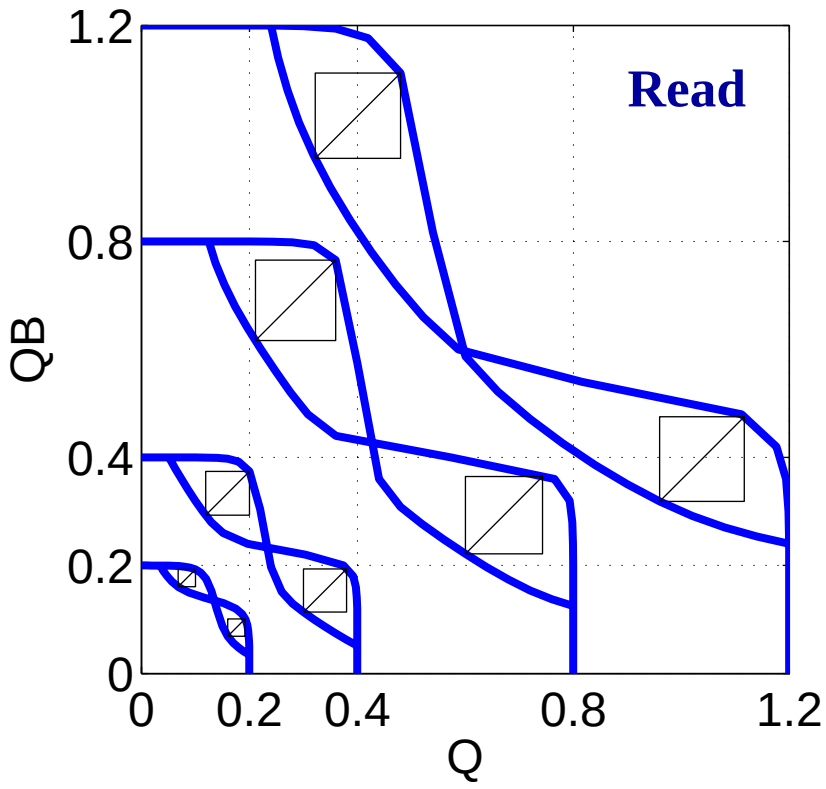
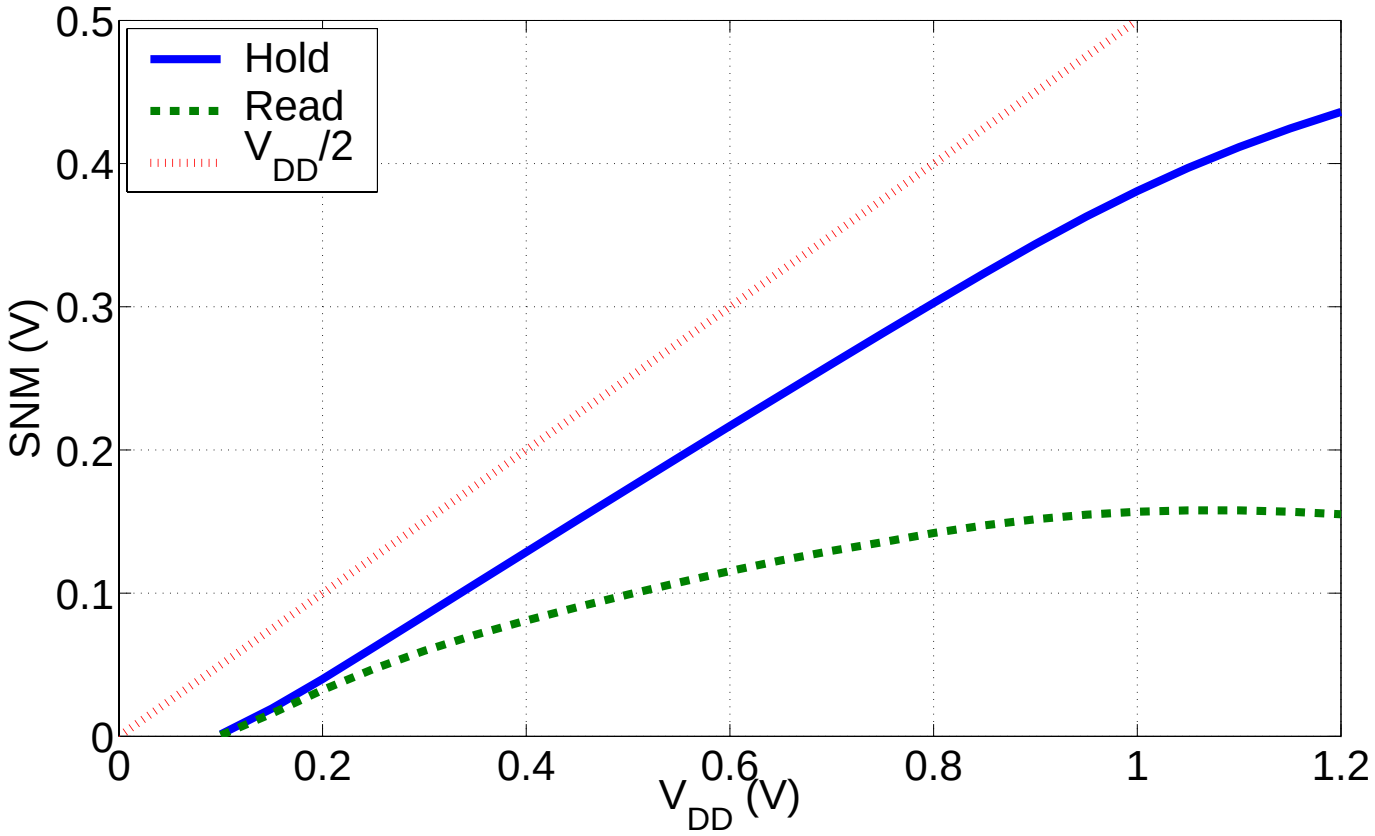
SNM Dependence on V_{DD}





