IBM Microelectronics

Modeling Small MOSFETs Using Ensemble Devices

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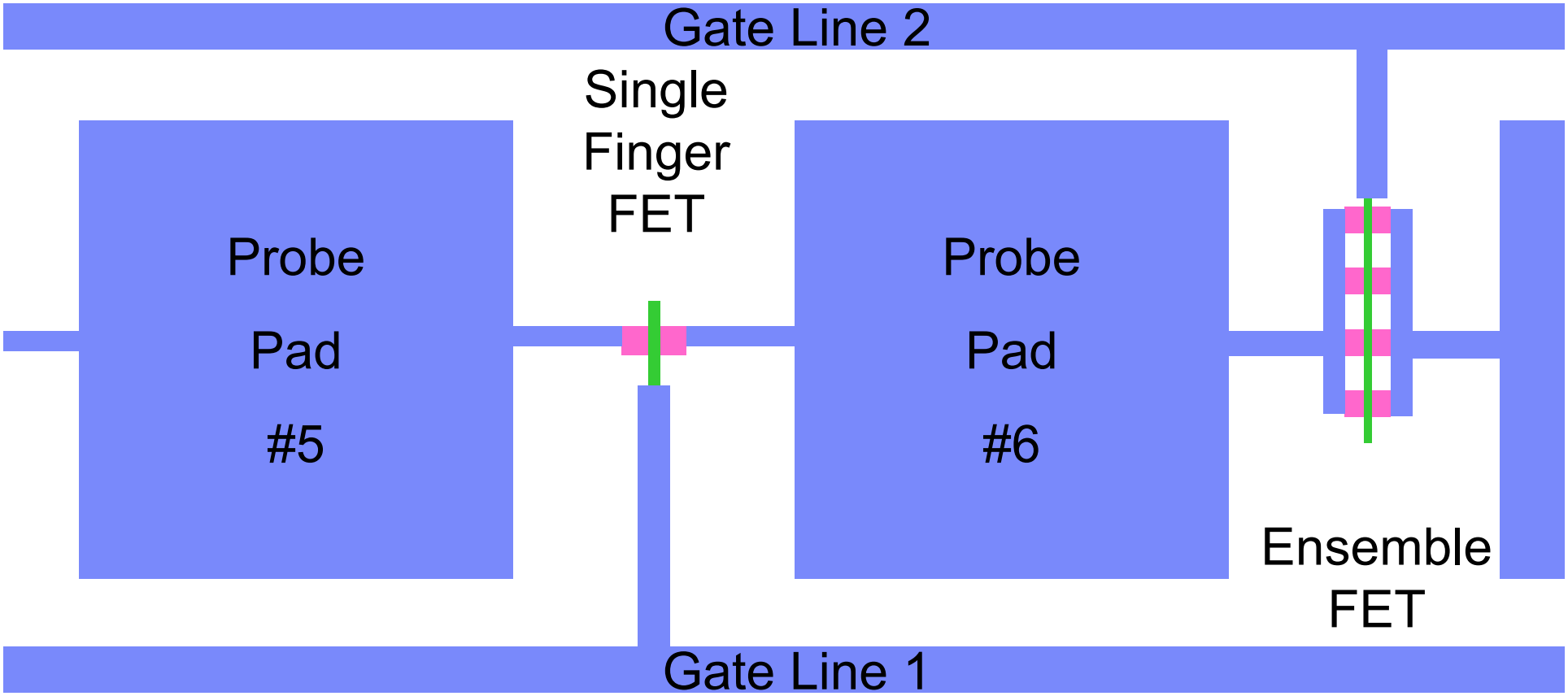
April 2006

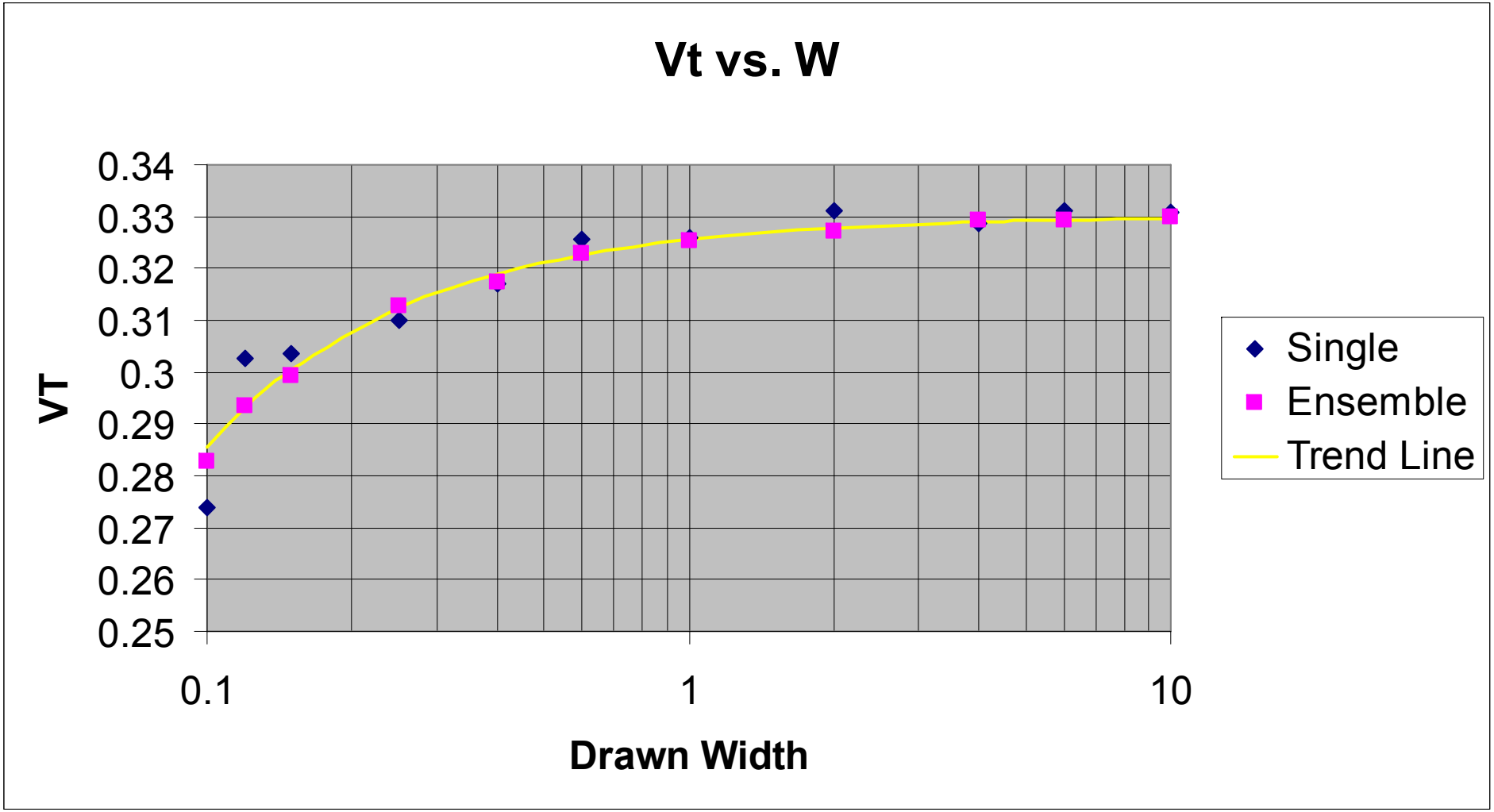
Outline

- **What's the problem and who cares**
- **What's the solution**
  - Alternative approaches
  - Recovering single finger current from ensemble data
  - The model implementation
- **Conclusions**

