

R3, an Accurate JFET and 3-Terminal Diffused Resistor Model

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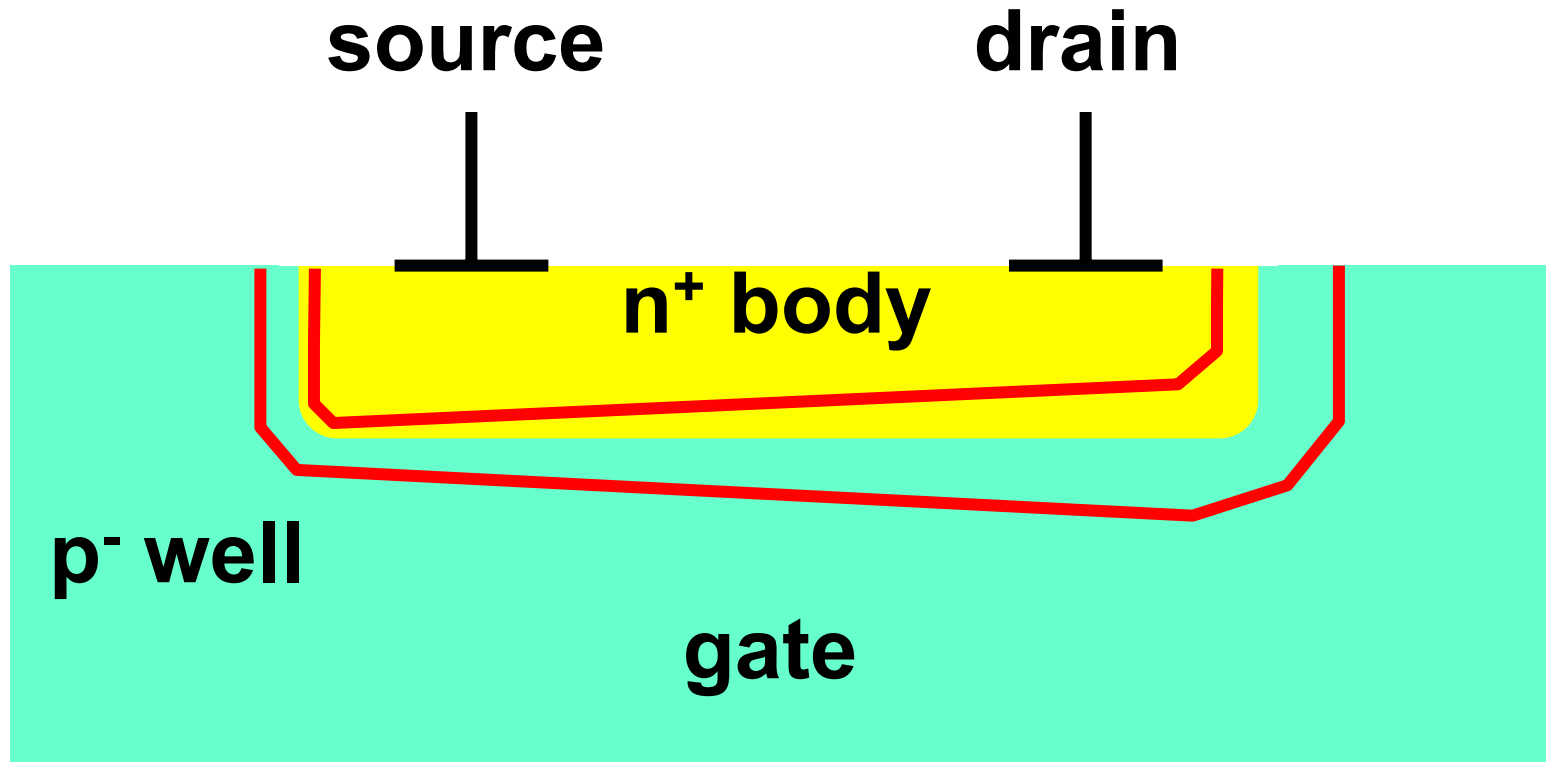
Outline

- **Introduction**
 - IC design need
 - Inadequacies of previous models
- **Depletion Pinching Model**
- **Velocity Saturation Model**
- **Saturation Voltage Calculation**
- **Self-Heating Model**
- **Summary**

Diffused Resistors

- Important elements in many analog ICs
- Some measures of circuit performance are sensitive to nonlinearities
 - $V=I \cdot R$ is inadequate
- Diffused resistors are really JFETs
- Accurate, physically based modeling has lagged behind MOSFETs and BJTs

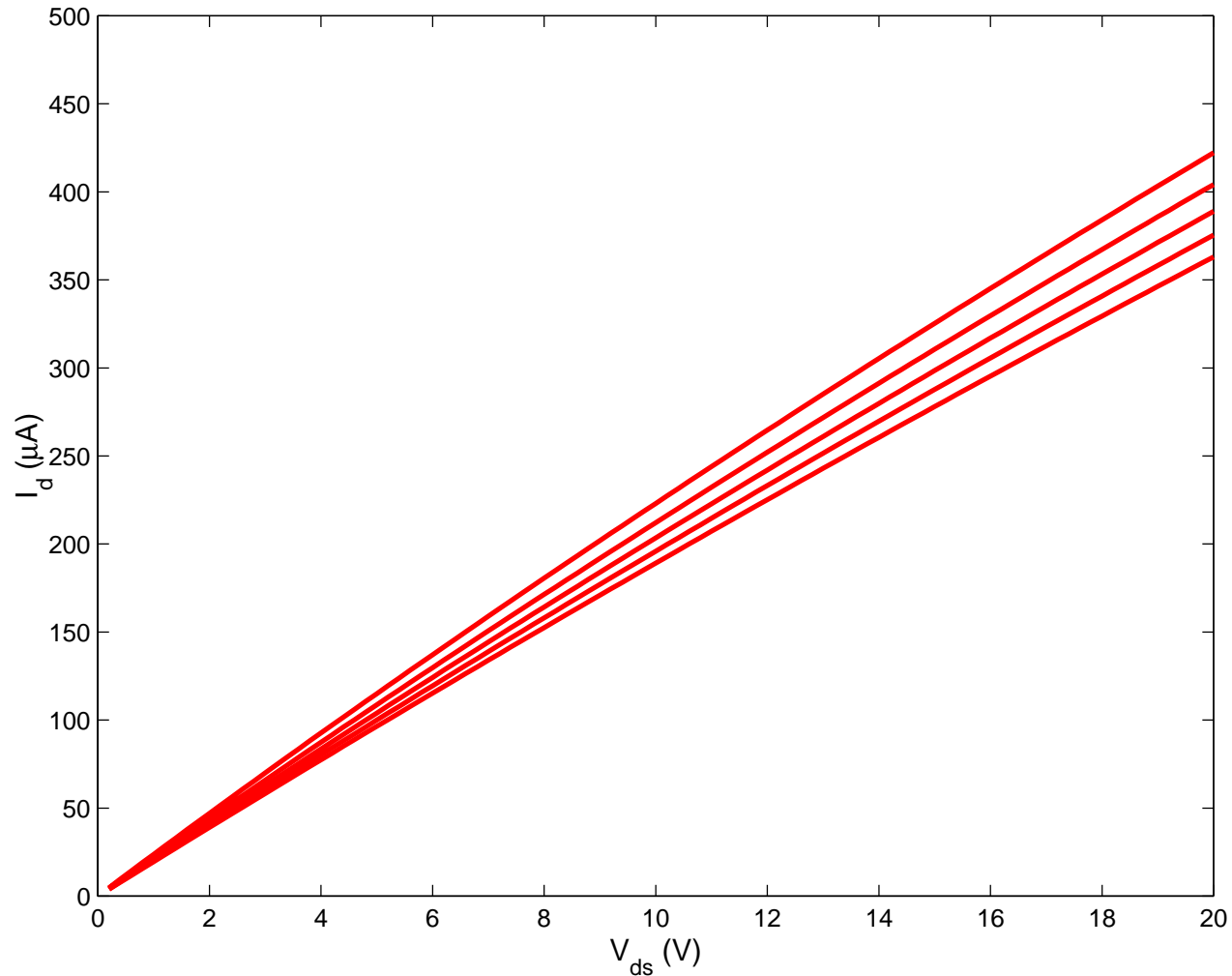
Diffused Resistor Cross-Section



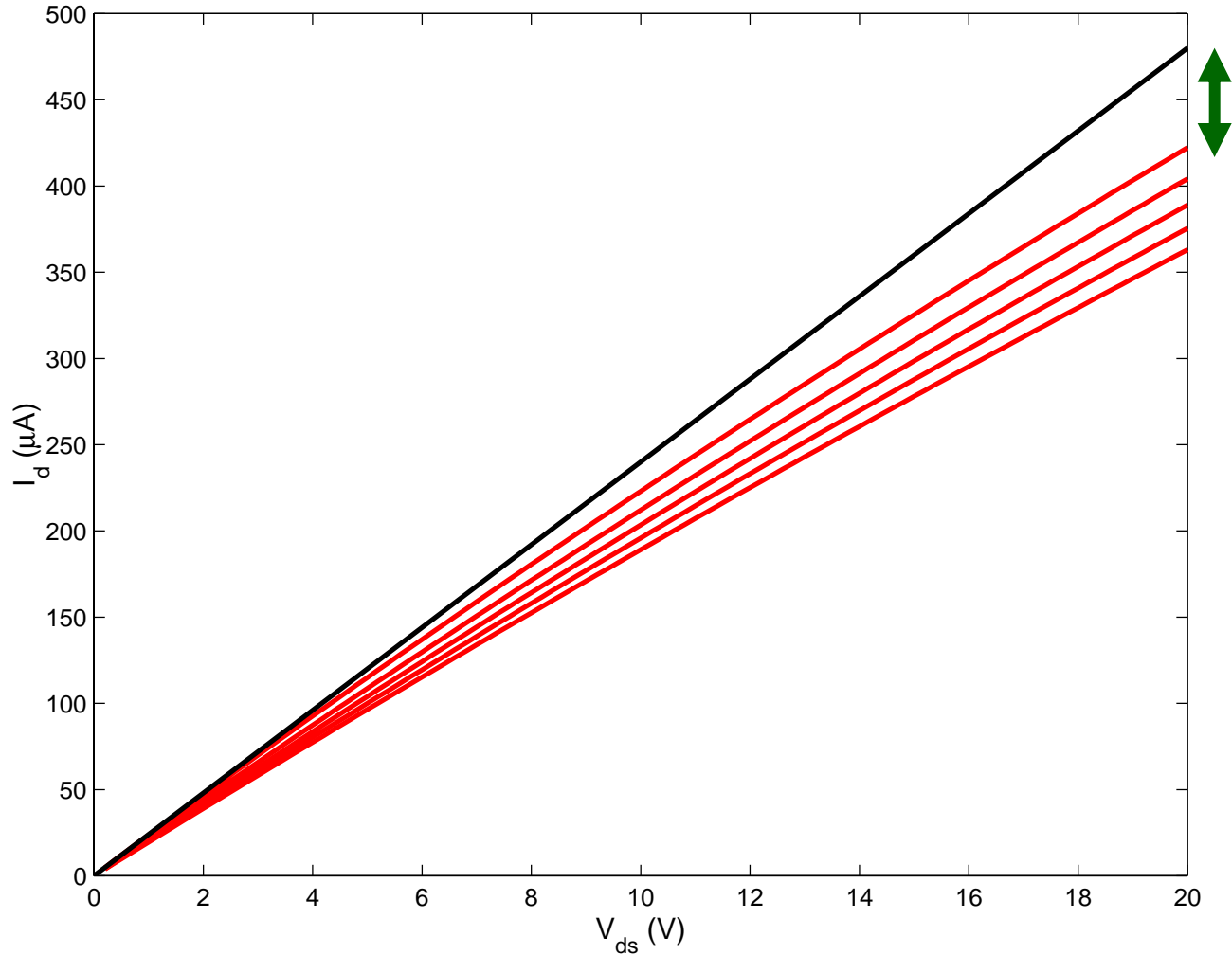
Diffused Resistors

- **Looking at $I(V)$ fits is inadequate, for distortion it is the difference between linear $I(V)$ and actual $I(V)$ that is key**
- **Behavior is affected by**
 - depletion pinching
 - velocity saturation
 - self-heating
 - nonlinear contact effects

