Noise in Short Channel MOSFETs

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Overview

- **Creativity in Analog / Mixed Signal IC Design**
- **DSM CMOS Effects on Analog Design**
- **Fundamental Noise Sources**
- **Applications**
- **Conclusion**

Overview

- **Creativity in Analog / Mixed Signal IC Design**
  - **Role of Creativity**
- DSM CMOS Effects on Analog Design
- Fundamental Noise Sources
- Applications
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Need for Creativity:

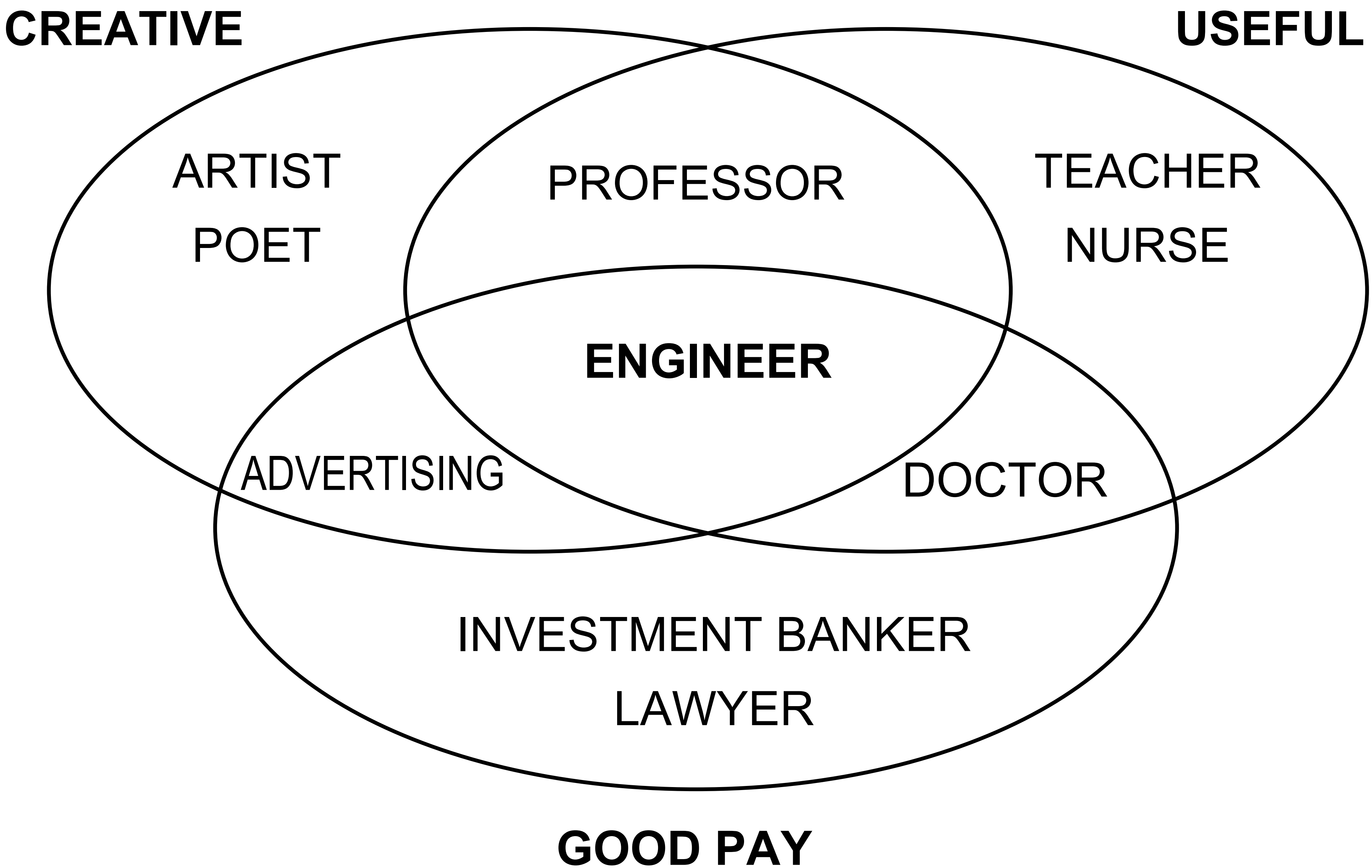
"… every company is betting on the ingenuity of its engineers to create the products that will conquer the market. And yet engineers' conferences and travels are cut, as if they don't make any contribution to creativity - the creativity that is required, ironically, at the very moment that its sources of inspiration are being cut."

- Willy Sansen,
***IEEE SSCS Magazine*,**
Summer 2009, p.4

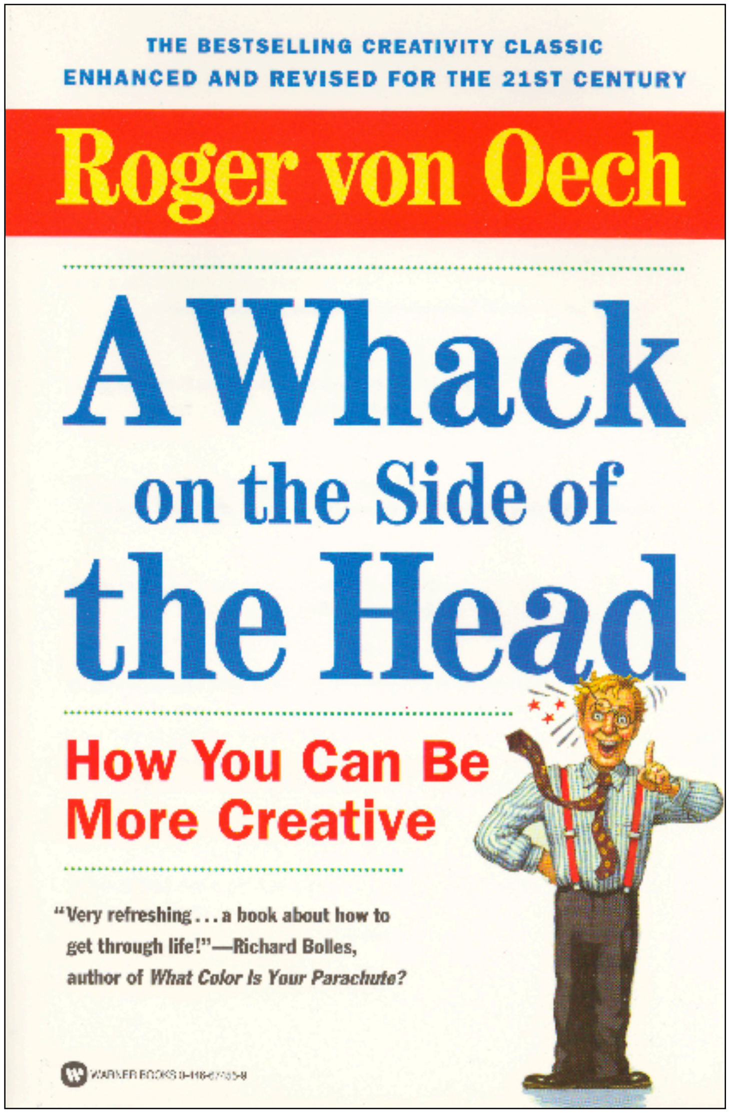
Why be creative?

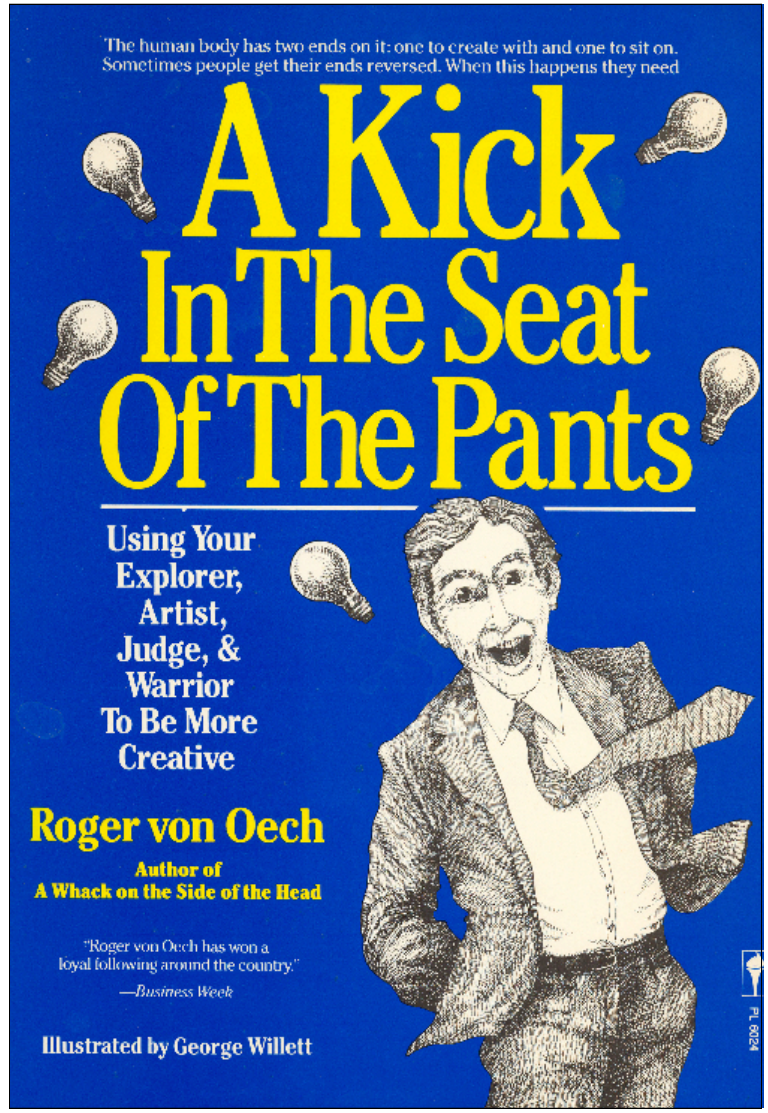
- Need
  - Easy problems solved already
  - Tough problems need creative solution
- Dealing with environment of change
  - Coping vs. thriving
- Human nature
  - Fun!

Career Classification



Creativity Resources





Creativity Framework

Explorer

Artist

Judge

Warrior

Example: Time (Stages of project)

Explorer	**Background Research**
	⇩
Artist	**Brainstorm Options**
	⇩
Judge	**Choose Solution**
	⇩
Warrior	**Implement Design**

Creativity Framework

Explorer	**Seek out new information**
	Survey the landscape
	Get off the beaten path
Artist	**Poke around in unrelated areas**
	Gather lots of ideas
	Shift your mindset
Judge	**Don't overlook the obvious**
	Look for unusual patterns
Warrior	

Creativity Framework

Explorer	Create something original
	Multiply options
	Use your imagination
Artist	Ask "what if" questions
	Play with ideas
	Look for hidden analogies
Judge	Break the rules
	Look at things backward
	Change contexts
Warrior	Play the fool

Creativity Framework

Explorer	Evaluate options
	Ask what's wrong
	Weigh the risk
Artist	Embrace failure
	Question assumptions
	Look for hidden bias
Judge	Balance reason and hunches
	Make a decision!
Warrior	

Creativity Framework

Explorer	Put decision into practice
	Commit to a realistic plan
	Get help
Artist	Find your real motivation
	See difficulty as challenge
	Avoid excuses
Judge	Persist through criticism
	Sell benefits not features
	Make it happen
Warrior	Learn from every outcome

Example: Modes of Thinking

Explorer

Artist

Judge

Warrior

Divergent
Soft
Qualitative

Convergent
Hard
Quantitative

Why a Creativity Model?

Education
- Standardized-test-numbed students
- Paralysis in face of open-ended problem

Designer
- Awareness of strengths, weaknesses
- Recognize preferences

Not Right or Wrong!
- One way of looking at process
- Orchard analogy

Creativity Framework

Explorer	**Survey the landscape**
Artist	**Break the rules**
Judge	**Question assumptions**
Warrior	**Learn from every outcome**

Overview

- Creativity in Analog / Mixed Signal IC Design
- **DSM CMOS Effects on Analog Design**
  - **Short Channel Effects**
  - **Noise Behavior**
- Fundamental Noise Sources
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Survey the landscape

