Symmetry Breaking in the Drain Current of Multi-Finger Transistors

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Outline

- **Review: Drain Current Symmetry in Multi-finger FET Models**

- **Drain Current Symmetry Breaking**
  - **Due to wire resistance**
  - **Due to contact resistance**
  - **Due to diffusion resistance**
  - **Due to self heating effect**
  - **Due to uncorrelated variations among fingers**

- **Summary**

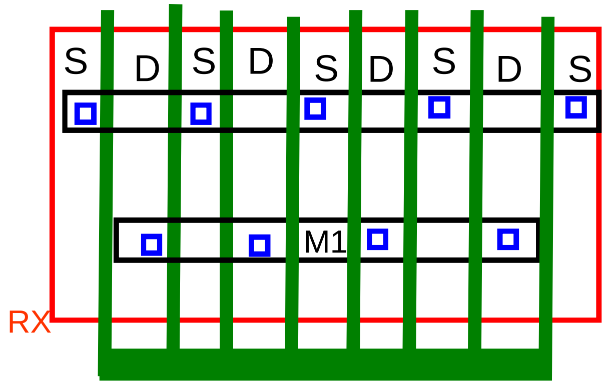
Drain Current Symmetry in Multi-finger FET Models

Multi-finger FETs are often used: Big drivers in standard cells, RF FETs.

Drain current in each finger channel has been treated to be highly symmetric:
Each finger channel has a same drain current.

Multi-finger FET

(N_f = 8)

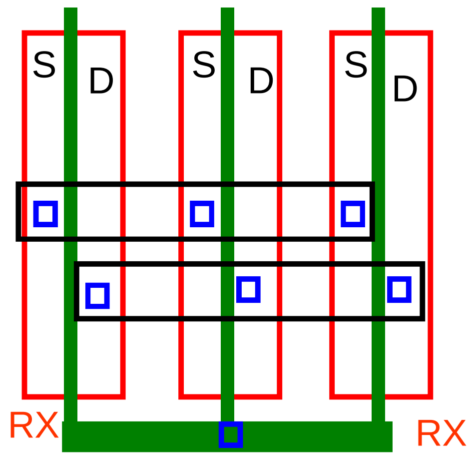


$$I_d(N_f) = N_f i_d$$

in compact models

Multiple diffusion regions

par = 3, N_f = 1
→ *m* = 3



In SPICE simulations, multiplicity *m* can be provided. SPICE simulator returns a drain current that is *m* times of single FET's drain current

$$I_d(m) = m i_d$$

In general, $m = par \bullet N_f$

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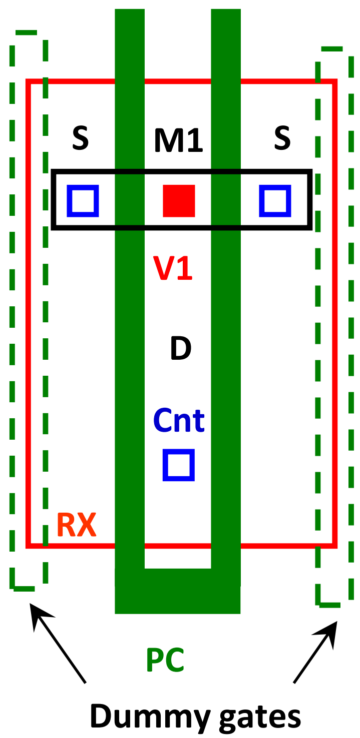
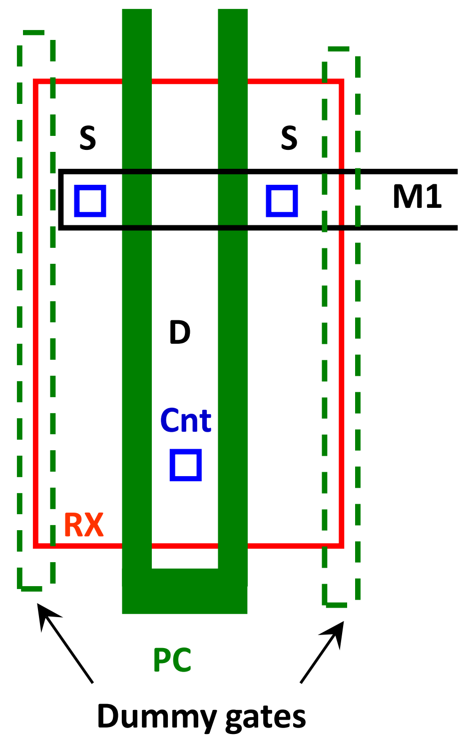
Symmetry Breaking Due to Wire Resistance





A symmetric layout:

→ Identical drain current in the left finger channel and in the right finger channel.

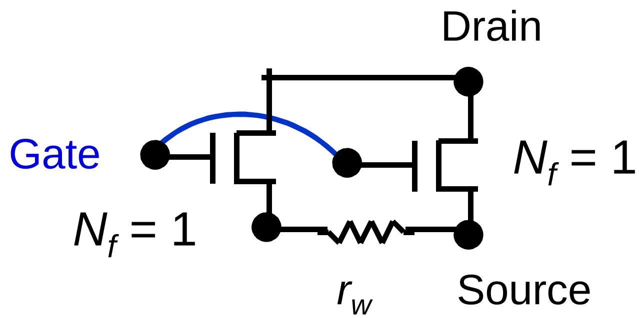
Layout is not fully symmetric:

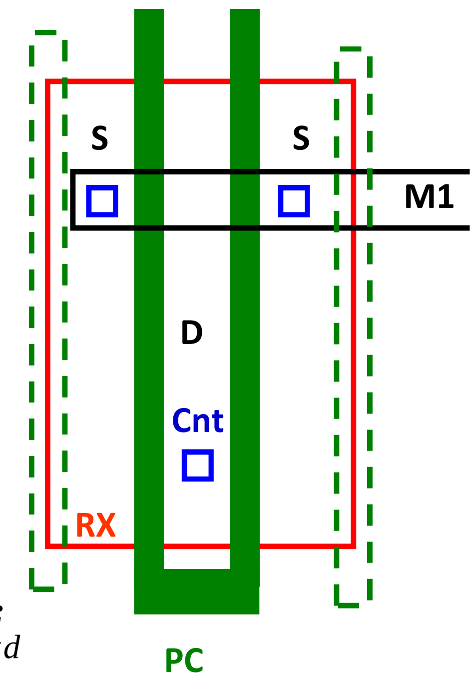
→ More wire resistance in the left-finger channel

→ Slightly less drain current in the-left finger **← Symmetry is broken**

A Two-Finger Transistor and Its SPICE Netlists

A detailed netlist:

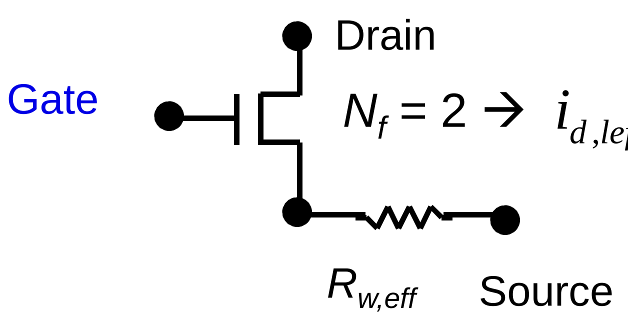




$$i_{d,left} < i_{d,right} = i_d$$

Per-finger average current: $\dfrac{I_{d,tot}}{2} = \dfrac{i_{d,left} + i_{d,right}}{2} < i_d$

