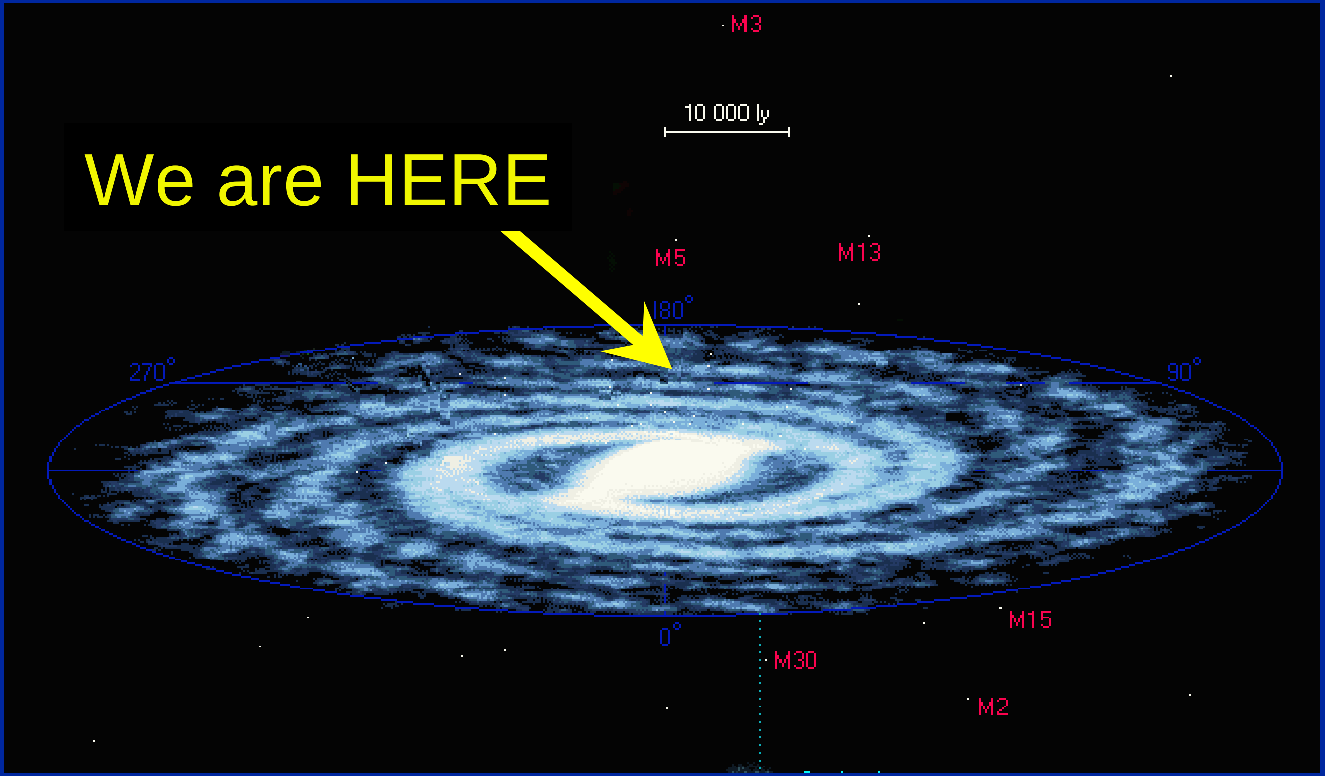
RF/analog integration with 90nm digital CMOS

Kelin J. Kuhn
Communications Technology Manager
45nm Device Group Leader
Portland Technology Development
Intel Corporation

OVERVIEW

- Context
  - What do people want to buy?
- Elements
  - What pieces do we need?
- Integration
  - How do we fit the pieces together?
- Summary

Putting things in context:



We are HERE

英特爾新增兩款Centrino成員

CNET新聞專區：John G. Spooner 27/01/2003

隨著三月C

英特爾將發
餐的一部份
接近英特爾

根據消息人
包括一款超
Pentium-
起跳，以及
Pentium-
跳。這幾款
Centrino
後，將可滿
品線的筆記

像標準的
樣，新款
處理器會
及無線模
牌作銷售

الاسم التجاري لتكنولوجيا "سنترينو" CENTRINO للأجهزة المحمولة >

نشر في الاثنين, يناير 13, 2003

إنتل تعلن عن الاسم التجاري لتكنولوجيا "سنترينو" Centrino للأجهزة المحمولة

بقلم Hassan Abdul Rahmann

ذكرت مصادر شركة إنتل اليوم أن تكنولوجيا
زة المحمولة تعد بمثابة
قنيتها المقبلة التي
مبيوتر اللاسلكية
ي الجديد أهمية أفضل
زة الكمبيوتر الدفترية
قة جديدة للأجهزة
ة، إلى جانب سمات
ان فترة أطول لحمل
تشكيلية التي تكفل سماكة
جداً للأجهزة المحمولة.
التجاري لتكنولوجيا

ニュース/トピックス

インテル、ノートパソコン向けテクノロジーの
ブランド"Centrino"を発表

2003年1月9日

インテル(株)は

Процессор Banias отныне будет называться Centrino

9 января 2003 года, 12:55; текст: Баир Гармаев

Intel дала официальное название новой технологии для нужд беспроводной связи и мобильных вычислений. Имя Centrino теперь будет обозначать новую архитектуру мобильных процессоров с пониженным энергопотреблением, меньшими размерами и улучшенной производительностью.

Технологии Centrino включают микропроцессор (ранее известный под кодовым именем Banias), соответствующие наборы микросхем и беспроводной протокол стандарта 802.11. Это первый случай, когда Intel выводит на рынок целый ряд продуктов под одним
первой половине 20

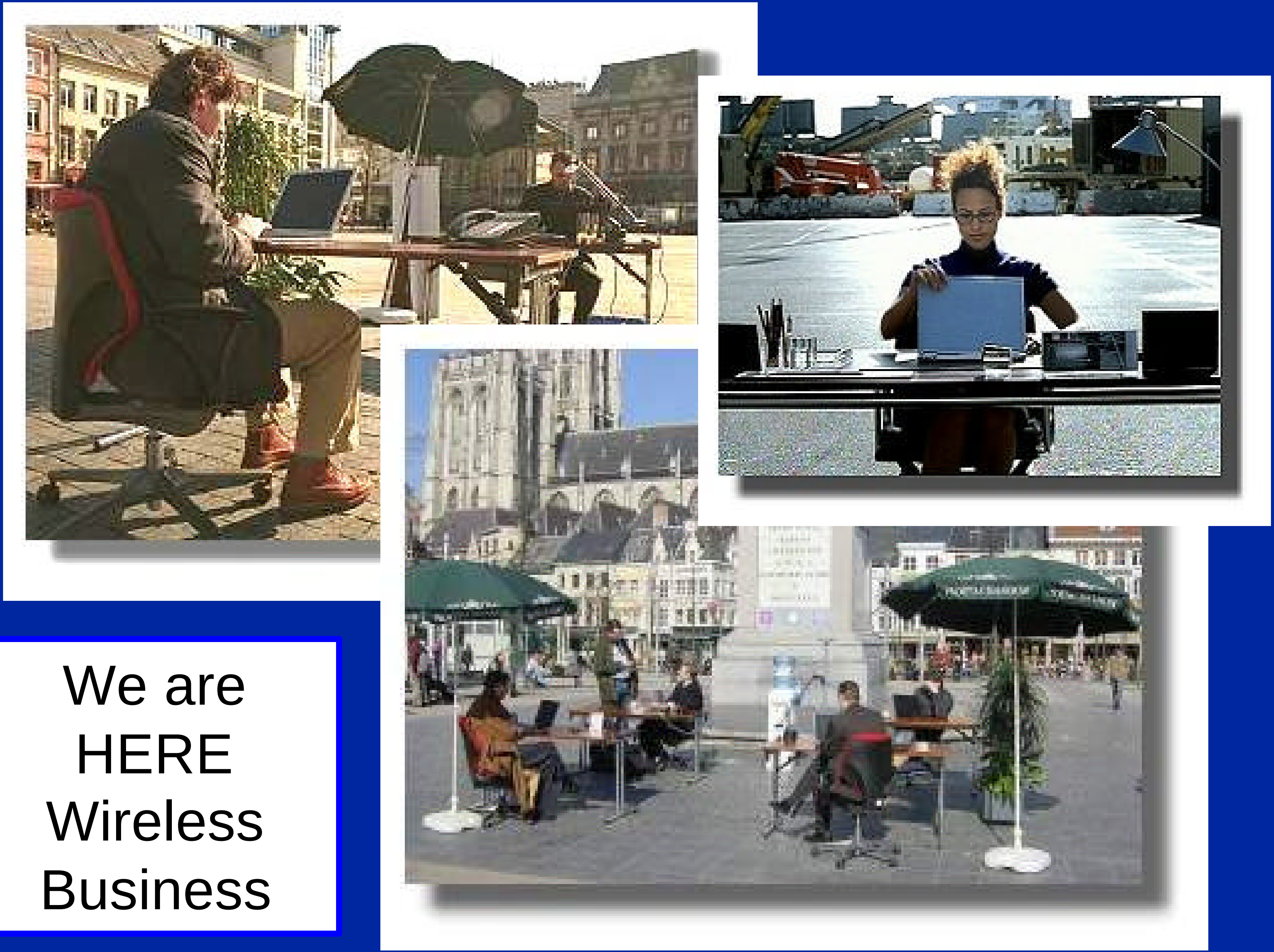
Thứ năm, 9/1/2003, 16:45 GMT+7

Intel công bố thương hiệu công nghệ di động Centrino

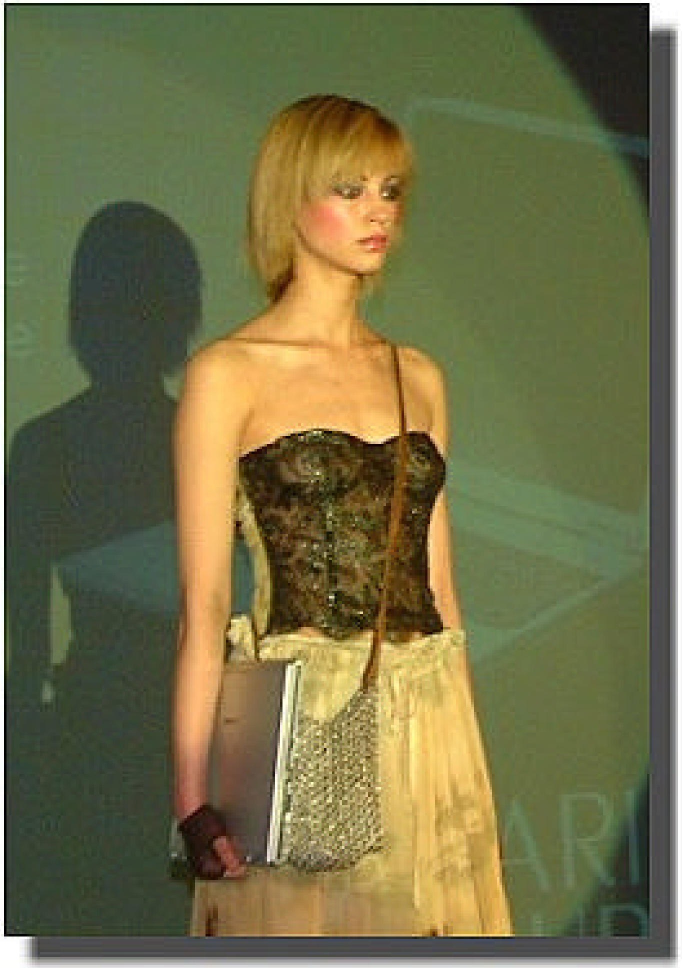
Hôm nay, nhà sản xuất chip hàng đầu thế giới thông báo chọn Centrino là thương hiệu mới cho công nghệ điện toán không dây thế hệ tiếp theo của hãng. Đây là lần đầu tiên Intel đặt tên chung cho một tổ hợp các sản phẩm.