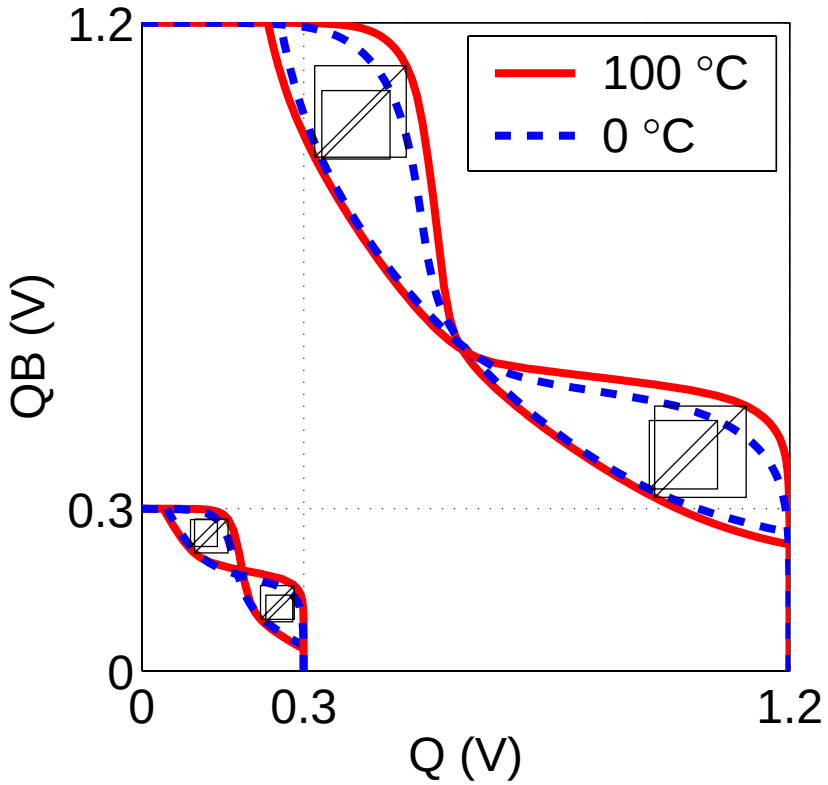
Read SNM less sensitive in above V_T operation