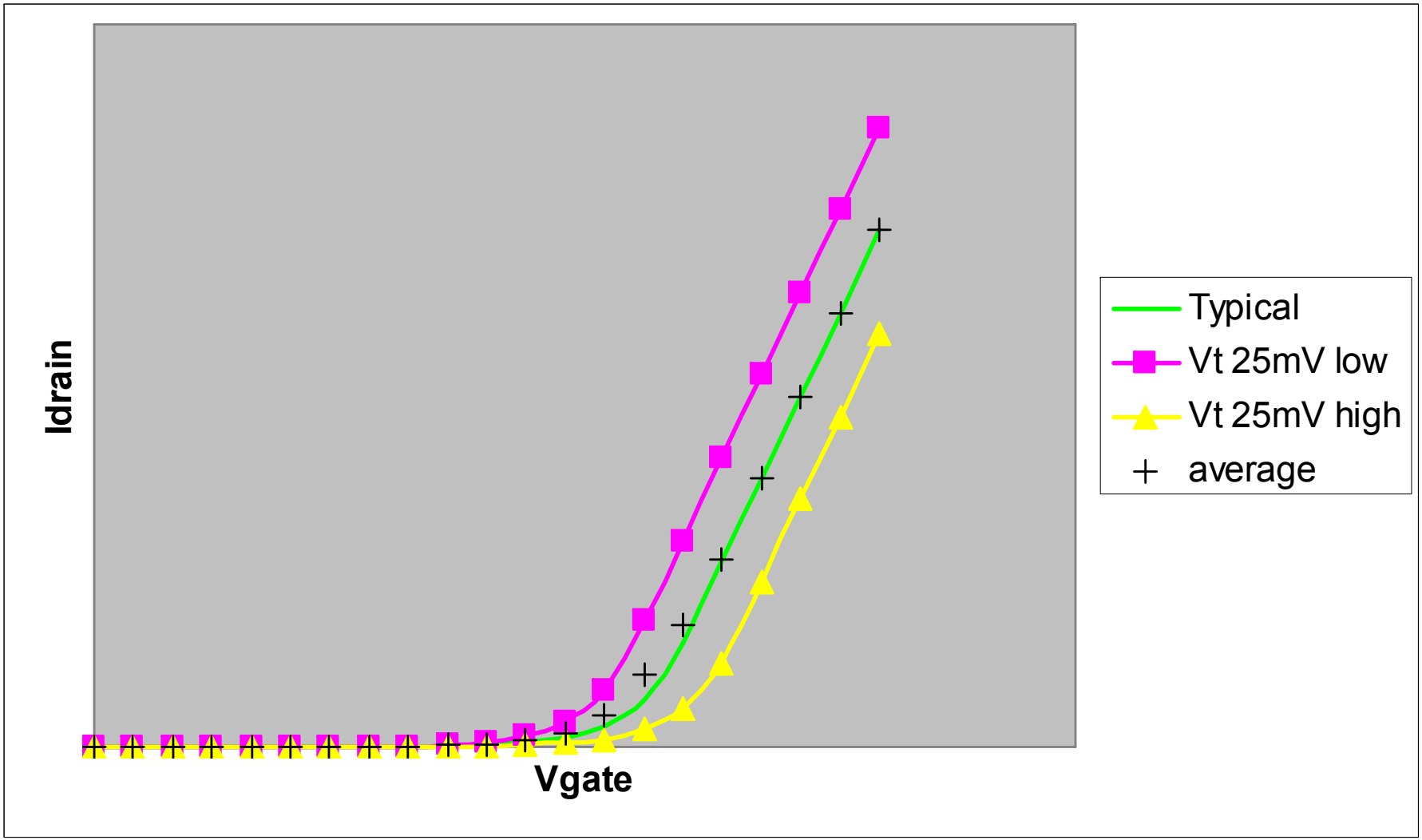
What is an ensemble device?