L=88 μ m Resistor



L=88 μ m Resistor



Self-Heating

- Conveniently viewed as an effective mobility reduction with voltage

$$\mu_{red} = \frac{R}{R_0} = 1 + \frac{R_{THA} T_{C1}}{\rho_s} \left(\frac{V_{ds}}{L} \right)^2$$

- Effect is significant in low sheet resistance devices
- Thermal time constant can be in electrical frequency band of interest

Existing Models

- **Polynomial resistor models**
- **SPICE JFET model**
 - inaccurate for depletion pinching modeling
 - no velocity saturation or self-heating
- **Depletion pinching models**
 - inaccurate velocity saturation modeling
 - incorrect saturation voltage calculation
 - important for well resistors
 - no self-heating

Depletion Pinching Model

- **Physically based bottom and sidewall depletion model by Booth**

$$I = \frac{q\mu_0 N x_0 W}{L} \left(1 - a \sqrt{\psi_a + \bar{V}} \right) \left(1 - \frac{b}{W} \sqrt{\psi_p + \bar{V}} \right) V_{ds}$$

- **Can be well approximated by**

$$I_{depl} = G_F \left(1 - D_F \sqrt{P + \bar{V}} \right) V_{ds}$$

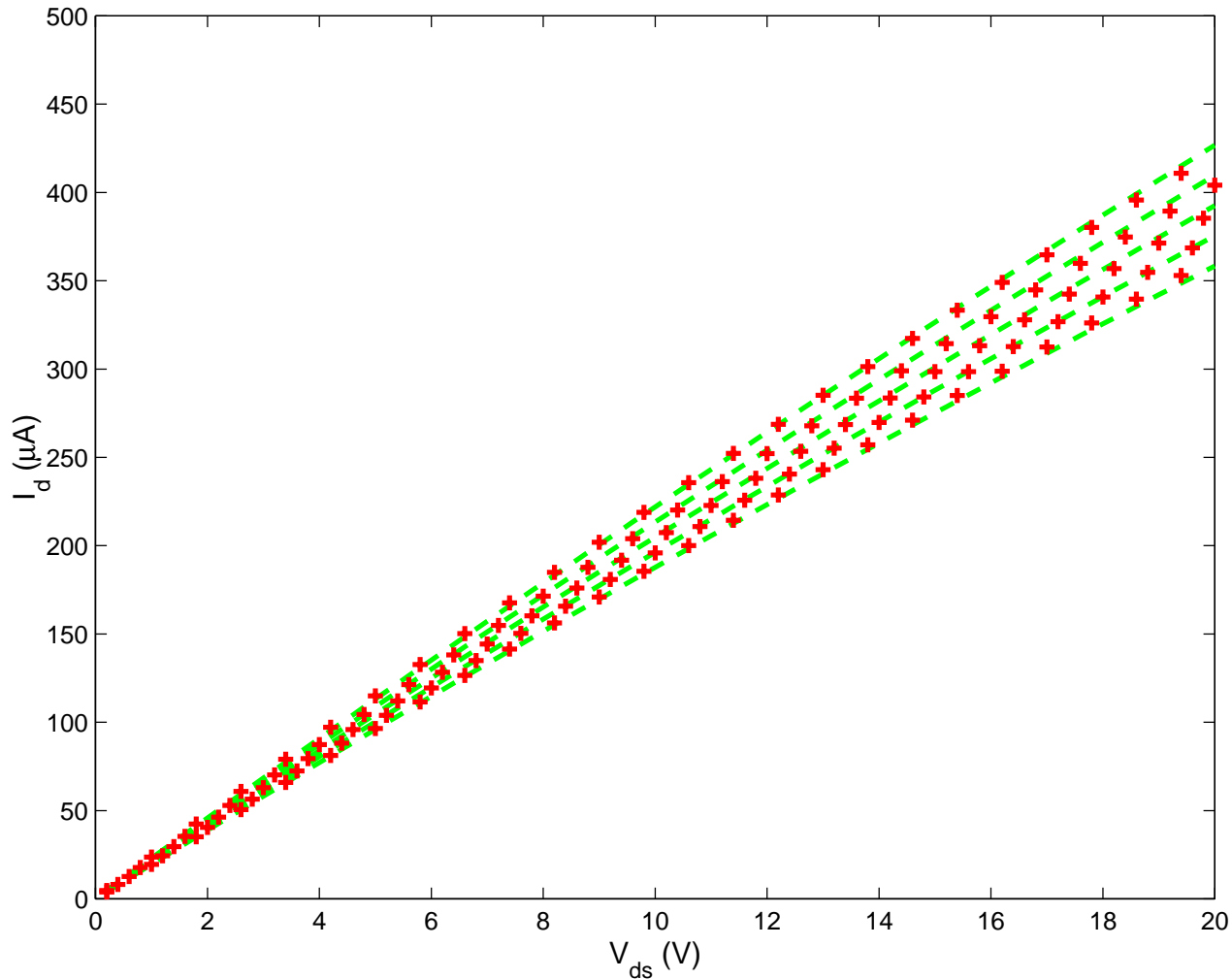
- **Depletion factor**

$$D_F = D_{F\infty} + D_{FW} / W + D_{FL} / L + D_{FWL} / WL$$

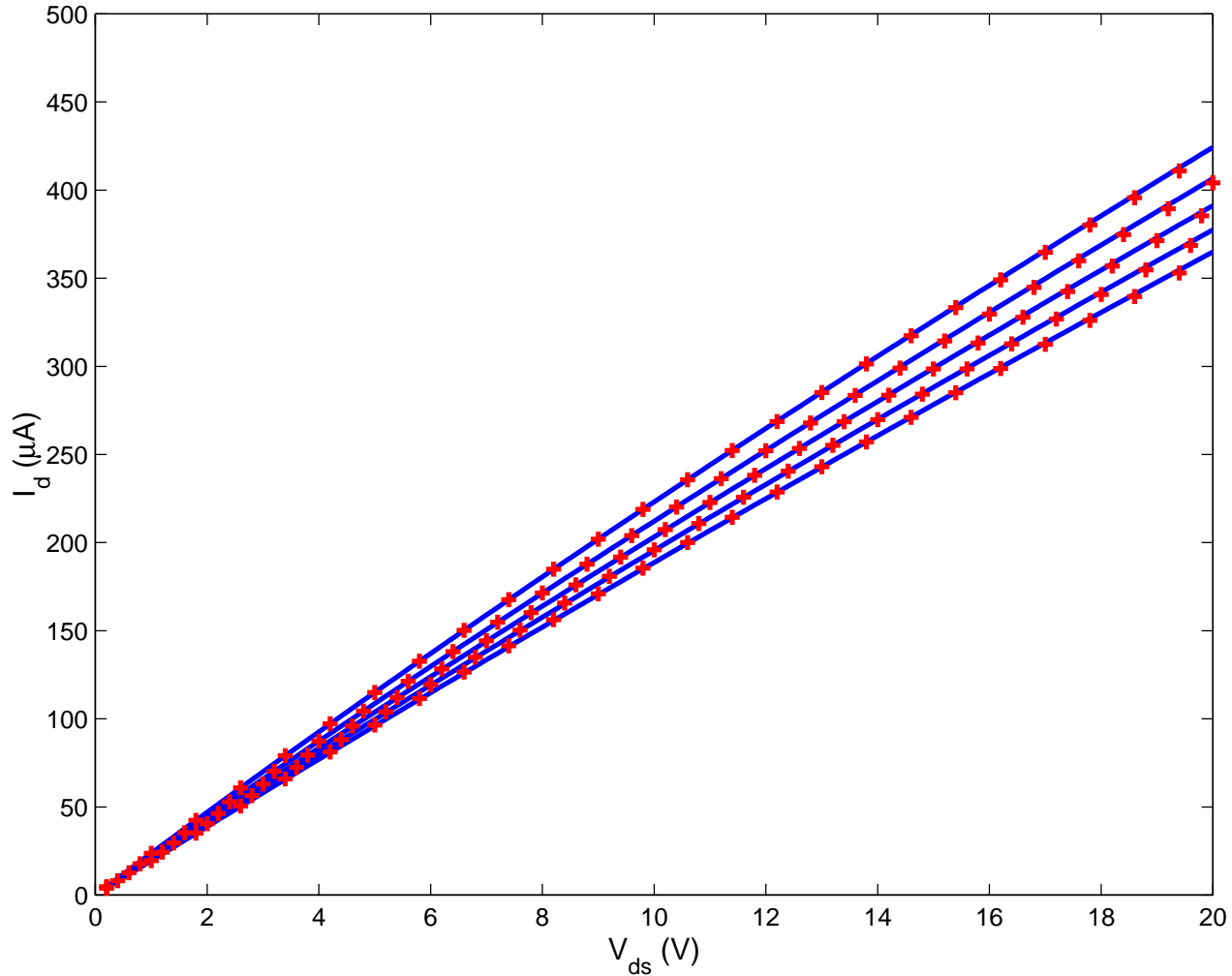
Depletion Pinching Model (cont'd)

- **Simplifies formulation with no change in fit to data**
- **Enables analytic saturation voltage calculation**
 - not possible with original formulation
 - source of inaccuracy in original model