Good Old Days

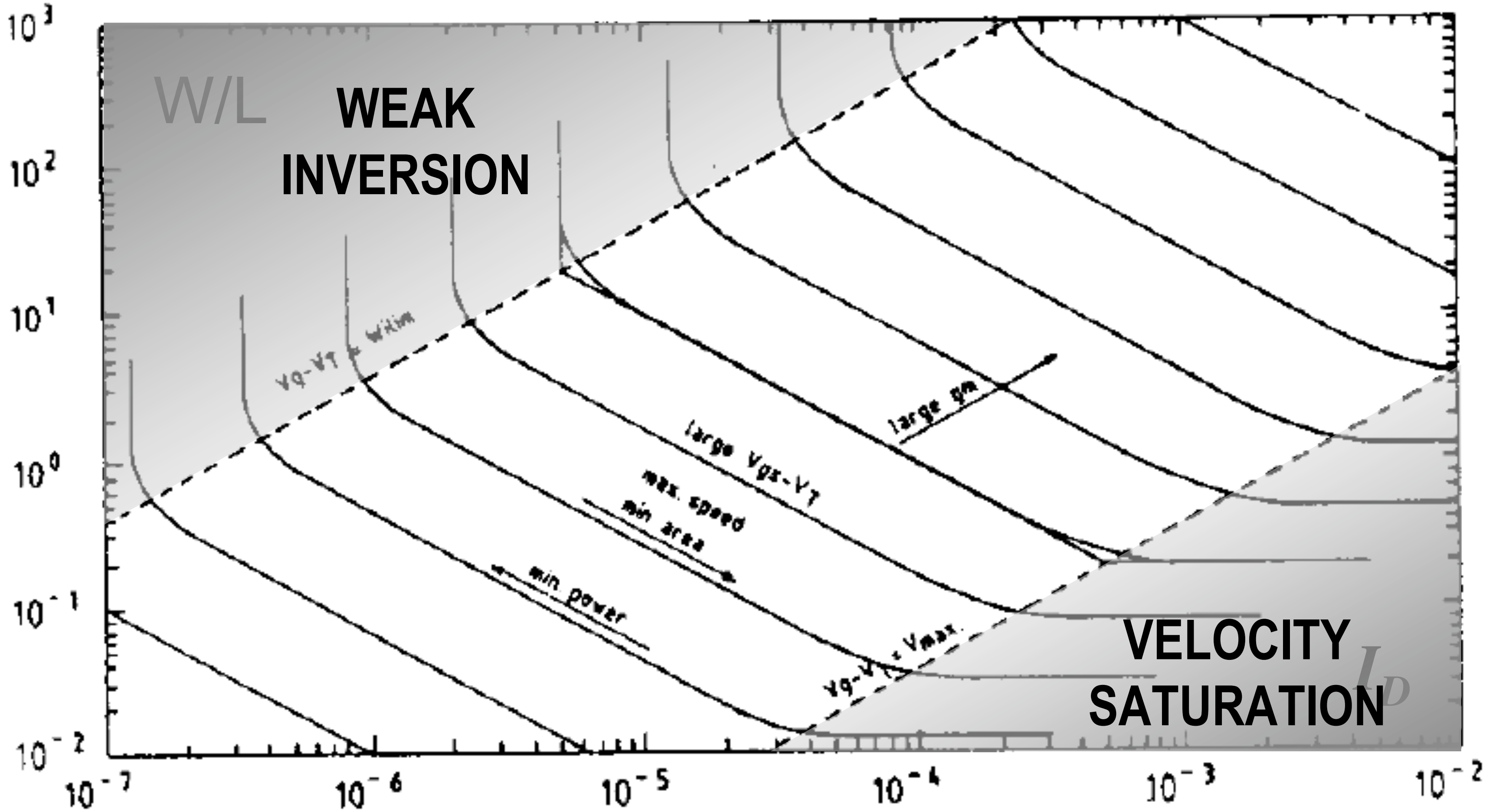
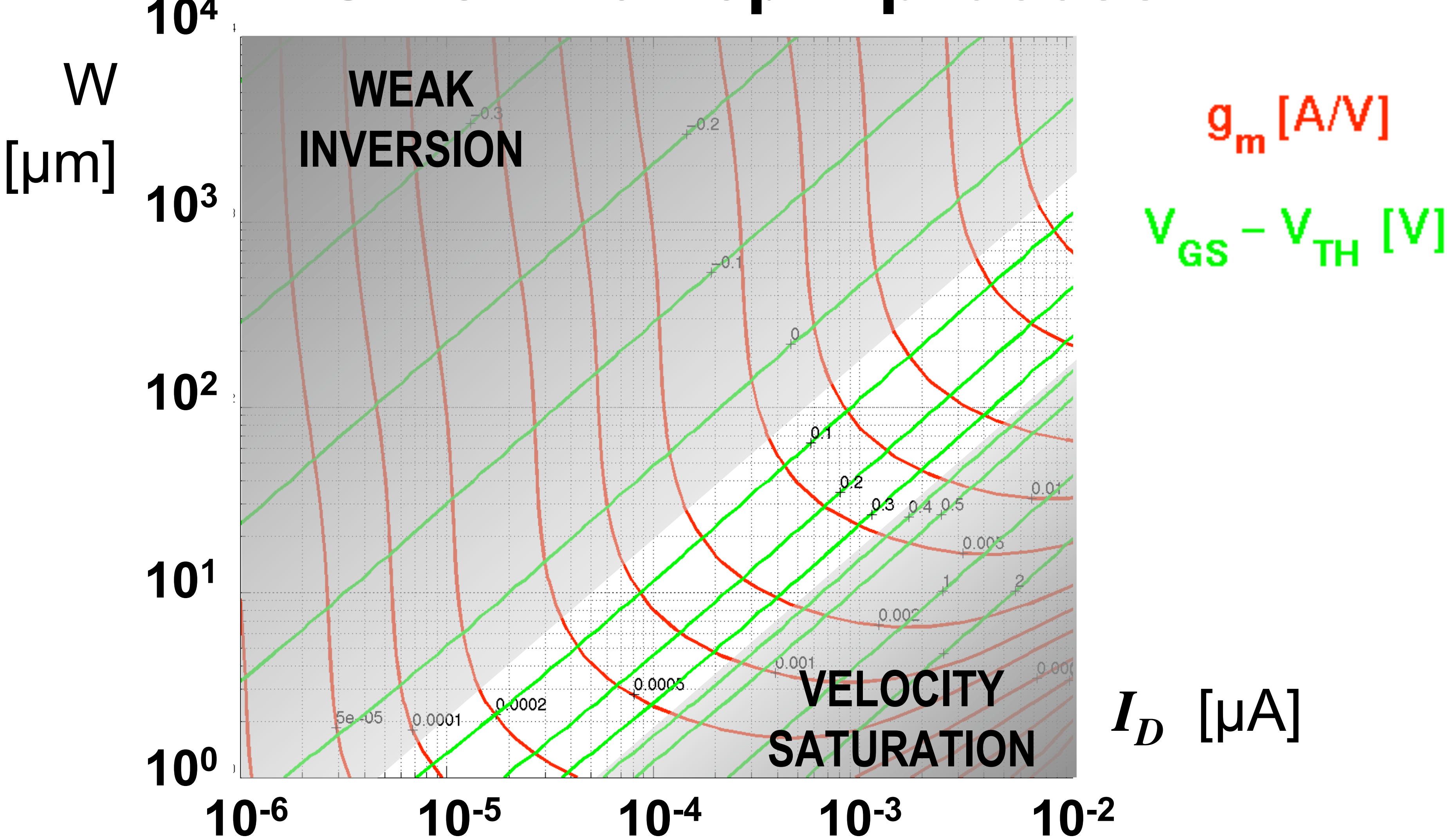


Fig.1: Curves of constant g_m in the I-W/L plane

- Large strong inversion region
  - "Square law", easy hand analysis

Op 't Eynde and Sansen, "Design and Optimization of CMOS Wideband Amplifiers," CICC 1989

TSMC L=0.25μm process



- ~~Square law~~
- **Graphical / numerical analysis**

MOSFET Noise

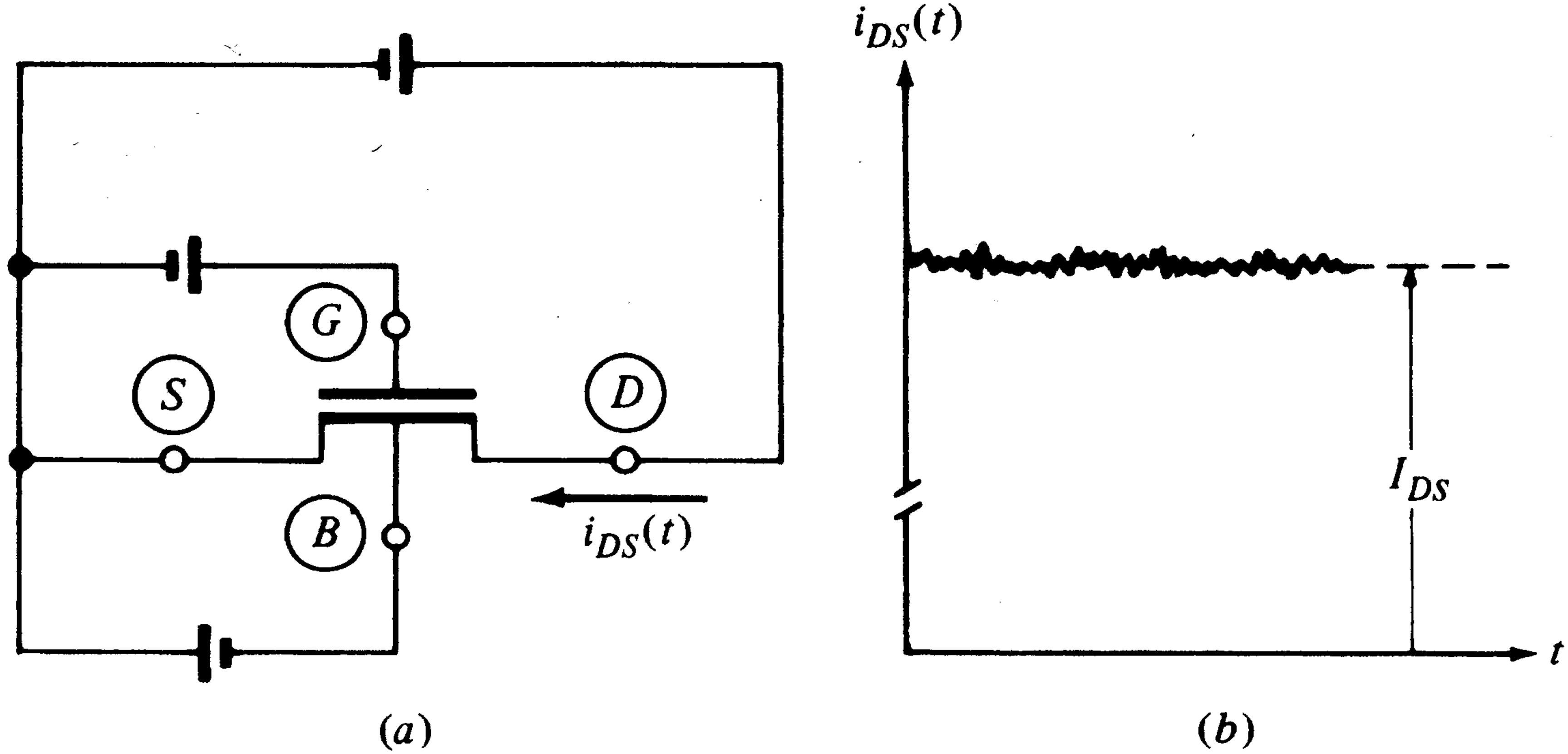
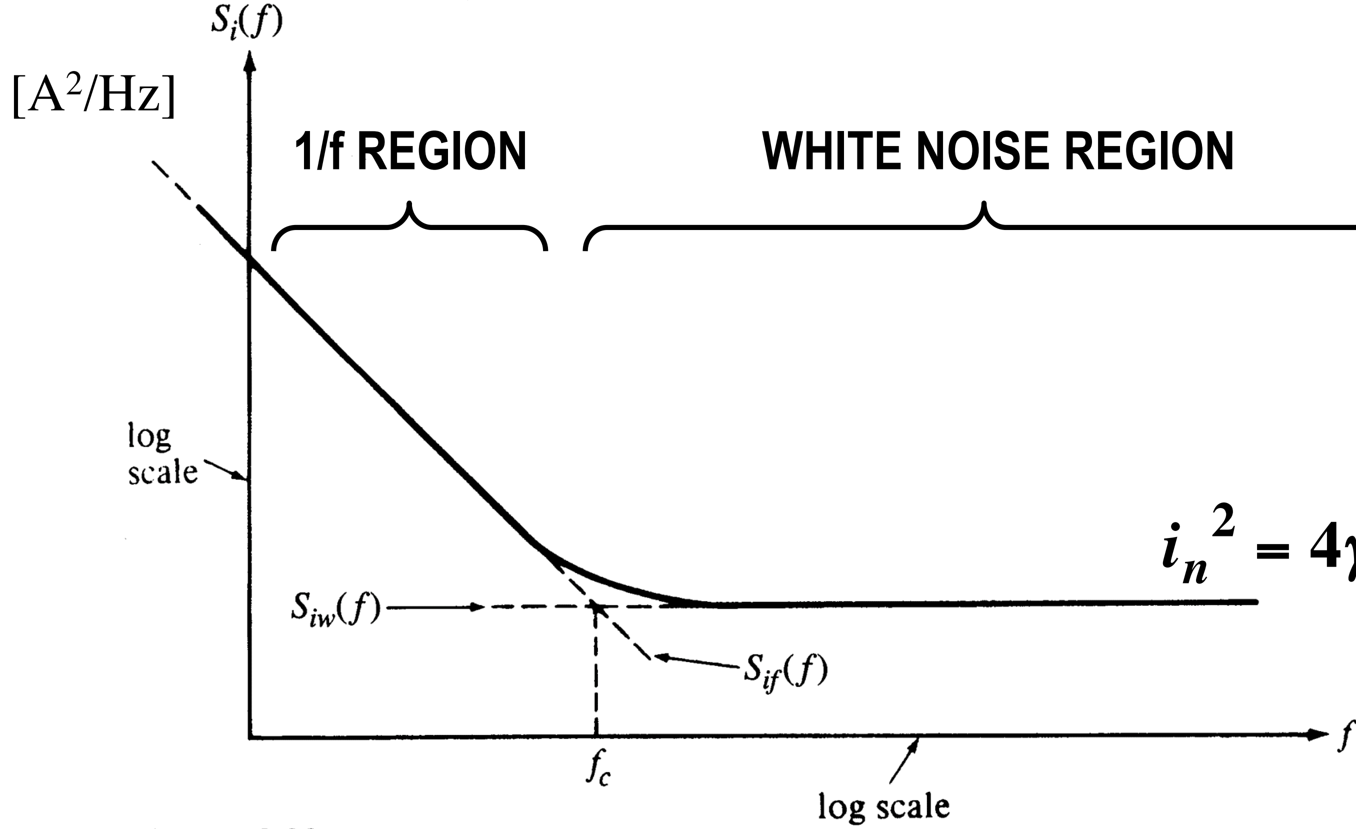


FIGURE 8.31
(*a*) A MOS transistor biased with fixed noiseless terminal voltages;
(*b*) the drain-to-source current for the connection in (*a*), including noise.