A reduced netlist for faster simulation:



$N_f = 2 \rightarrow\ i_{d,left} = i_{d,right}$

Approximation: Each finger channel carries a same amount of drain current

$$R_{w,eff} = \left(\frac{1}{2}\right)^2 r_w = \frac{1}{4} r_w$$

Per-finger average current: $\dfrac{I_{d,tot}}{2} < i_d$

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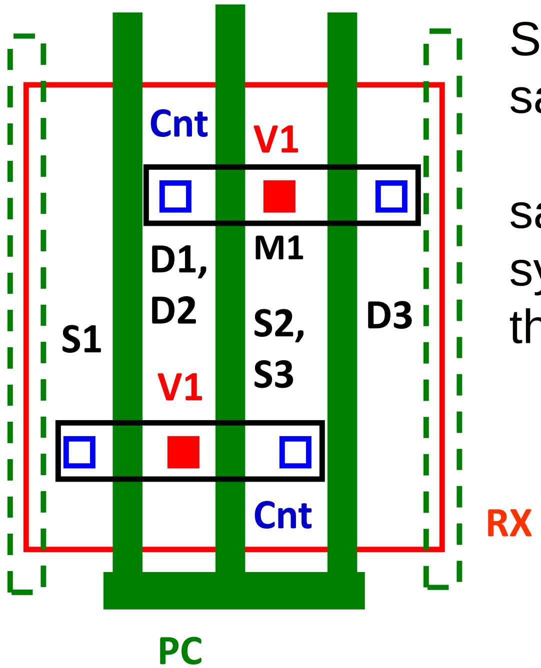
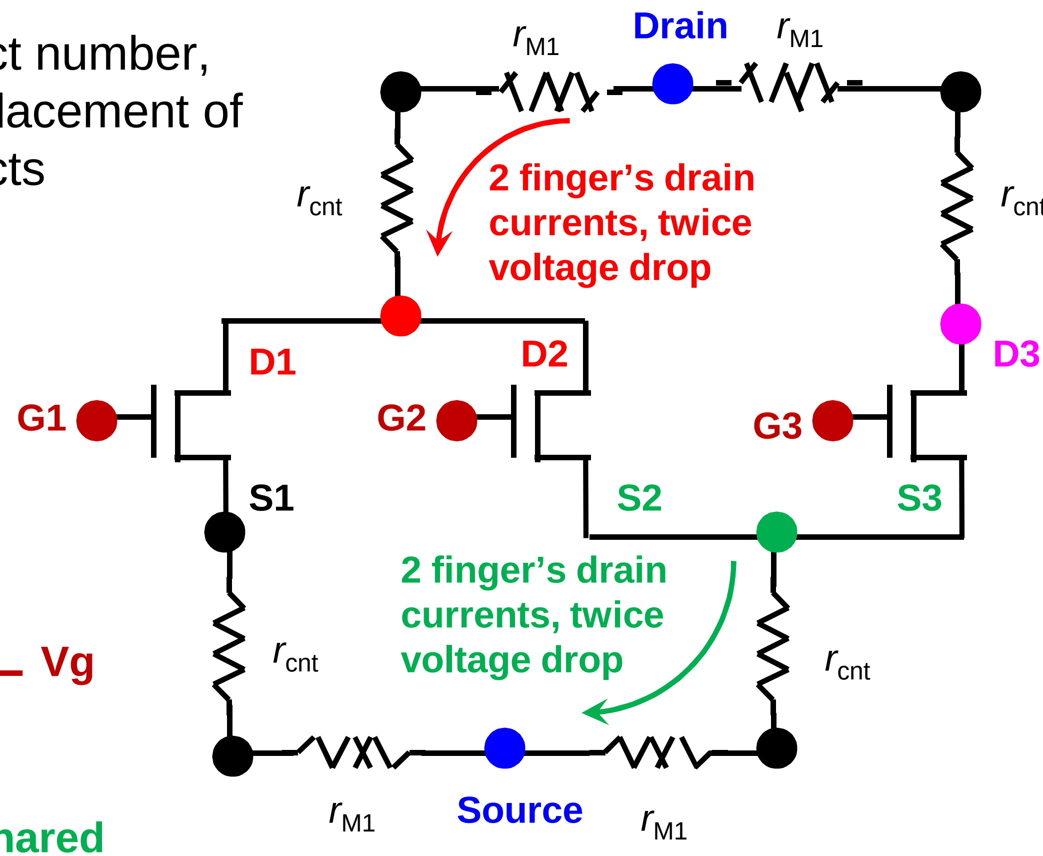
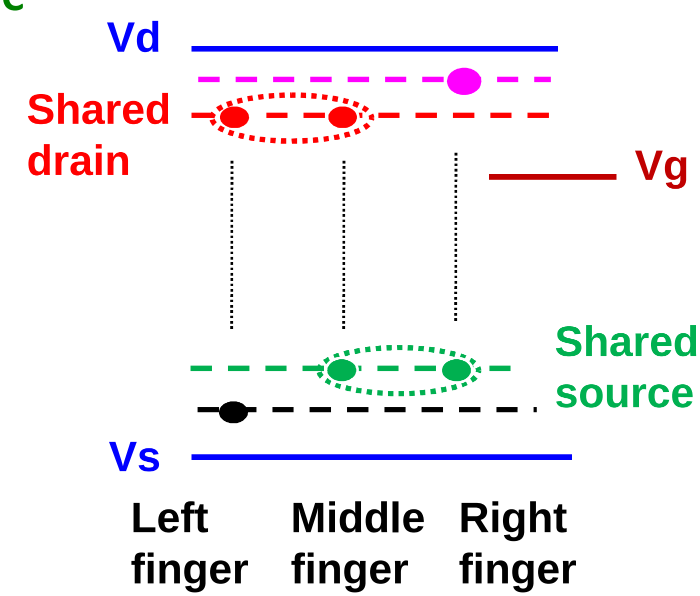
Symmetry Breaking Due to Contact Resistance (1)



Same source-side R_W, same drain-side R_W.