Thương hiệu công nghệ di

We are HERE



We are
HERE
Wireless
Business



We are
HERE
Wireless
Life

The National Telecommunications and Information Administration (NTIA) Frequency Assignment Chart

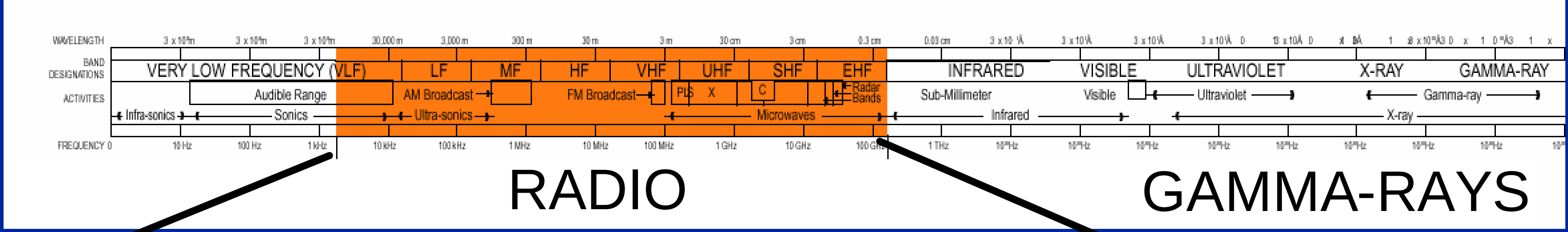
We are HERE

***W**ireless **E**thernet **C**ompatibility **A**lliance* (WECA) → WiFi
WiMAX, 75Mb/sec; 105 feet (802.11)→ 10miles (802.16)

The National Telecommunications and Information Administration (NTIA) Frequency Assignment Chart

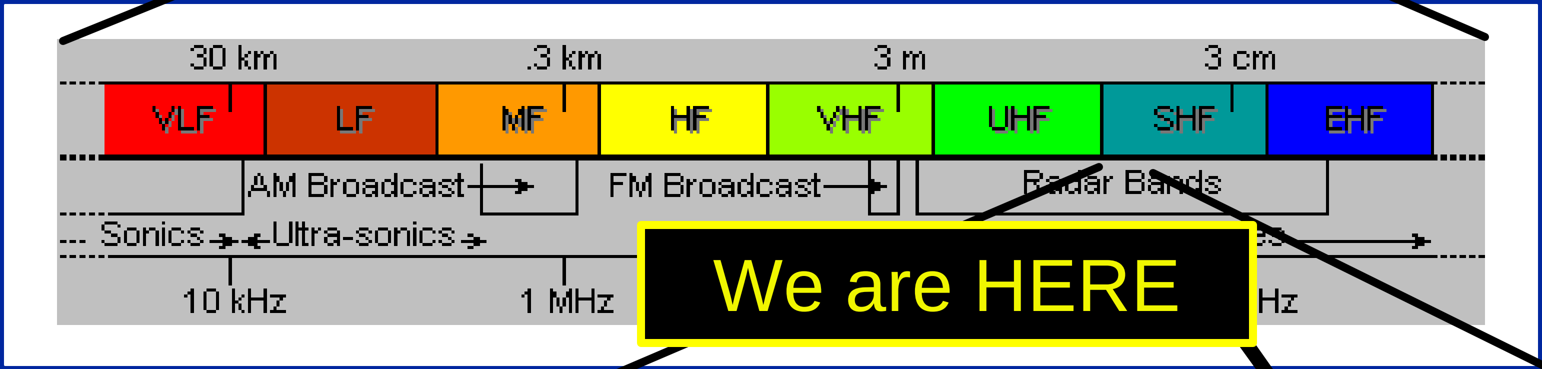
We are HERE

FCC 1985 (NCR, Apple, SBL), 1990 Vic Hayes (NCR), 1997 802.11b, 1999 Apple iBook, then Flickenger (SF) Townsend (NY); 2002 Intel Centrino



RADIO

GAMMA-RAYS



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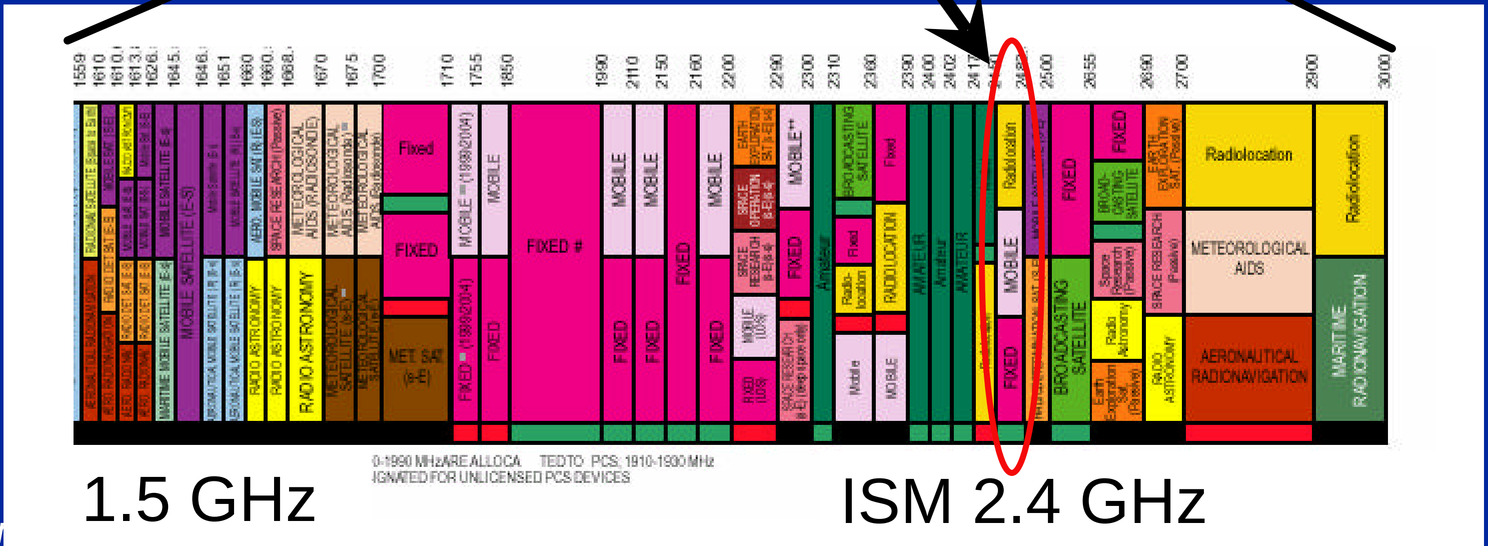
Caregroup, MA



1.5 GHz

ISM 2.4 GHz

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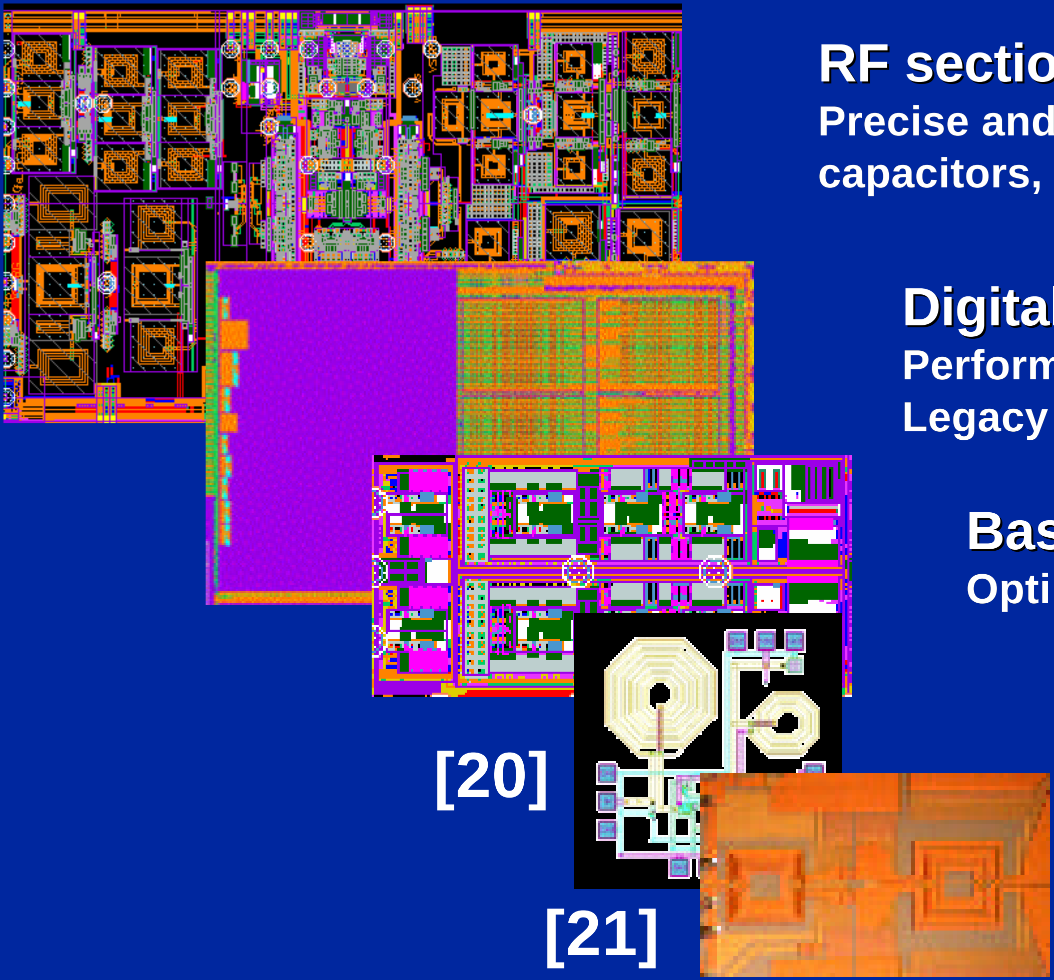
What are the critical blocks?