Y. Tsividis, "Operation and Modeling of the MOS Transistor" New York: Oxford University Press, 2008.

MOSFET Noise p.s.d.



$$\overline{i_n^2} = 4\gamma kTg_m = \frac{8}{3}kTg_m$$

FIGURE 8.33
A typical plot of the drain-noise current power-spectral density versus frequency in log-log axes. Subscript *i* refer to total noise, *iw* to white noise, and *if* to flicker noise.

- **Saturation, strong inversion operation**
- **Where does factor γ=2/3 come from?**

Y. Tsividis, "Operation and Modeling of the MOS Transistor" New York: Oxford University Press, 2008.

Submicron CMOS: Noise behavior

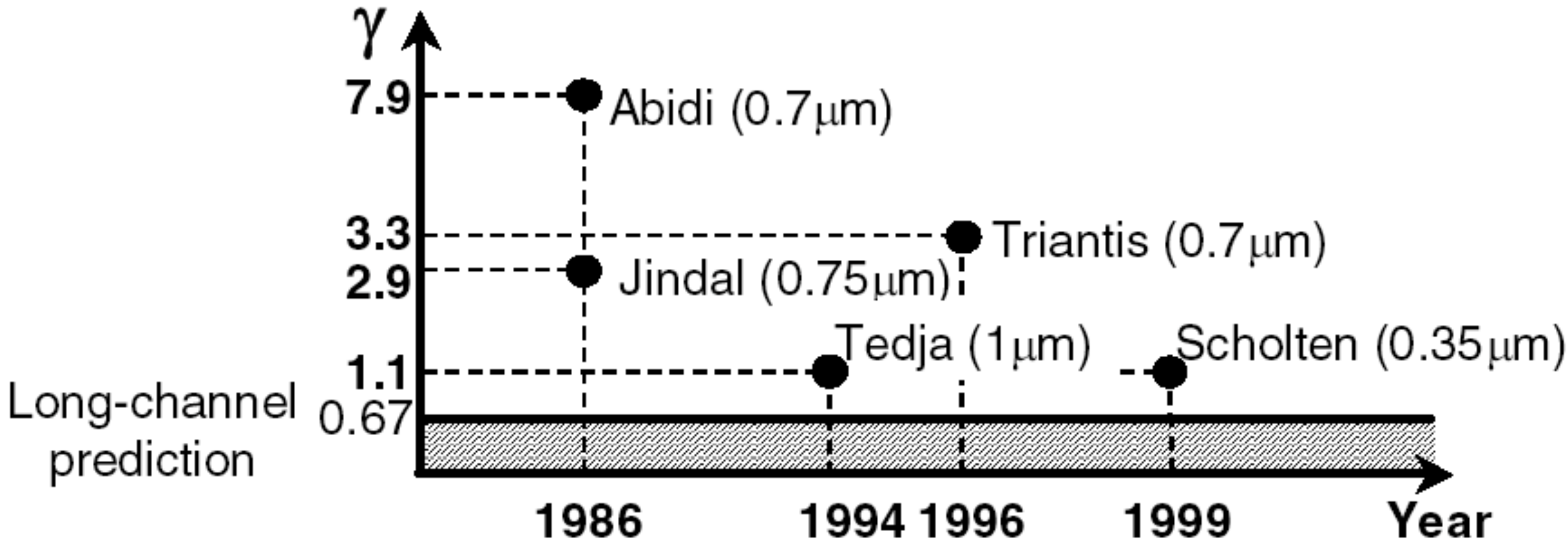


Fig. 1. Some reported values of Gamma noise factor in various technologies.

⇒ **Gamma factor γ > 2/3 ?!?**
Disagreement with long channel model?

Question assumptions

Navid, Lee, and Dutton," A Circuit-Based Noise Parameter Extraction Technique for MOSFETs," *ISCAS 2007*, pp. 3347-3350

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- DSM CMOS Effects on Analog Design
- **Fundamental Noise Sources**
  - **Shot Noise**
  - **Thermal Noise**
- Applications
- Conclusion

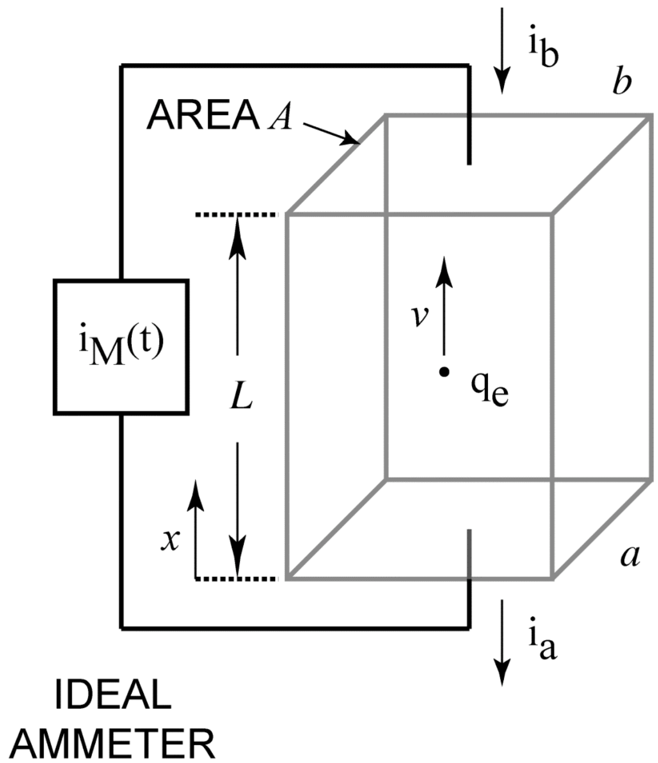
Shot Noise

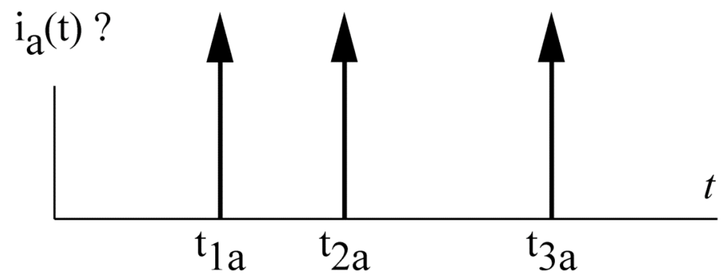
- Current noise density for DC current I_{DC}

$$i_n^2 = 2q_e I_{DC}$$

- Where does this come from?
- Key assumption:
  - Electron arrivals independent events

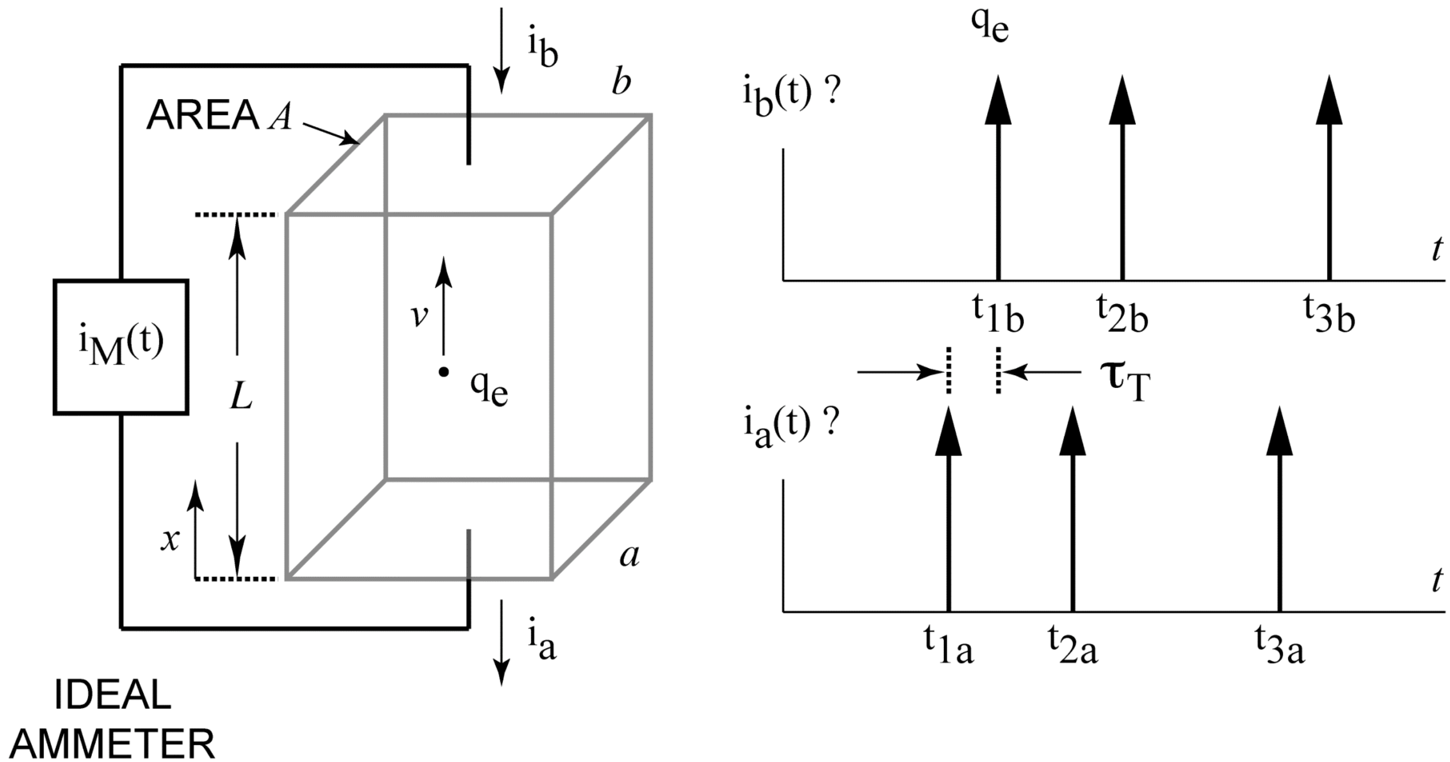
Shot Noise





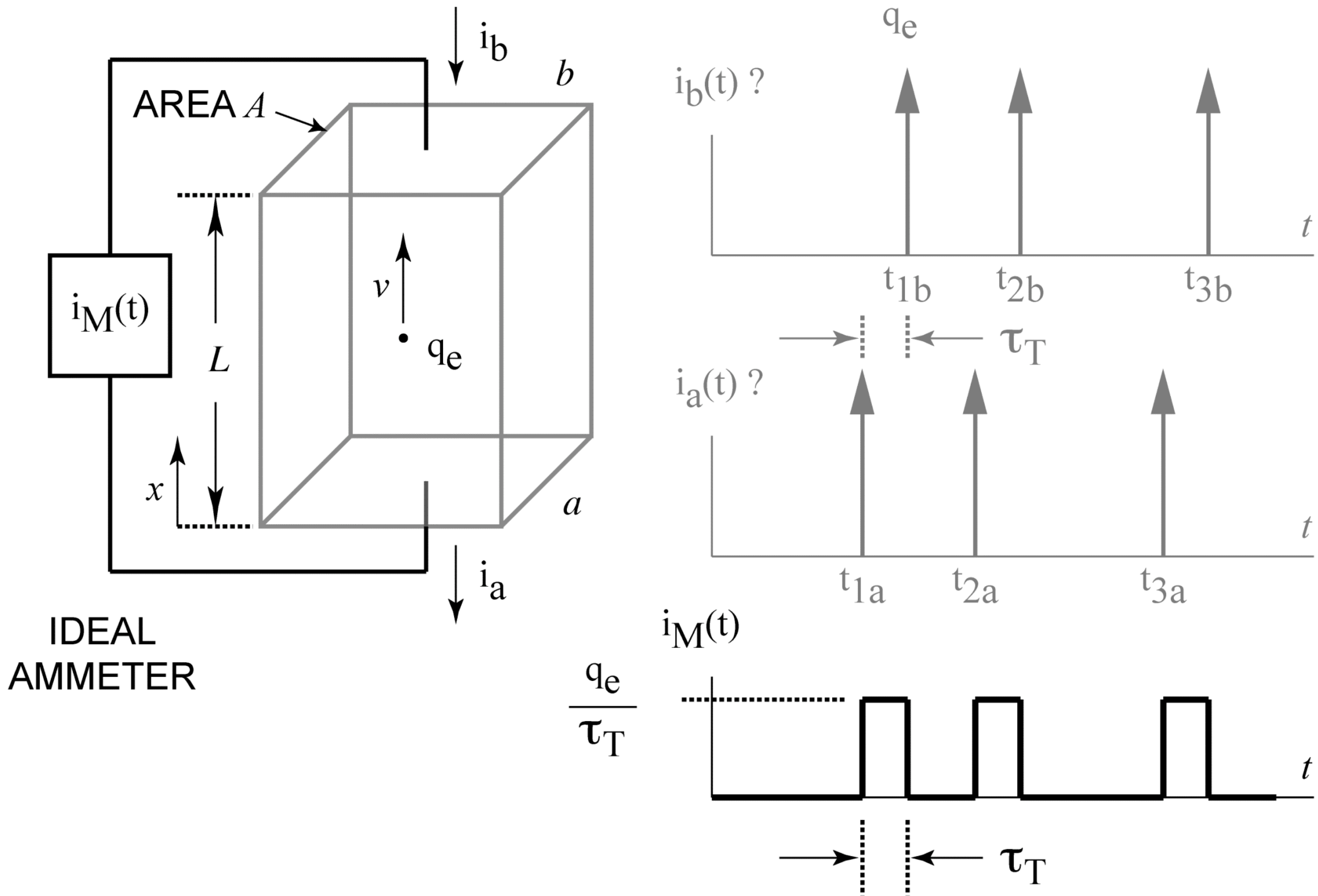
- **What is current measured by ammeter?**