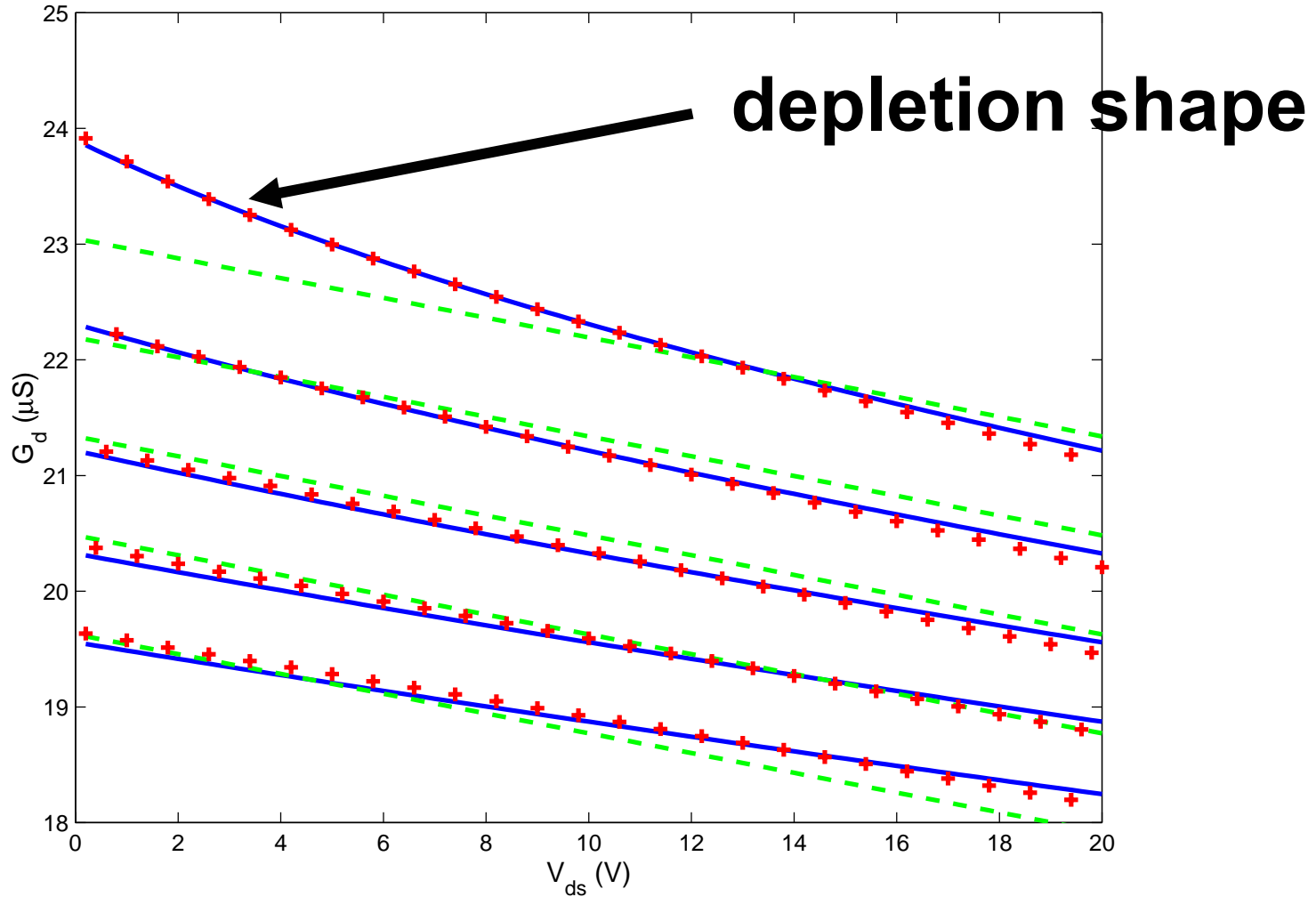
L=88 μ m Data and SPICE JFET Model



L=88 μ m Data and New Model



$L=88\mu\text{m}$ Conductance $G=I_d/V_{ds}$



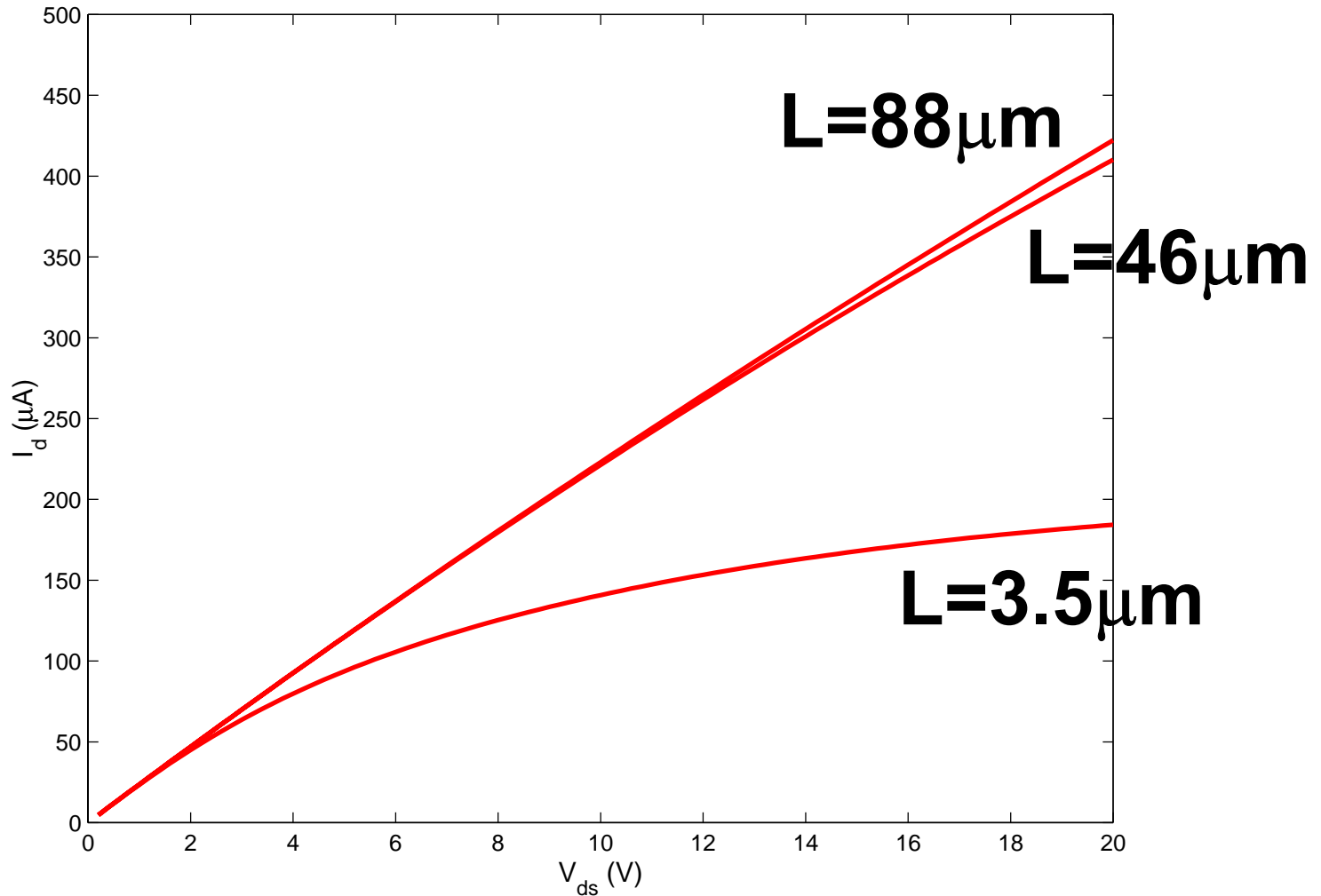
Velocity Saturation

- **Generally assumed only to be important for “short” devices**
 - affects linearity (distortion) for relatively long devices
- **Common formulations are inaccurate**

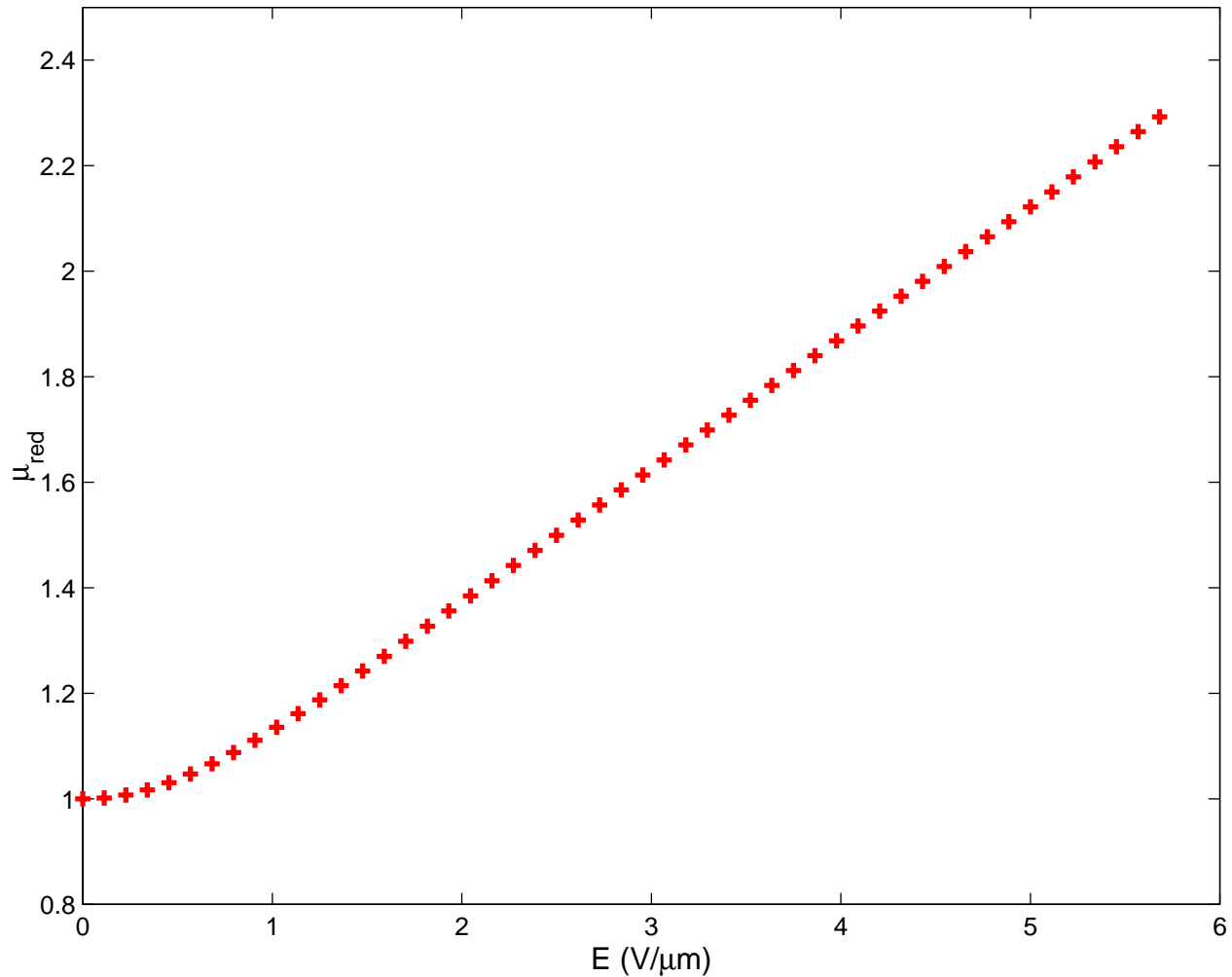
$$\mu_{red}(V) = 1 + \frac{\mu_0}{v_{sat}} \frac{|V|}{L}$$

$$\mu_{red}(V) = \sqrt{1 + \left(\frac{\mu_0}{v_{sat}} \frac{|V|}{L} \right)^2}$$