[20]

[21]

RF section requires:
Precise and matched inductors, capacitors, resistors and varactors

Digital section requires:
Performance and low power logic, Legacy voltage support

Baseband/analog requires:
Optimized small signal parameters

LNA section requires:
Low noise components, Noise/cross talk immunity

PA requires:
High Ft and BV

Nerds love WiFi design :-)

The problem of “feature creep”

Strategy for “feature creep”

KISS

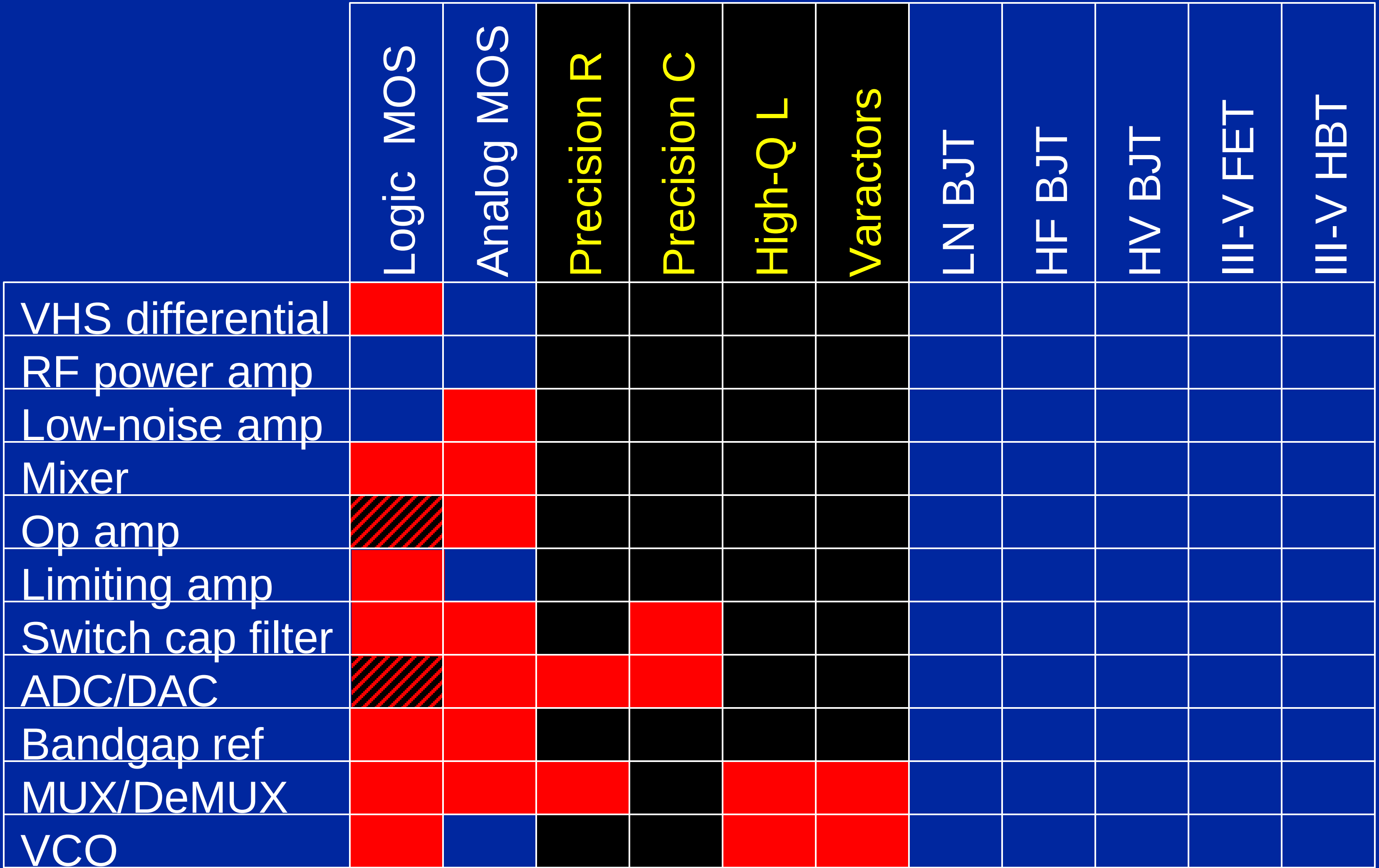
(Keep it SIMPLE, STUPID!)

Matching Circuit Needs to Device Type

	Logic MOS	Analog MOS	Precision R	Precision C	High-Q L	Varactors	LN BJT	HF BJT	HV BJT	III-V FET	III-V HBT
VHS differential	🟥	⬛									
RF power amp	⬛	⬛									
Low-noise amp	⬛	🟥									
Mixer	🟥	🟥									
Op amp	▨	🟥									
Limiting amp	🟥	⬛									
Switch cap filter	🟥	🟥									
ADC/DAC	▨	🟥									
Bandgap ref	🟥	🟥									
MUX/DeMUX	🟥	🟥									
VCO	🟥	⬛									

Logic and analog MOS are the foundation for the majority of critical communications circuits

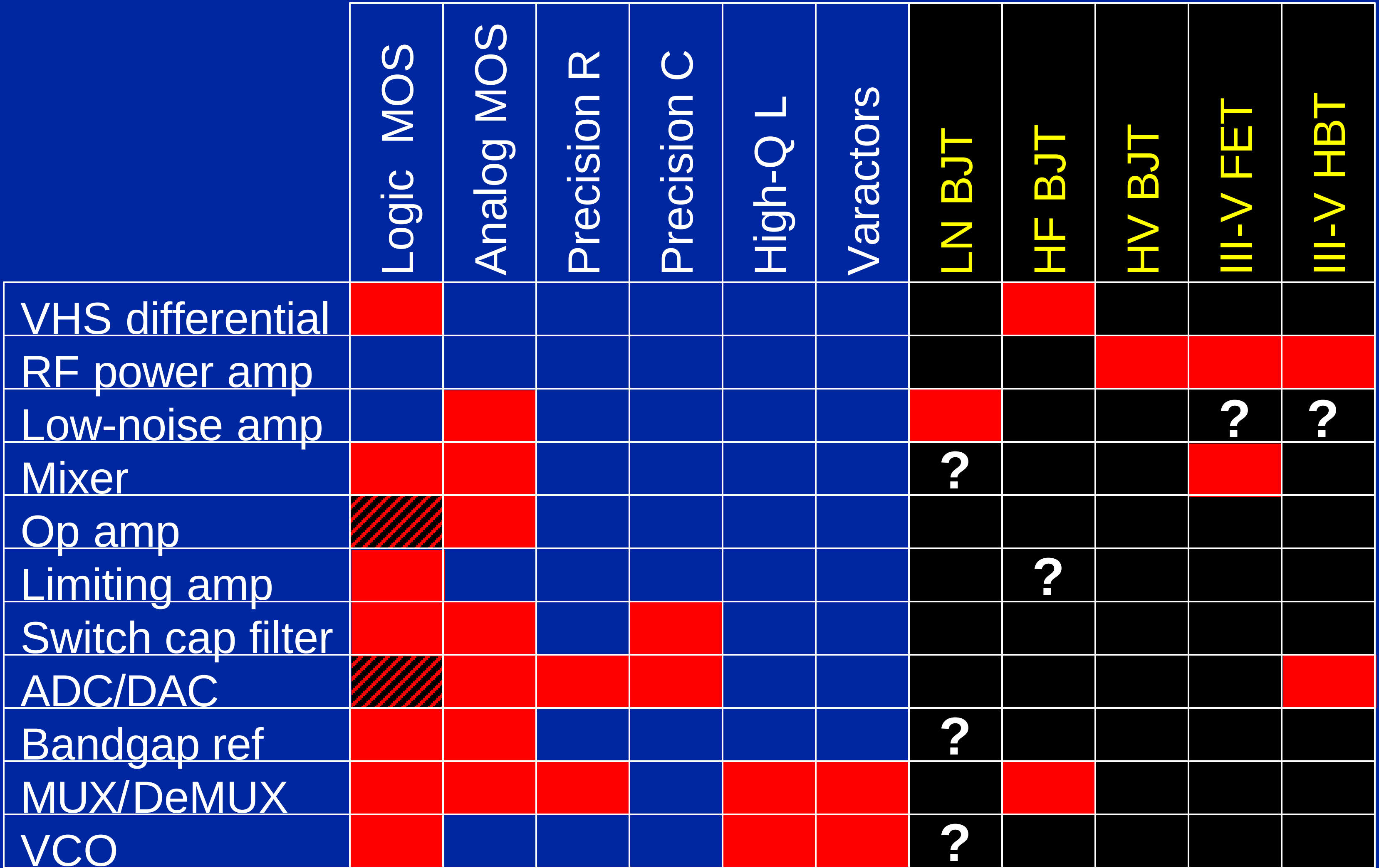
Matching Circuit Needs to Device Type



	Logic MOS	Analog MOS	Precision R	Precision C	High-Q L	Varactors	LN BJT	HF BJT	HV BJT	III-V FET	III-V HBT
VHS differential	🟥										
RF power amp											
Low-noise amp		🟥									
Mixer	🟥	🟥									
Op amp	▨	🟥									
Limiting amp	🟥										
Switch cap filter	🟥	🟥		🟥							
ADC/DAC	▨	🟥	🟥	🟥							
Bandgap ref	🟥	🟥									
MUX/DeMUX	🟥	🟥	🟥		🟥	🟥					
VCO	🟥				🟥	🟥					

Precision single elements are key to many circuits

Matching Circuit Needs to Device Type



	Logic MOS	Analog MOS	Precision R	Precision C	High-Q L	Varactors	LN BJT	HF BJT	HV BJT	III-V FET	III-V HBT
VHS differential	🟥							🟥			
RF power amp									🟥	🟥	🟥
Low-noise amp		🟥					🟥			?	?
Mixer	🟥	🟥					?			🟥	
Op amp	▨	🟥									
Limiting amp	🟥							?			
Switch cap filter	🟥	🟥		🟥							
ADC/DAC	▨	🟥	🟥	🟥							🟥
Bandgap ref	🟥	🟥					?				
MUX/DeMUX	🟥	🟥	🟥		🟥	🟥		🟥			
VCO	🟥				🟥	🟥	?				

Most circuits have multiple implementation paths,
exploiting redundancy is critical to process simplification

OVERVIEW

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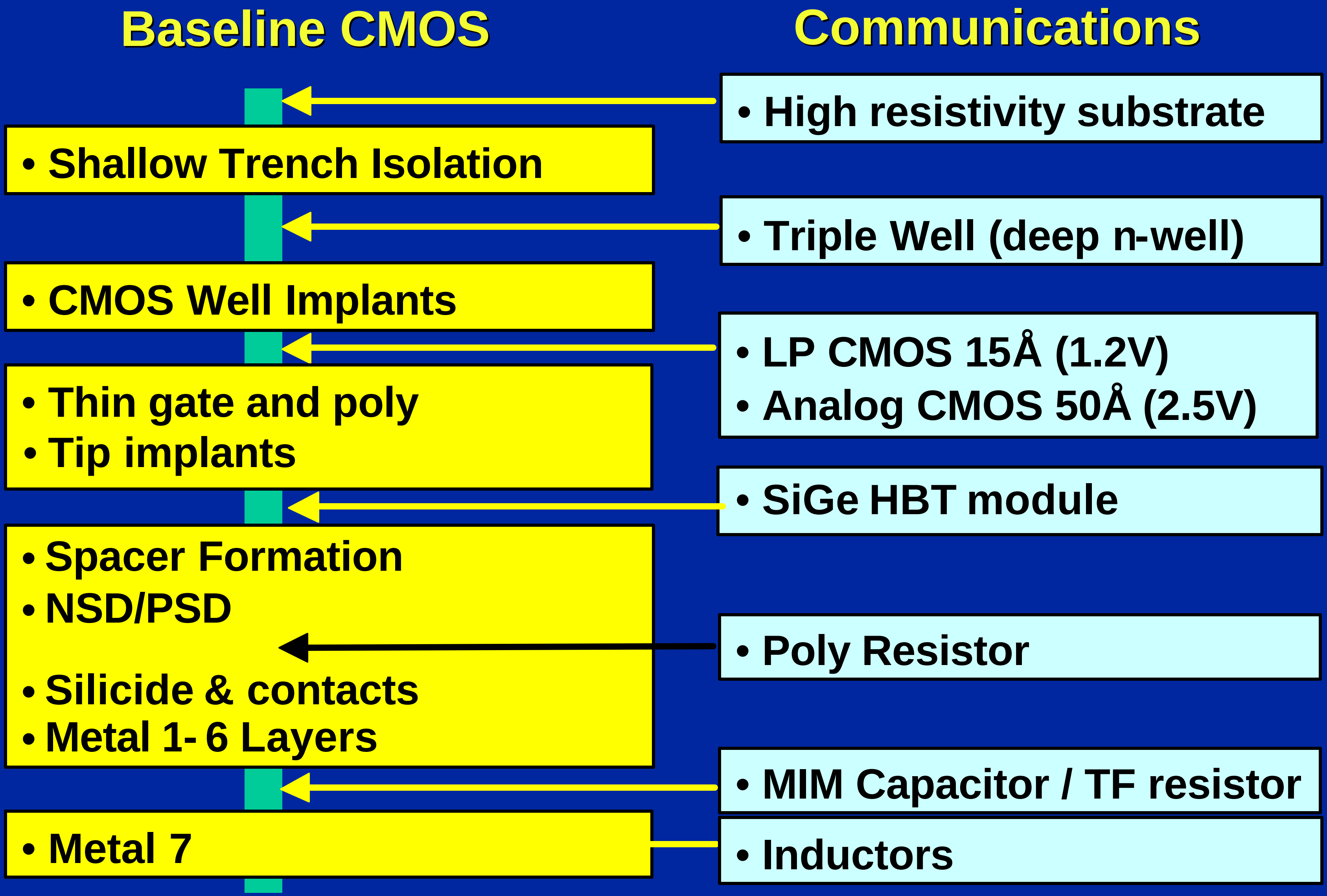
Integration Challenges