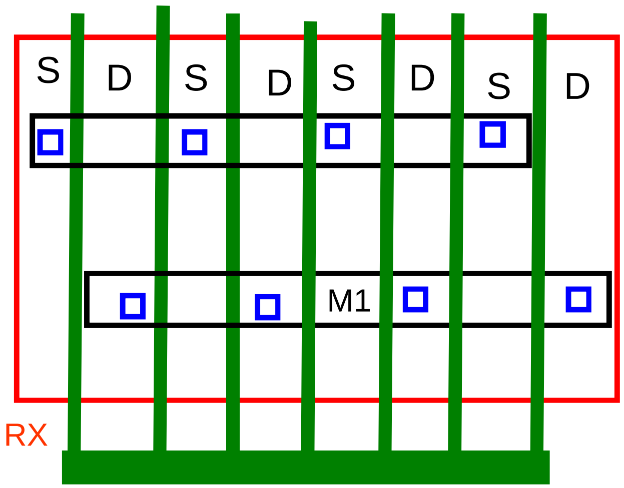
same contact number, symmetric placement of those contacts





Ignored diffusion R in the above netlist

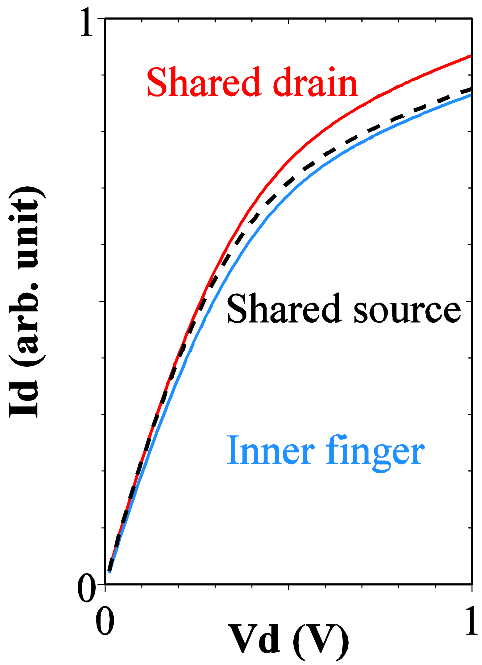
Symmetry Breaking Due to Contact Resistance (2)



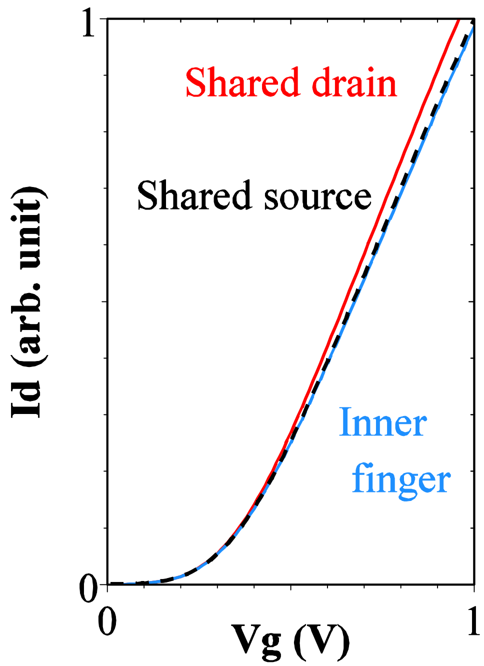
Multi-finger FET

$N_f = 7$

Effect of contact R alone
on drain current



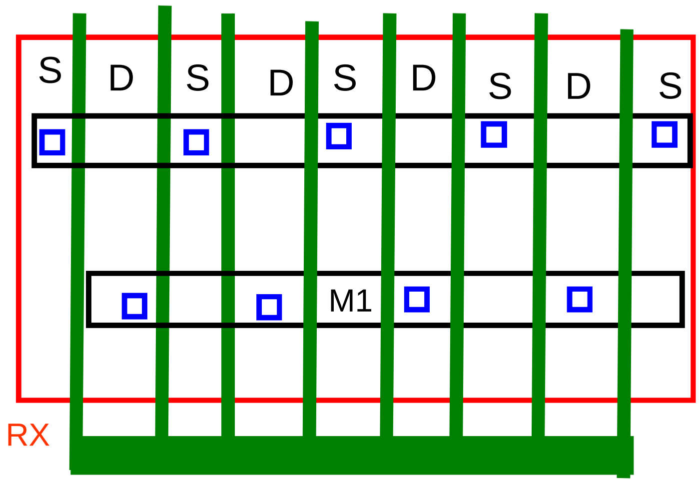
Vg = Vdd = 0.9 V



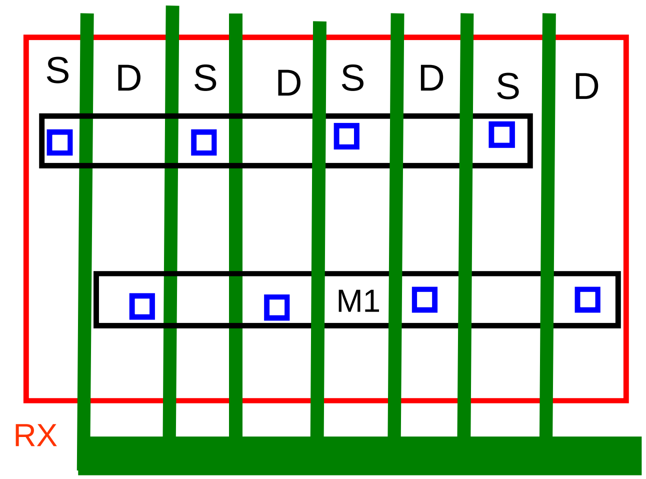
Vd = Vdd

Symmetry is broken

Effective Source/Drain Contact Resistance (1)

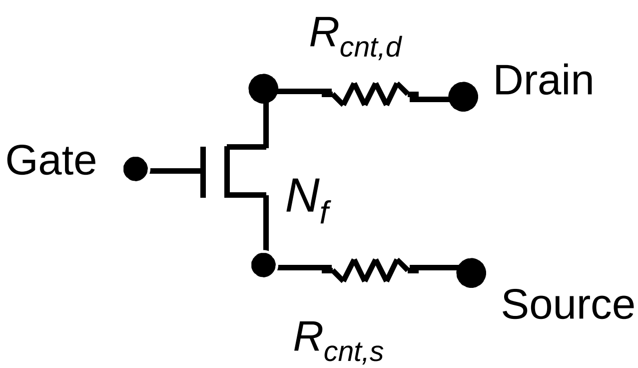


Even N_f



Odd N_f

To reduce simulation time, we still want to use a single FET instance plus a source-side effective $R_{cnt,s}$ element and a drain-side effective $R_{cnt,d}$ element.



$$R_{cnt,s}(\mathrm{old}) = \frac{r_{cnt}}{n_s}, \quad R_{cnt,d}(\mathrm{old}) = \frac{r_{cnt}}{n_d}$$

r_{cnt} – Contact R in a single diffusion region;

n_s – Number of source; n_d – Number of drain

Effective Source/Drain Contact Resistance (2)

Old effective contact R formula assumes a same amount of drain current passing through each **contact**, which is not true.

Approximation: The drain current passing through each **finger channel** is the same.

$$R_{cnt,s/d} = \sum_{k=1}^{n_{s/d}} \left(\frac{I_{cnt,k}}{I_{tot}} \right)^2 r_{cnt}$$