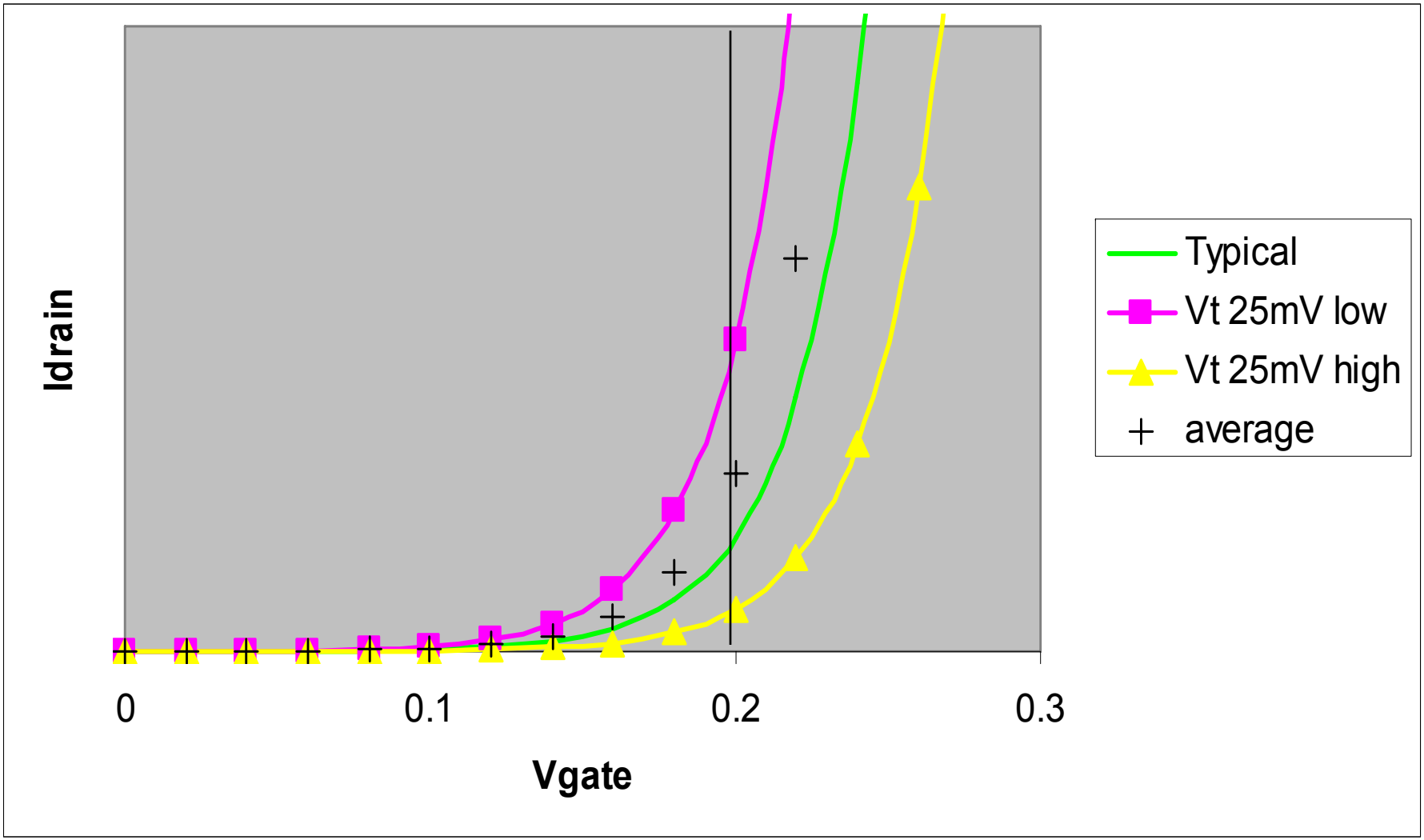
Why use Ensemble Devices



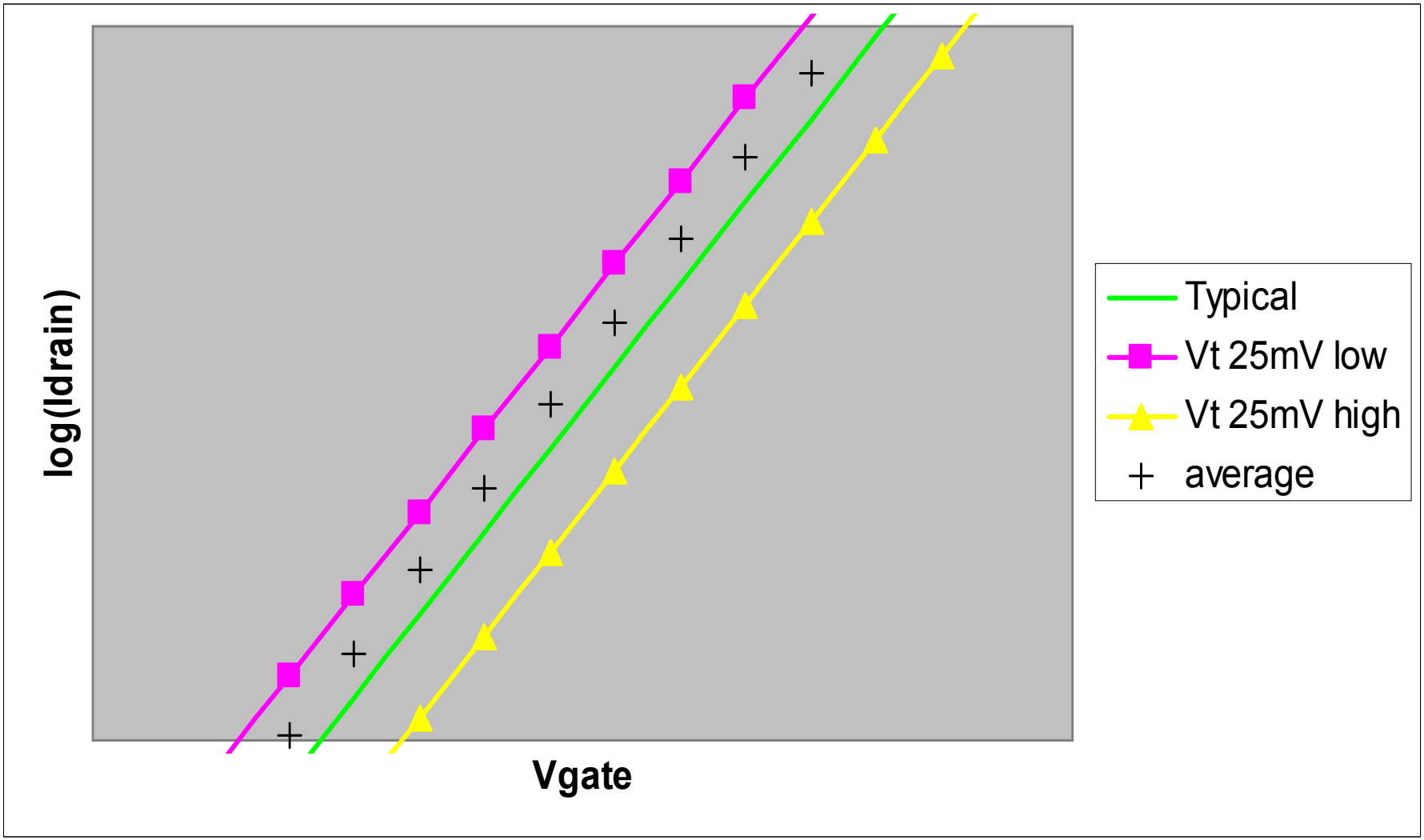
Comparison of Typical and Mean (above Vt)



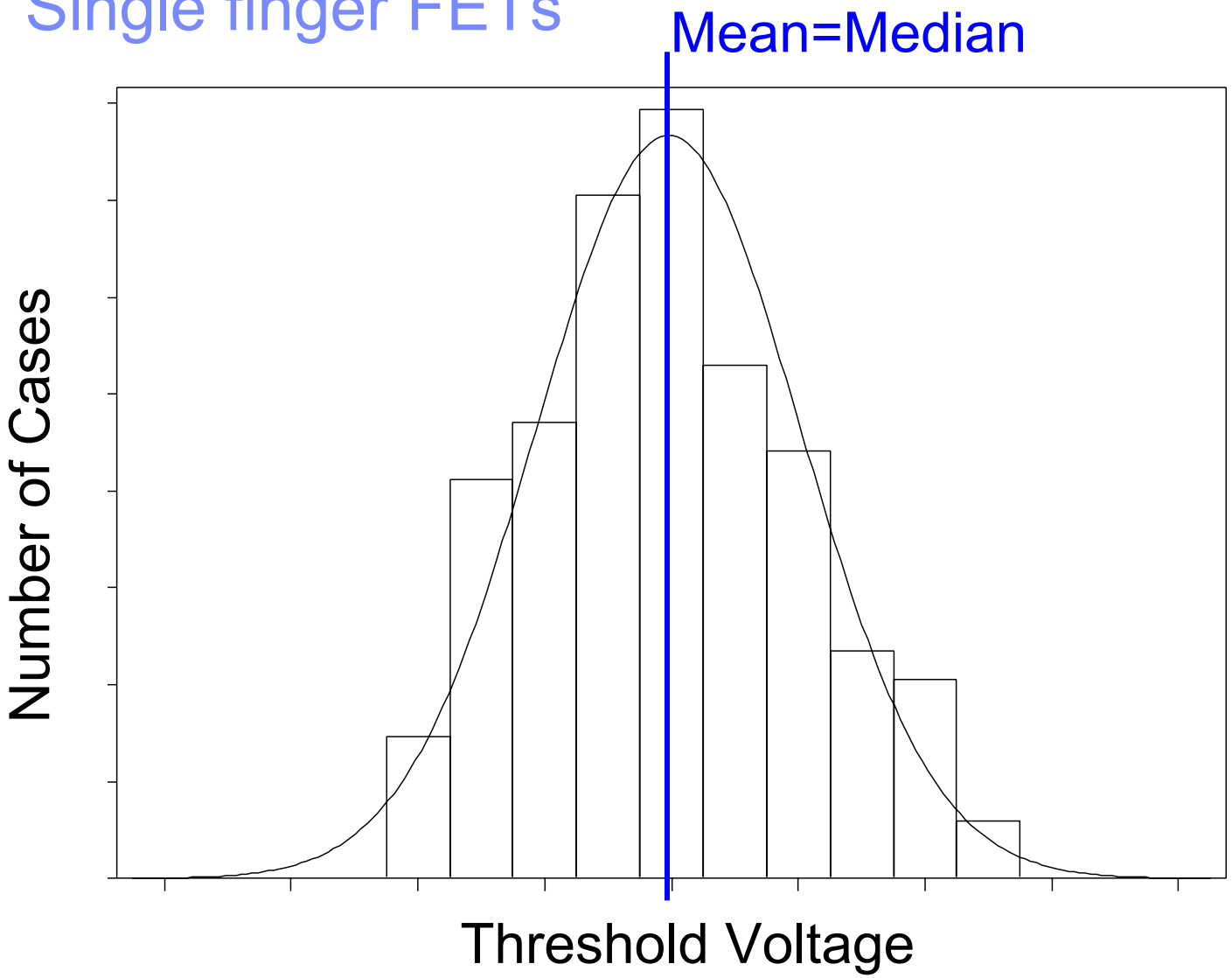
Comparison of Typical and Mean (below Vt)