Shot Noise



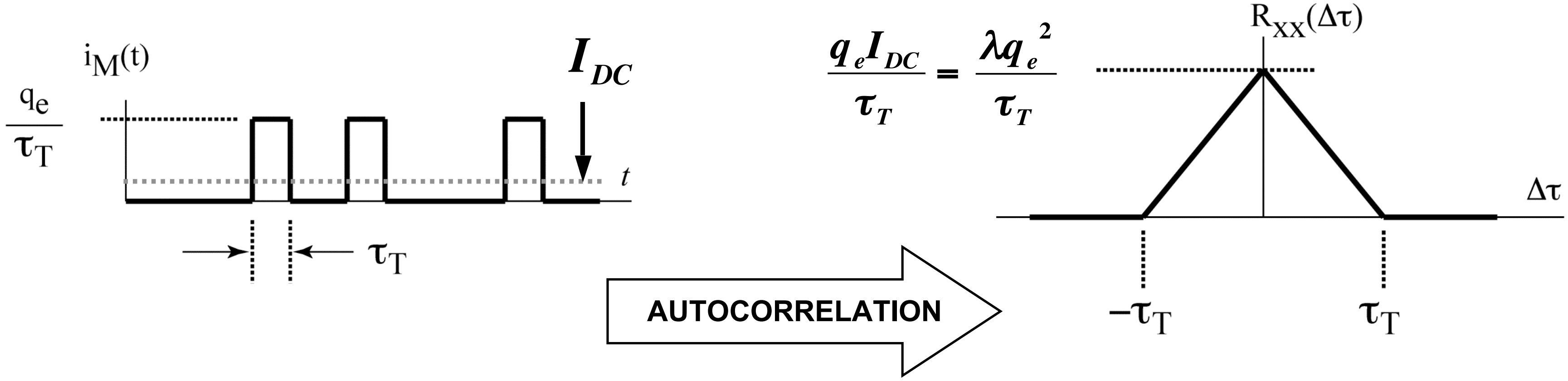
- **What is current measured by ammeter?**

Ramo-Shockley Theorem



- **Current measured by ammeter:**
  - **–Randomly arriving pulses with area q_e**

Poisson Process

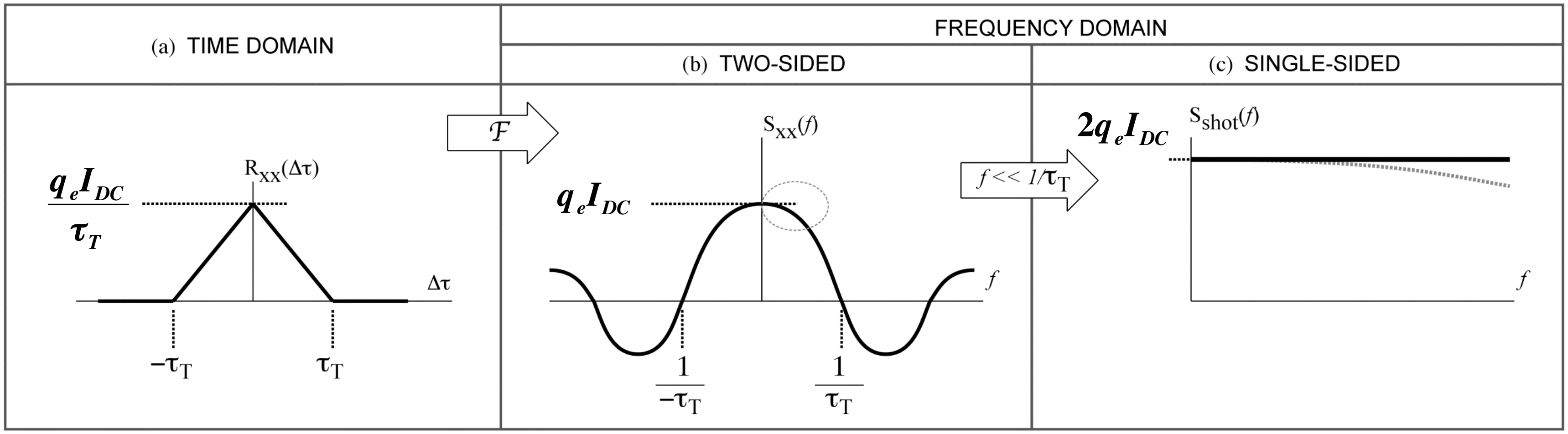


- **Average arrival rate** λ [sec^{-1}]
- **Average DC current:**

$$I_{DC} = \lambda q_e$$

- **Autocorrelation: time domain description of random process**

Shot Noise Power Spectral Density



- **Wiener-Khinchine theorem**
  - **Autocorrelation → frequency domain p.s.d**
- **Frequency domain**
  - **For frequencies < $1/\tau_T$**

$$i_n^2 = 2q_e I_{DC}$$

Shot Noise Power Spectral Density

- Key Points:
  - Discrete nature of charge is essential
  - Carrier transits are independent events
  - Carriers do not interact with each other or with any medium
  - Temperature not a factor

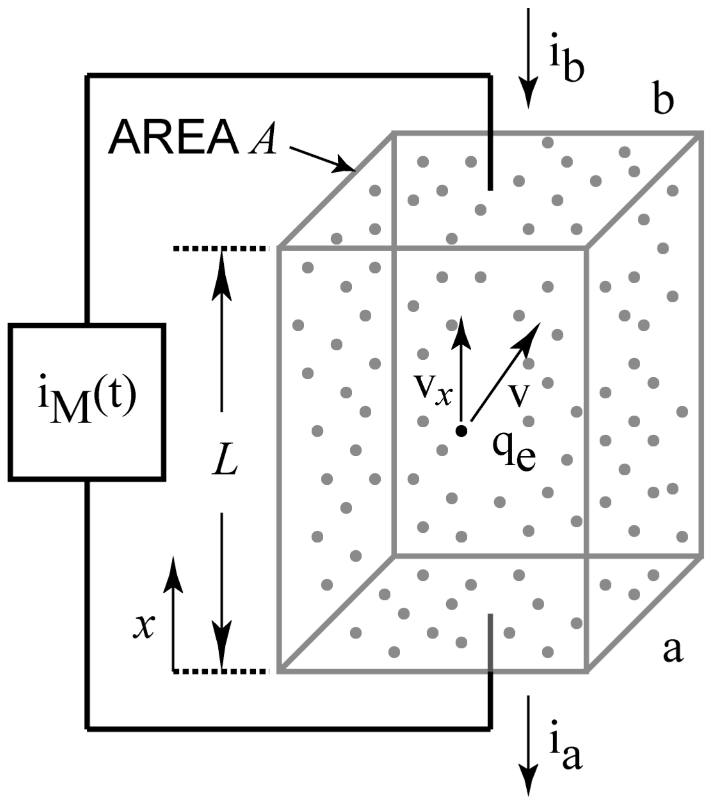
Thermal Noise

- Current noise density for resistor

$$i_n^{\,2} = \frac{4kT}{R}$$

- Where does this come from?
- Assumption:
  - Carriers in thermal equilibrium

Thermal Noise in Resistor



- **Assumption:**
  - **Carriers in thermal equilibrium**
- **Random velocity vectors** v
- **Only** v_x **component contributes to current**

Boltzmann's Constant k

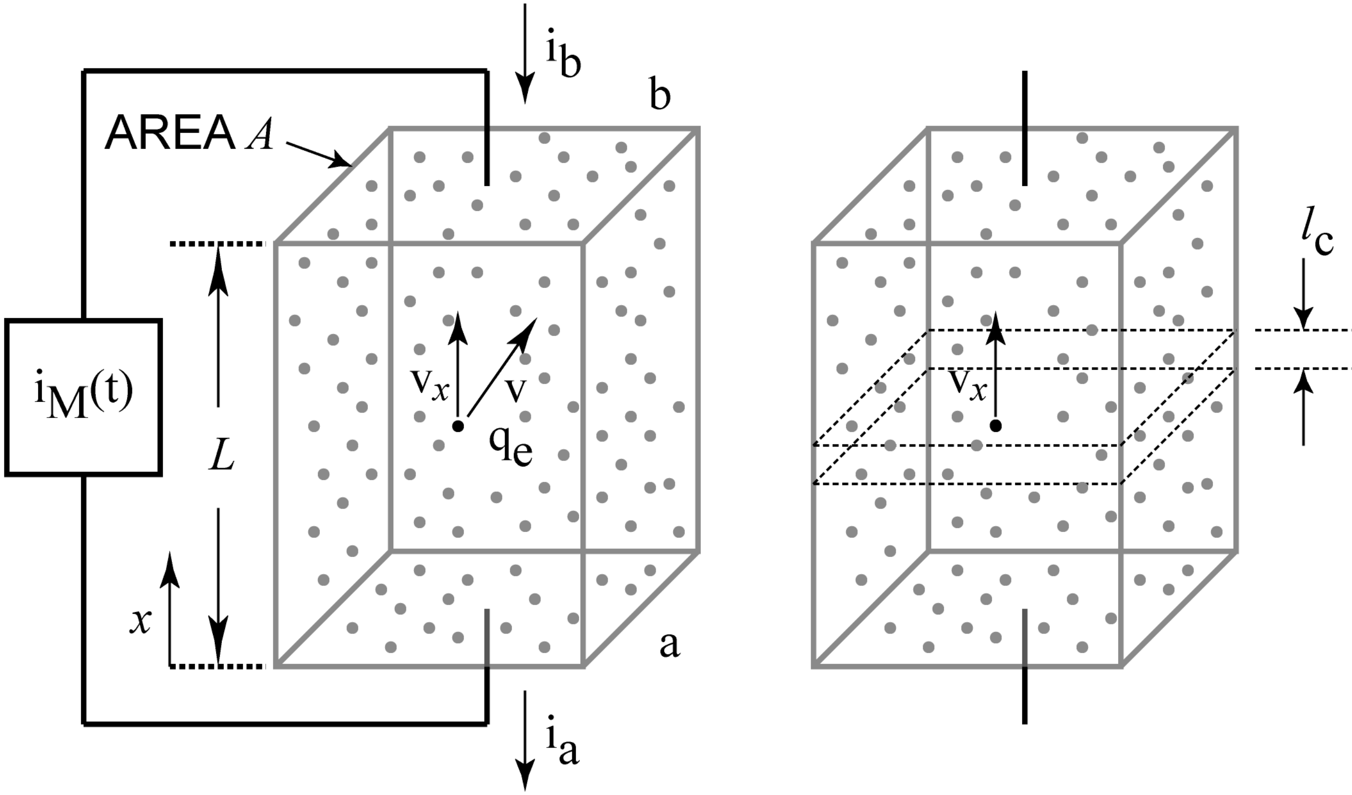
- k = 1.38 E-23 J/K Meaning?
- Thermodynamics: Equipartition theorem
  - Independent energy storage modes in a system at equilibrium have average energy of kT/2
  - Equivalent statements:

"Temperature in this room is 293K"

"Average kinetic energy (in each of x, y, z directions) for each air molecule in this room is 2.02E-21 joule"

$$\frac{kT}{2} = \frac{\left(1.38E-23\left[J/K\right]\right)\left(293\left[K\right]\right)}{2} = 2.02E-21\left[J\right]$$

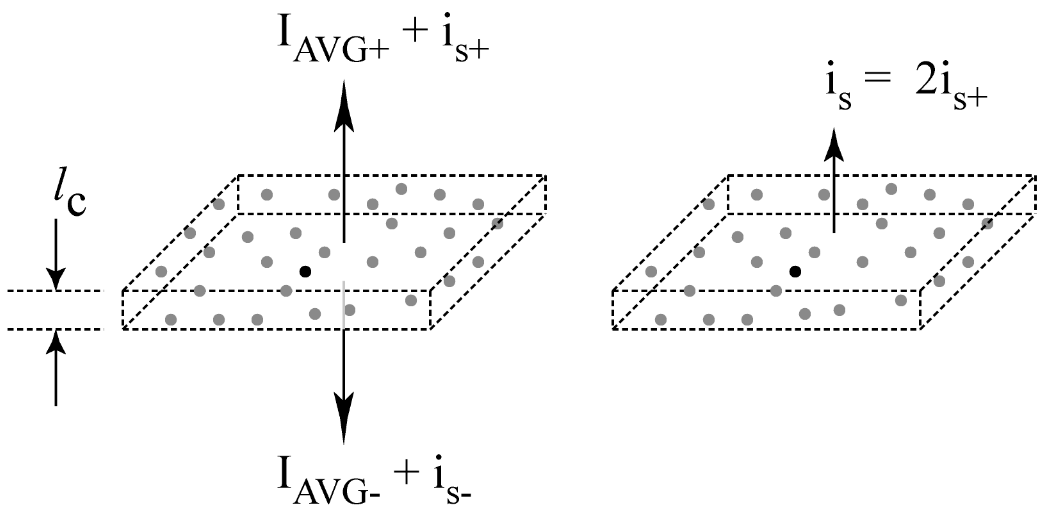
Thermal Noise



- **Approximate collision statistics:**

Mean free path	l_c	**0.1 µm**
Mean free time	τ_c	**1 ps**
Velocity (rms)	v_x	**0.1 µm/ps**