THE CHALLENGES OF INTEGRATION



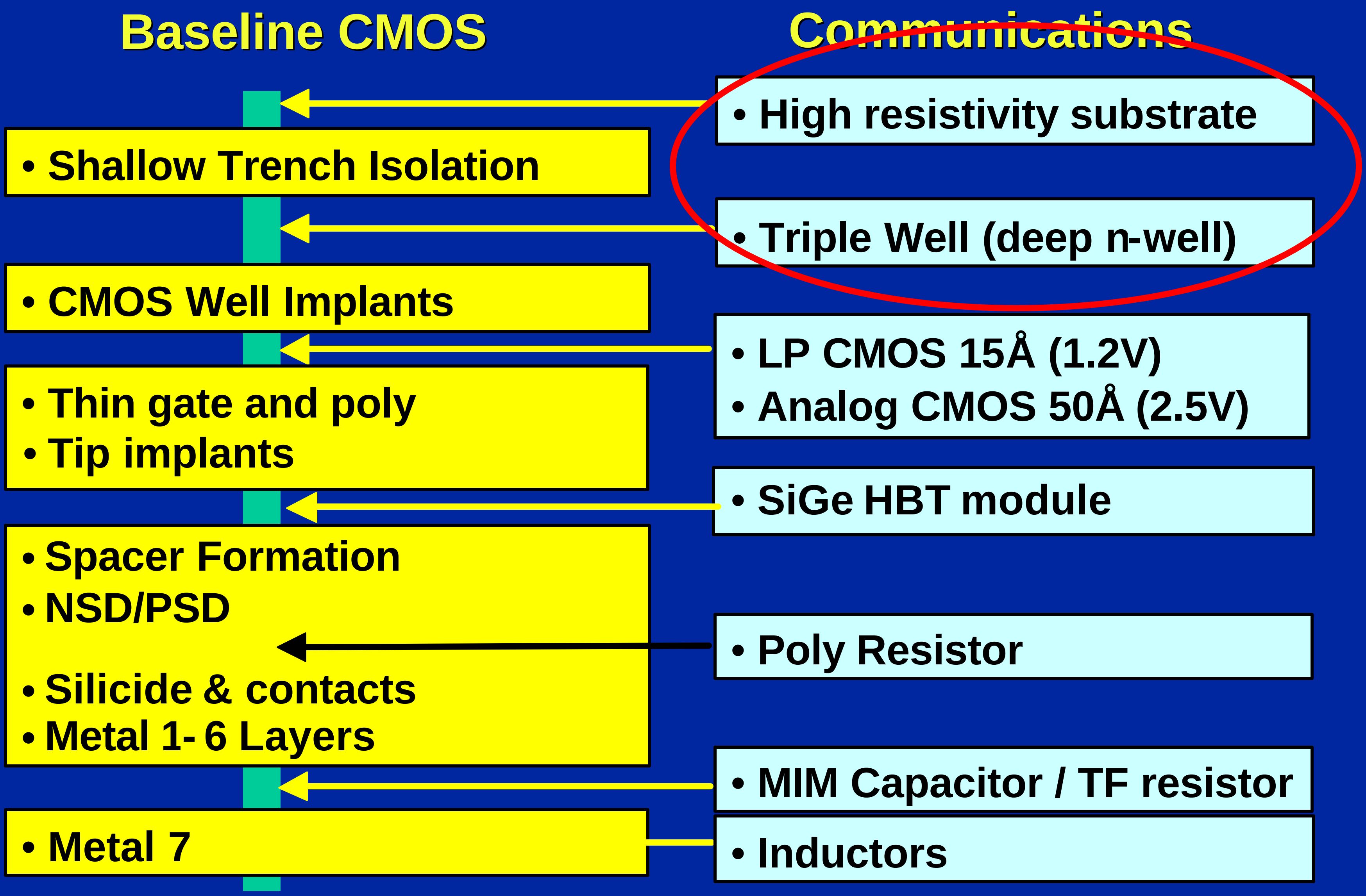
Baseline CMOS

- Shallow Trench Isolation
- CMOS Well Implants
- Thin gate and poly
- Tip implants
- Spacer Formation
- NSD/PSD
- Silicide & contacts
- Metal 1- 6 Layers
- Metal 7

Communications

- High resistivity substrate
- Triple Well (deep n-well)
- LP CMOS 15Å (1.2V)
- Analog CMOS 50Å (2.5V)
- SiGe HBT module
- Poly Resistor
- MIM Capacitor / TF resistor
- Inductors

THE CHALLENGES OF INTEGRATION



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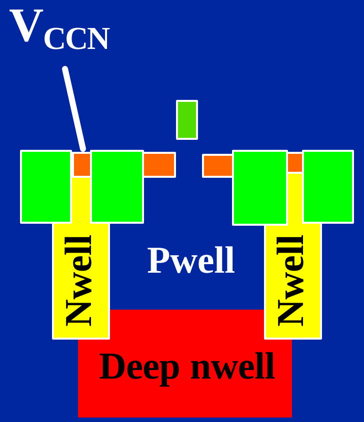
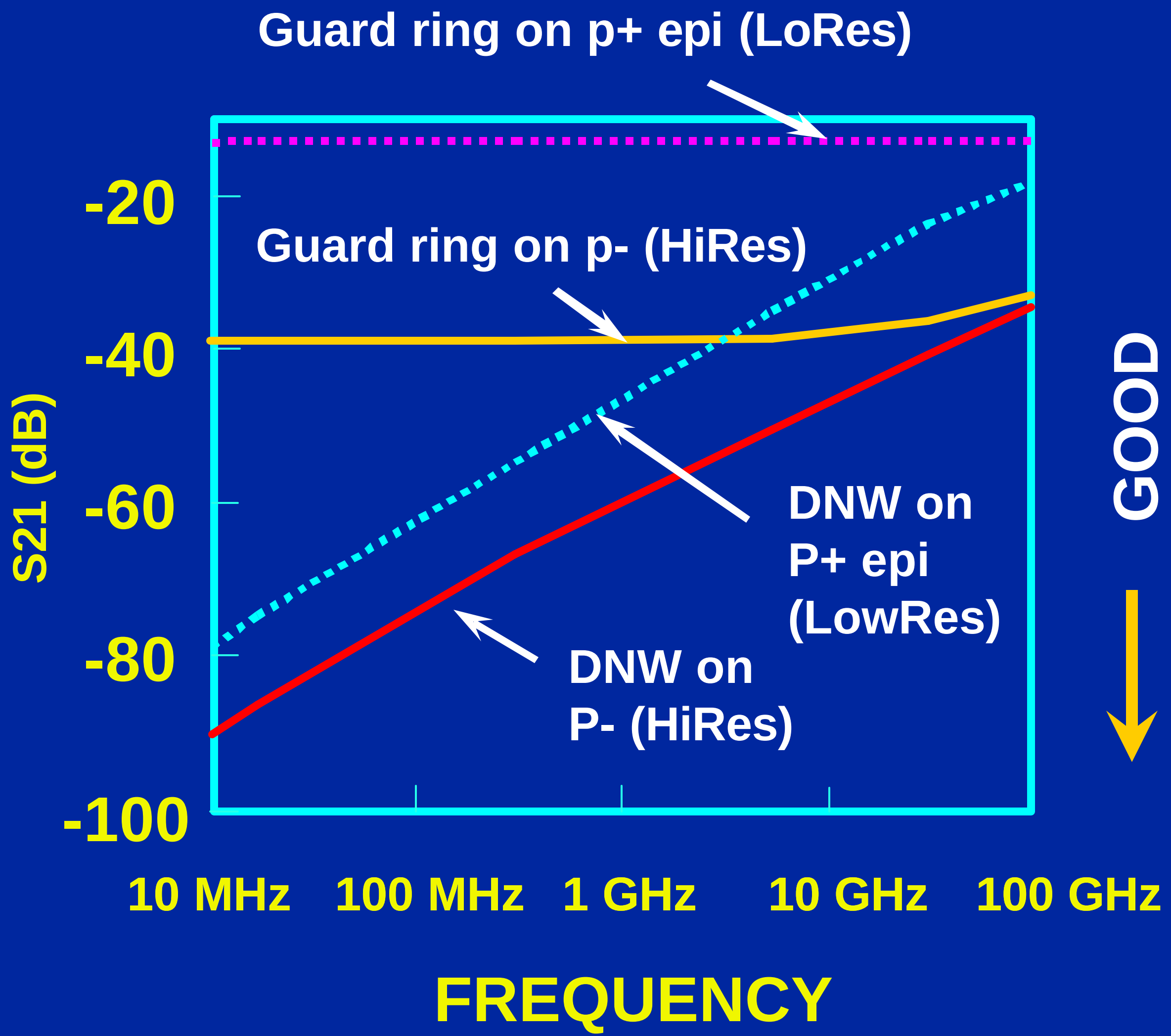
Noise Isolation

METHODS:

- High resistivity substrate
- Guard rings
- Deep nwell

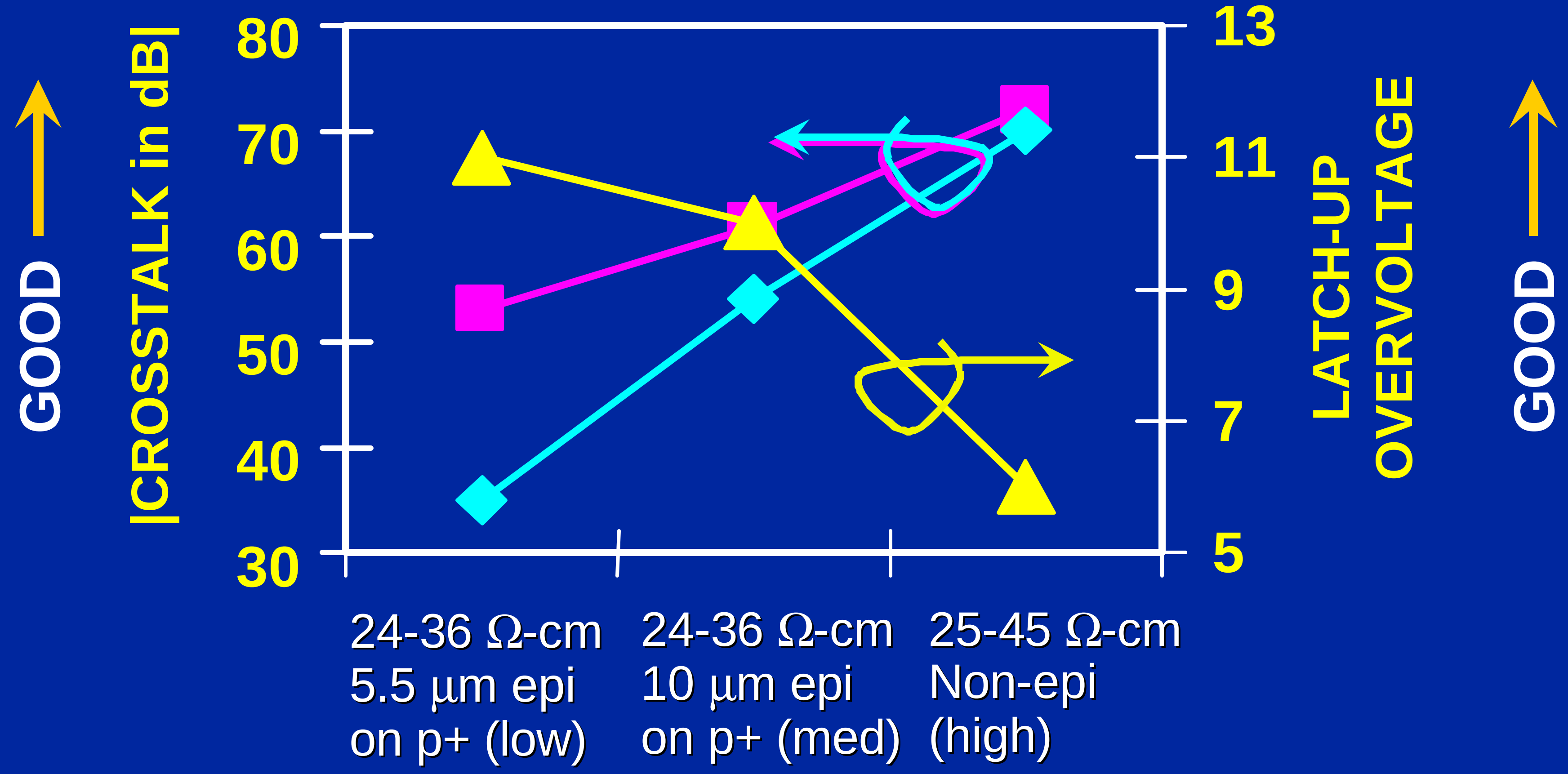




S21 = forward transmission gain/loss (common RF isolation metric)

K. Kuhn, et al. IEDM 2002

Substrates: Latch-up, P- versus P+ epi



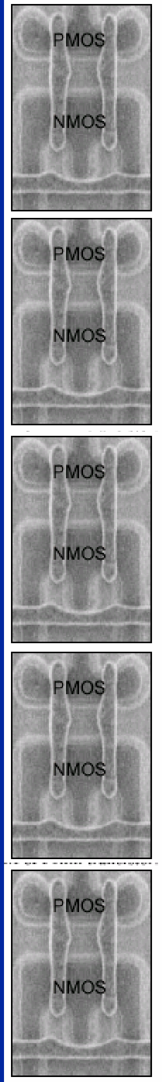
<u>Merrill, R.B.; Young, W.M.; Brehmer, K.</u> *"Effect of substrate material on crosstalk in mixed analog/digital integrated circuits,"   Electron Devices Meeting, 1994.*

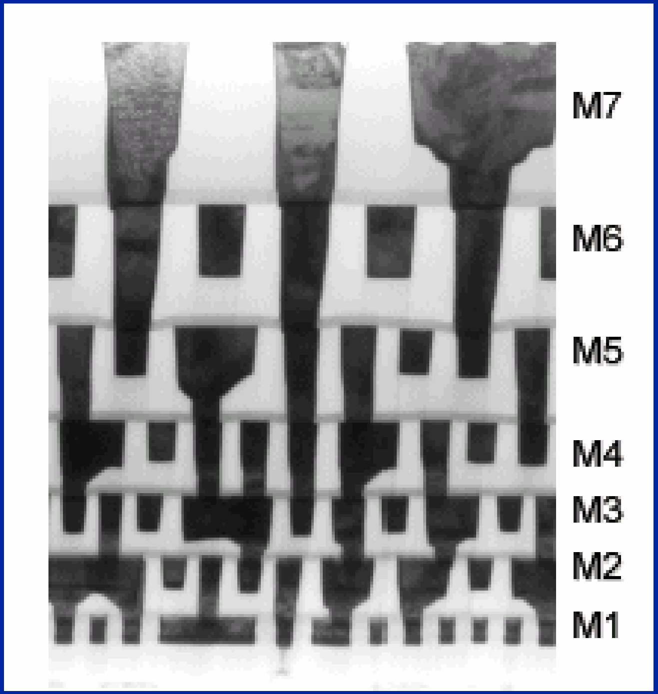
Challenges of DNW integration

DNW RESIST

~ 5 BITCELLS HIGH!

~ 2X HEIGHT OF ENTIRE 90nm BACK-END





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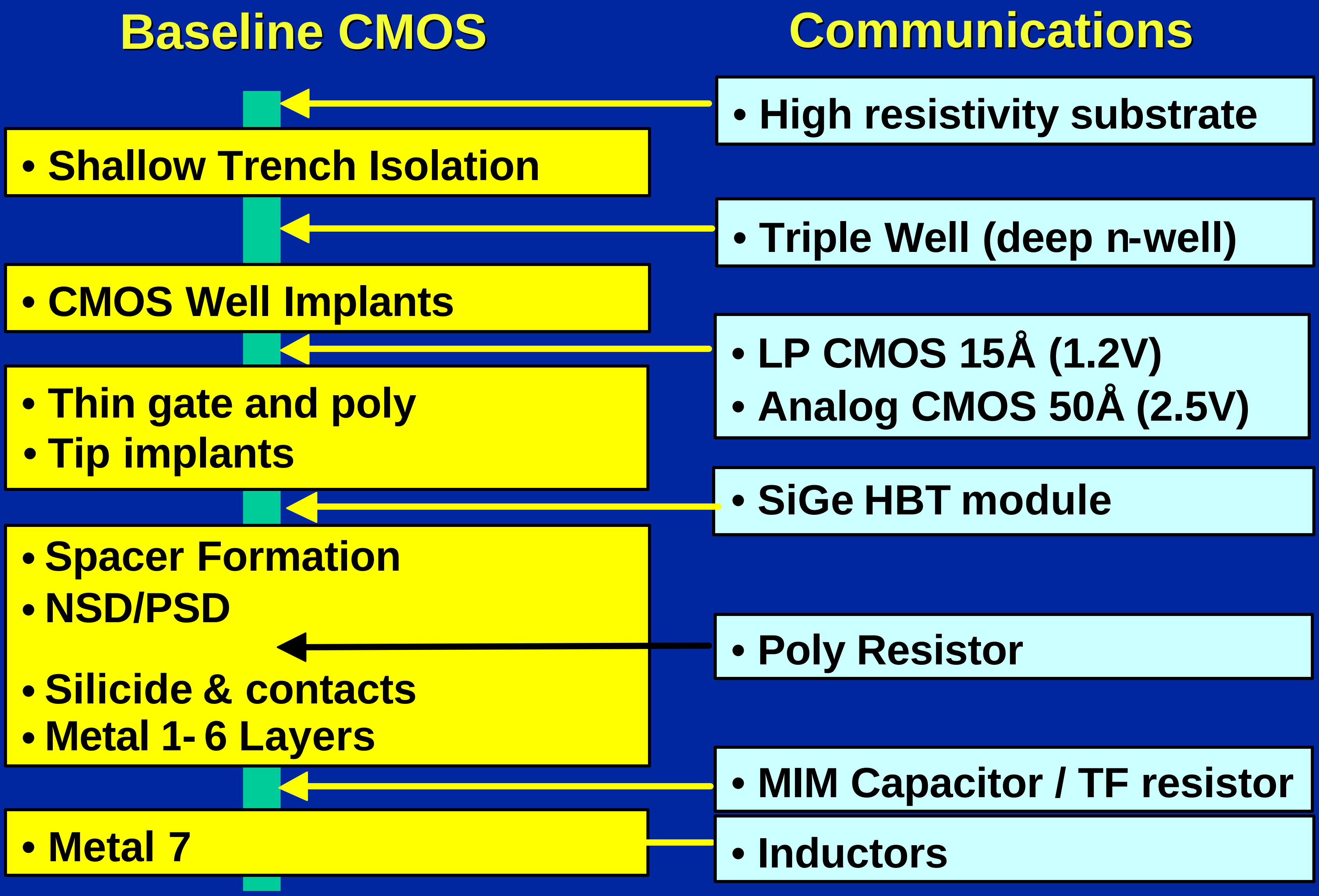