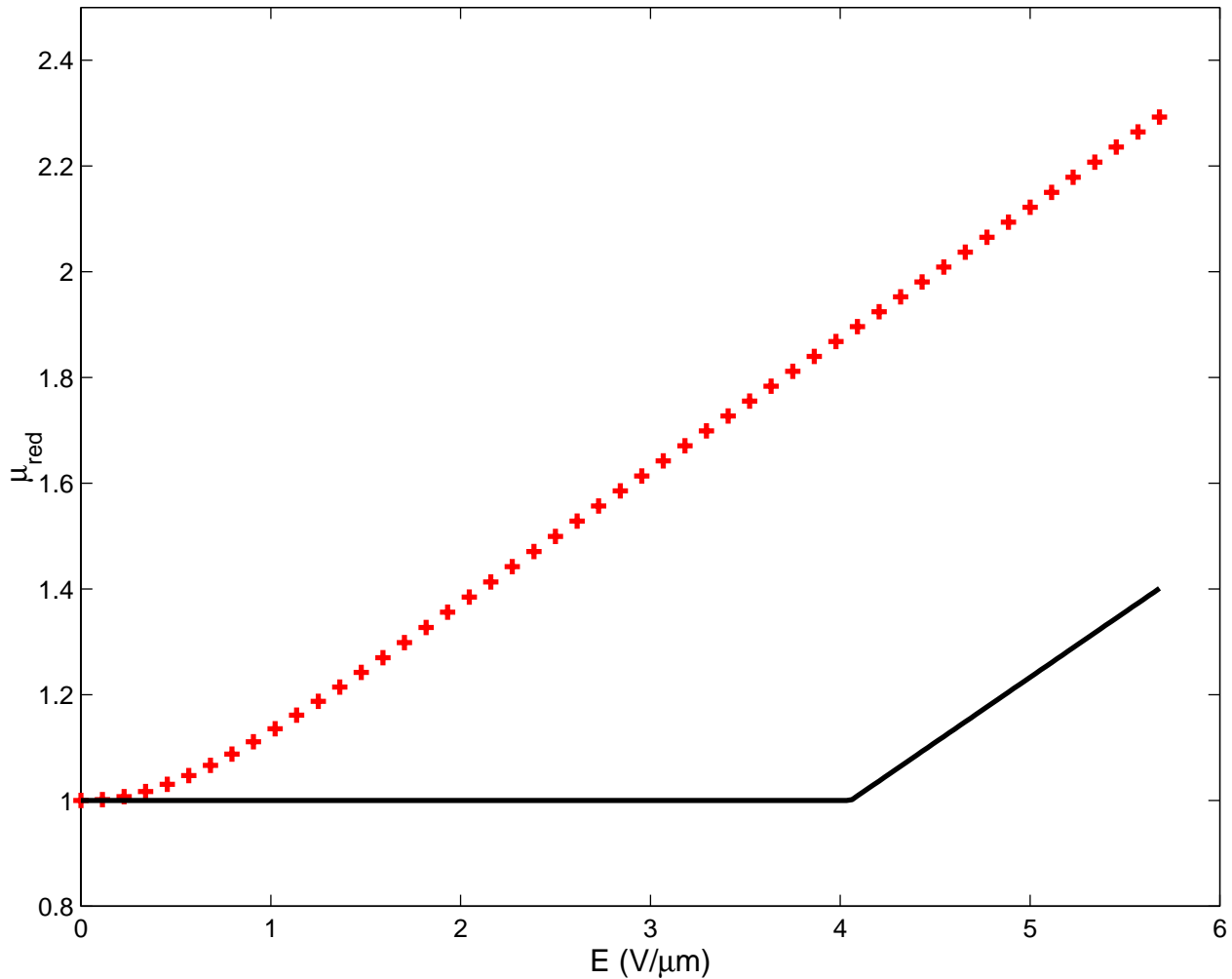
Normalized I(V) over Length



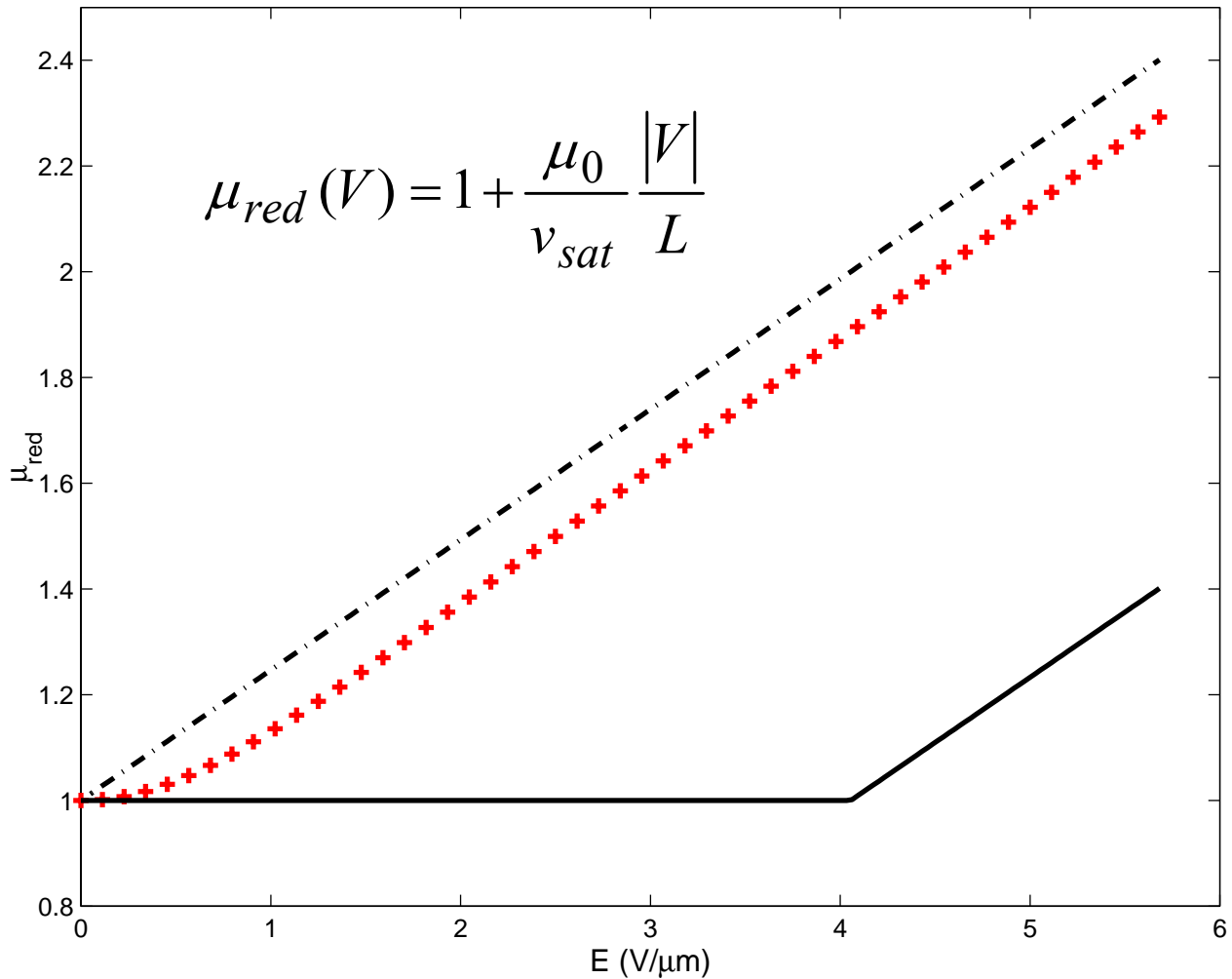
μ_{red} from Velocity Saturation Data



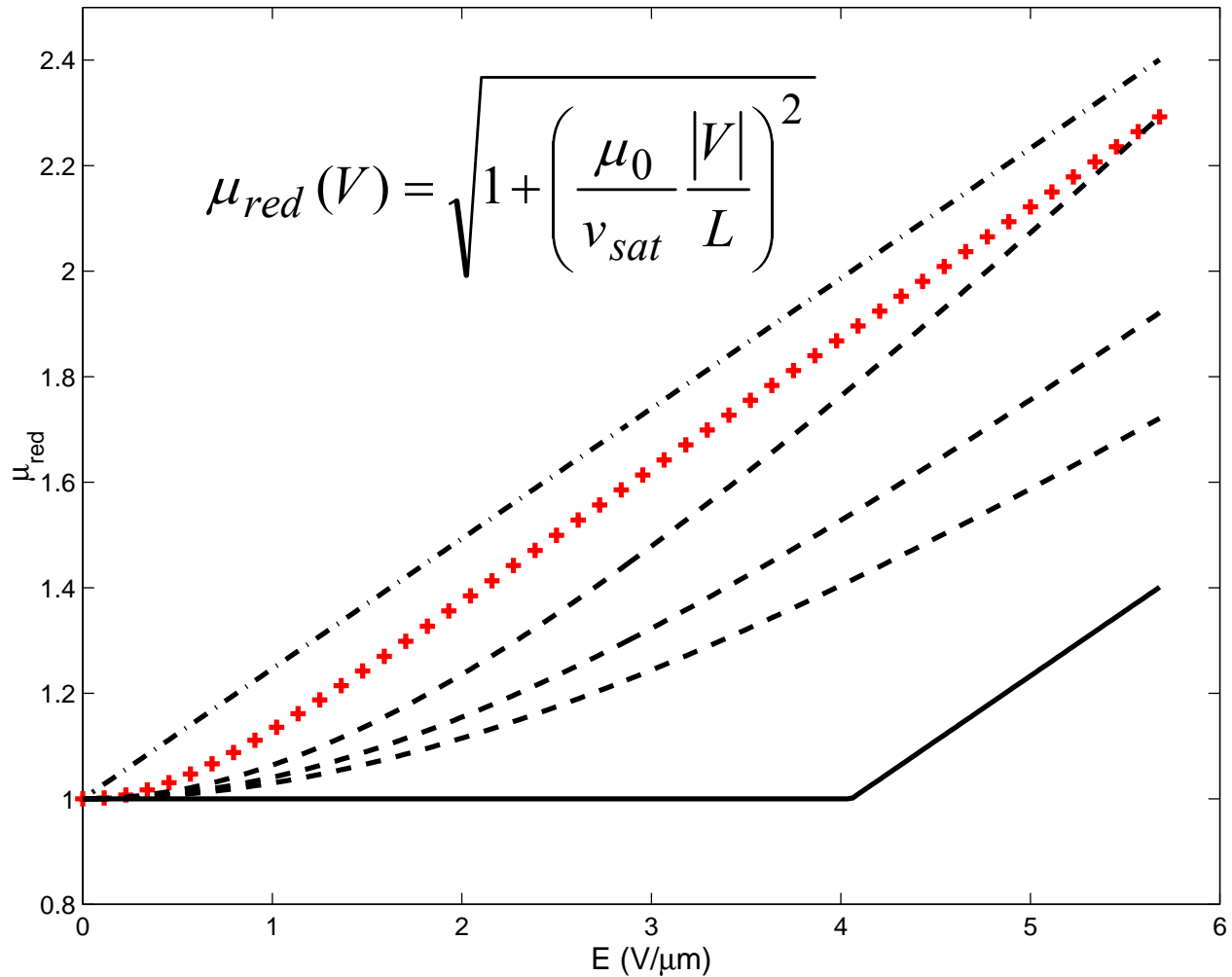
Hard Saturation Model



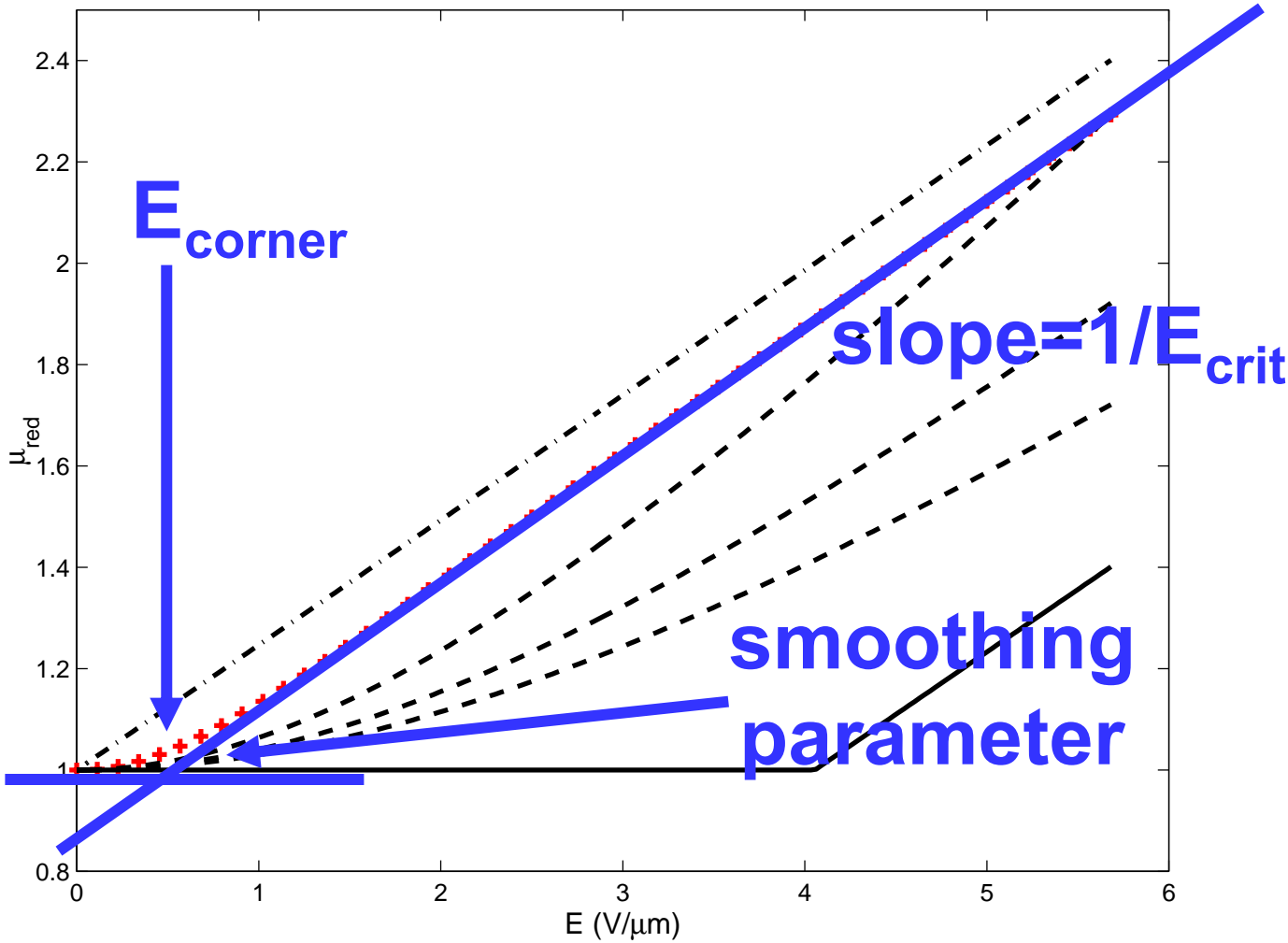
Linear Model



Quadratic Model, Various v_{sat}



Empirical Model



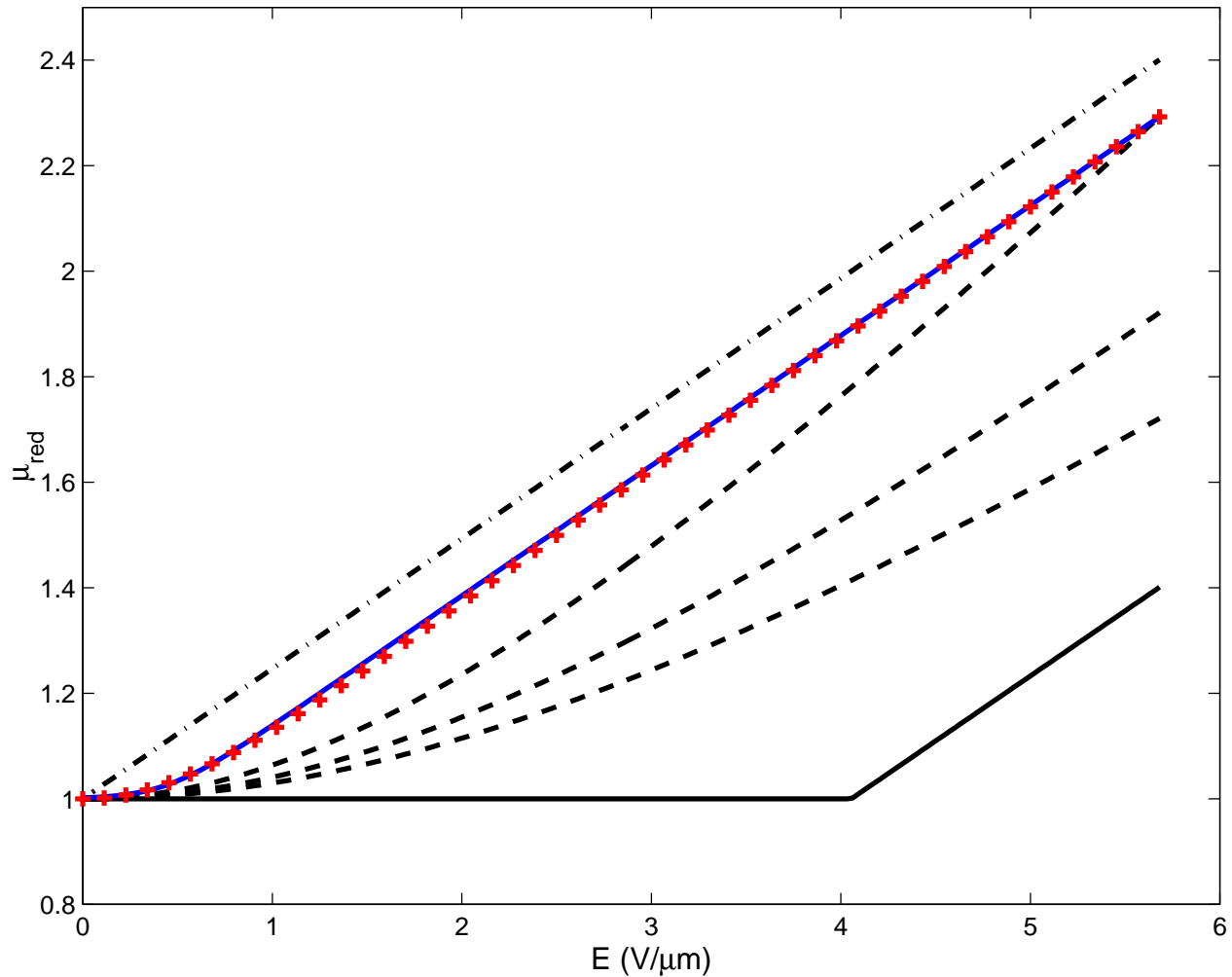
Empirical Velocity Saturation Model

$$\mu_{red} = 1 + \sqrt{\left(\frac{E - E_{ce}}{2E_{cr}}\right)^2 + U} + \sqrt{\left(\frac{E + E_{ce}}{2E_{cr}}\right)^2 + U} - \frac{E_{co}}{E_{cr}}$$

$$U = d\mu E_{ce} / E_{cr}$$