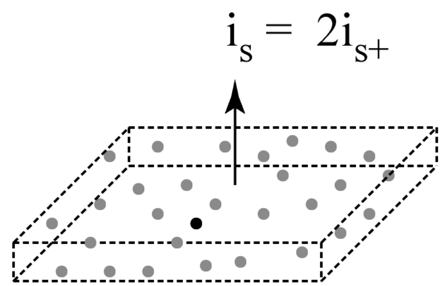
Thermal Noise

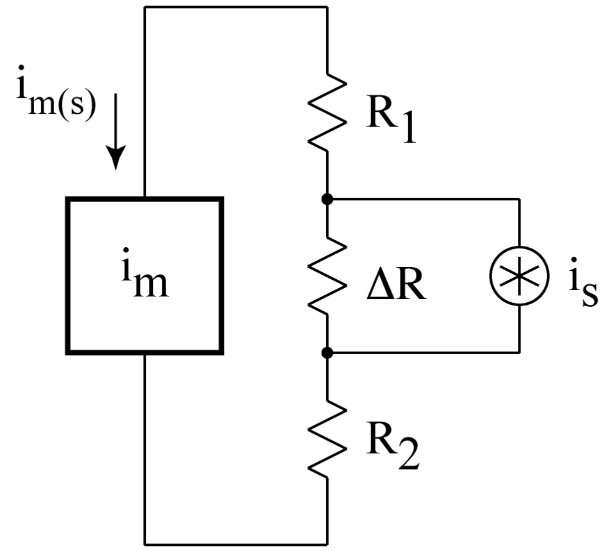


- **Consider "slice" equal to mean free path l_c**
- **During one mean free time τ_c**
  - **On average, half of carriers exit each way:** $I_{AVG+} = I_{AVG-}$
- **Shot noise components $i_{s+} = -i_{s-}$ correlated**
  - **Noise current from "slice" $i_s = 2i_{s+}$**

Sarpeshkar, Delbruck, and Mead, "White noise in MOS transistors and resistors," *IEEE Circuits & Devices Magazine*, Nov. 1993

Thermal Noise



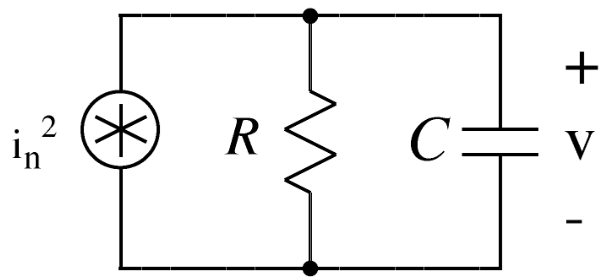


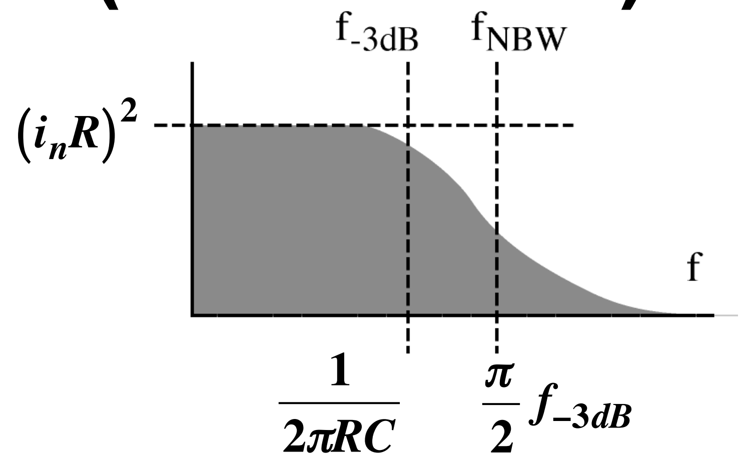
- **Sum (independent) contributions from slices**
- **Noise current seen by external ammeter $i_{m(s)}$ reduced by current divider factor: ΔR of slice, total resistance $R = R_1 + \Delta R + R_2$**
- **Relating to R using mobility definition gives**

$$\overline{i_n^2} = \frac{4kT}{R}$$

Sarpeshkar, Delbruck, and Mead, "White noise in MOS transistors and resistors," *IEEE Circuits & Devices Magazine*, Nov. 1993

Thermal Noise (Alternative)





- **Equipartition, rms energy in capacitor:**

$$\frac{1}{2} C v^2 = \frac{kT}{2} \quad \Rightarrow \quad v^2 = \frac{kT}{C}$$

- **Integrate noise p.s.d. over noise bandwidth:**

$$v^2 = (i_n R)^2 \left(\frac{\pi}{2} \frac{1}{2\pi RC} \right) \quad \Rightarrow \quad v^2 = i_n^{\ 2} \frac{1}{4RC}$$

- **Equate:**

$$\frac{kT}{C} = i_n^{\ 2} \frac{1}{4RC} \quad \Rightarrow \quad \boxed{i_n^{\ 2} = \frac{4kT}{R}}$$

Thermal Noise Power Spectral Density

- **Key Points:**
  - **Discrete nature of charge is not essential**
    - **Can also be derived from equipartition only (e.g. kT/C noise)**
  - **Carrier scattering: interact with medium, thermal equilibrium**
  - **Carrier transits are not independent due to interaction with medium**
  - **Temperature is important to determine carrier average kinetic energy / velocity**

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  - Oscillator Jitter
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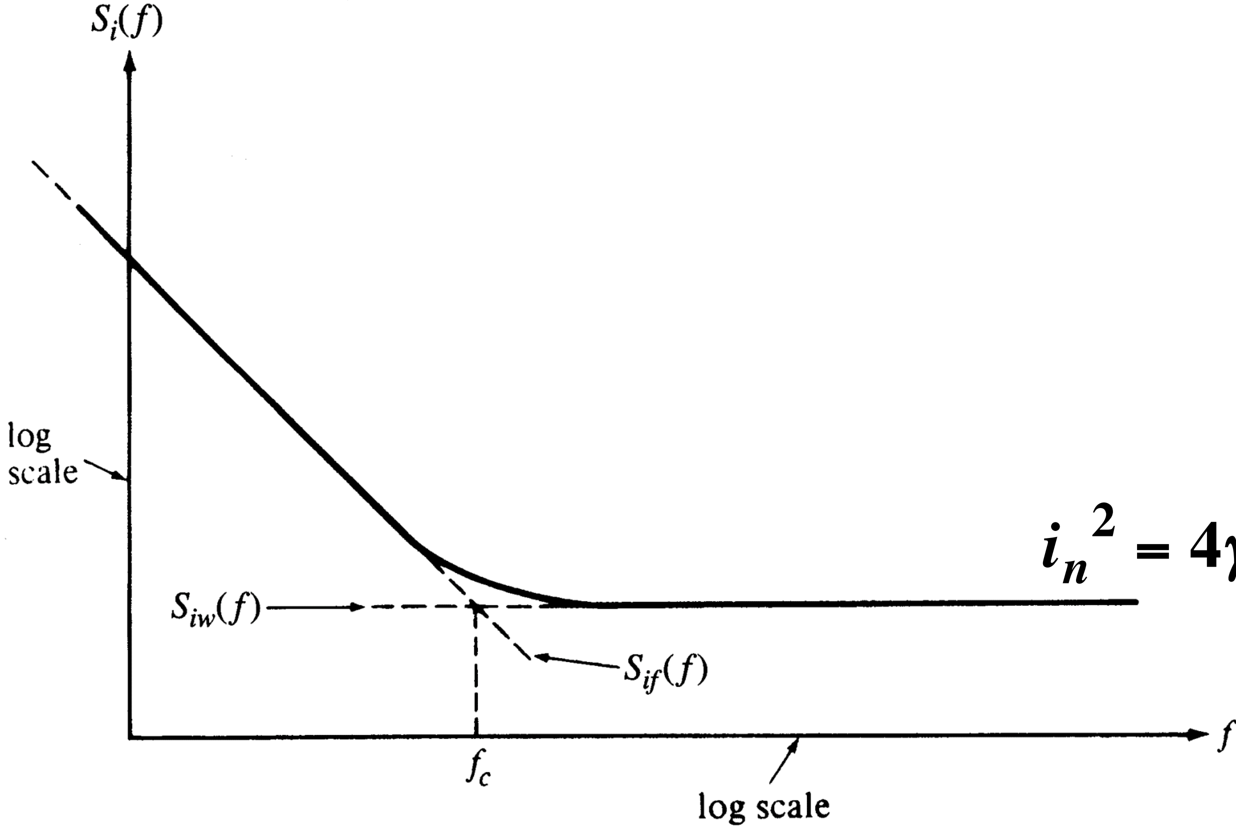
MOSFET Channel Noise Density



$$\overline{i_n^2} = 4\gamma kTg_m = \frac{8}{3}kTg_m$$

- Where does this come from?
- Assumption:
  - –Resistive channel segments

Y. Tsividis, "Operation and Modeling of the MOS Transistor" New York: Oxford University Press, 2008.

MOSFET Noise Analysis

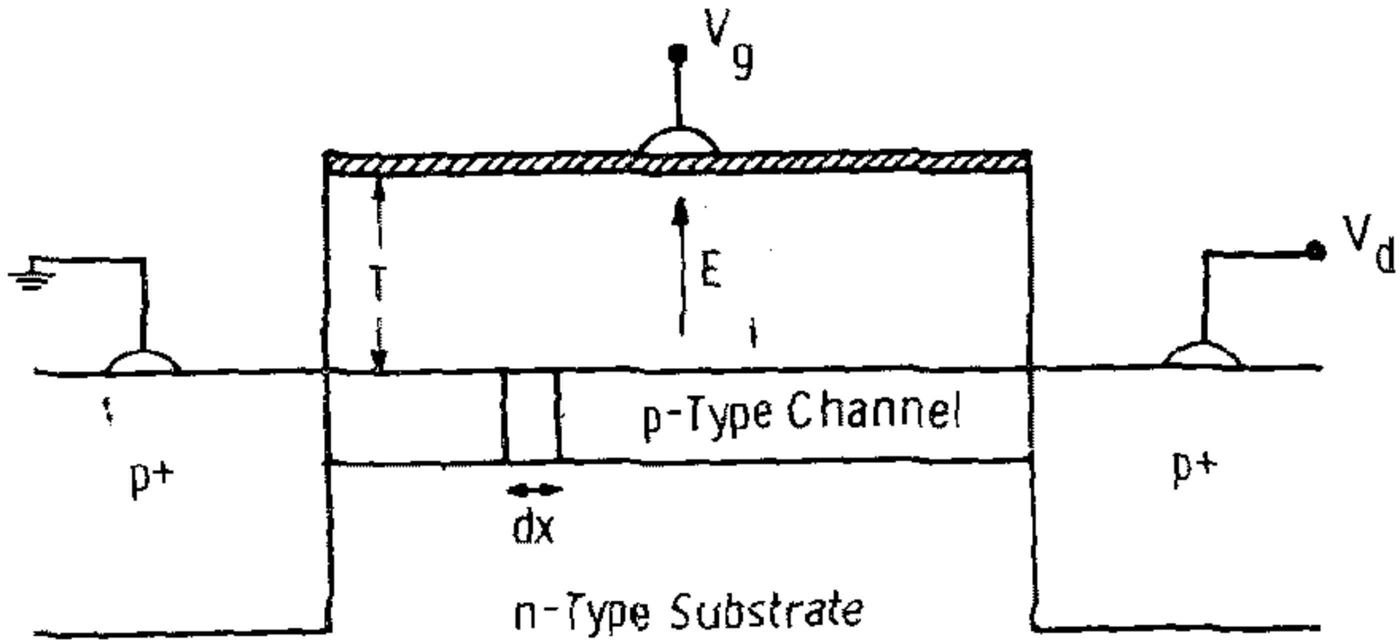


Fig. 6. Schematic representation of MOS transistor.

- Model: Thermal noise dv for differential segment dx of MOSFET channel
- Integrate over channel length L
- Gamma factor γ = 2/3 falls out of integral

A. Jordan and N. Jordan, "Theory of noise in MOS devices," *IEEE Trans. Electron Devices*, March, 1965

MOSFET Noise Analysis

- **Key assumption:**
  - **Carrier behavior in channel determined by mobility (resistive) behavior**