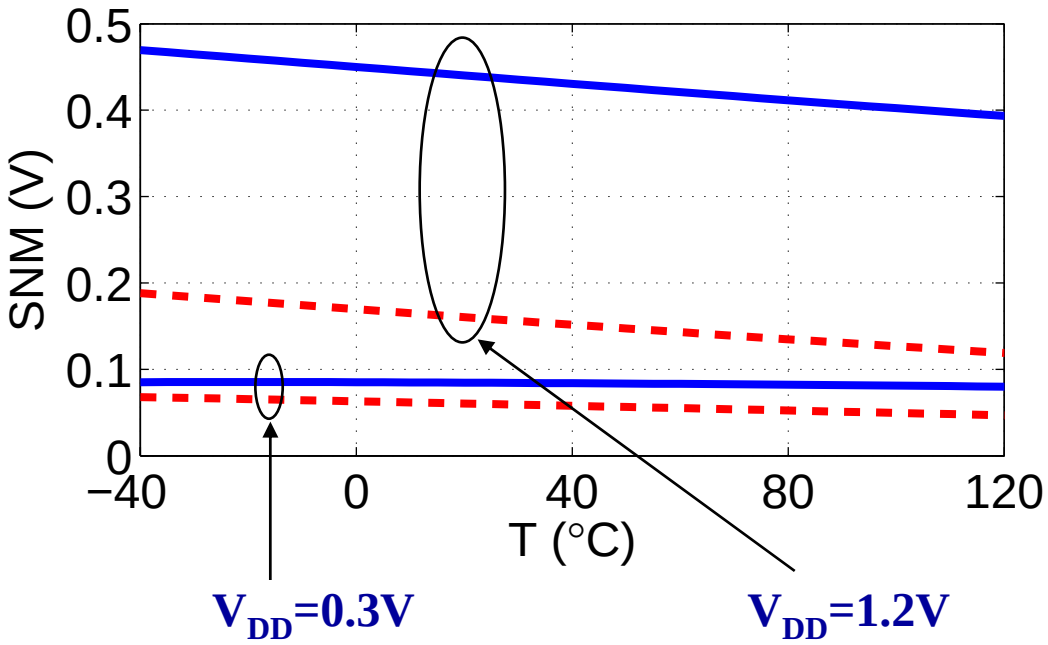
SNM Dependence on V_{DD}



V_{DD} noise affects SNM by less than half

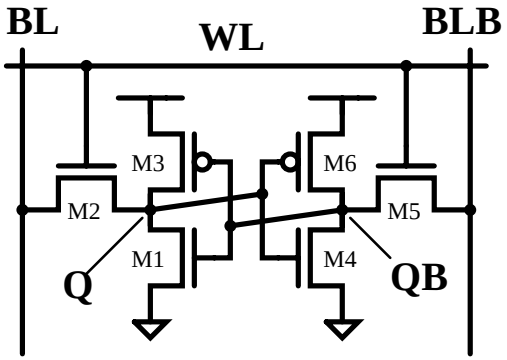
SNM Dependence on Temperature



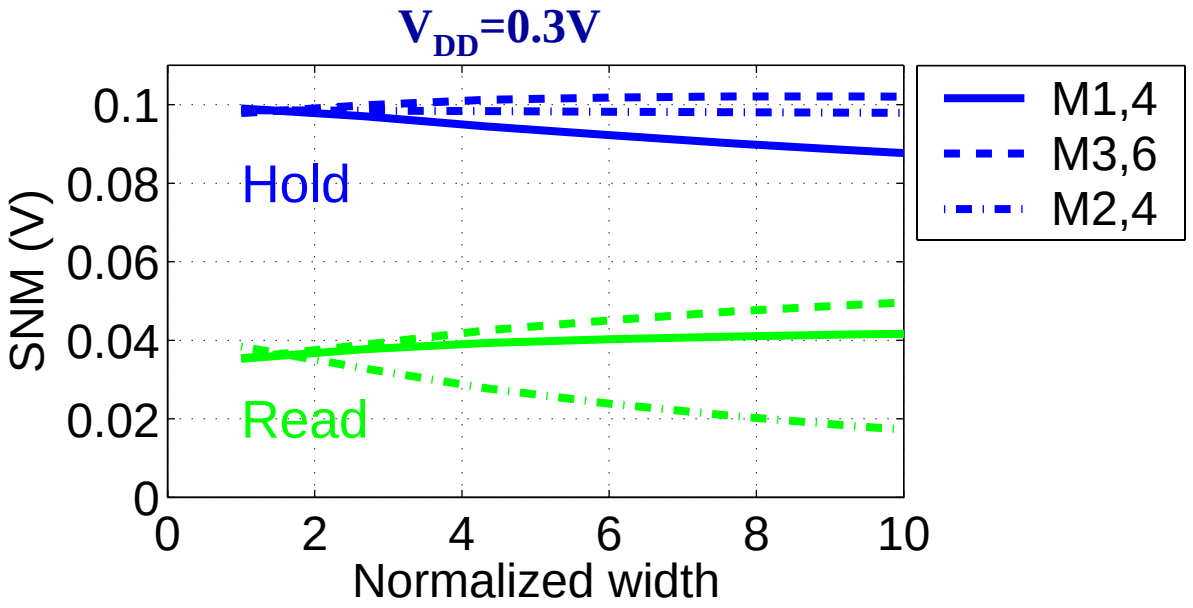


Temperature impact not large because it affects pFETs and nFETs similarly

Transistor Sizing Impact on SNM

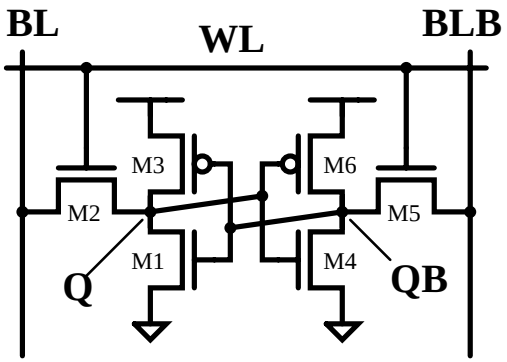


e.g. $$QB = V_{th}\frac{n_1 n_3}{n_1+n_3}\left(\ln\frac{I_{S3}}{I_{S1}} + \ln\left(\frac{1-\exp((-V_{DD}+Q)/V_{th})}{1-\exp(-Q/V_{th})}\right)\right) + \frac{n_1 V_{DD}}{n_1+n_3} + \frac{n_1 n_3}{n_1+n_3}\left(\frac{V_{T1}}{n_1}-\frac{V_{T3}}{n_3}\right)$$