$$E_{ce} = \sqrt{E_{co}^2 + (2d\mu E_{cr})^2} - 2d\mu E_{cr}$$

New Velocity Saturation Model



Saturation Voltage

- **Original Booth model saturation voltage was empirical factor less than pinchoff**

$$V_P = 1/D_F^2 - P \quad \left(I_{depl} = G_F \left(1 - D_F \sqrt{P + \bar{V}} \right) V_{ds} \right)$$

– did not link to $g_{ds}=0$

– can have glitches and/or $g_{ds} < 0$ at V_{sat}

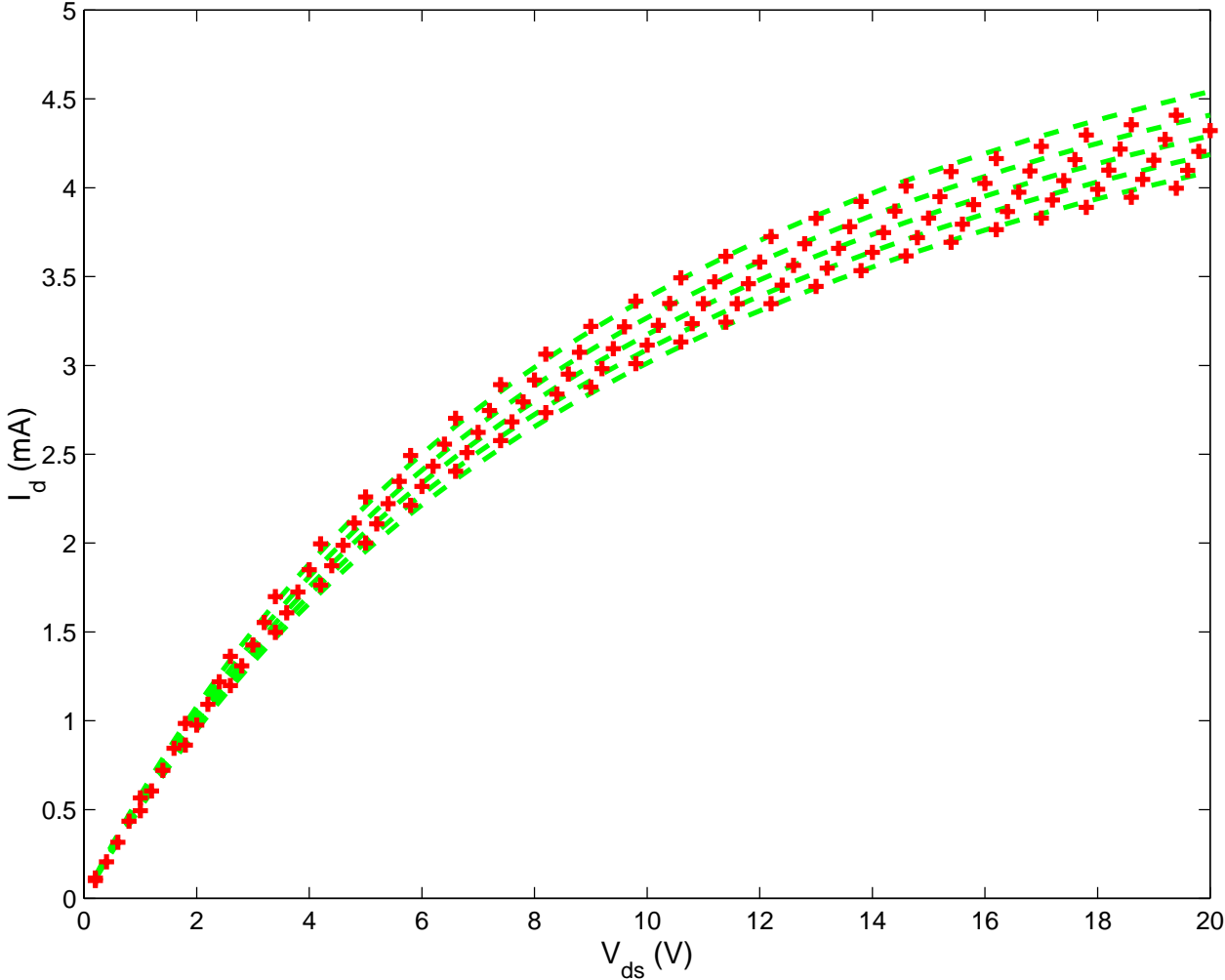
- **Depletion model has $g_{ds}=0$ when**

$$V_{sat} = \frac{1 - 3D_F^2 (P + V_{sg}) + \sqrt{1 + 3D_F^2 (P + V_{sg})}}{9D_F^2 / 4}$$

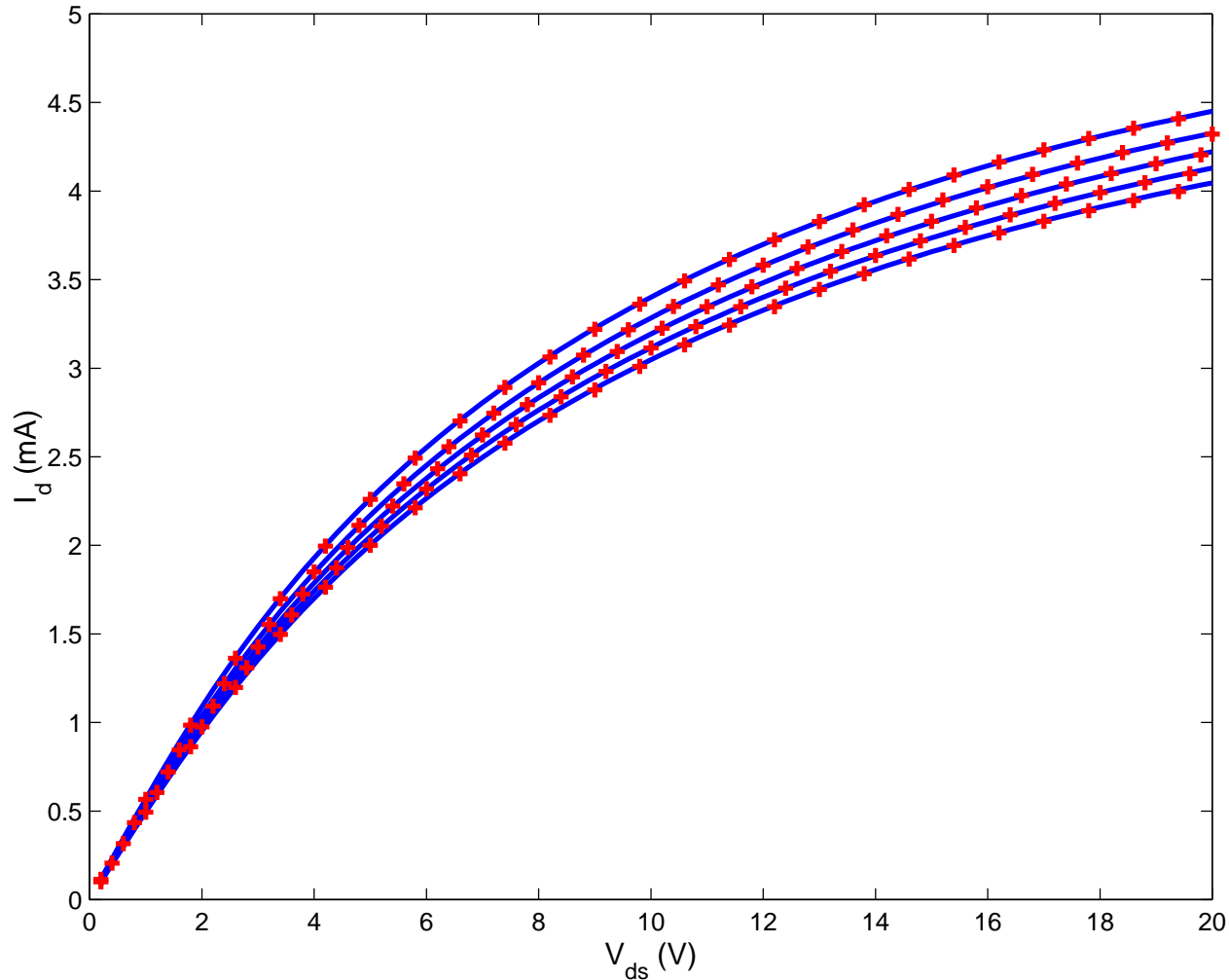
Saturation Voltage (cont'd)