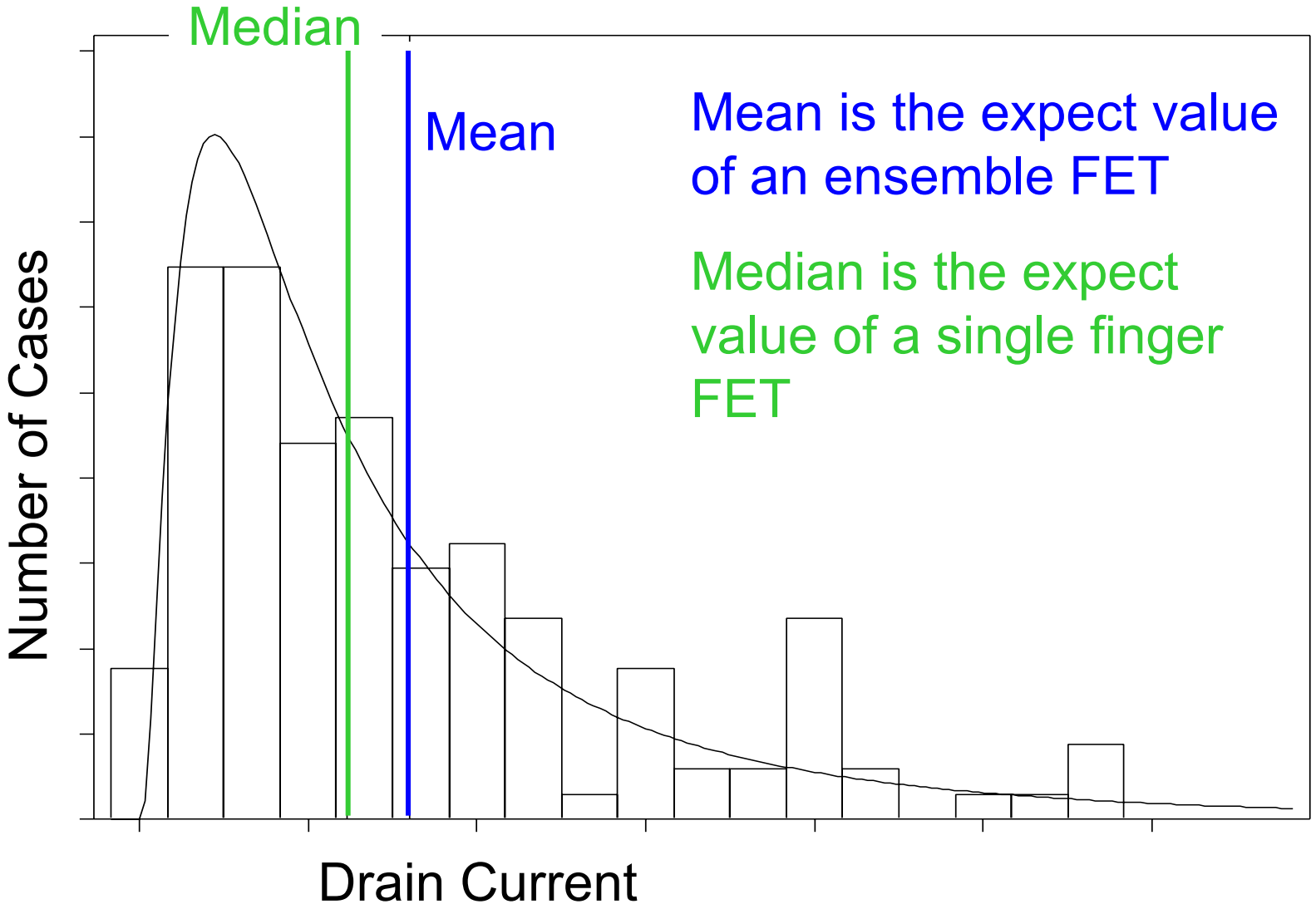
Comparison of Typical and Mean (below Vt)



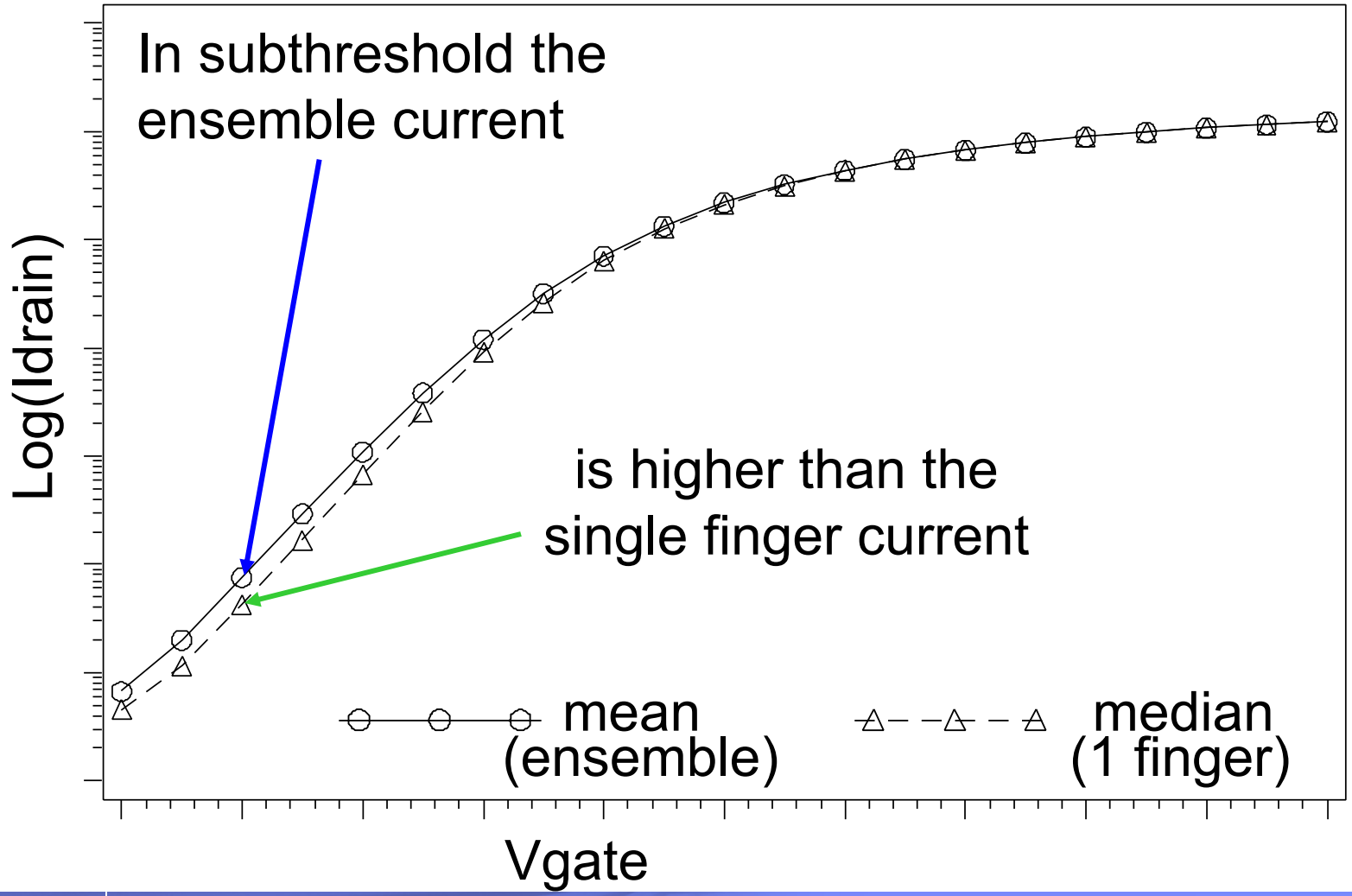
Threshold Voltage (Measured Data)
Single finger FETs