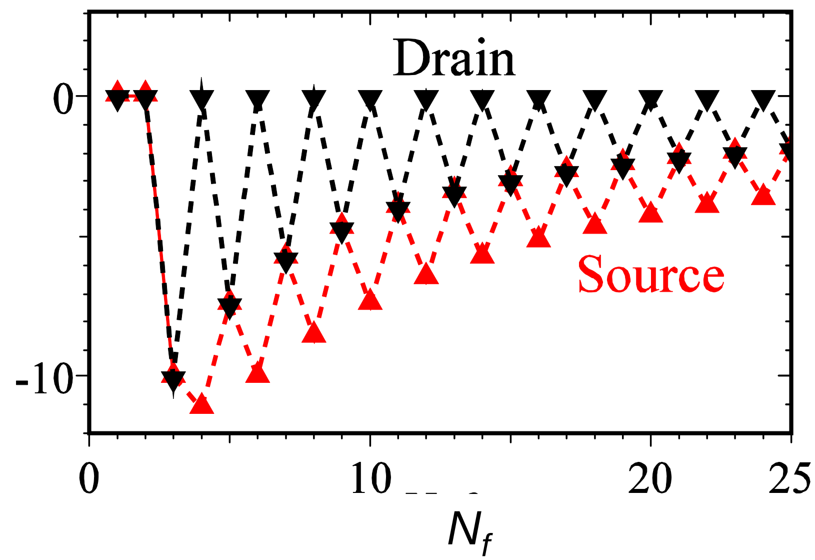
$$\frac{I_{cnt,k}}{I_{tot}} = \frac{1}{N_f}$$ Outer contact

$$\frac{I_{cnt,k}}{I_{tot}} = \frac{2}{N_f}$$ Inner contact

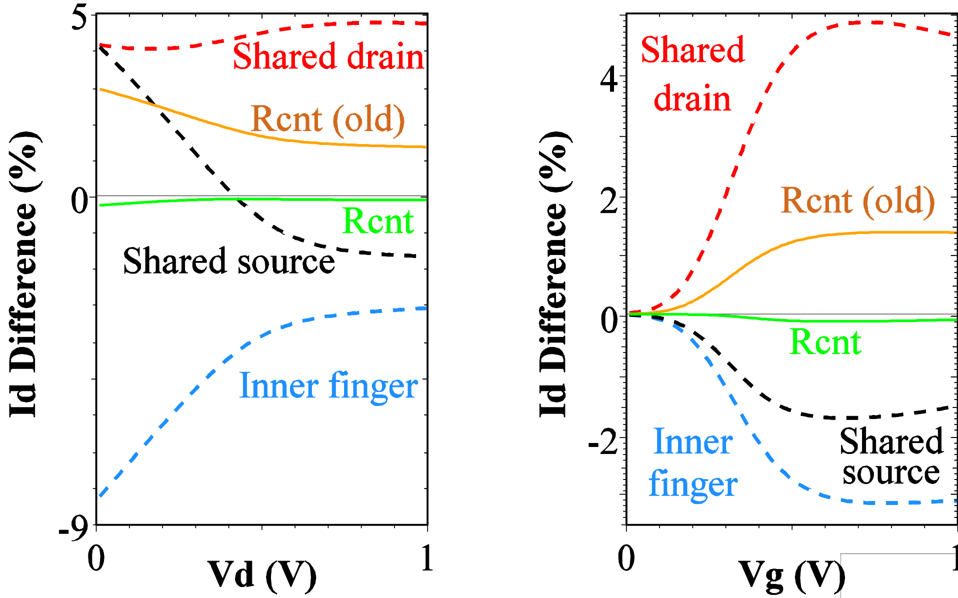
$$R_{cnt,s} = R_{cnt,d} = \frac{2N_f - 1}{N_f^2} r_{cnt}\ , \quad \text{odd } N_f$$

$$R_{cnt,s} = \frac{2N_f - 2}{N_f^2} r_{cnt}\ ,\ R_{cnt,d} = \frac{2}{N_f} r_{cnt}\ , \text{even } N_f$$

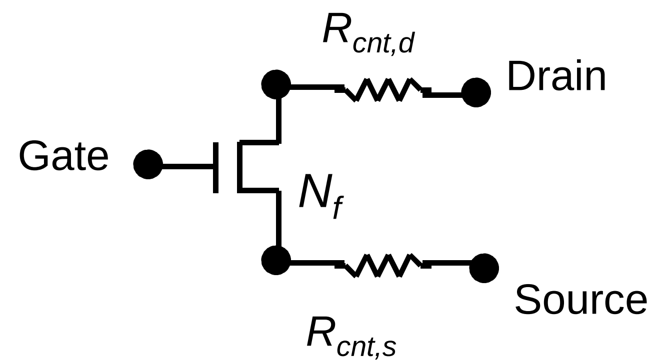
[R(old)/R_{cnt} – 1] (%)