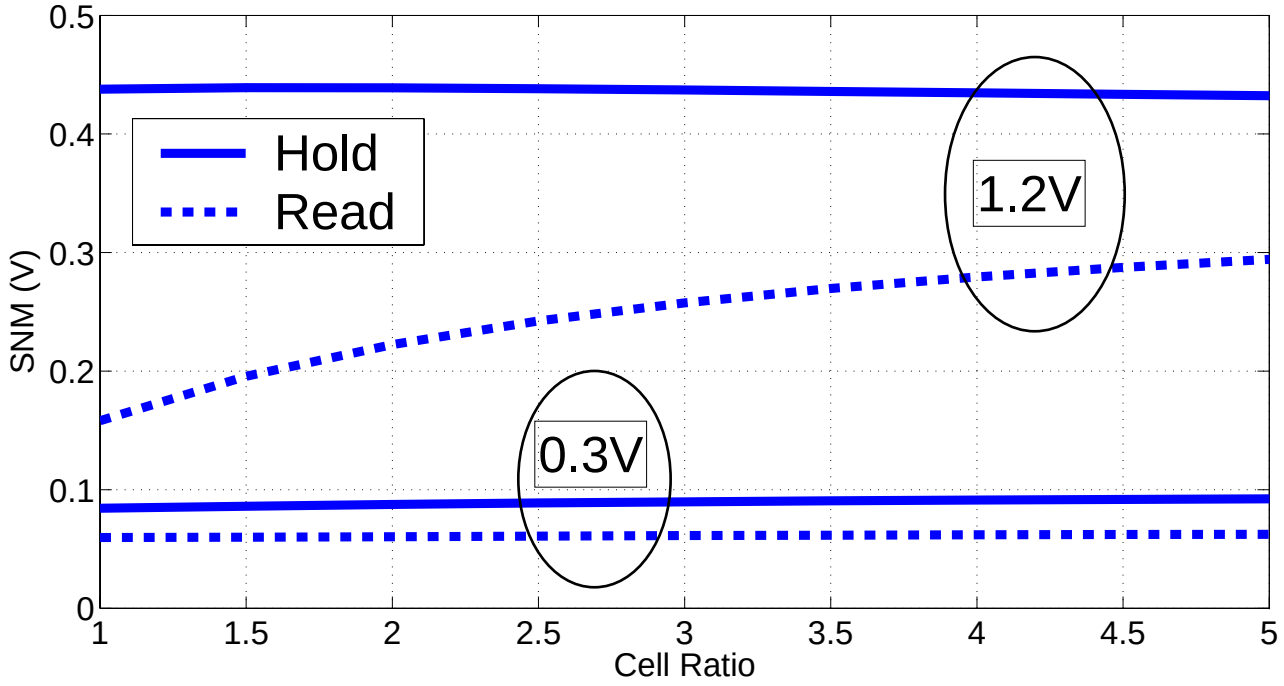


Sizing impact not so large because of logarithmic impact on VTCs

Cell Ratio and Sub-threshold SNM



Cell ratio = $(W/L)_1 / (W/L)_2$ or $(W/L)_4 / (W/L)_5$



Cell ratio much less important for sub-threshold SNM

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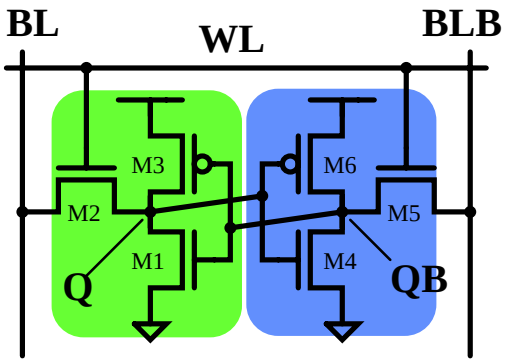
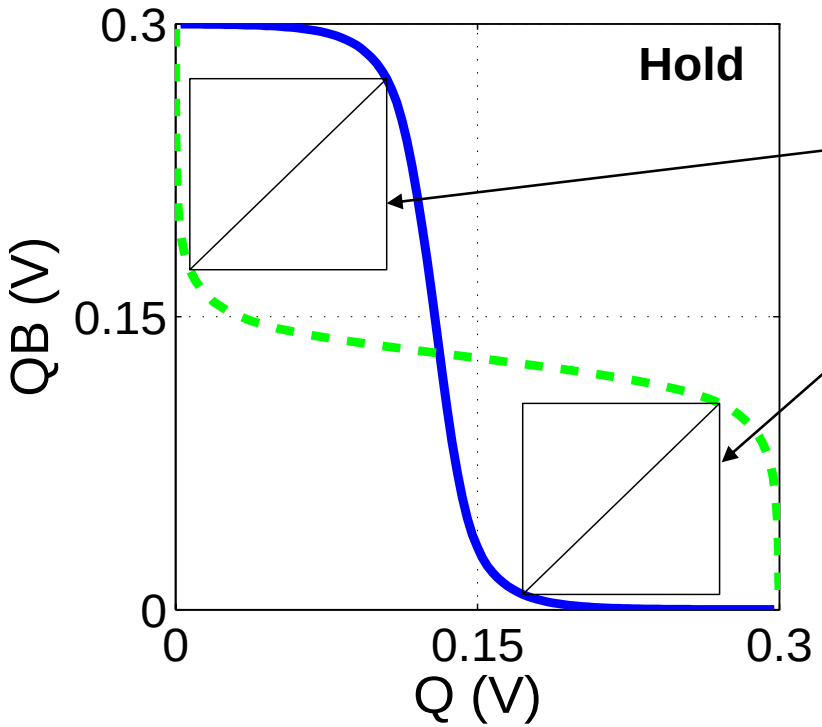
Impact of Mismatch on SNM



Until now, we have assumed that the two sides of the bitcell are symmetric. With mismatch, that is not true.