- Depletion pinching model $g_{ds}=0$ point does not account for velocity saturation
 - need to account for arbitrary form, but this does not lead to a closed form solution
- If velocity saturation μ_{red} model is less than the actual form, this gives a saturation voltage less than where $g_{ds}=0$ with the full model
 - guarantees g_{ds} will not become negative
- Closed form solution from $\mu_{red}(V) = 1 + \frac{V_{ds}/L - E_{co}}{E_{cr}}$

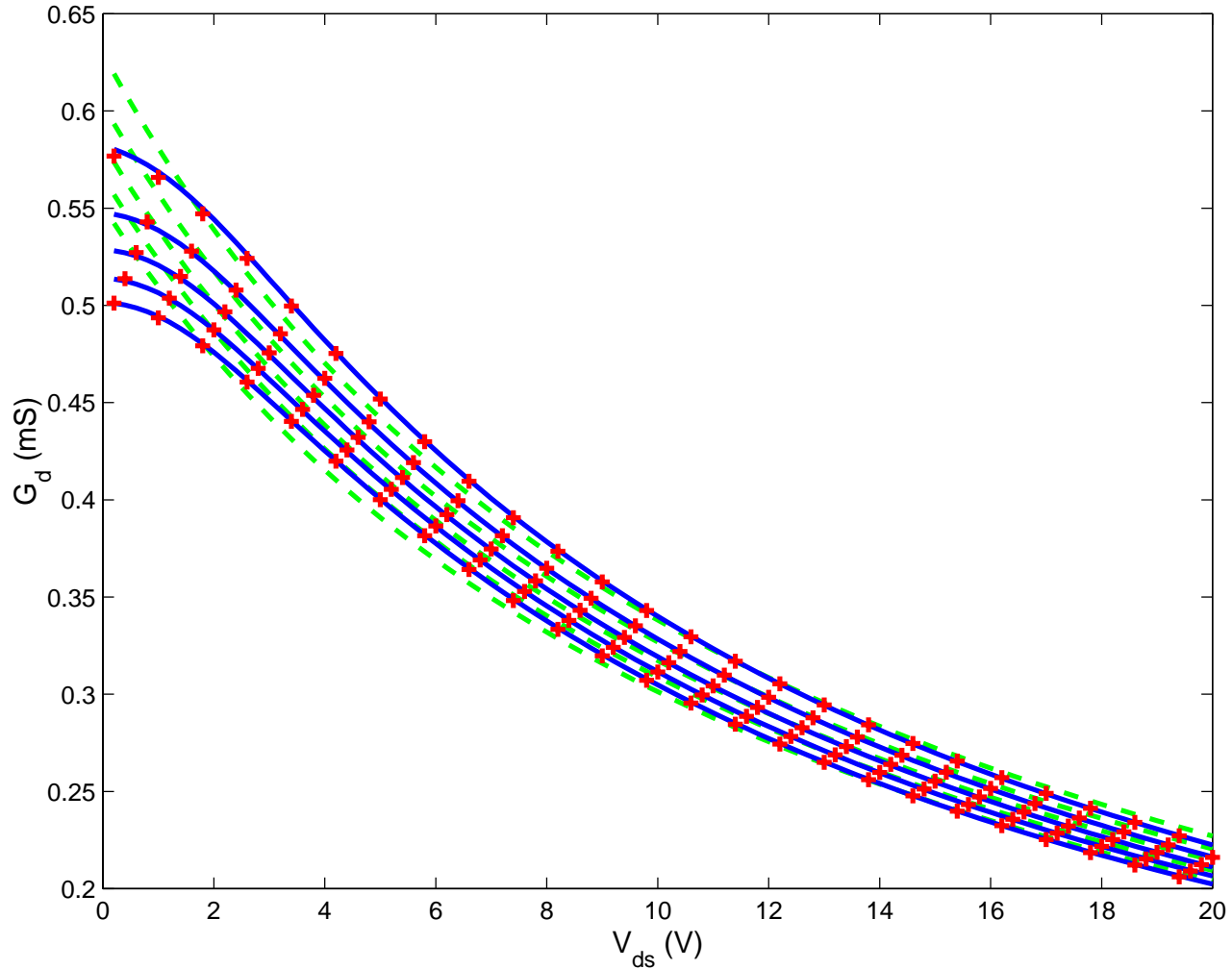
L=3.5μm Data and Linear μ_{red} Model



L=3.5 μ m Data and New μ_{red} Model

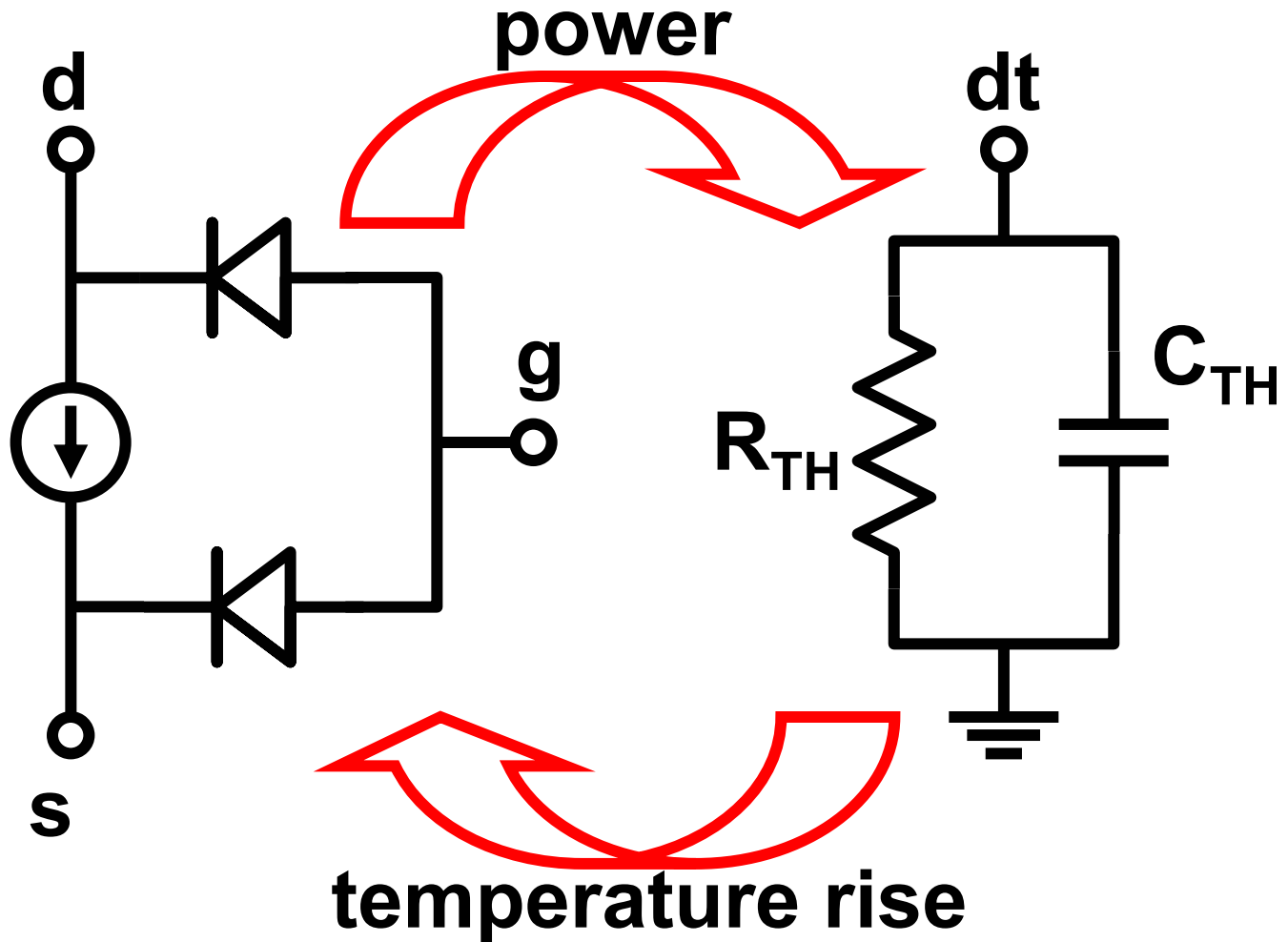


$L=3.5\mu\text{m}$ Conductance $G=I_d/V_{ds}$



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Self-Heating



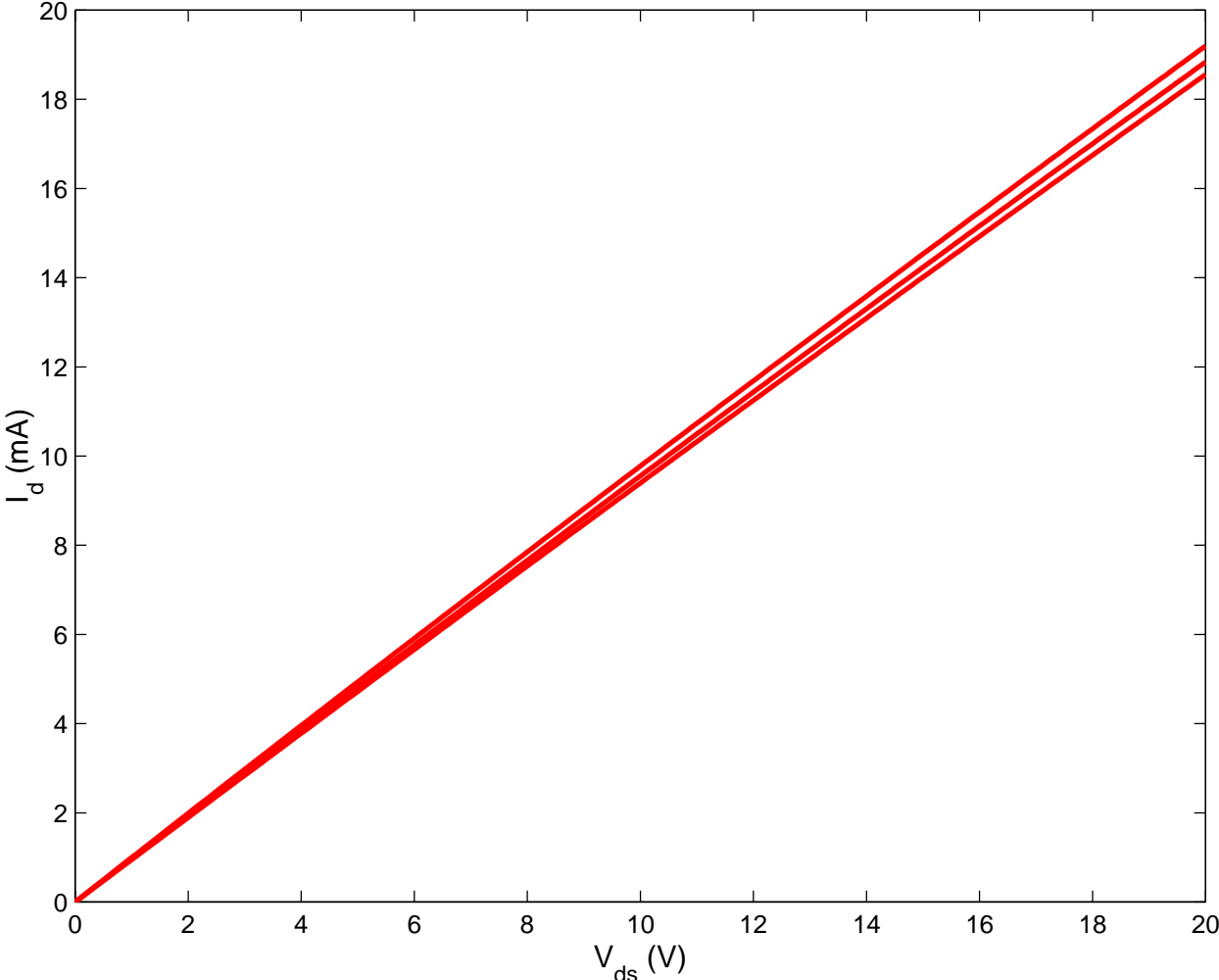
Miscellaneous

- **Effective width includes**
 - width dependent effect width
 - finite dopant source model
 - webbing (dog bone) model