Ask "what if" questions

- **What if it's not a resistor?**

Velocity Saturation

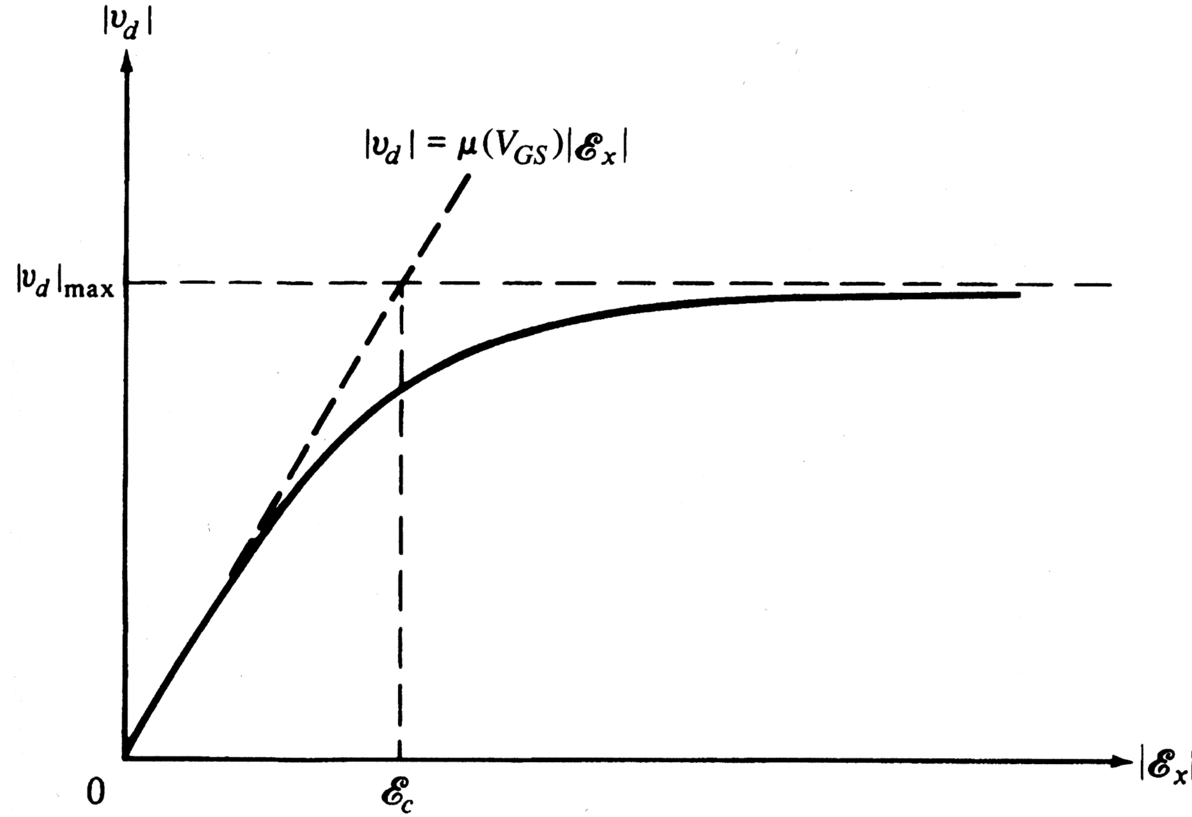
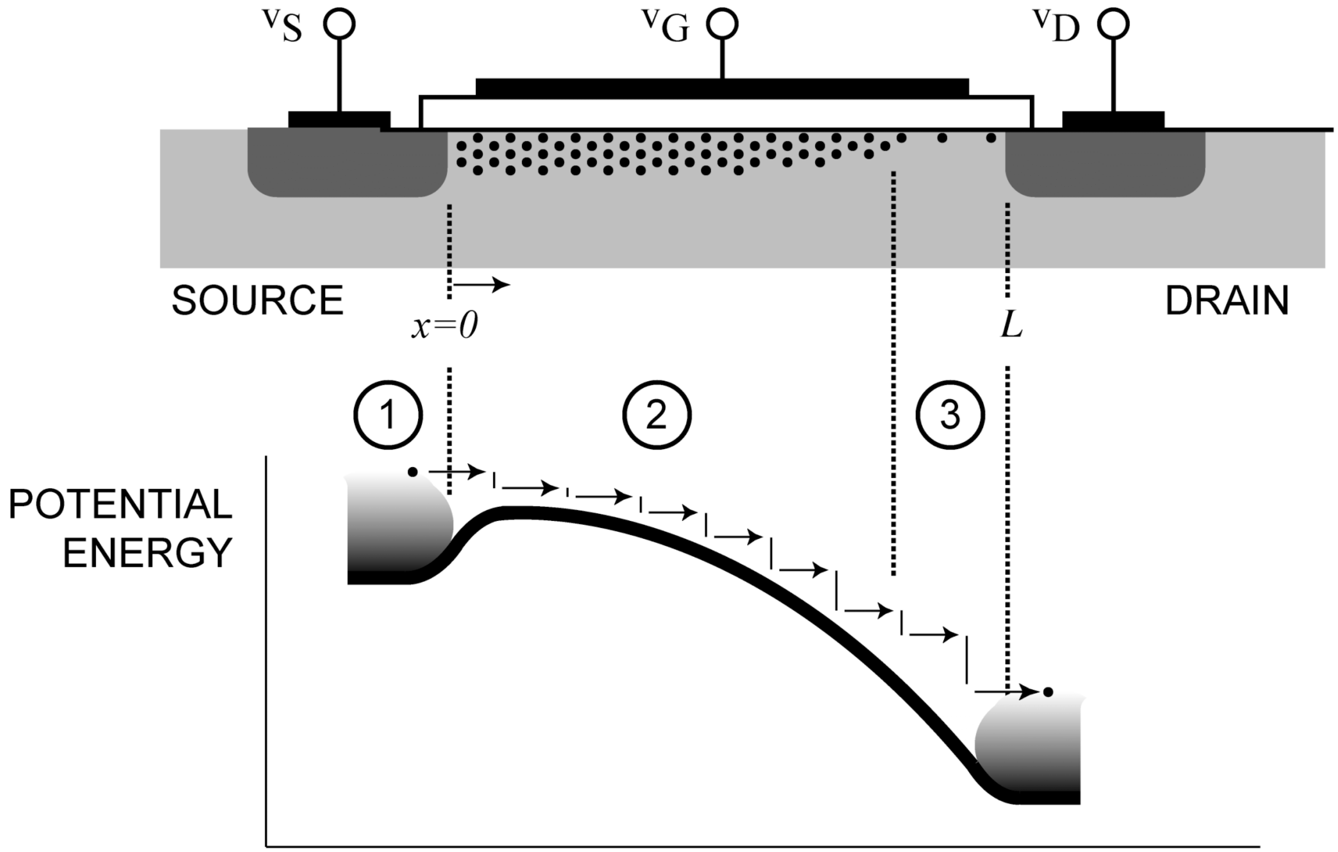


FIGURE 6.22
Magnitude of carrier velocity in the inversion layer vs. magnitude of longitudinal component of electric field, $|\mathscr{E}_x|$. $\mu(V_{GS})$ is the low $|\mathscr{E}_x|$ field surface mobility at a given V_{GS} (see Sec. 4.10).

- **Deviation from mobility model at high field**
  - **"High field" ⇔ Small dimensions**

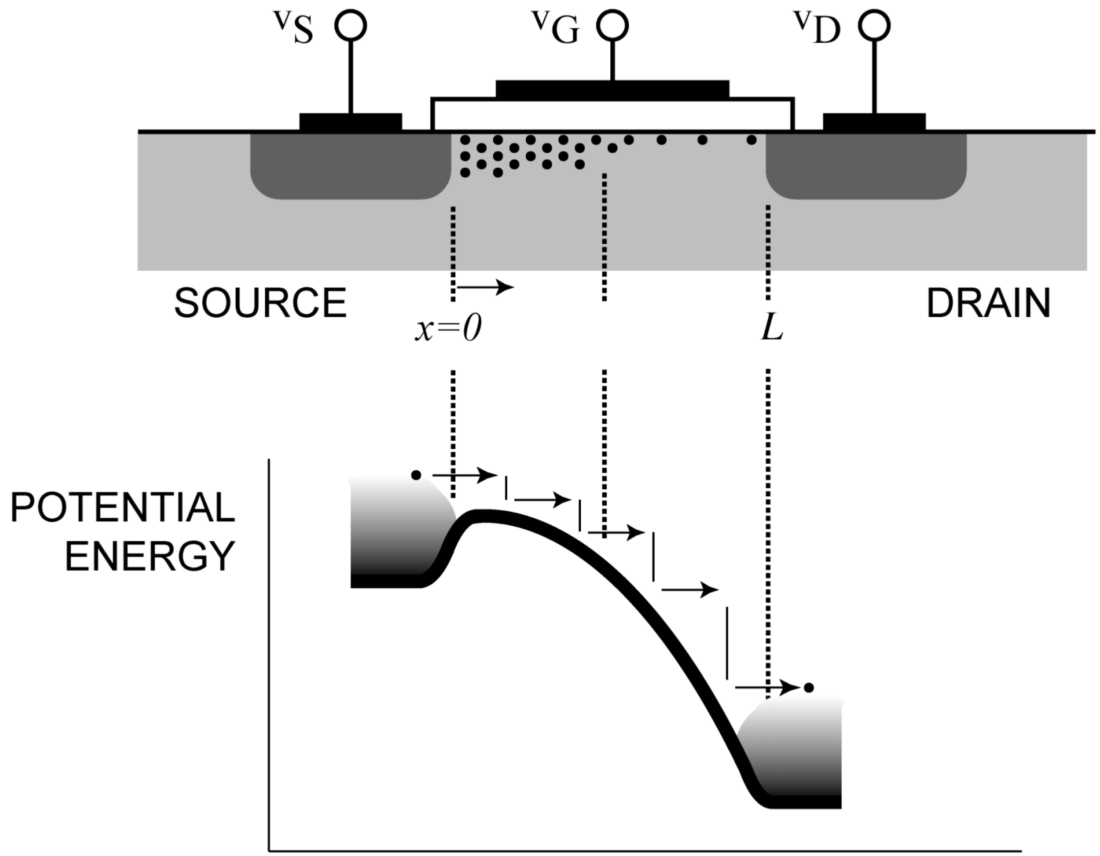
Y. Tsividis, "Operation and Modeling of the MOS Transistor" New York: Oxford University Press, 2008.

MOSFET Potential Energy (L ~ μm)



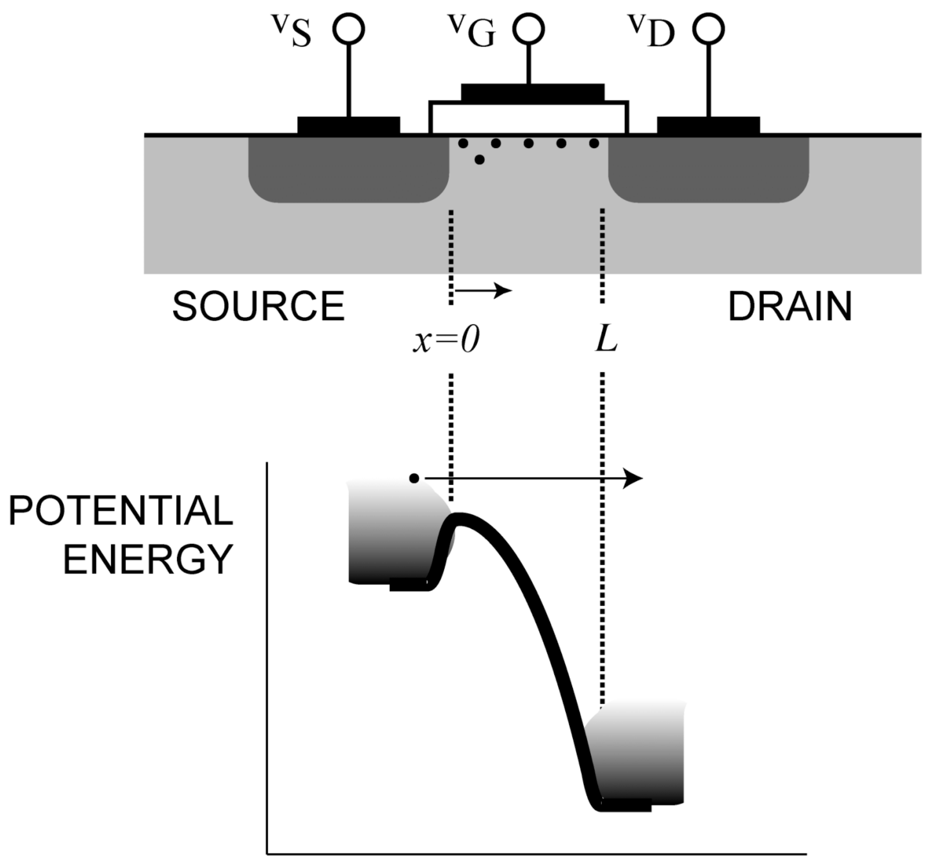
1. **Carrier injection into channel**
2. **Low field motion modeled by mobility**
3. **Velocity saturated region**

MOSFET Potential Energy (L < µm)



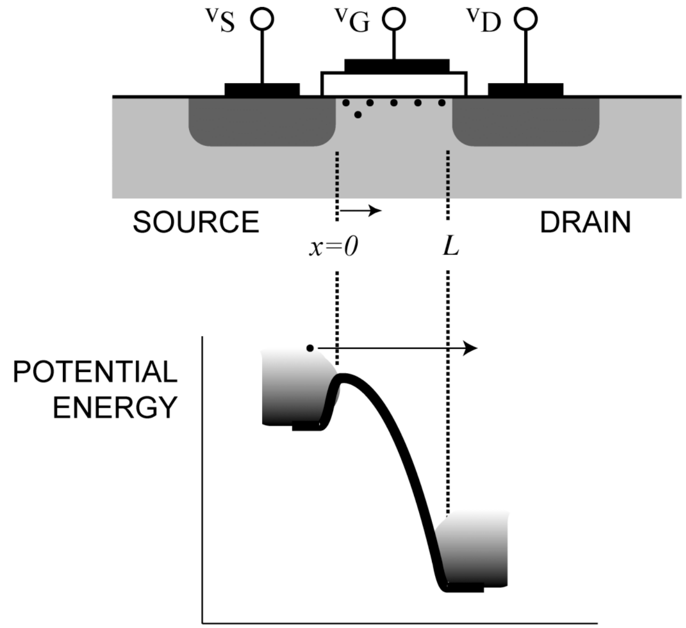
- **Velocity saturated region is a greater fraction of channel**
- **Carriers still interact due to collisions**

MOSFET Potential Energy (L << µm)