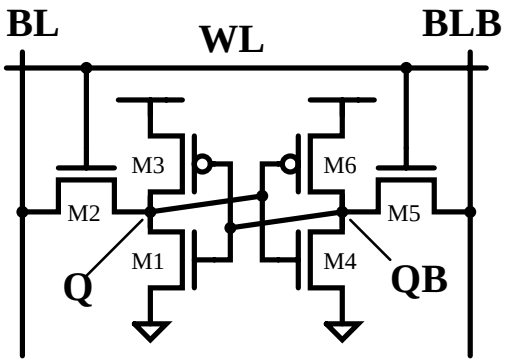


SNM high

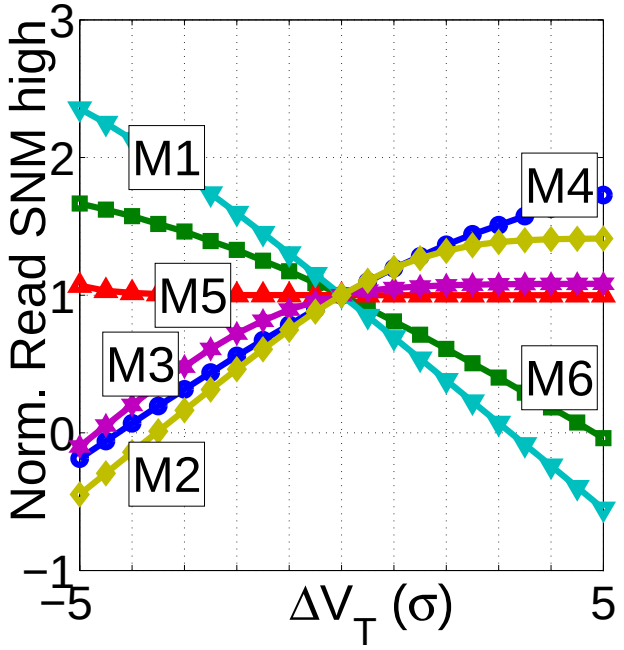
SNM low

SNM is the minimum of SNM high and SNM low, which are different due to mismatch

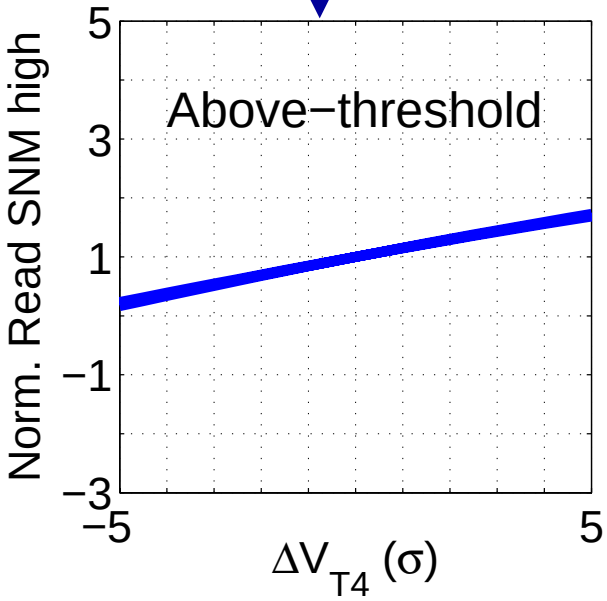
Single FET V_T mismatch

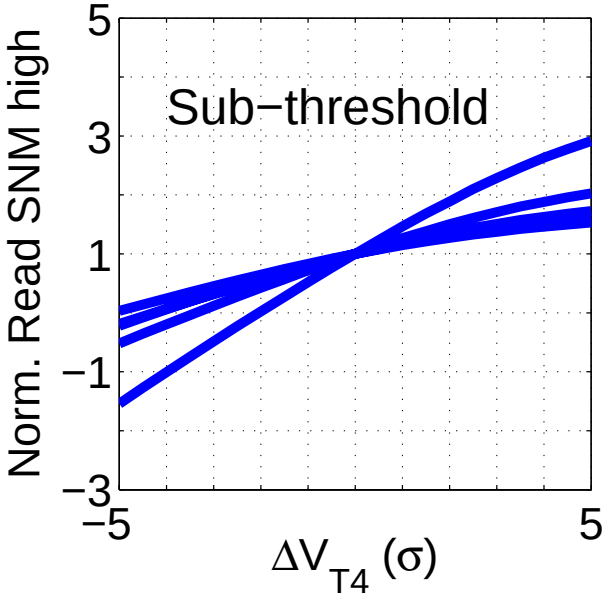


Sensitivity of SNM to single FET mismatch is roughly linear.