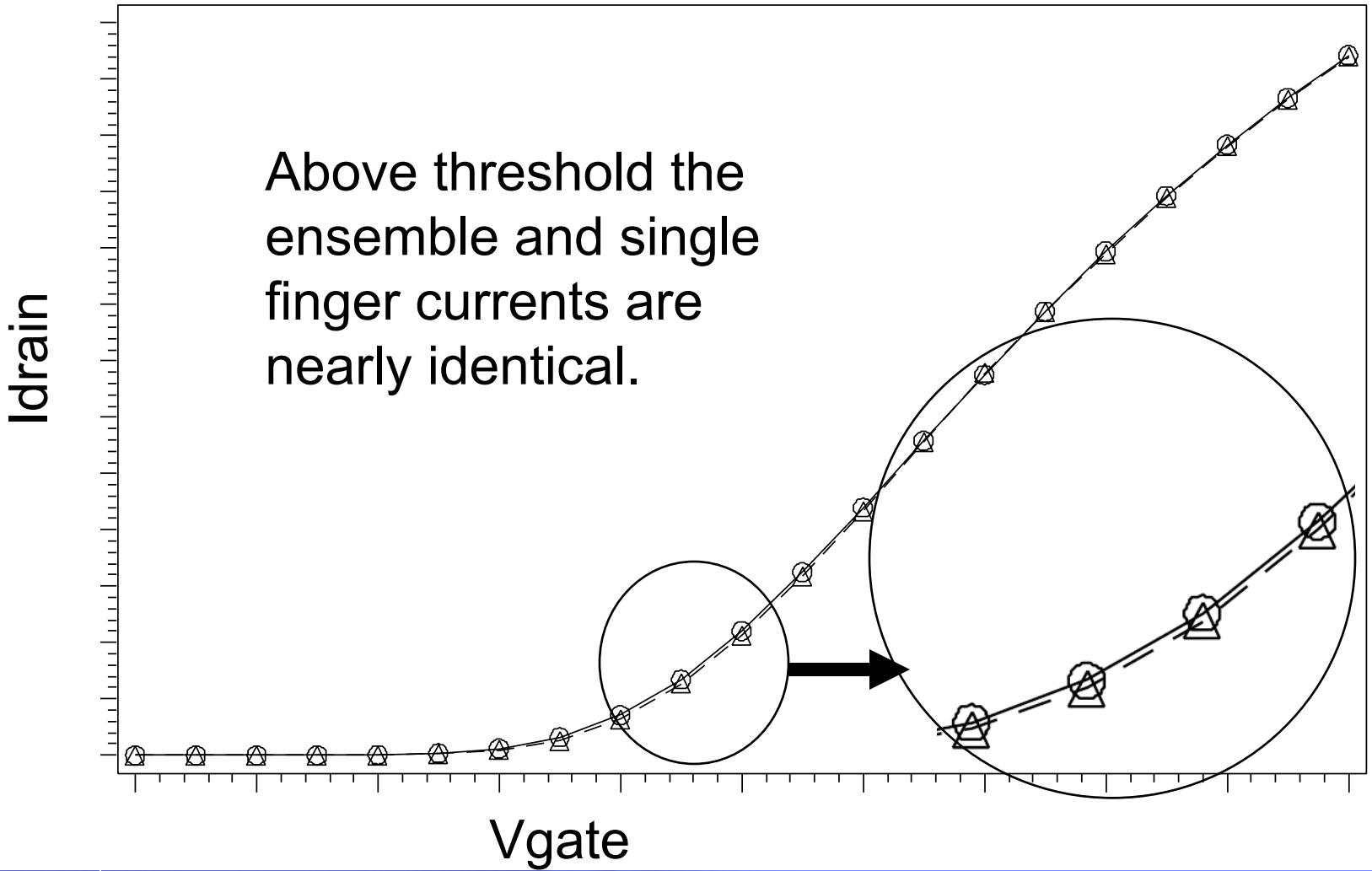
Subthreshold current at constant Vg (Measured Data)
Single finger FETs