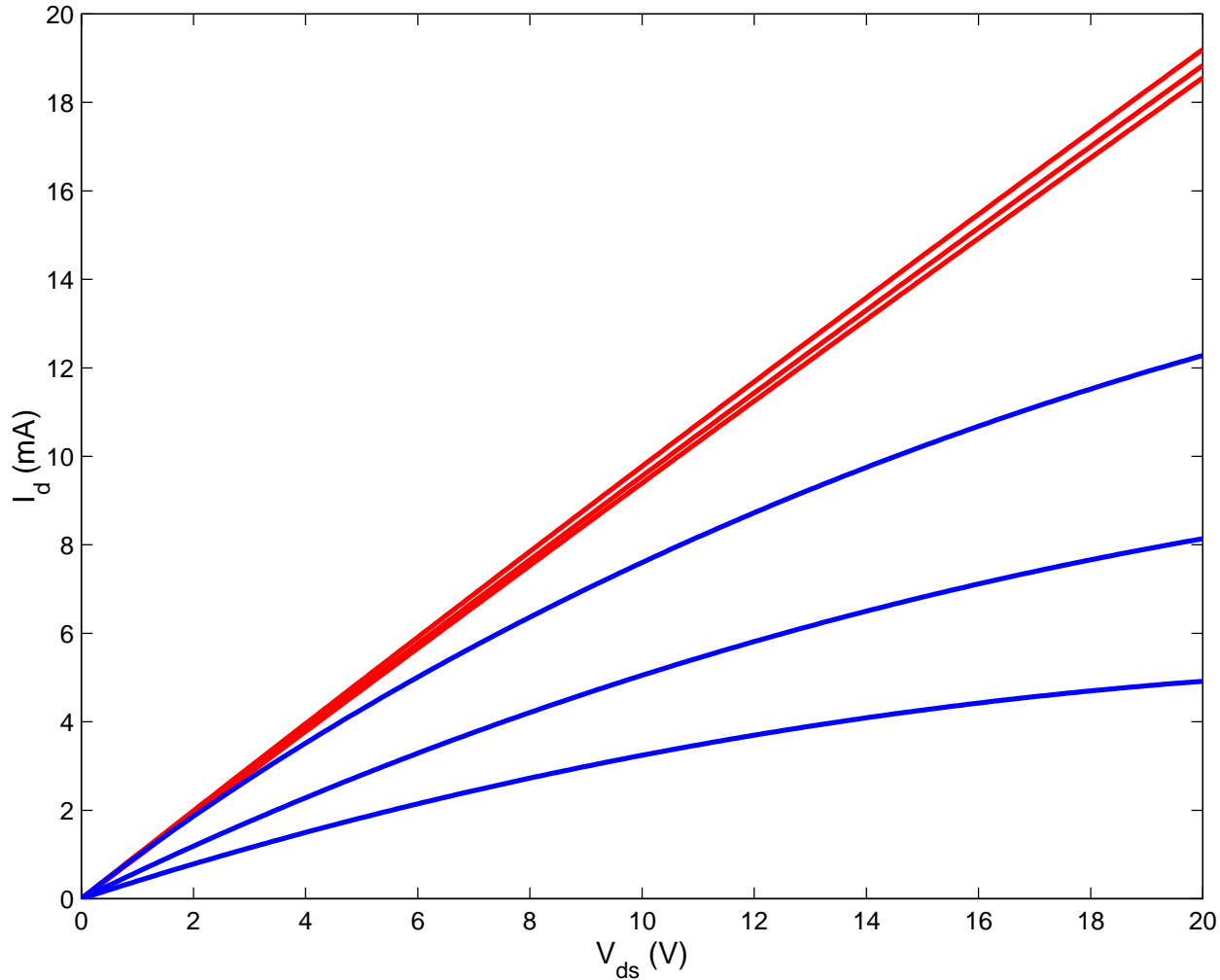
$$W_{eff} = \frac{W + D + K_D W / (W + D) \left(1 - \exp(-W/W_N) \right)}{1 - K_L D W / W_{dog} L}$$