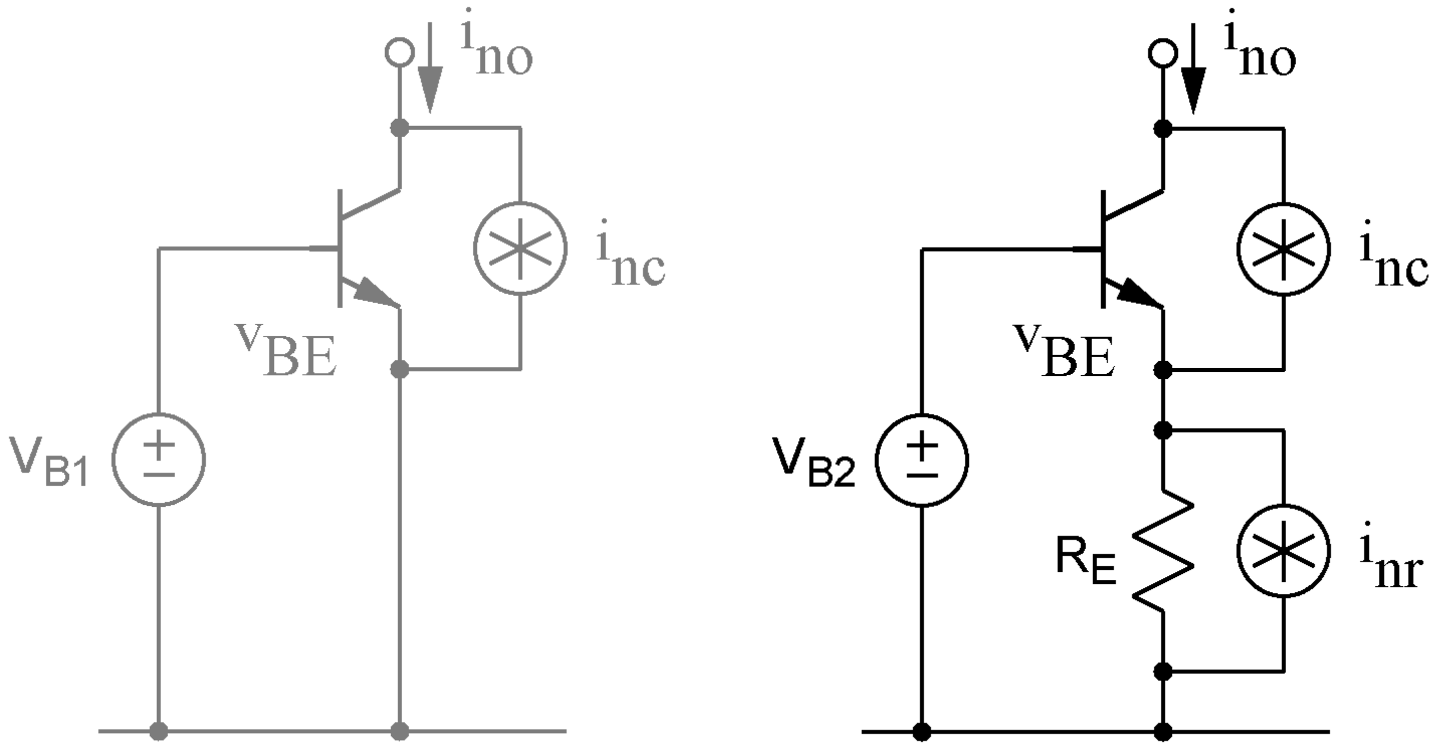
- Channel length L ~ mean free path l_c
- "Ballistic": no interaction due to collisions
- No thermal equilibrium

L < l_c "Breaking the Rules"



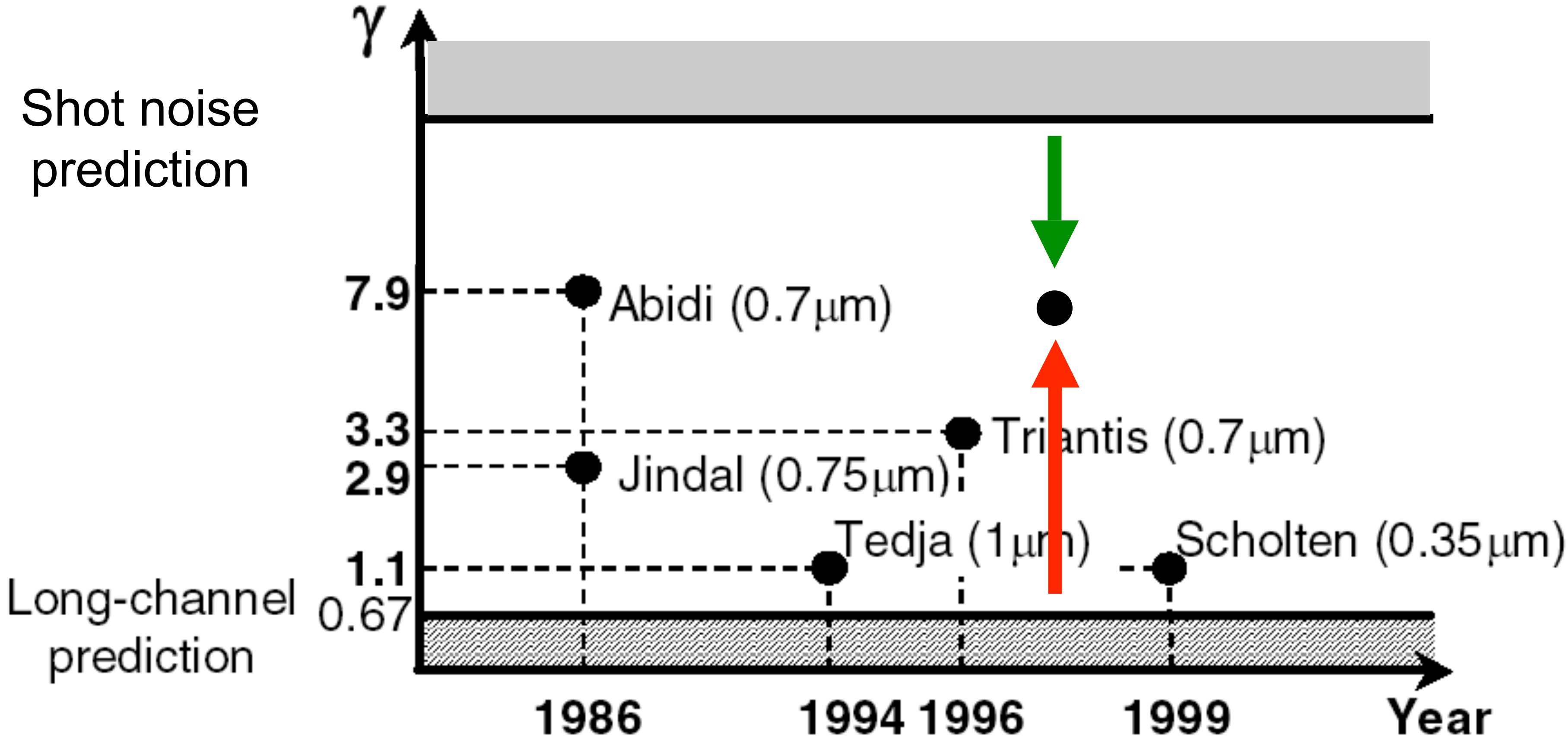
- **L < mean free path l_c**
- **No thermal equilibrium**
- **No reason to expect any validity for a thermal noise / resistance model that assumed mobility and thermal equilibrium**
- **Behavior dominated by statistics of carrier injection at source**
  - **Shot noise! But not full shot noise:**
  - **Presence of injected carrier modifies potential profile; changes probability of injection**

Analogy: Bipolar Transistor



- **Output current noise i_{no} for isolated bipolar transistor is full shot noise i_{nc} of collector current**
- **With degeneration resistor: Not full shot noise:**
- **Voltage drop across R_E modifies v_{BE} ; feedback reduces variation in i_{no} due to i_{nc}**

Submicron CMOS: Noise behavior



⇒ **Don't interpret as γ increase**

⇒ **Interpret as shot noise suppression**

Navid, Lee, and Dutton," A Circuit-Based Noise Parameter Extraction Technique for MOSFETs," ISCAS 2007, pp. 3347-3350

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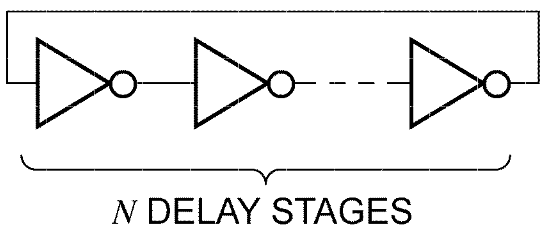
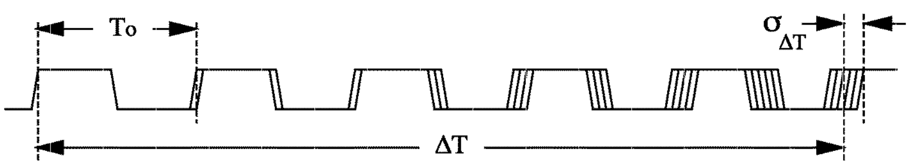
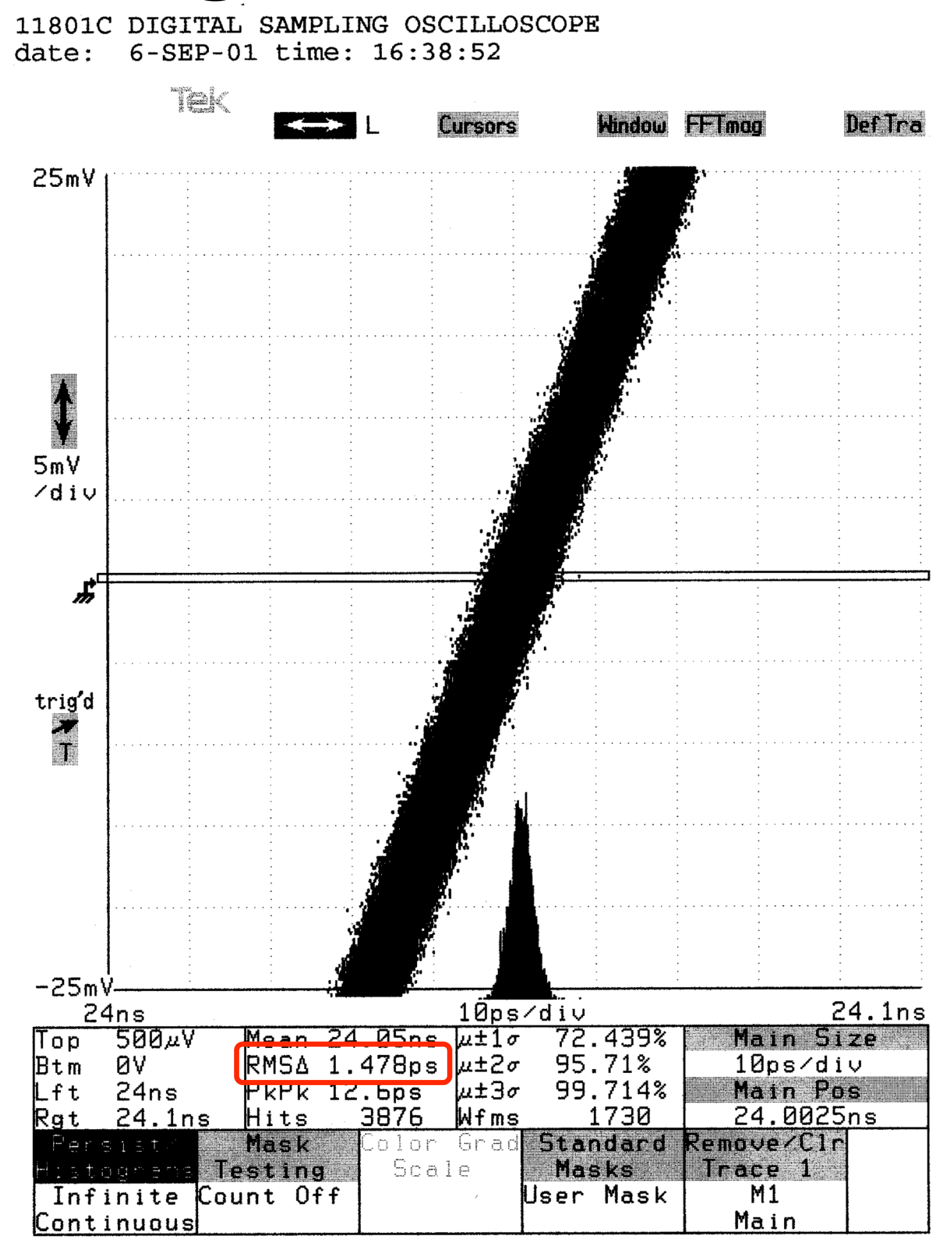
Jitter Example: Ring Oscillator