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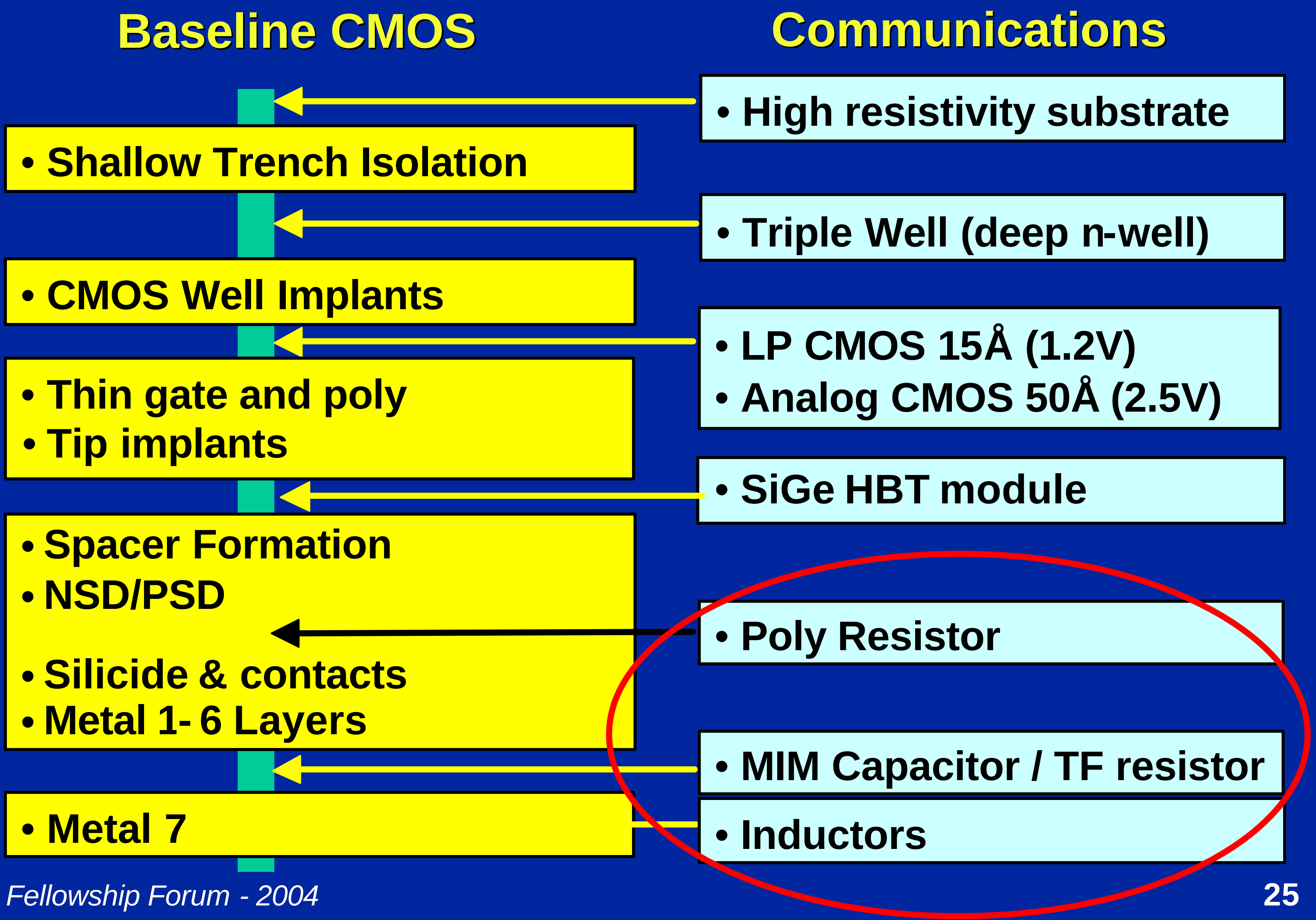

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Why so much fuss about PASSIVES?

In the digital design world, performance is typically not determined by passive design elements … However, in analog/mixed-signal design, performance is ultimately limited by the accuracy of the passive components in the technology.

Allstot, D.J., and Black, Jr., W.C., "Technology Design considerations for monolithic MOS switched-capacitor filtering systems," Proceedings IEEE, Vol. 71, pp. 967-986, August 1983.

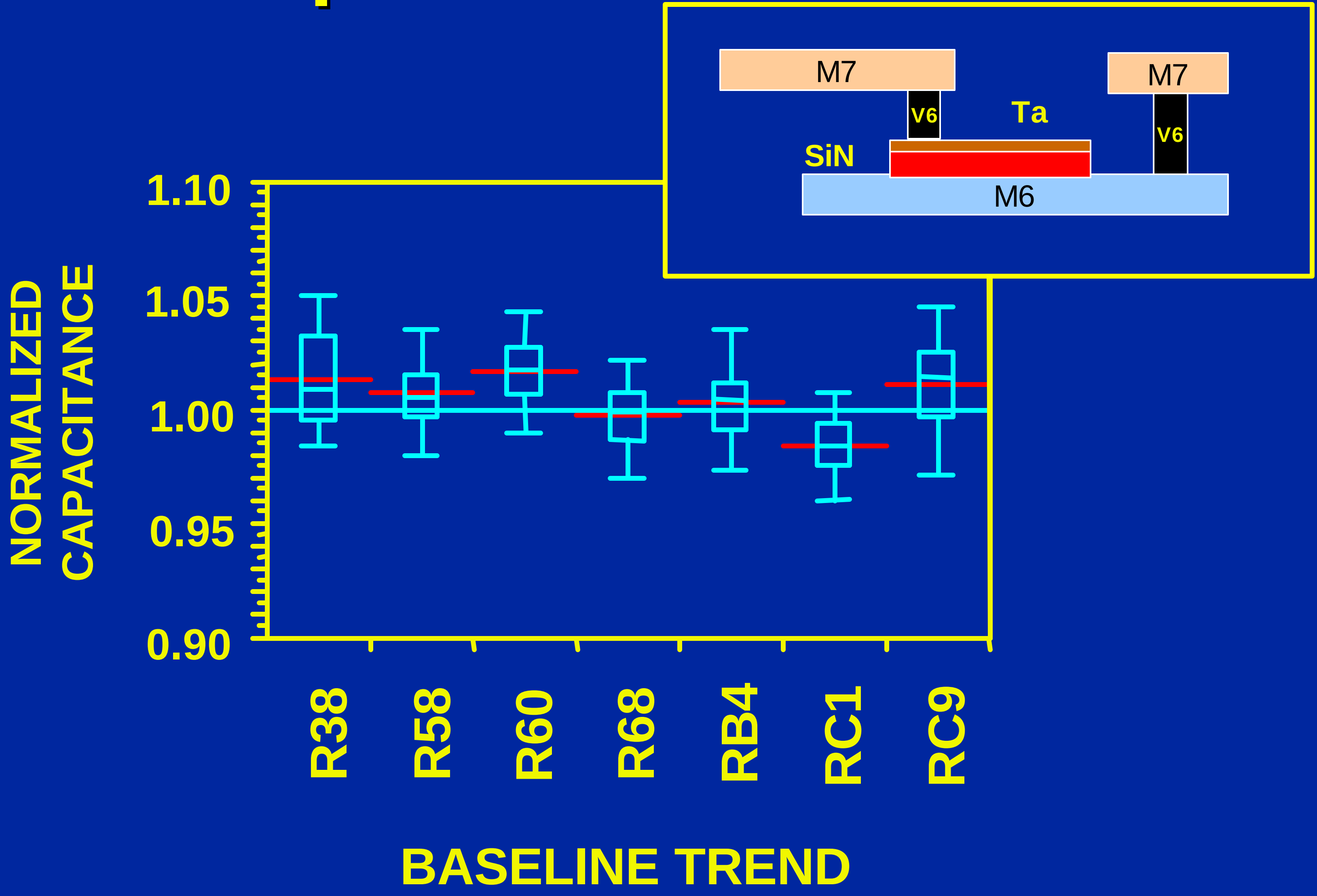
Wikner, J.J., and Tan, N., "Influence of circuit imperfections on the performance of DACs," Analog Integrated Circuits Signal Processing, Vol. 18, pp. 7-20, 1999.

McCreary, J.L., "Matching properties and voltage and temperature dependence of MOS capacitors," IEEE J. Solid-State Circuits, Vol. SC-16, pp. 608-616, June 1981.

Ulrich, R.K., "Getting Aggressive with Passive Devices," IEEE Circuits and Devices, Sept. 2000, pp. 17-25.

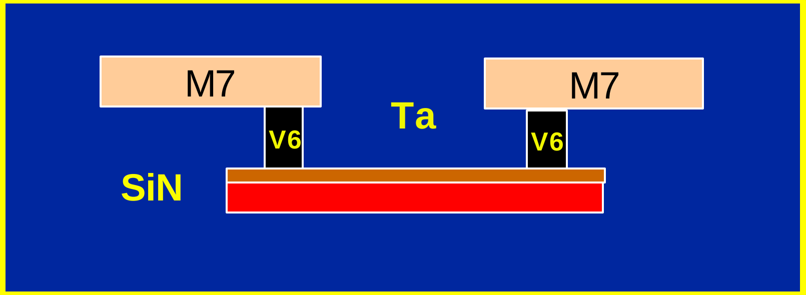
Lee, T.H., and Wong, S.S., "CMOS RF Integrated Circuits at 5GHz and Beyond," Proceedings of the IEEE, Vol. 88, No. 10, October 2000.