Above threshold SNM can use 1st order series model

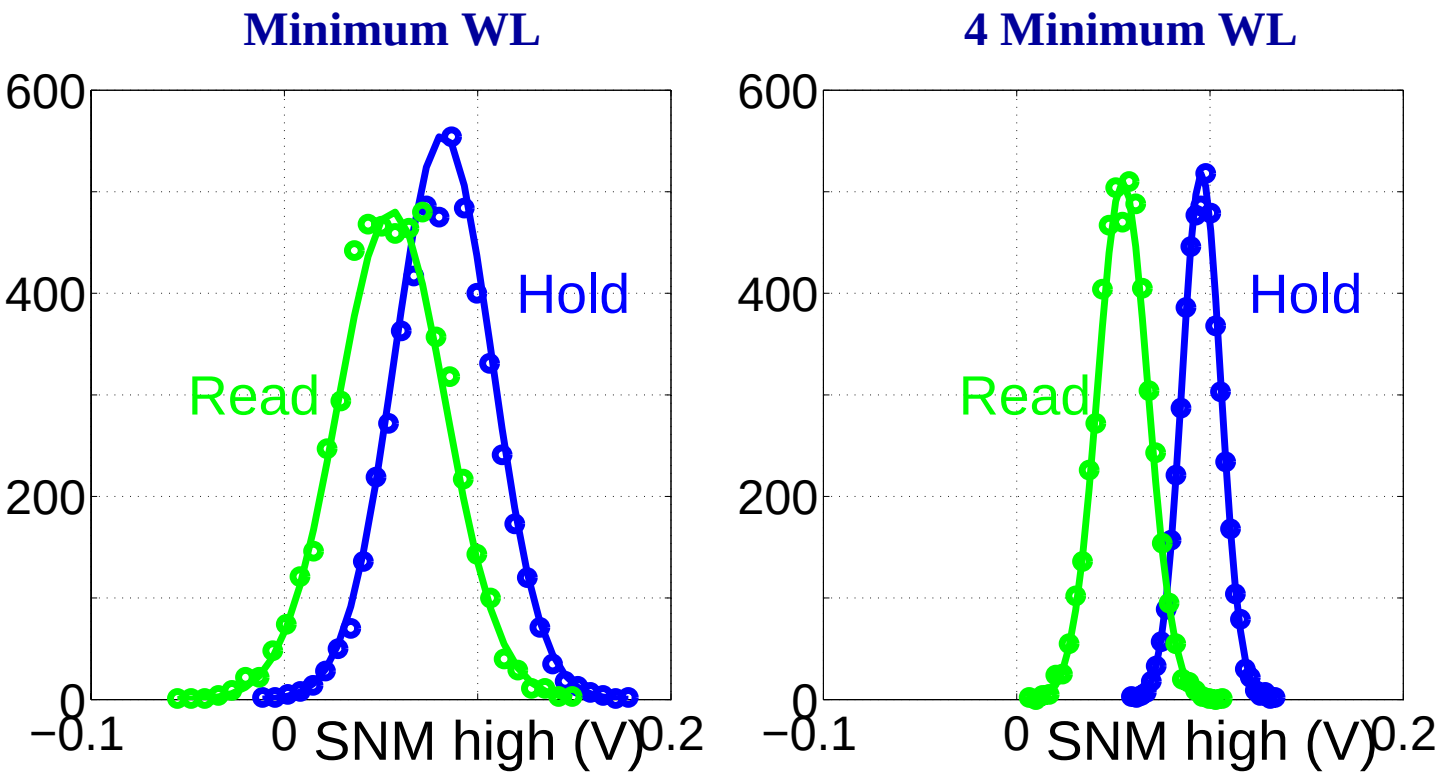




Cannot use 1st order series model for sub-threshold SNM

Mismatch SNM Distributions

Random mismatch in all 6 transistors



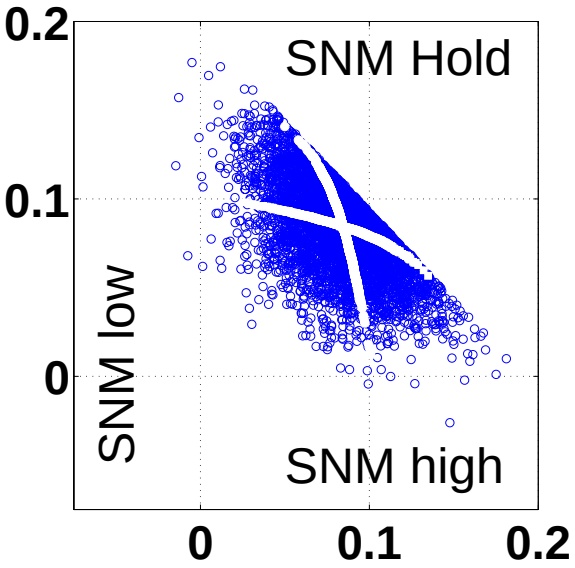
Like above-threshold, SNM high and SNM low are normally distributed with threshold voltage mismatch

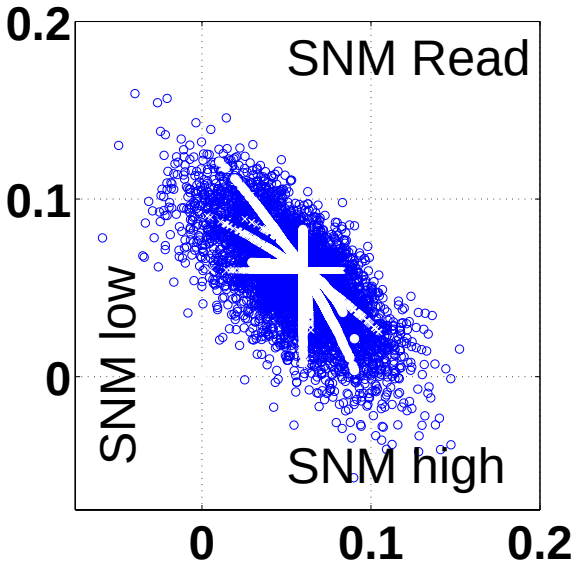
Modeling PDF for Mismatch

SNM is min(SNM high, SNM low);
Tail is most important for yield

If SNMhigh, SNMlow are independent and identically distributed (iid), then the pdf for SNM is:

$$f_{SNM}=2f_{SNMhigh}(1-F_{SNMhigh})$$





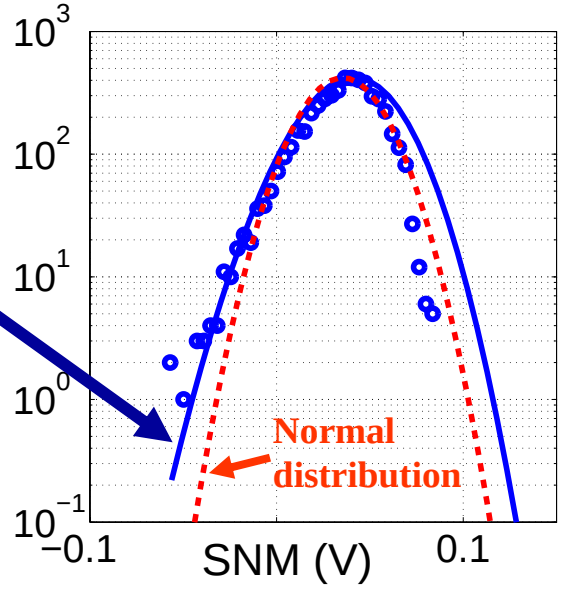
SNM high and SNM low are nearly identically distributed, but NOT independent