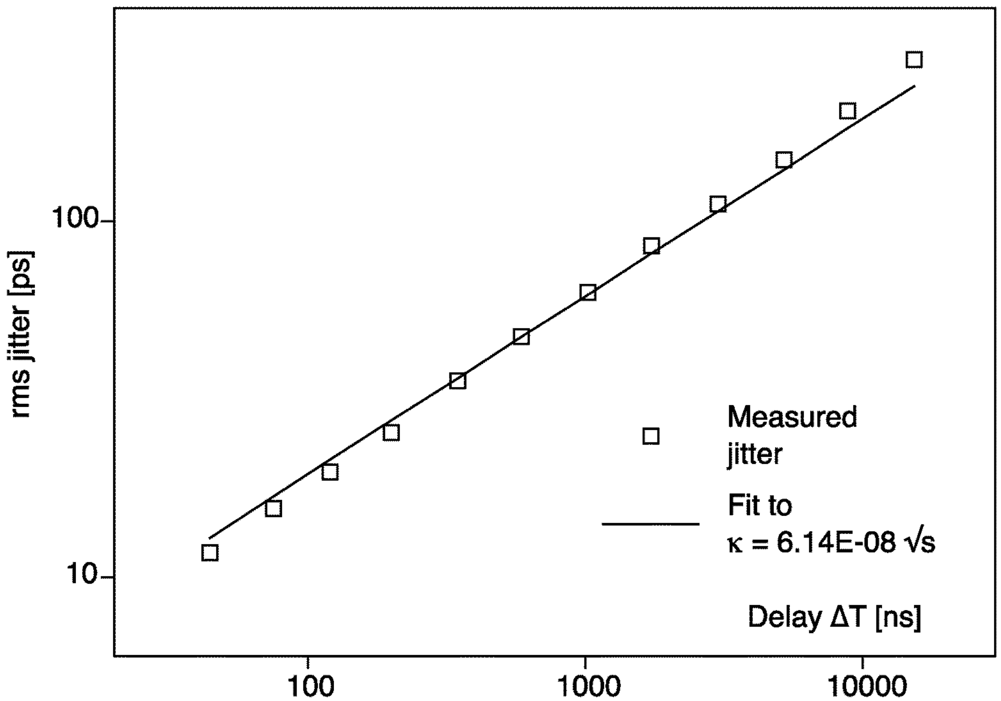


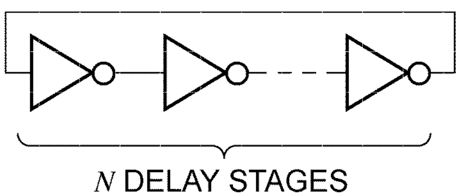


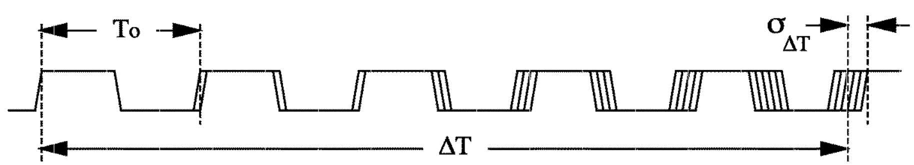


- **Time-domain noise (jitter) on clock transitions**
- **Characterized by standard deviation σ (ps rms)**

Jitter Example: Ring Oscillator



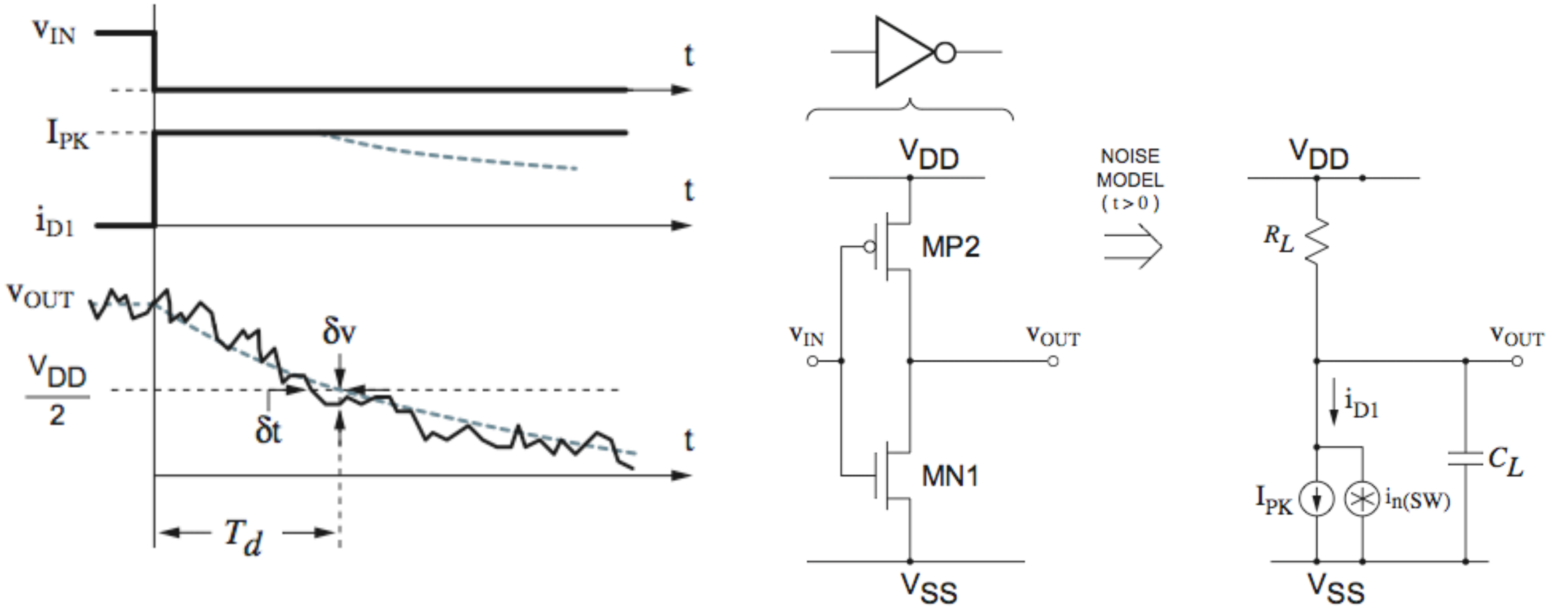




- **Plot jitter vs. time interval ΔT**
- **Increases as square root: jitter $\sigma = \kappa\sqrt{\Delta T}$ delay**
- **κ frequency-independent figure-of-merit**

McNeill and Ricketts, "The Designer's Guide to Jitter in Ring Oscillators," Springer, 2009

Jitter at the Gate Delay Level



- **MOSFET noise adds uncertainty to gate delay T_d**
- **Statistics of MOSFET noise can be related to oscillator figure-of-merit κ**

McNeill and Ricketts, "The Designer's Guide to Jitter in Ring Oscillators," Springer, 2009

How to Improve Jitter?

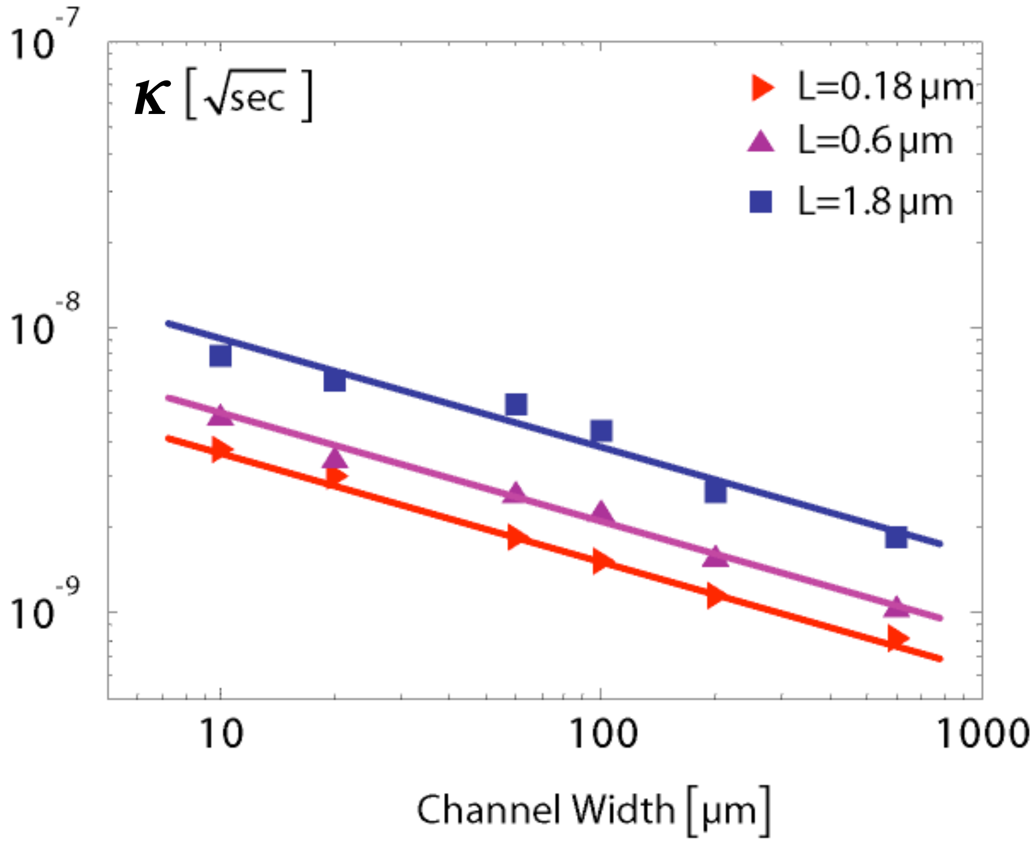
- **Burn more power**
- **Oscillator figure-of-merit κ of form**

$$\kappa \propto \sqrt{\frac{kT}{POWER}}$$

- **Derived from thermal noise model**
- **Intuitively, as oscillator power increases, random thermal energy is a smaller fraction of waveform**

McNeill and Ricketts, "The Designer's Guide to Jitter in Ring Oscillators," Springer, 2009

Oscillator Jitter κ vs. W



- **Scales as predicted** $\kappa \propto \sqrt{W}$

Chengxin Liu, "Jitter in Oscillators …," PhD Dissertation, WPI, 2006

How to Improve Jitter?

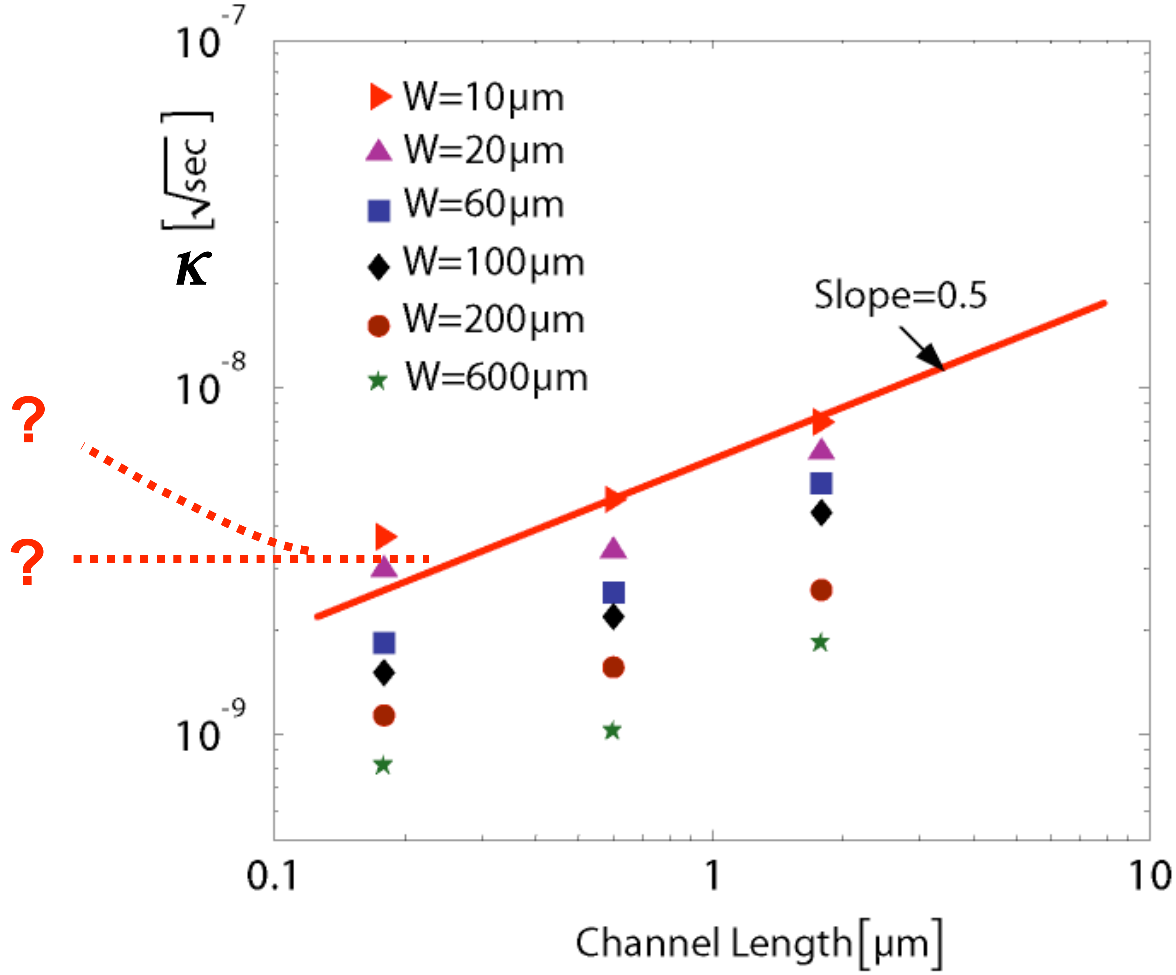
- **Burn more power**
- **Oscillator figure-of-merit κ of form**

$$\kappa \propto \sqrt{\frac{kT}{POWER}}$$

- **Derived from thermal noise model**
- **How does this behave as L shrinks?**

McNeill and Ricketts, "The Designer's Guide to Jitter in Ring Oscillators," Springer, 2009

Oscillator Jitter κ vs. L



- **Deviation from predicted $\kappa \propto \sqrt{1/L}$ for L < 1µm**
- **Inflection or minimum?**

Chengxin Liu, "Jitter in Oscillators …," PhD Dissertation, WPI, 2006

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- Creativity in Analog / Mixed Signal IC Design
- DSM CMOS Effects on Analog Design
- Fundamental Noise Sources
- Applications
- **Conclusion**

Learn from every outcome

DSM CMOS Conclusions

- Survey the landscape
  - Noise behavior changes for short L
- Question assumptions
  - Mobility model
- Ask "what if" questions
  - What if it's not a resistor?
- Learn from every outcome
  - Jitter example: Scaling may not provide benefits for analog as one might expect from long channel model

Design Drivers in DSM CMOS

Explorer

Artist

Judge

Warrior

Environment: Decreasing ability to predict analog performance from simple assumptions / models

Add ^Digital Complexity

⇩

Eliminate ^Analog Complexity

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