Accuracy of Effective S/D Contact Resistance

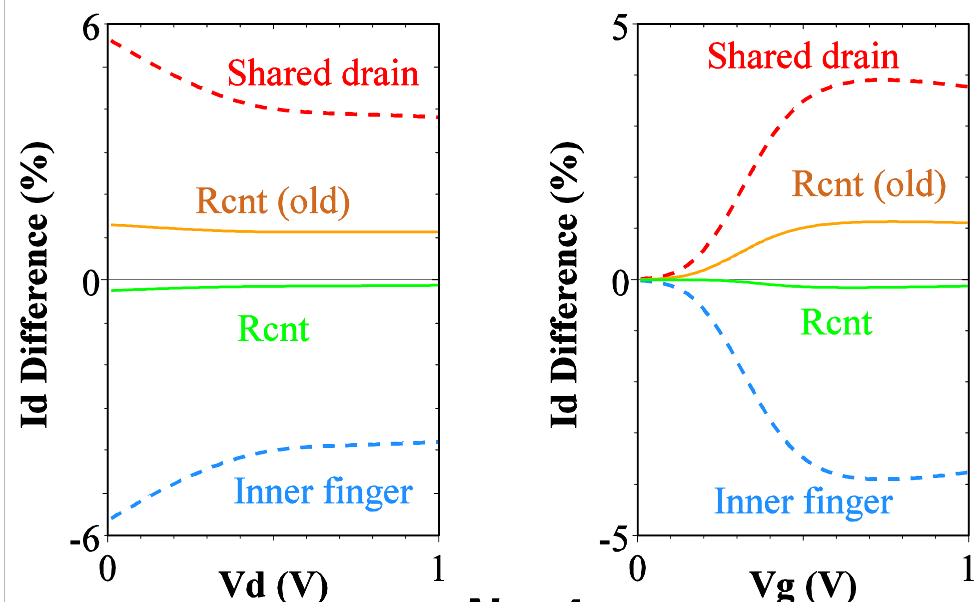


Vd = Vdd



$N_f = 3$

Vg = Vdd = 0.9 V



Base Id: Full netlist, I_{tot} / N_f

Only contact R is included

$N_f = 4$

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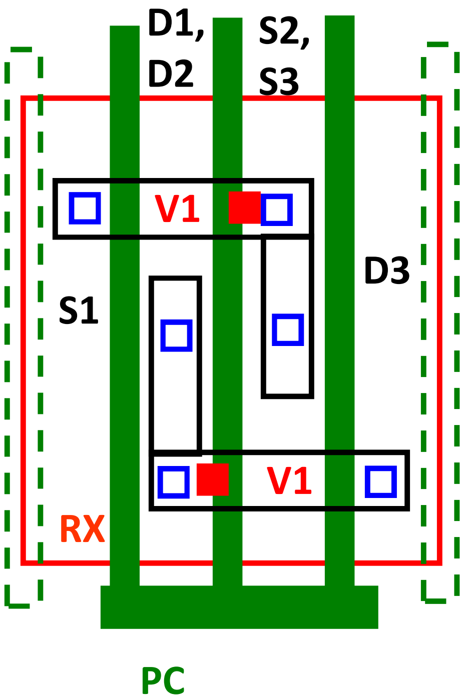
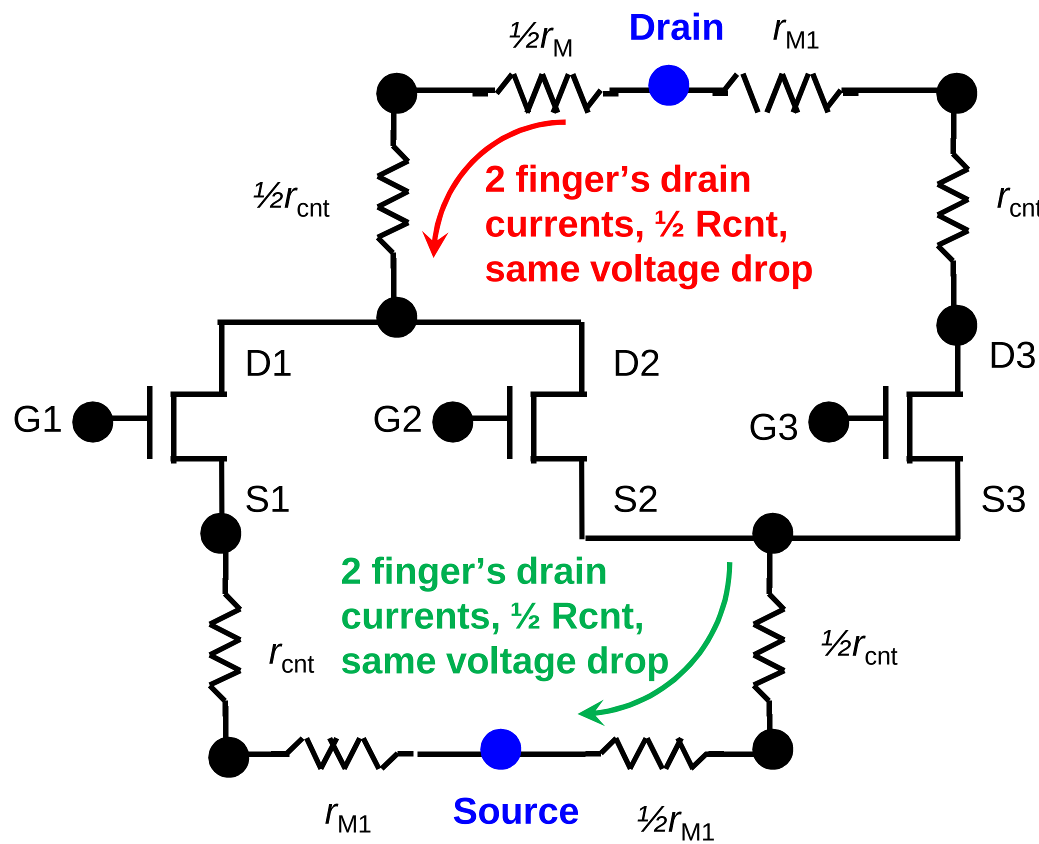
Full Utilization of Available Breakdown Voltage



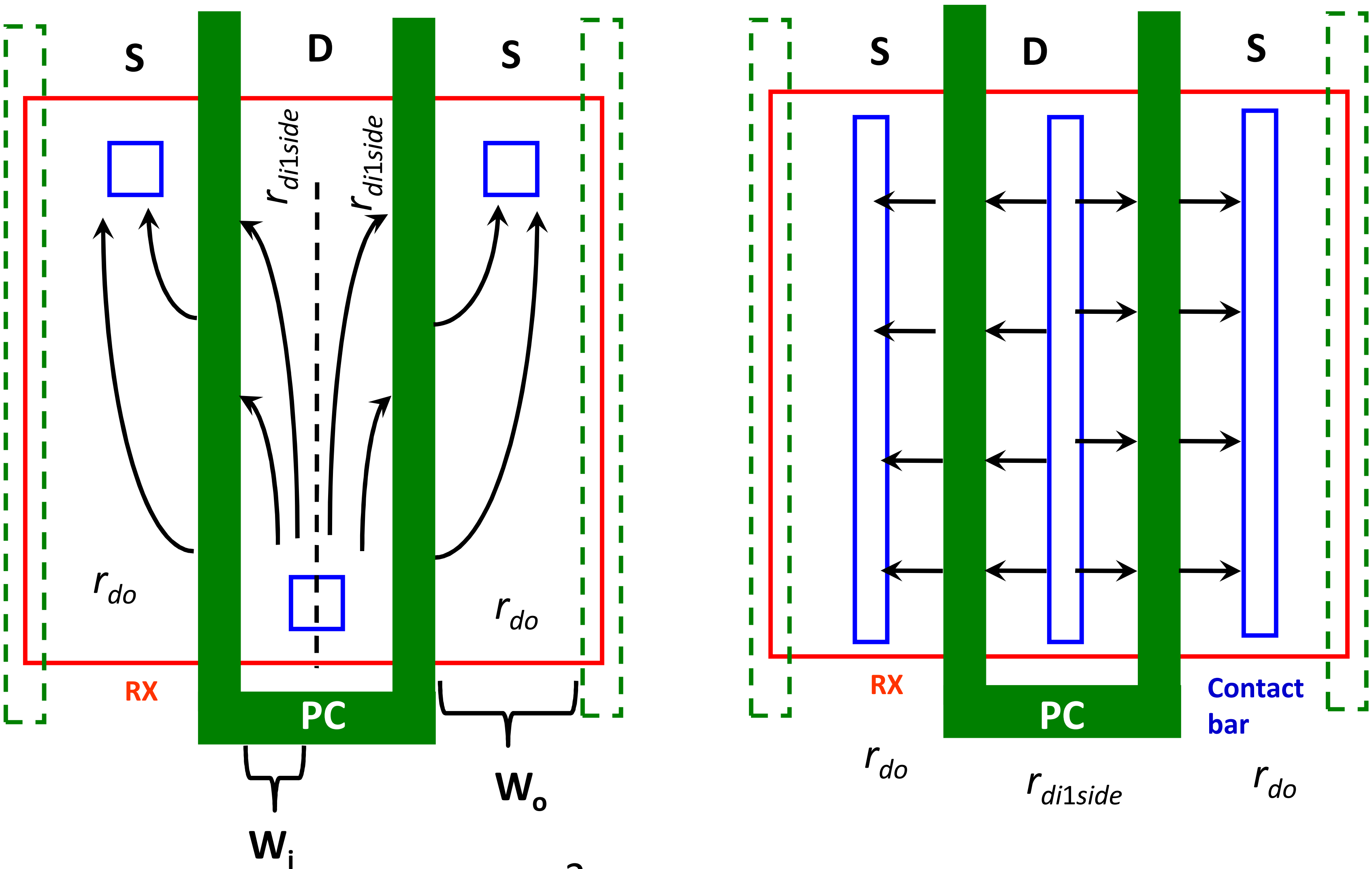


Contact number in an inner diffusion region: contact number in an outer diffusion region = 2 : 1.

Ignored diffusion R in the above netlist

No more symmetry breaking?