Simulations Compared to Model

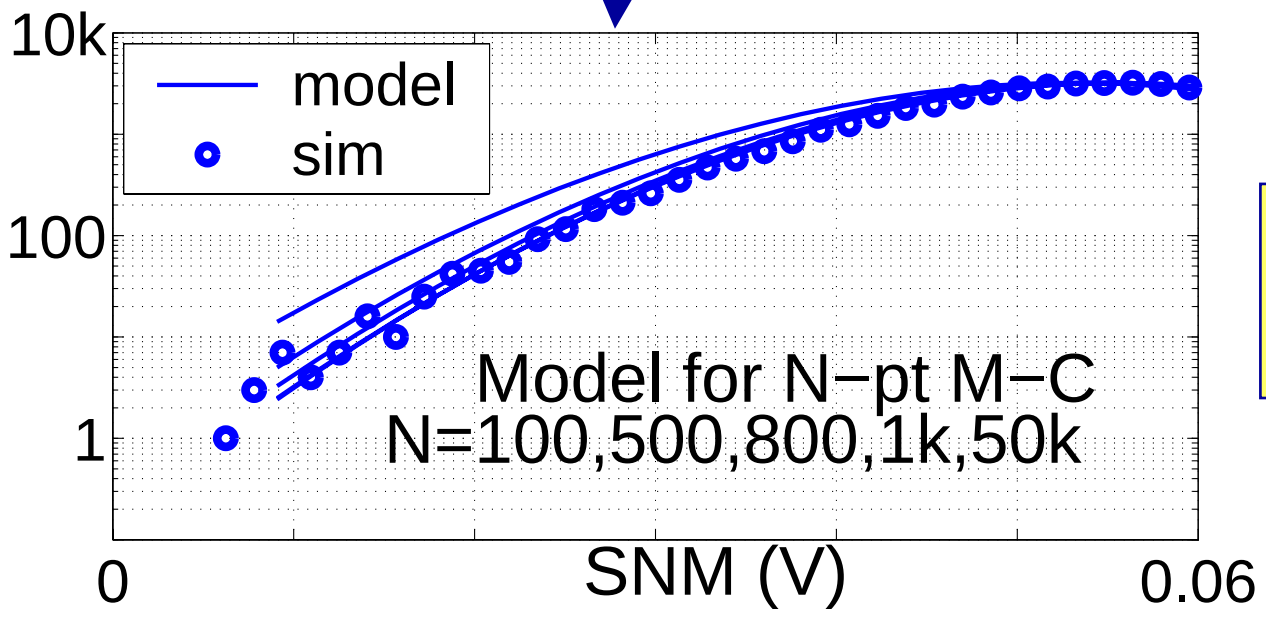
Try the model anyway:

$$f_{SNM} = 2 f_{SNMhigh}(1 - F_{SNMhigh})$$

Model matches well for the worst-case tail

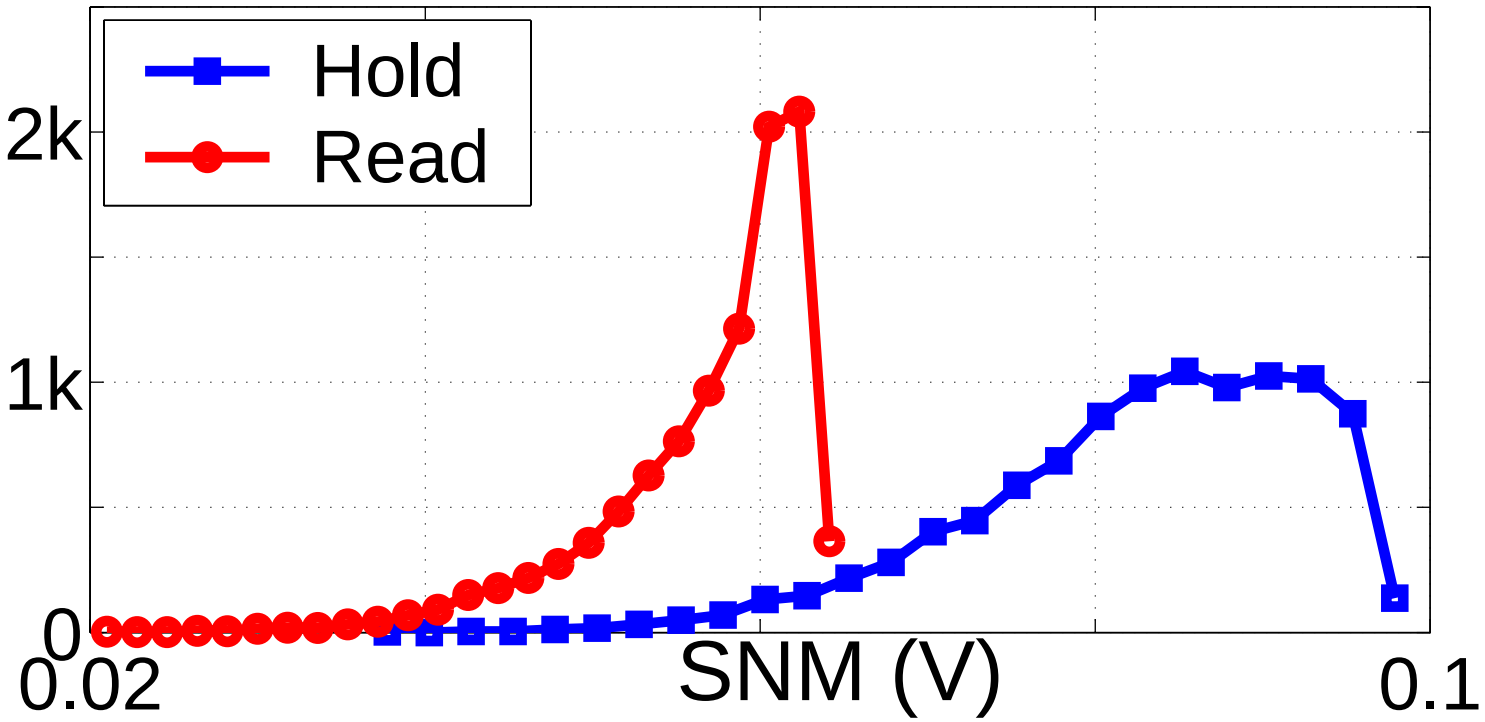


1k model within 3% of 50k model



Model based on short sims is accurate for much longer sims

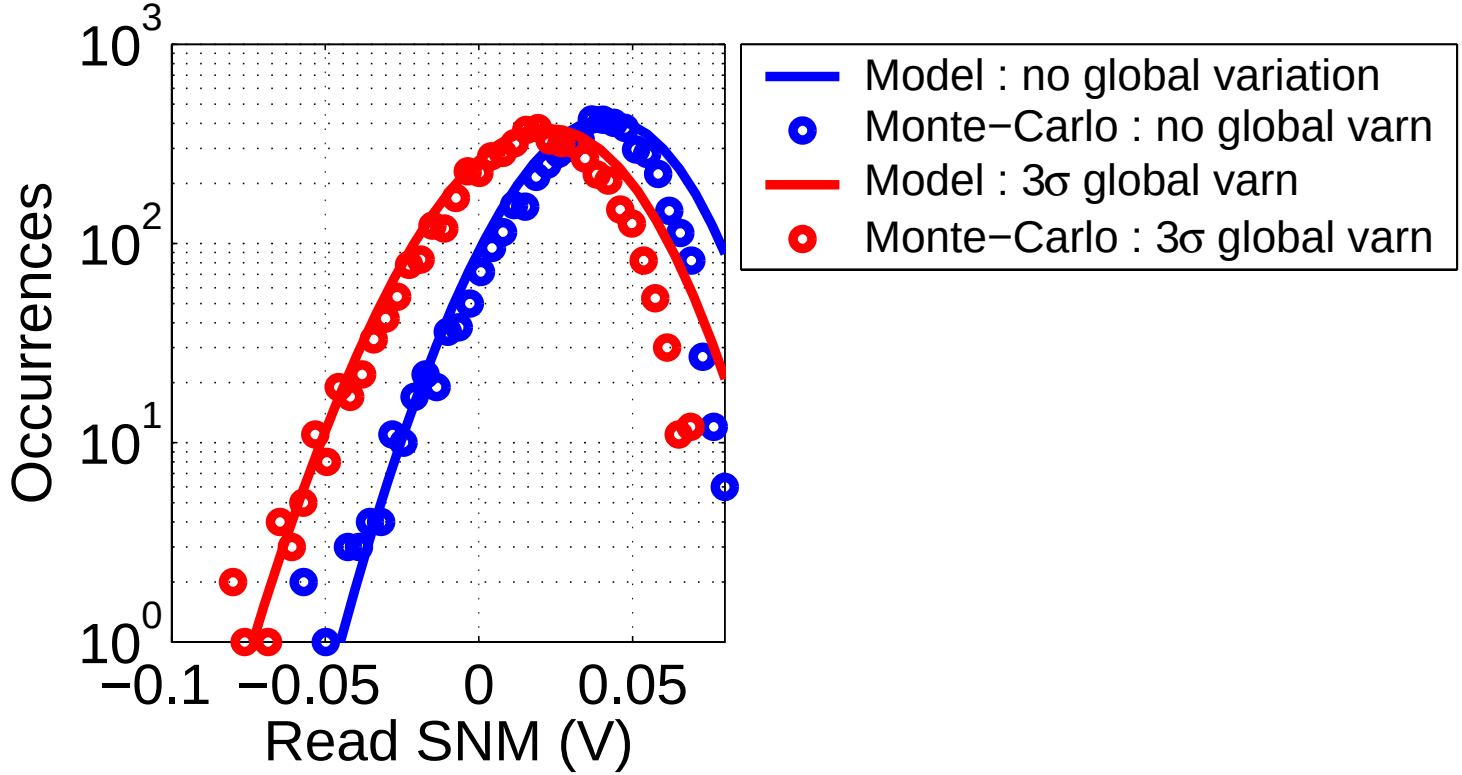
Global Process Corner Variation



Global variation causes variation in SNM

Global Variation and Local Mismatch

When mismatch occurs in addition to global variation, the mismatch distribution shifts.



Model still works with global variation and mismatch

Conclusions

- SNM limits sub-threshold memory yield
- SNM most strongly depends on mismatch and global variation
- Proper modeling for the tail of the SNM distribution allows fast estimation of SNM yield