Measured current from many single finger FETs

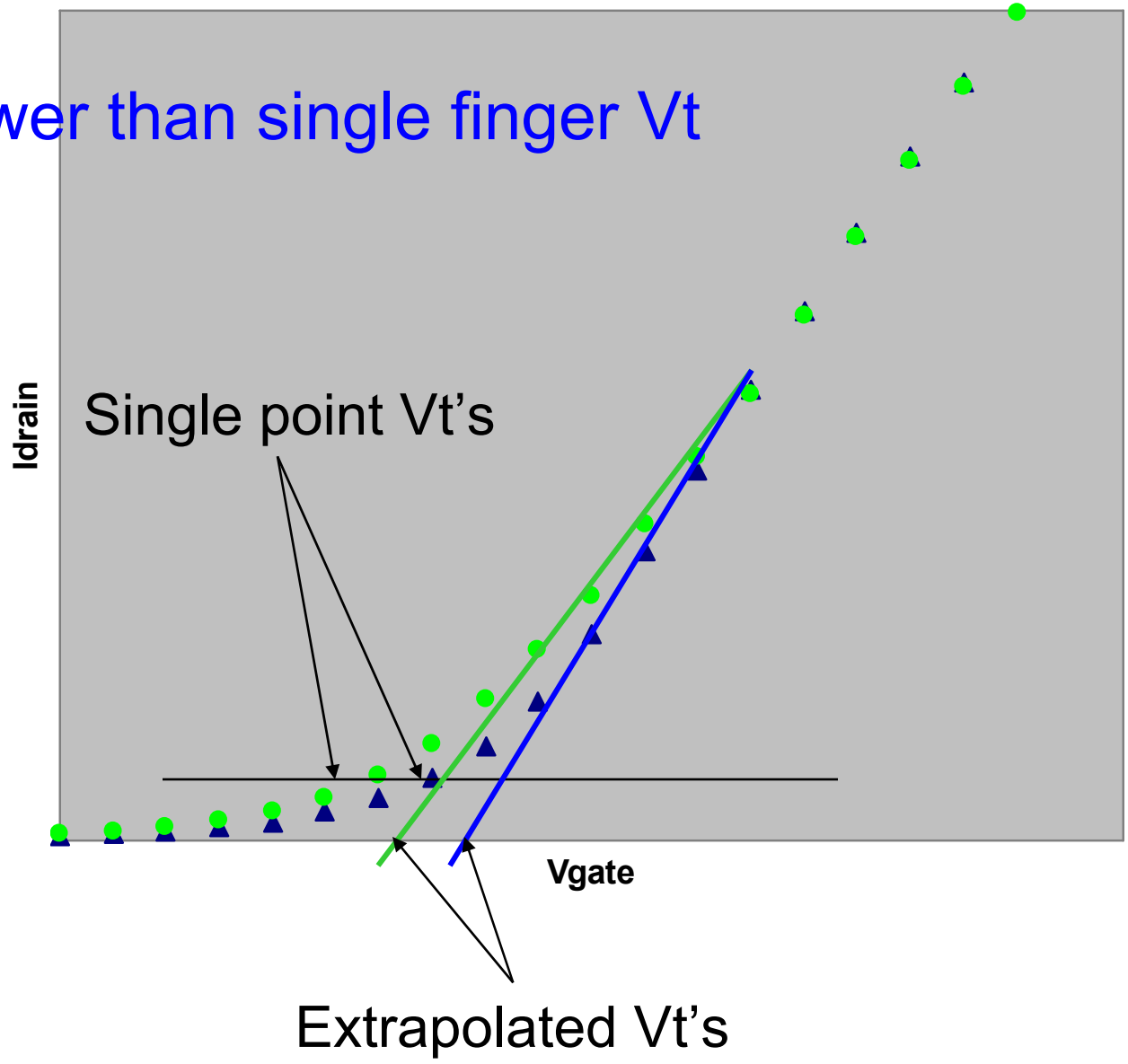


Measured current from many single finger FETs



Ensemble Vt is lower than single finger Vt

Measured Data
Mean Vt

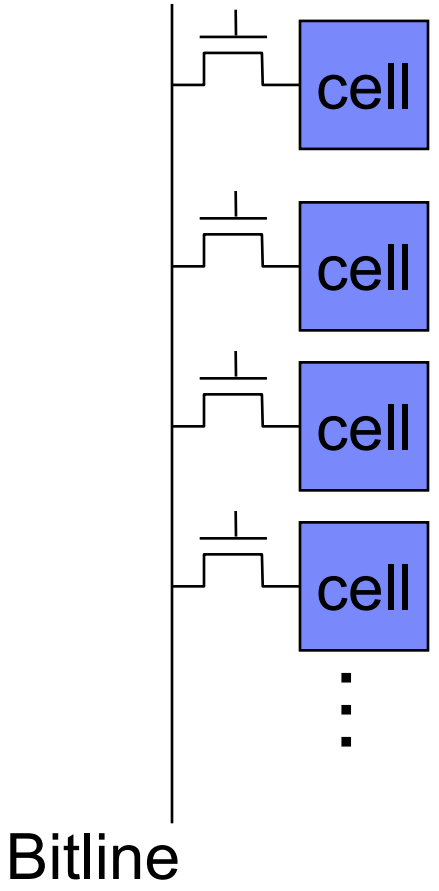


What if we just ignore this effect

- **Wide devices will be modeled correctly**
- **Narrow devices above threshold will be modeled correctly**
- **Narrow device Vt will be too low**
  - Modeling data is too low
  - Targets from ensemble FETs are too low
- **Narrow device subthreshold currents are too high**

What circuits designs will be impacted

- **SRAM designs**
- **To understand the behavior of a bitline need the correct ensemble current**
- **To understand the behavior of a cell need the correct single finger current.**

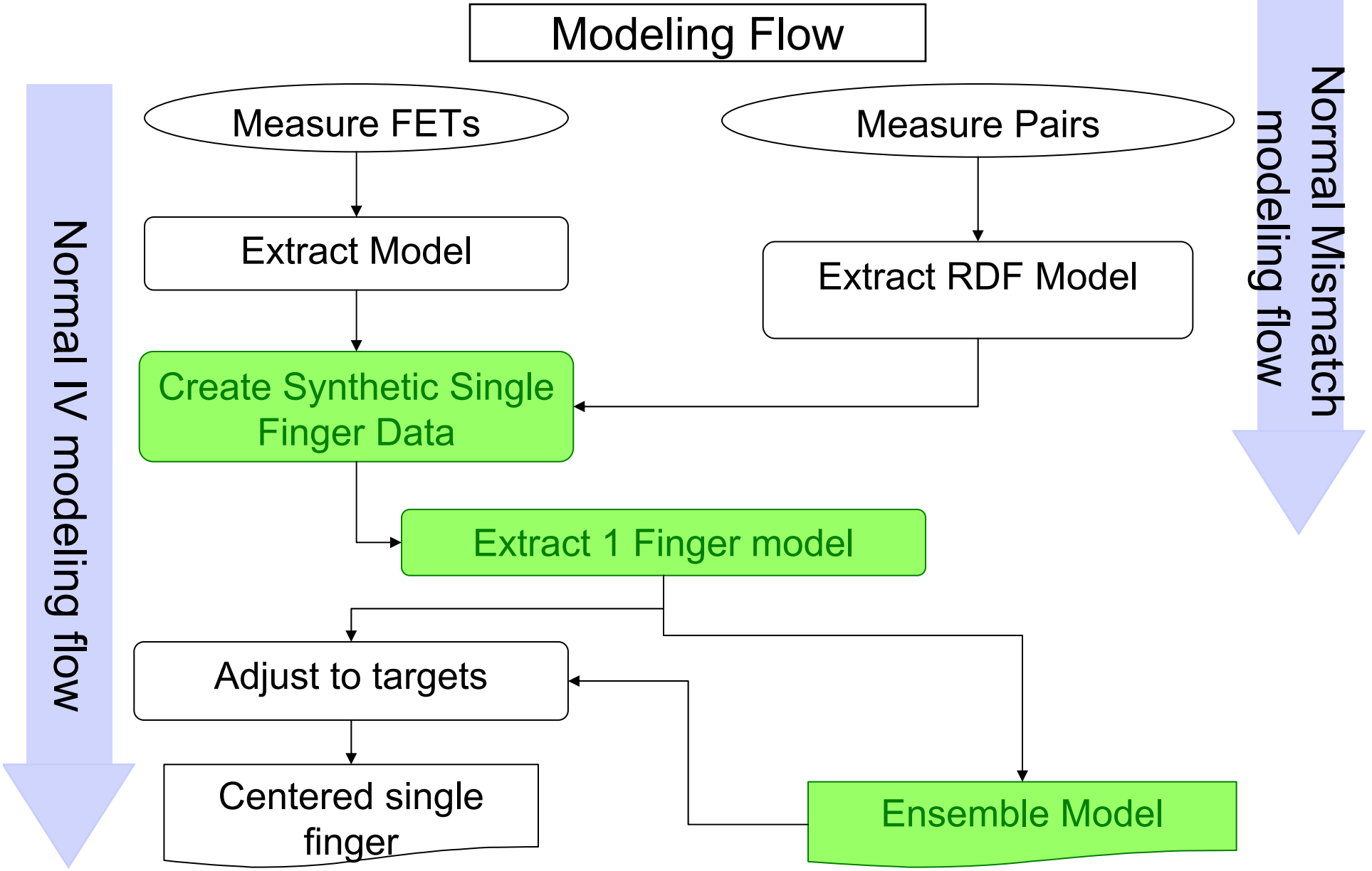


What to do about it?