- **Gate voltage exponentially limited to V_p**
 - gives subthreshold current

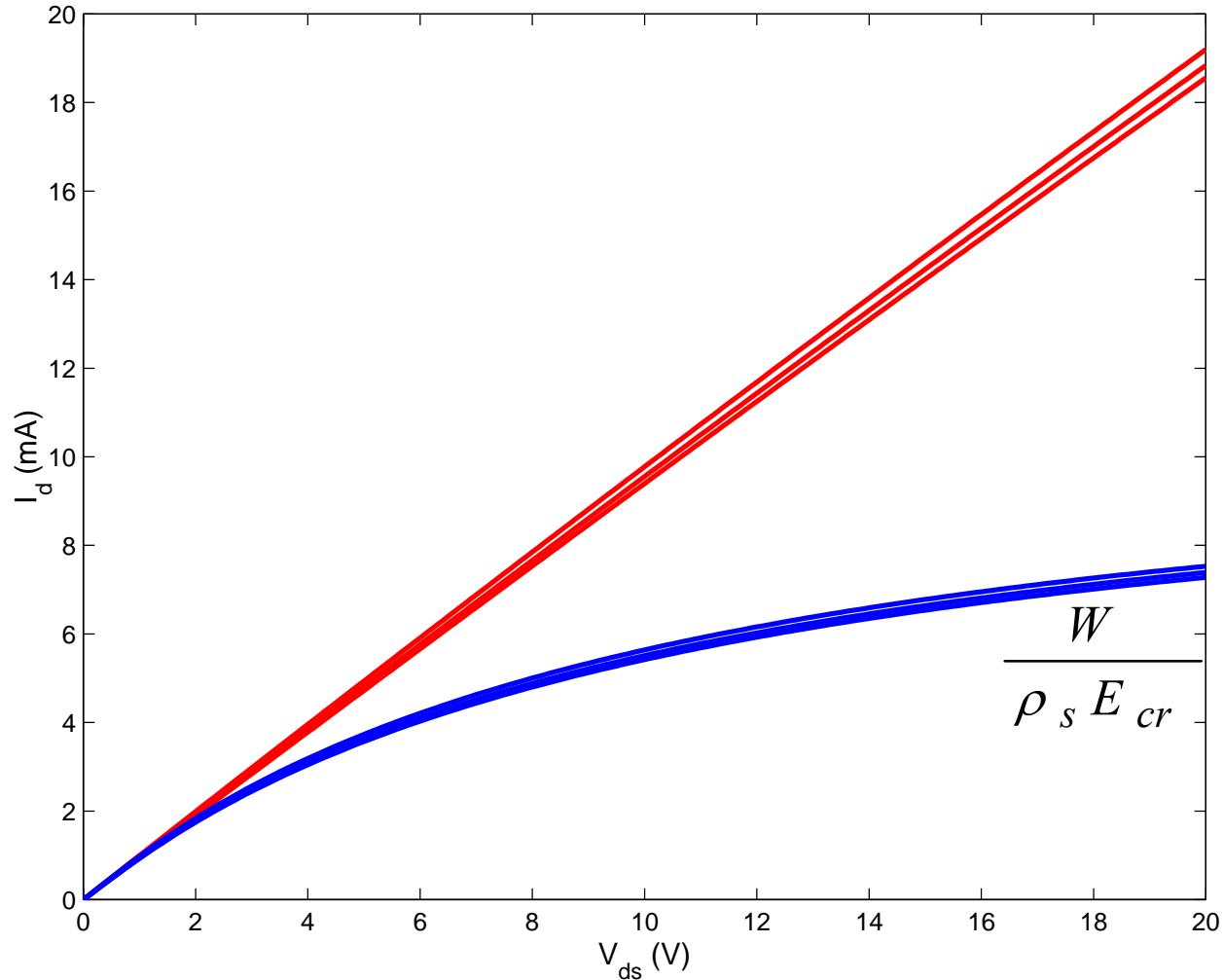
Weak Depletion Pinching



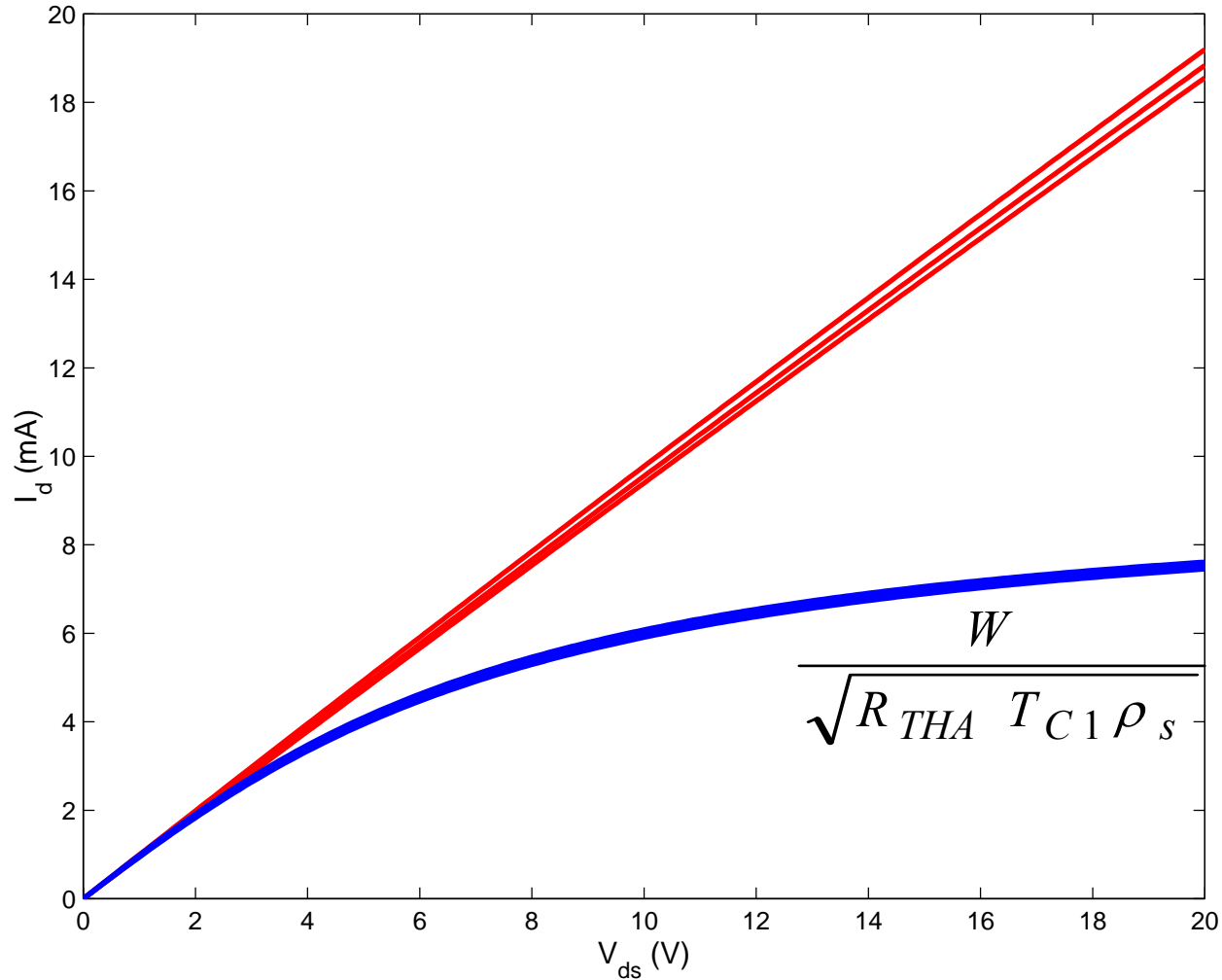
Strong Depletion Pinching



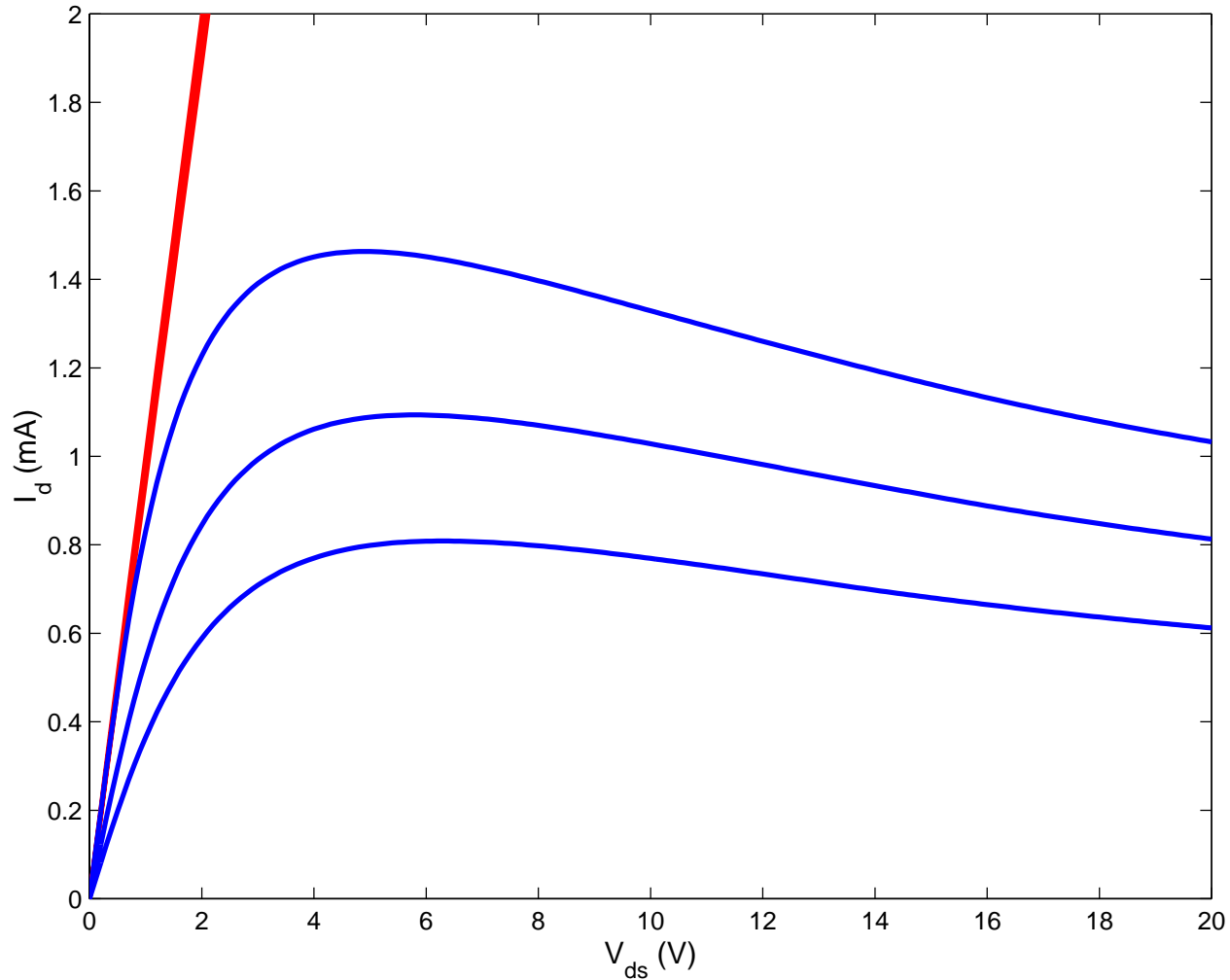
Strong Velocity Saturation



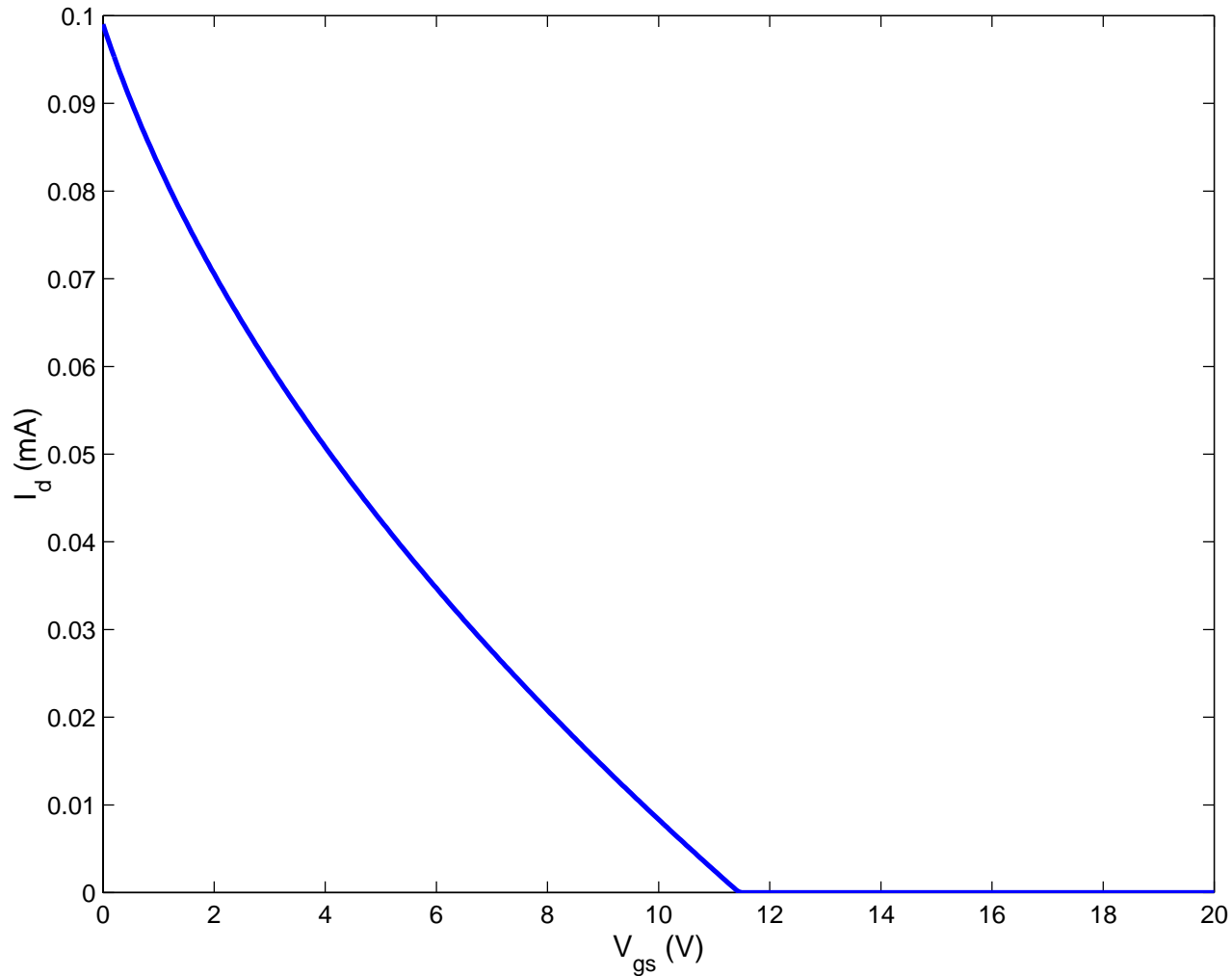
Strong Self-Heating



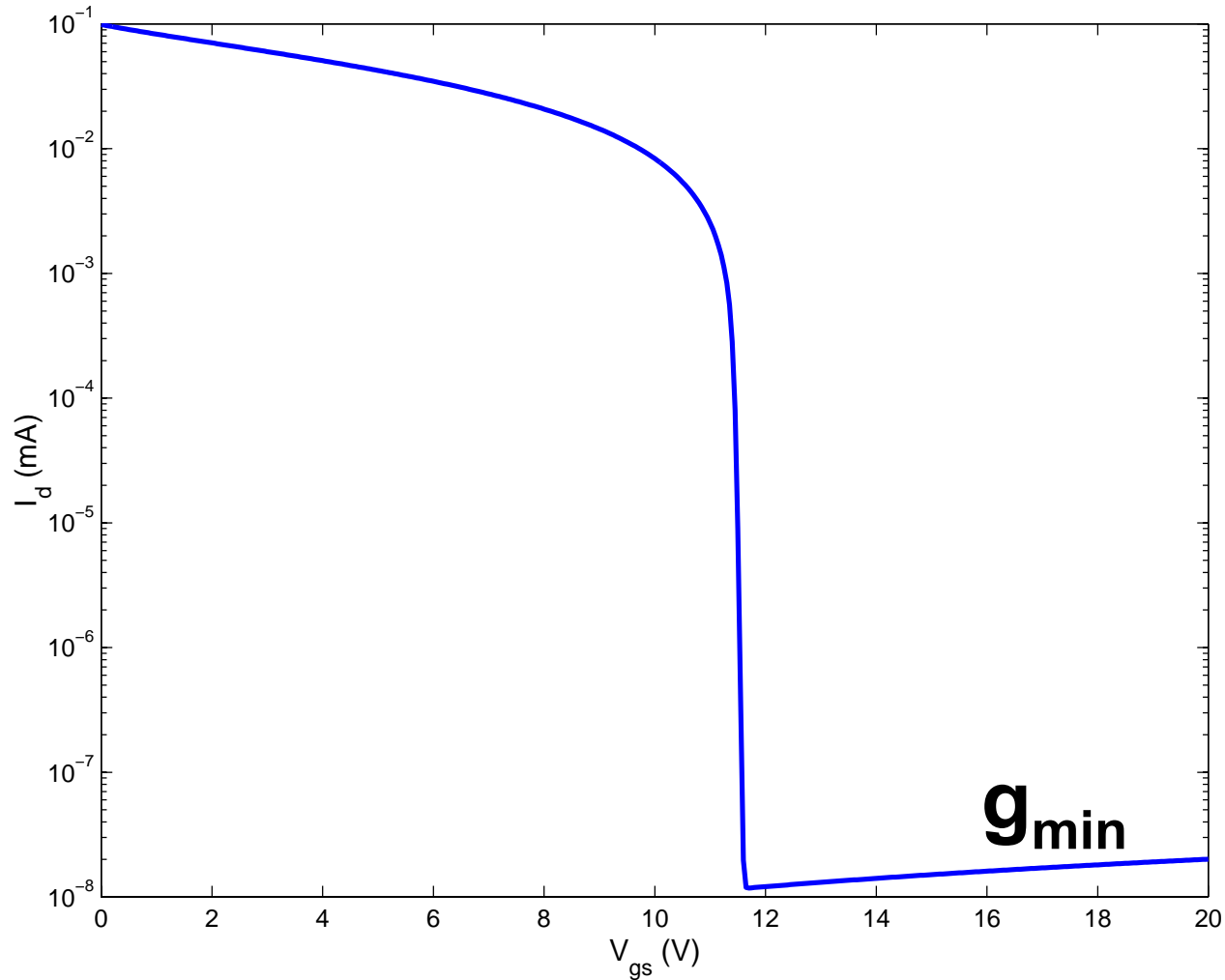
All Effects Important



Subthreshold Modeling



Subthreshold Modeling



Summary

- **Accurate resistor models are important for analog design**
 - existing polynomial and SPICE JFET models are inadequate
- **Presented improved 3-terminal diffused resistor and JFET model, with**
 - accurate depletion pinching model
 - accurate velocity saturation model and saturation voltage calculation
 - self-heating