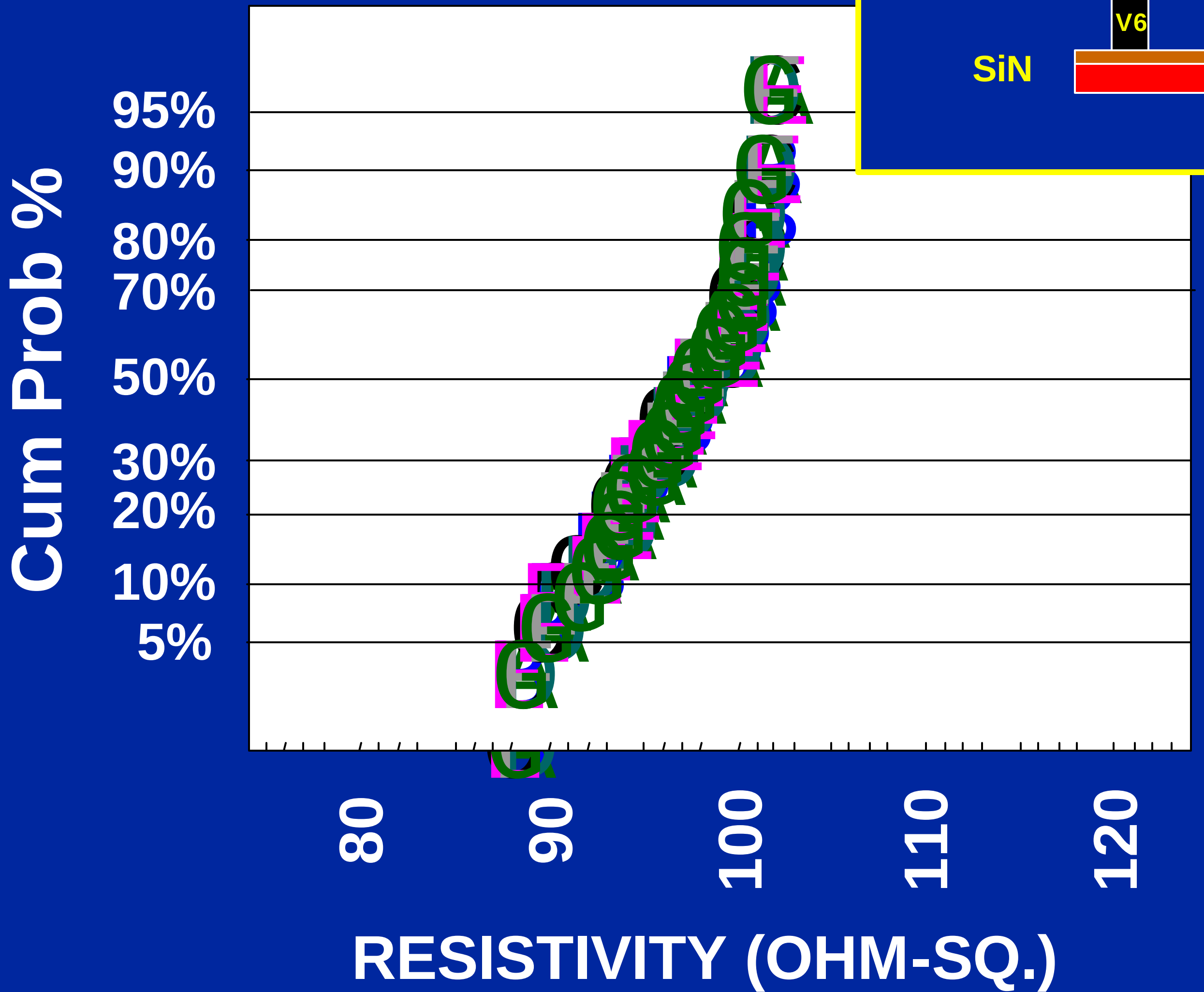
MIM Capacitor



K. Kuhn, et al. IEDM 2002

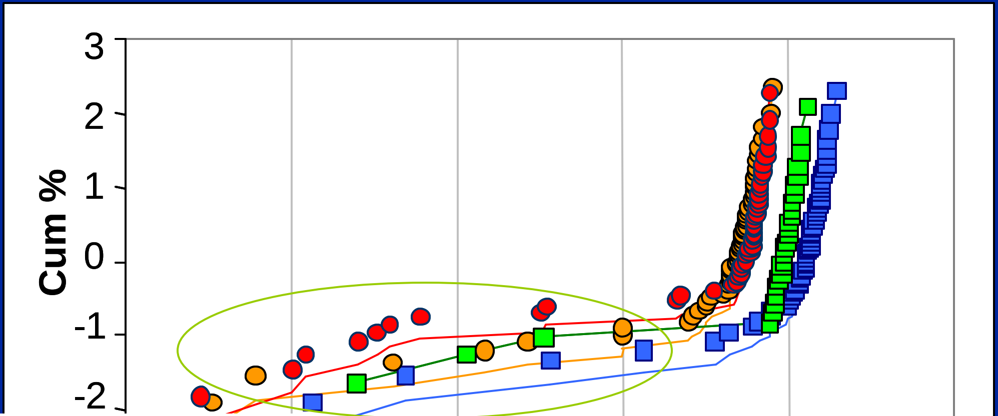
MIM Resistor

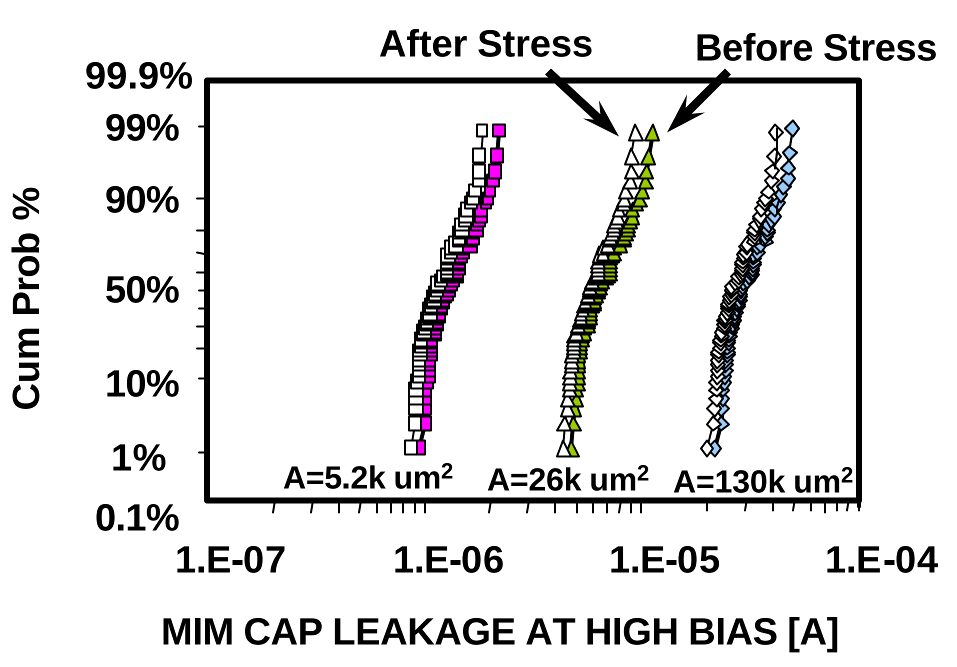




Challenges of MIM integration

OLD Process >

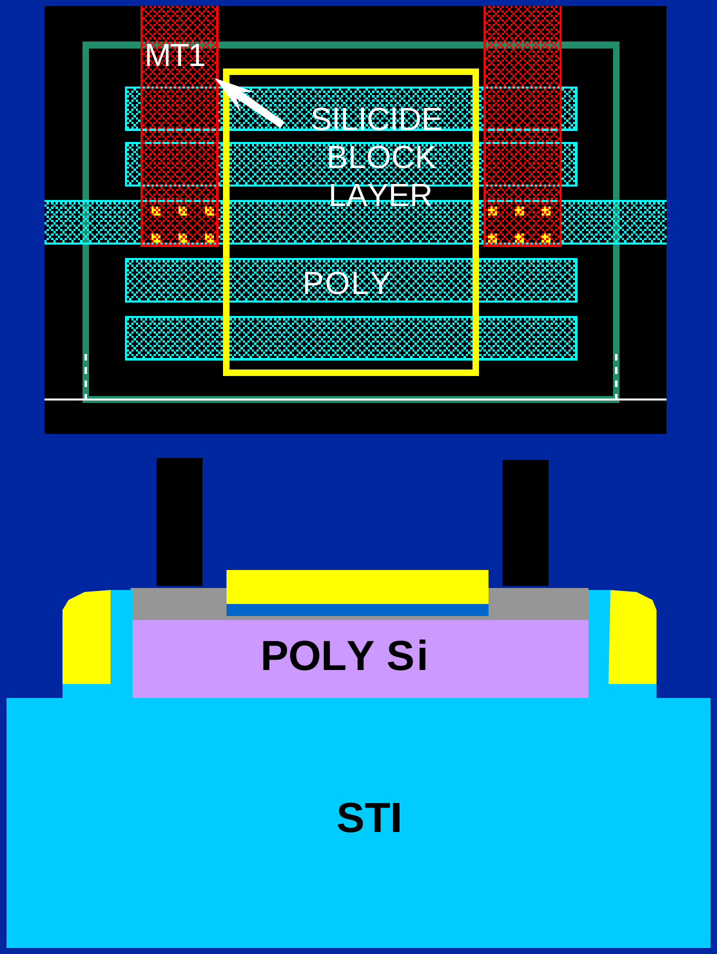




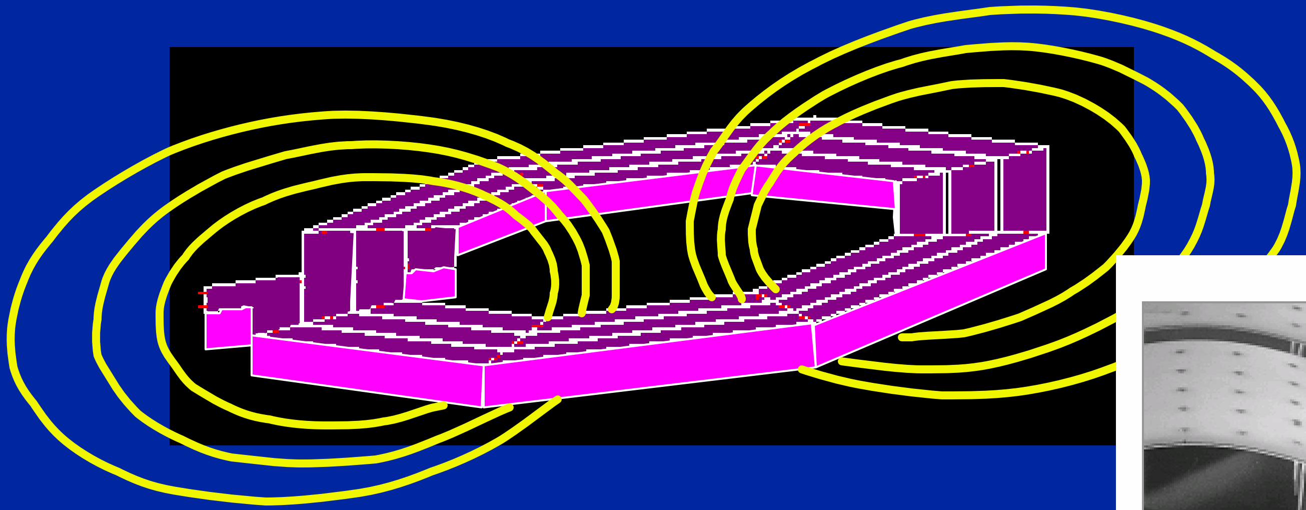
< New Process

Cu pre-stress T > later T, Cu-CMP will relax the stress by removing bulk continuous Cu. Low hillocks.
Cu pre-stress T < later T →interaction between the tensile Cu and compressive stress from ILD. Severe hillocks.
Fix = counterintuitive = increase pre-Cu anneal T