Silicide Diffusion Resistance



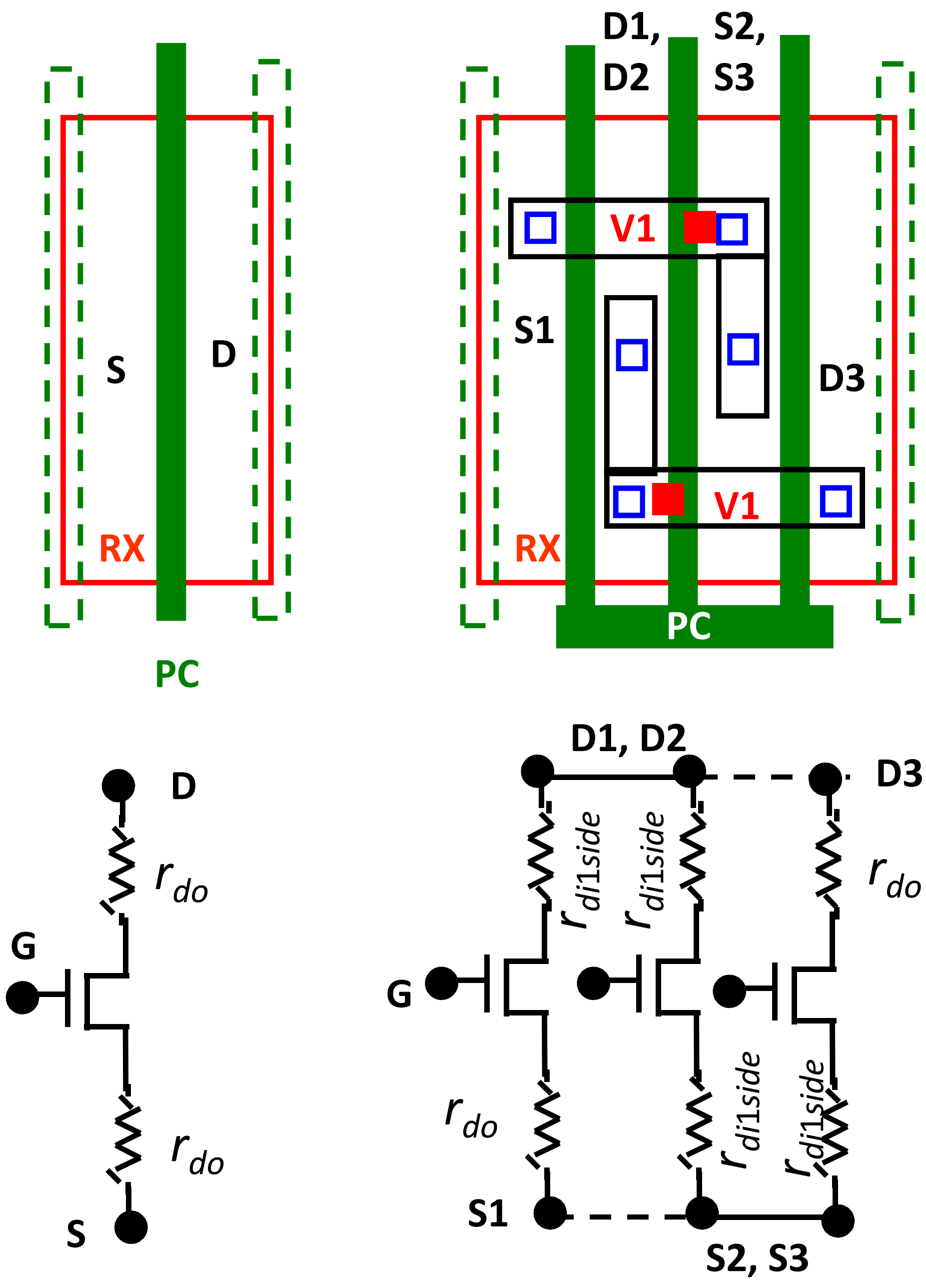
$W_i = ½W_o$

$r_{di1side} \approx 2r_{do}$

$r_{di1side} \approx r_{do}$

In general, $1 \leq r_{di1side} / r_{do} \leq 2$

Symmetry Breaking Due to Diffusion Resistance



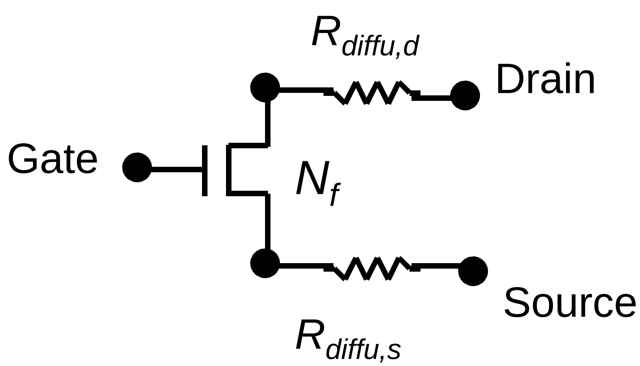
Since $r_{di1side} > r_{do}$,

$$i_{d,inner} < i_{d,outer} < i_{d,\mathrm{singleFinger}}$$

(due to silicide diffusion resistance only)

Symmetry is broken

Effective Source/Drain Diffusion Resistance



For efficient SPICE simulations, we want to use a single FET instance to represent a multi-finger FET
→ Need effective source and drain diffusion R

Approximation: The drain current passing through each finger channel is the same.

$$R_{diffu,s} = R_{diffu,d} = \frac{r_{do} + (N_f - 1) r_{di1side}}{N_f^2}, \quad \text{odd } N_f;$$

$$R_{diffu,s} = \frac{2r_{do} + (N_f - 2) r_{di1side}}{N_f^2}, \; R_{diffu,d} = \frac{r_{di1side}}{N_f}, \text{ even } N_f.$$

Limit 1: When $r_{di1side} = r_{do}$, $\quad R_{diffu,s} = R_{diffu,d} = \frac{r_{do}}{N_f}$, both even and odd N_f.

Limit 2: When $r_{di1side} = 2r_{do}$,
$R_{diffu,s}$ and $R_{diffu,d}$ reduce to the form of previous contact R expressions.