- **You can adjust your off currents and Vt for the ensemble effects in your measurements.**
  - Single finger currents will be correct.
  - Correct mean and distributions of ensemble devices can be calculated by Monte Carlo with each finger as a separate instance
  - Ensemble devices modeled with nf>1 or m=>1 will not be modeled correctly

What to do about it?

- **You can include a calculation in your model to adjust model parameters for number of parallel fingers**
  - Single finger currents will be correct.
  - Ensemble devices modeled with nf=>1 or m=>1 will be correct.
  - Monte Carlo and skew calculations will be correct for any number of fingers in an instance.


Modeling Flow
Measure FETs
Measure Pairs
Extract Model
Extract RDF Model
Create Synthetic Single Finger Data
Extract 1 Finger model
Adjust to targets
Centered single finger
Ensemble Model
Normal IV modeling flow
Normal Mismatch modeling flow

Create Synthetic Single Finger Data

1. **Write ensemble current as a sum of finger currents**
   - Assume all fingers are identical except for Vt
   - Assume Vt's are normally distributed
   - Assume exponential like behavior of derivatives of Idrain w.r.t. Vgate
2. **Invert the equation to get single finger current from measure or simulated ensemble current**

Write ensemble current as sum of finger currents

- **Express each finger current as the same function of (Vg-Vt plus a unique Vt delta)**
- **Expand in a Taylor series in the Vt delta and sum**

$$I_i = I_0 + \frac{dI}{dV_g}\Delta_i + \frac{1}{2}\frac{d^2I}{dV_g^2}\Delta_i^2 + \ldots$$

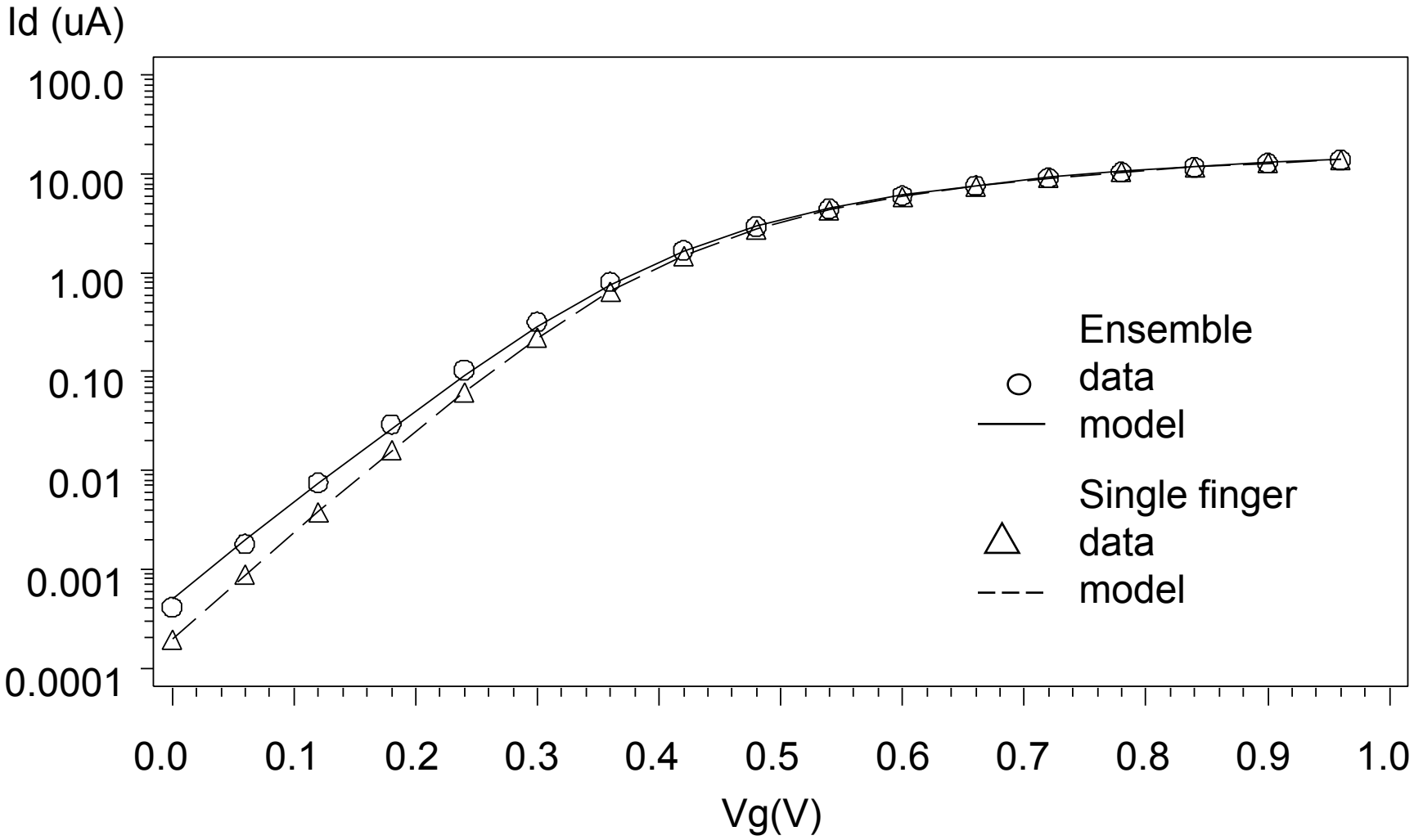
$$I_e = I_0 + \frac{dI}{dV_g}\sum_i \Delta_i + \frac{1}{2}\frac{d^2I}{dV_g^2}\sum_i \Delta_i^2 + \ldots$$

- **Deltas are normally distributed so we can evaluate sums over powers of delta using known properties of the normal distribution**
- **Can measure the second derivative and assuming exponential behavior calculate higher derivatives from that**
- **Variance of Vt is measured with matched pairs of FETs**