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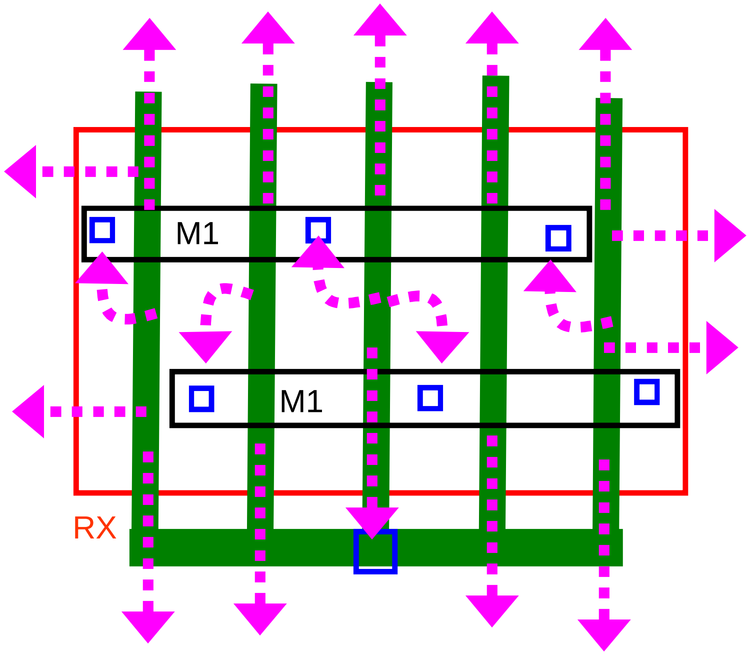
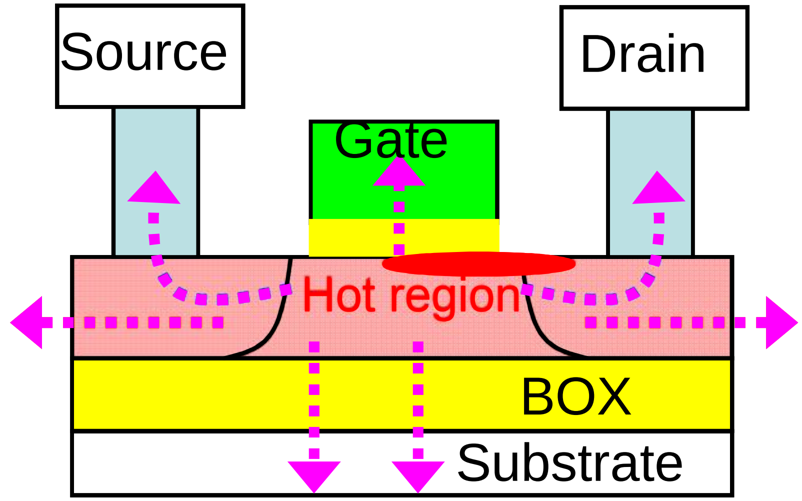
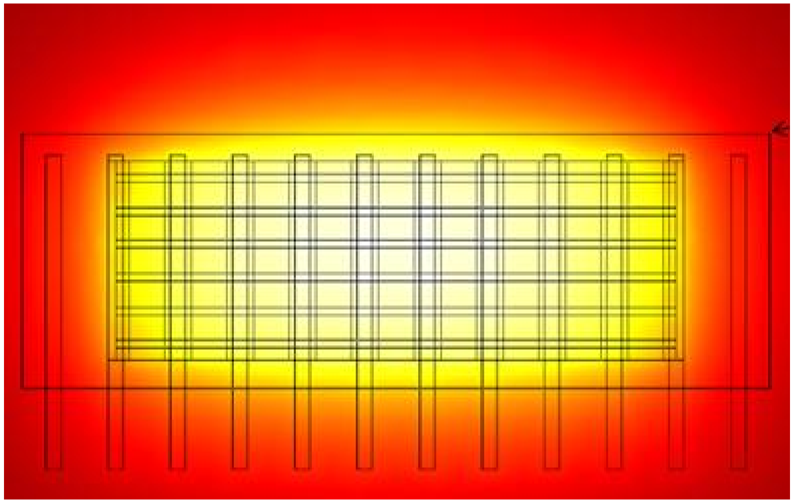
Self Heating in FETs





Energy dissipated near the drain is conducted away through BOX/substrate, contacts and gate

$\Delta T = R_{th} \bullet$ Power



Thermal resistance $$R_{th} = \frac{1}{G_{th,A}A + G_{th,P}P}$$

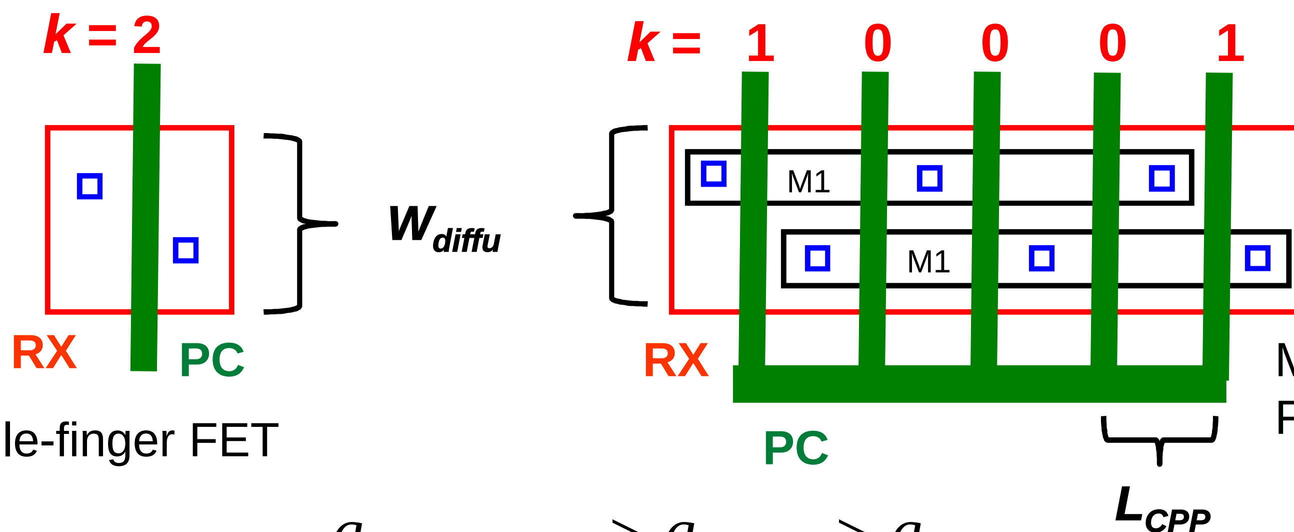
Ignored the difference between outer and inner finger channels

14nm FinFET, C. Scott, IBM Research

An Improved Self-Heating Characterization

Inner- and outer-finger channels in a multi-finger FET and a single-finger channel have different ΔT values due to self heating

$$g_{th,n} \equiv \frac{1}{r_{th,n}} = G_{th,A} L_{CPP} W_{diffu} + G_{th,P} (2L_{CPP} + kW_{diffu}), \qquad \sum_{n=1}^{N_f} g_{th,n} = \frac{1}{R_{th}}$$



Single-finger FET

Multi-finger FET

$$g_{th,\text{singleFinger}} > g_{th,outer} > g_{th,inner}$$

Effect of self heating on drain current:

$$r_{th,\text{singleFinger}} < r_{th,outer} < r_{th,inner}$$

$$i_{d,she} = \frac{i_d}{1 + r_{th} i_d v_{ds}},$$

$$i_{d,she,\text{singleFinger}} > i_{d,she,outer} > i_{d,she,inner}$$

Symmetry is broken

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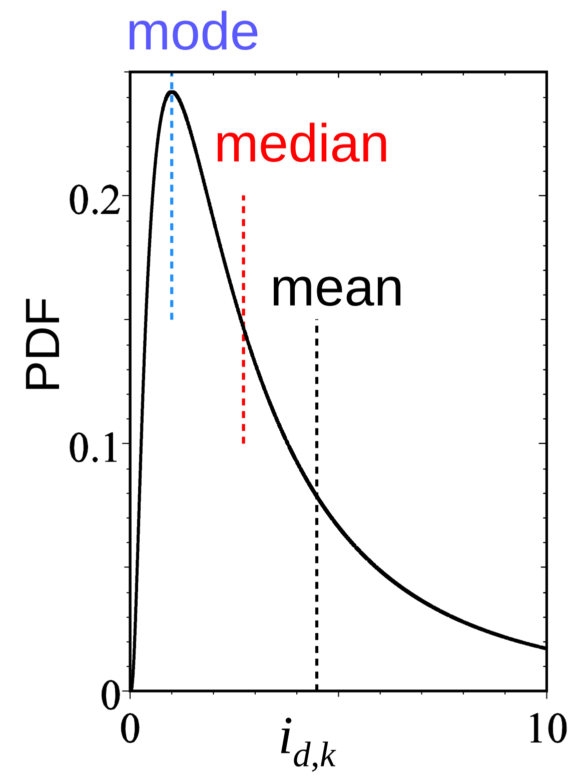
Sub-threshold Drain Current

Ignore the effects of wire R, contact R, diffusion R, self heating, stress, etc.

Consider uncorrelated random variations among different fingers of a multi-finger FET. Focus on sub-threshold drain current and Vt variations.

Distribution of sub-threshold drain current in each finger: A log-normal distribution;

$$i_{d,k} \propto \exp\left(\frac{V_{gs} - v_{t,k}}{n v_t}\right)$$

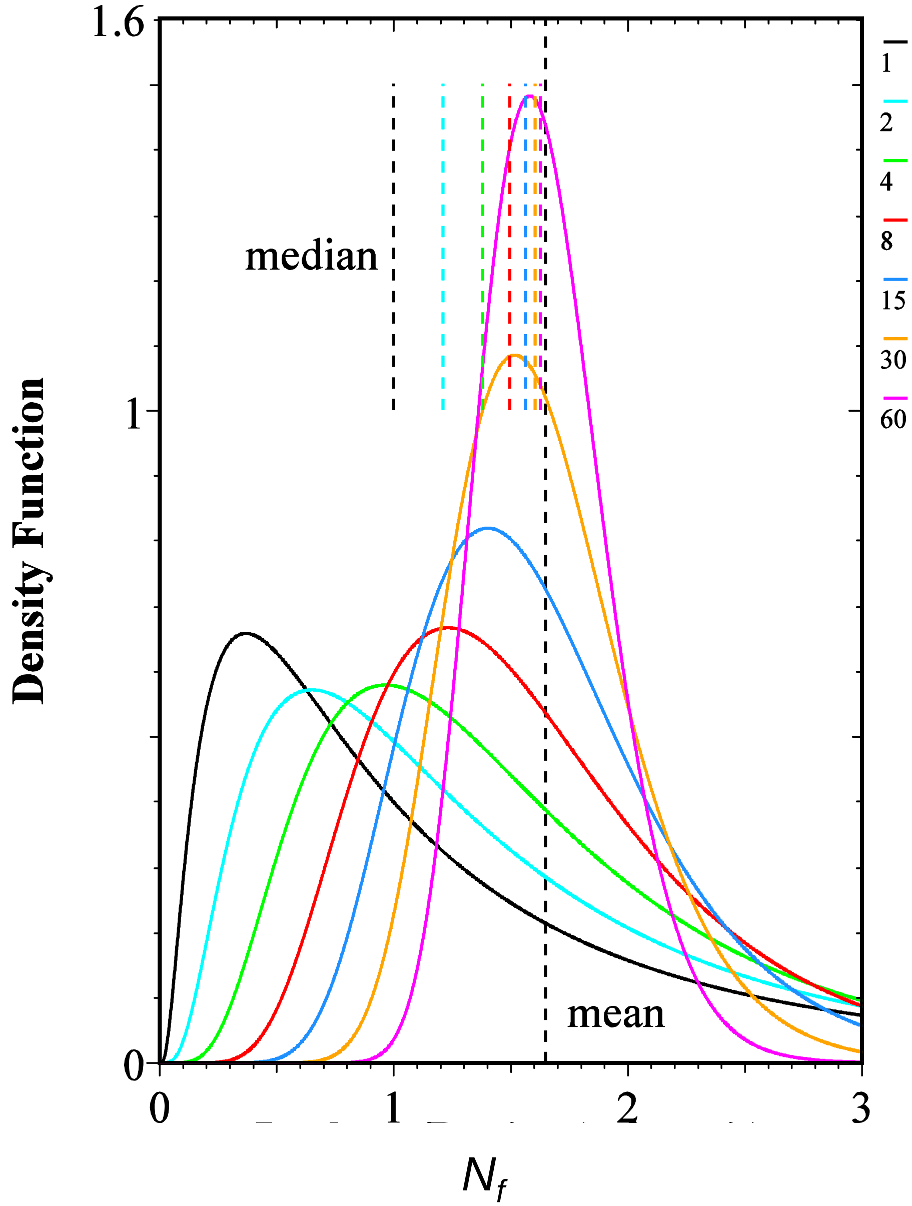


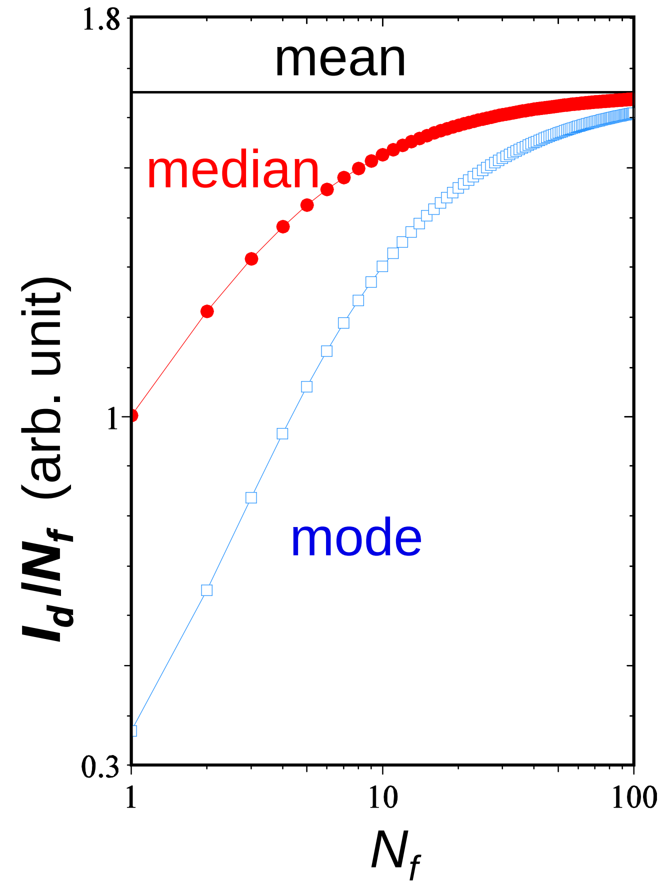
Total sub-threshold drain current:
A sum of N_f partially correlated log-normal distributions.

$$I_d = \sum_{k=1}^{N_f} i_{d,k}$$

Symmetry is kept in mean drain current: $$\frac{\langle I_d \rangle}{N_f} = i_d(\text{mean})$$

Symmetry Breaking Due to Uncorrelated Variations





$$\frac{I_d(\text{median})}{N_f} > i_d(\text{median}), \quad N_f \geq 2$$

Symmetry is broken in median drain current.

Summary

- **Showed that there is a symmetry breaking in the drain current of multi-finger FETs**
  - **Cause: From exterior to interior, each of wire R, contact R, diffusion R, self heating, uncorrelated random variations alone**
  - **Effect: The drain current in one or more fingers to be different from that in other fingers, or**
  - **Effect: The per-finger drain current is different from the drain current of a corresponding single-finger FET**
- **Presented analytic expressions for effective contact and diffusion resistances that can be used with a single instance of FET model to represent a whole multi-finger FET**
- **Presented an improved self-heating characterization and modeling approach**