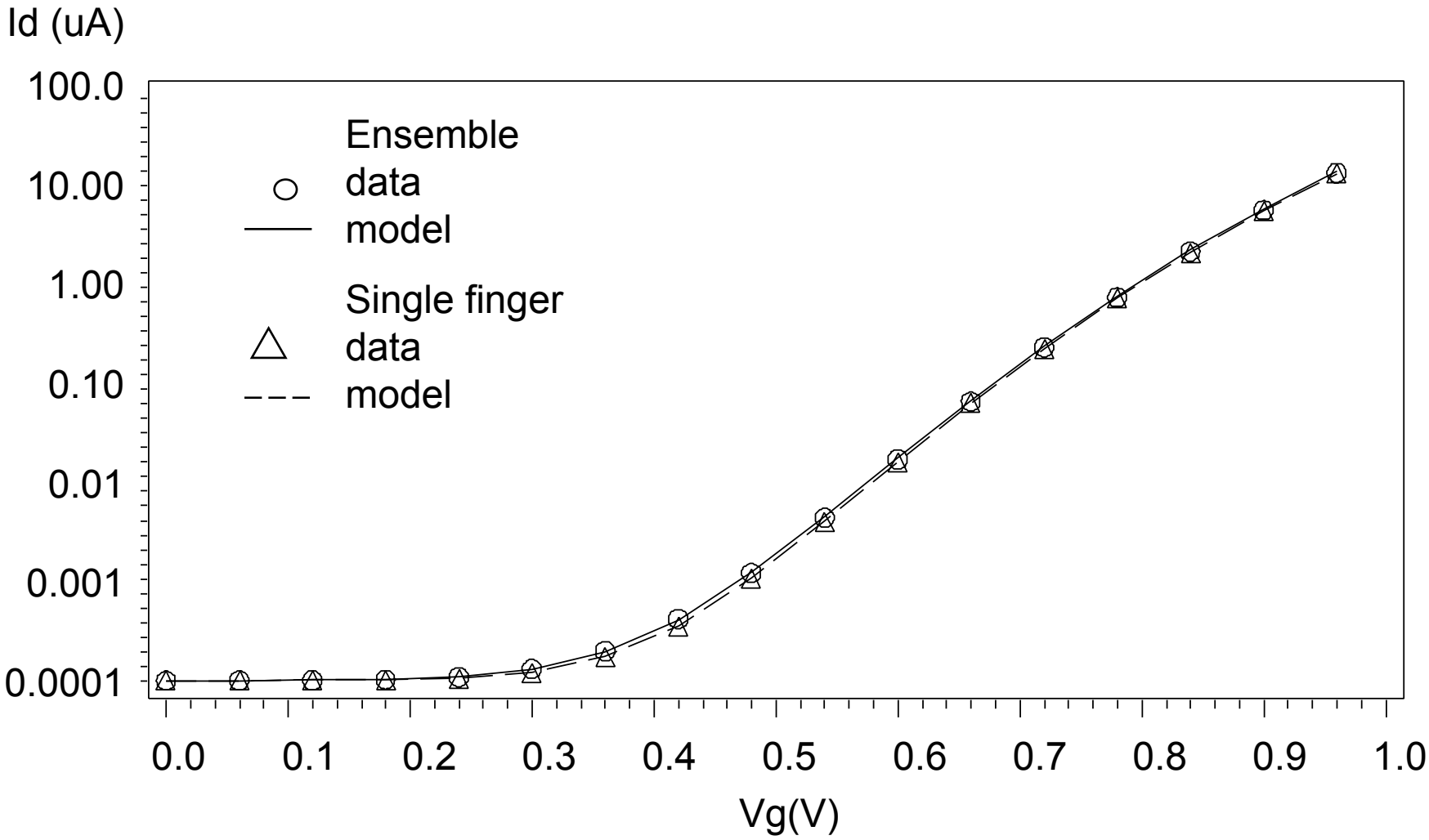
Extract single finger model

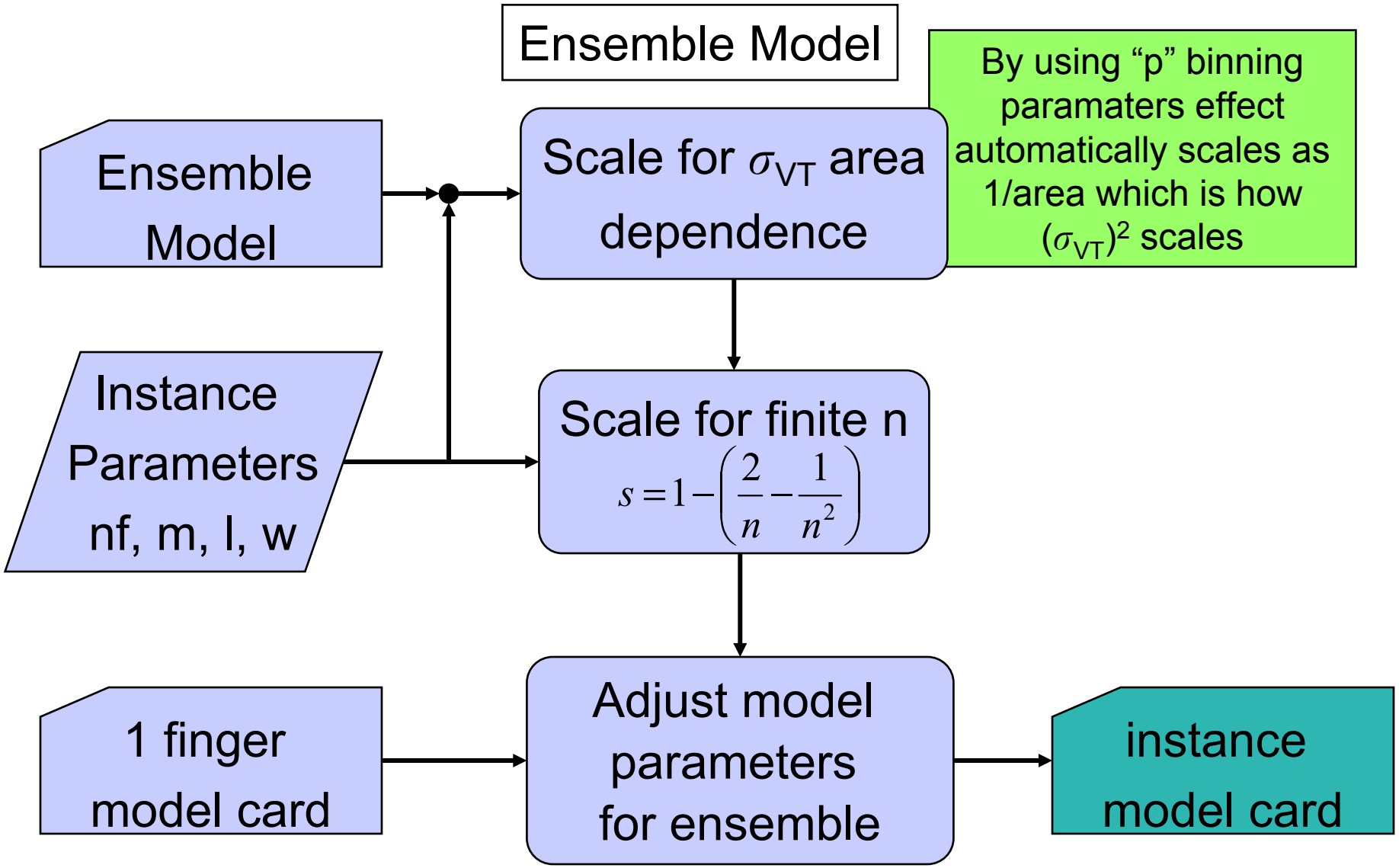
- **Only need to adjust a few parameters to**
  - Shift Vt in the subthreshold
  - Keep Vt fixed above threshold
  - Smooth the transition between them
- **In BSIM4 three parameters do a nice job**
  - voff
  - nfactor
  - vth0

Ensemble data generated by Monte Carlo



Ensemble data generated by Monte Carlo




Ensemble Model
By using "p" binning paramaters effect automatically scales as 1/area which is how $(\sigma_{VT})^2$ scales
Ensemble Model
Scale for σ_{VT} area dependence
Instance Parameters nf, m, l, w
Scale for finite n
$s = 1 - \left(\frac{2}{n} - \frac{1}{n^2}\right)$
1 finger model card
Adjust model parameters for ensemble
instance model card

Conclusions

- **Average finger current of a typical ensemble FET does not equal typical single finger current.**
- **Single finger current can be recovered from ensemble measurements.**
- **Both ensemble and single finger current can be modeled by a properly constructed model.**