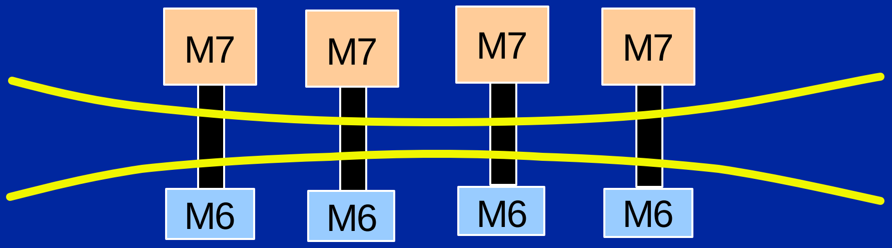
Challenges of poly resistor integration



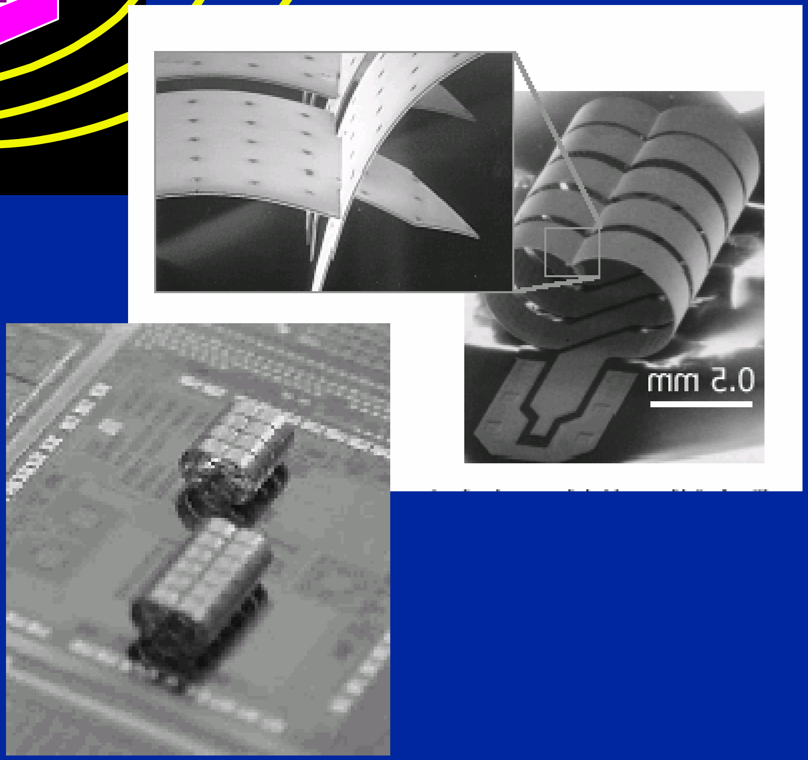
In-plane and out-of-plane inductors



Planar spiral

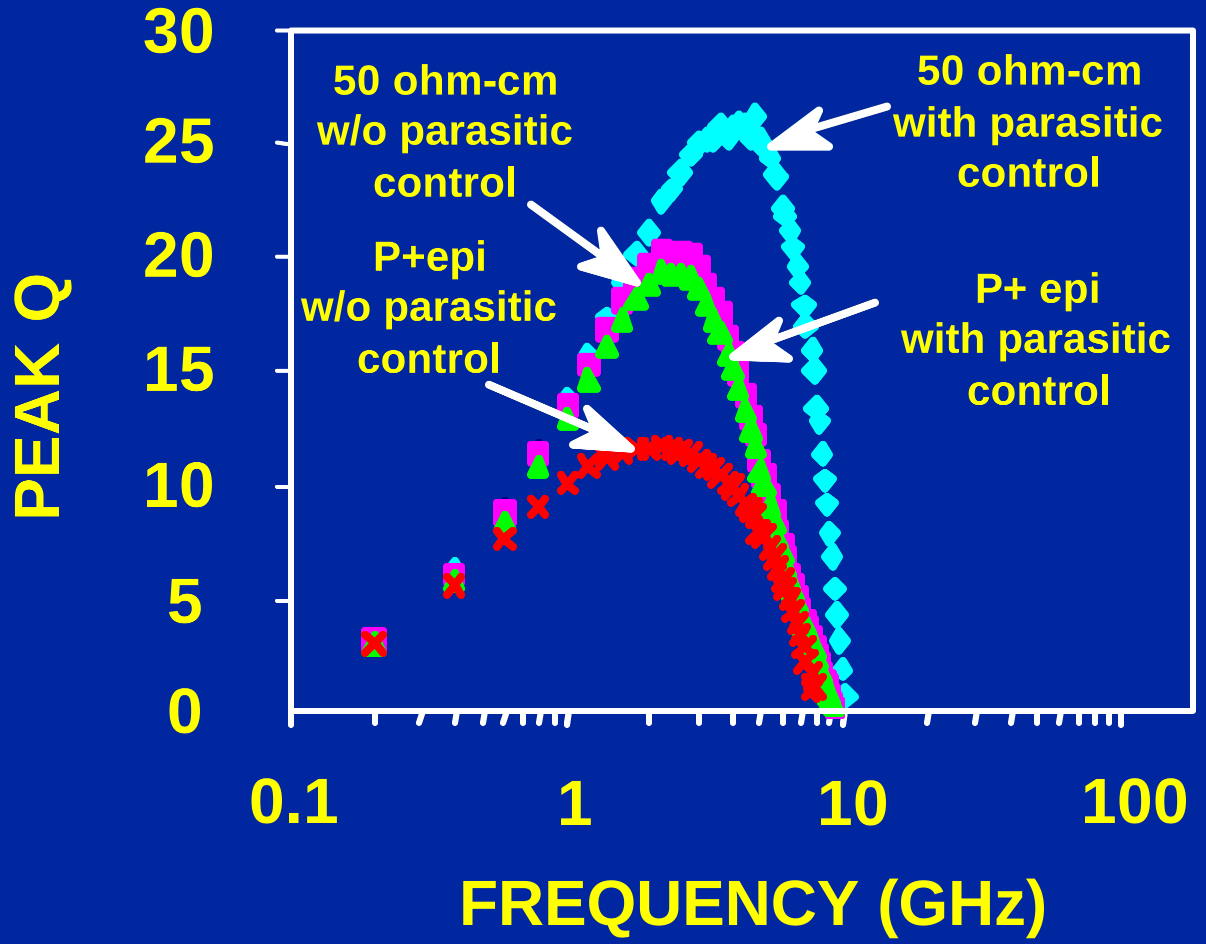


MT6/MT7



Self-assembled
K. Schuylenberg (IEDM'2002)

Hi-Q Inductors and substrates



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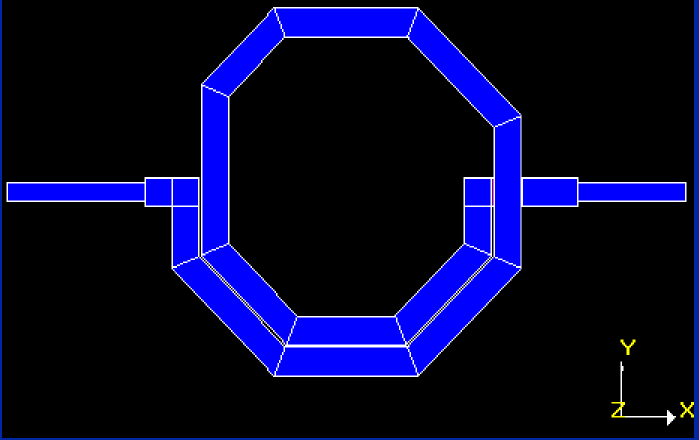
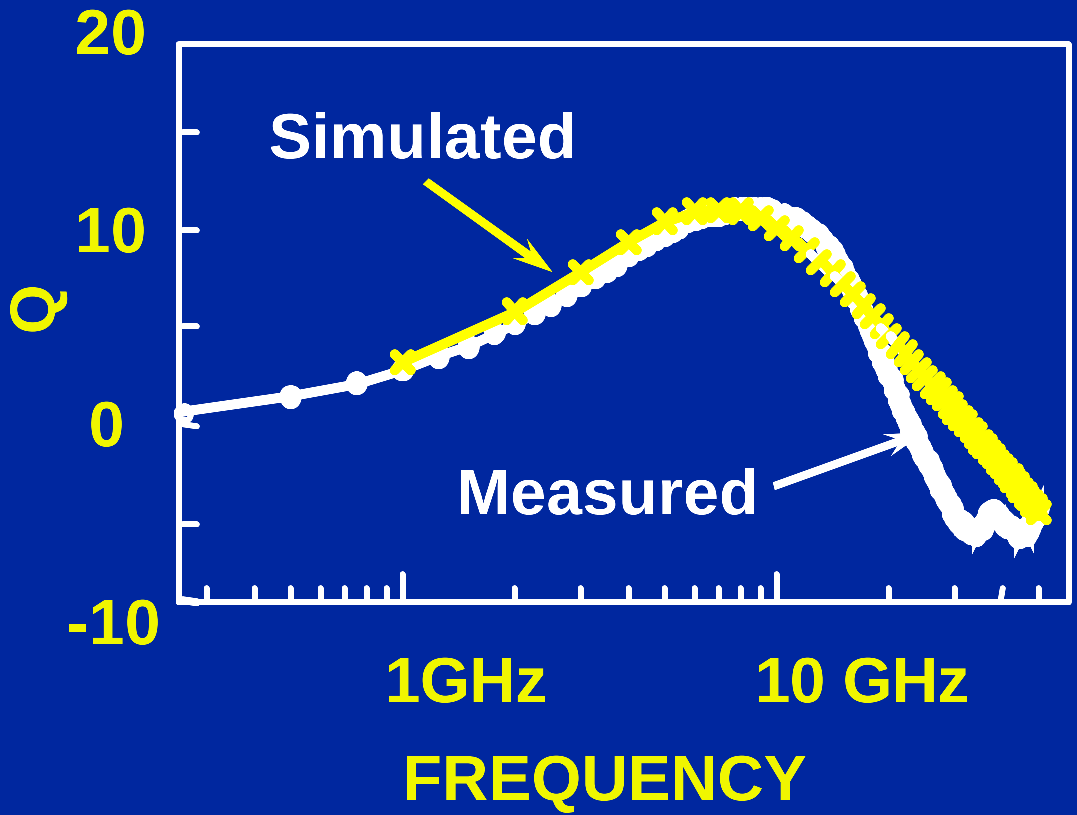
Measured versus simulated Q

Inductor Dimension:
Do = 154 um W = 12 um
S = 1 um T = 1.5





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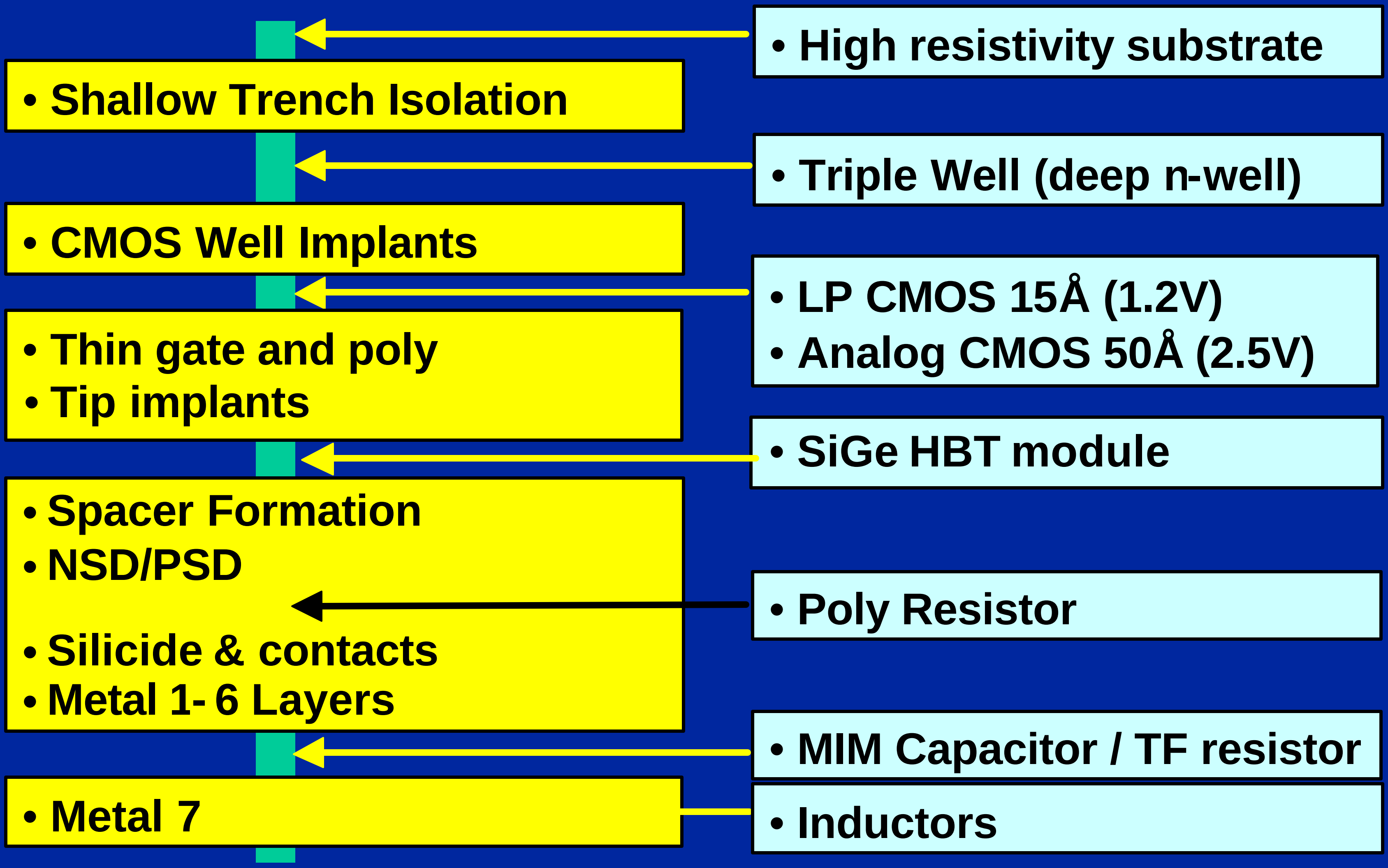
THE CHALLENGES OF INTEGRATION



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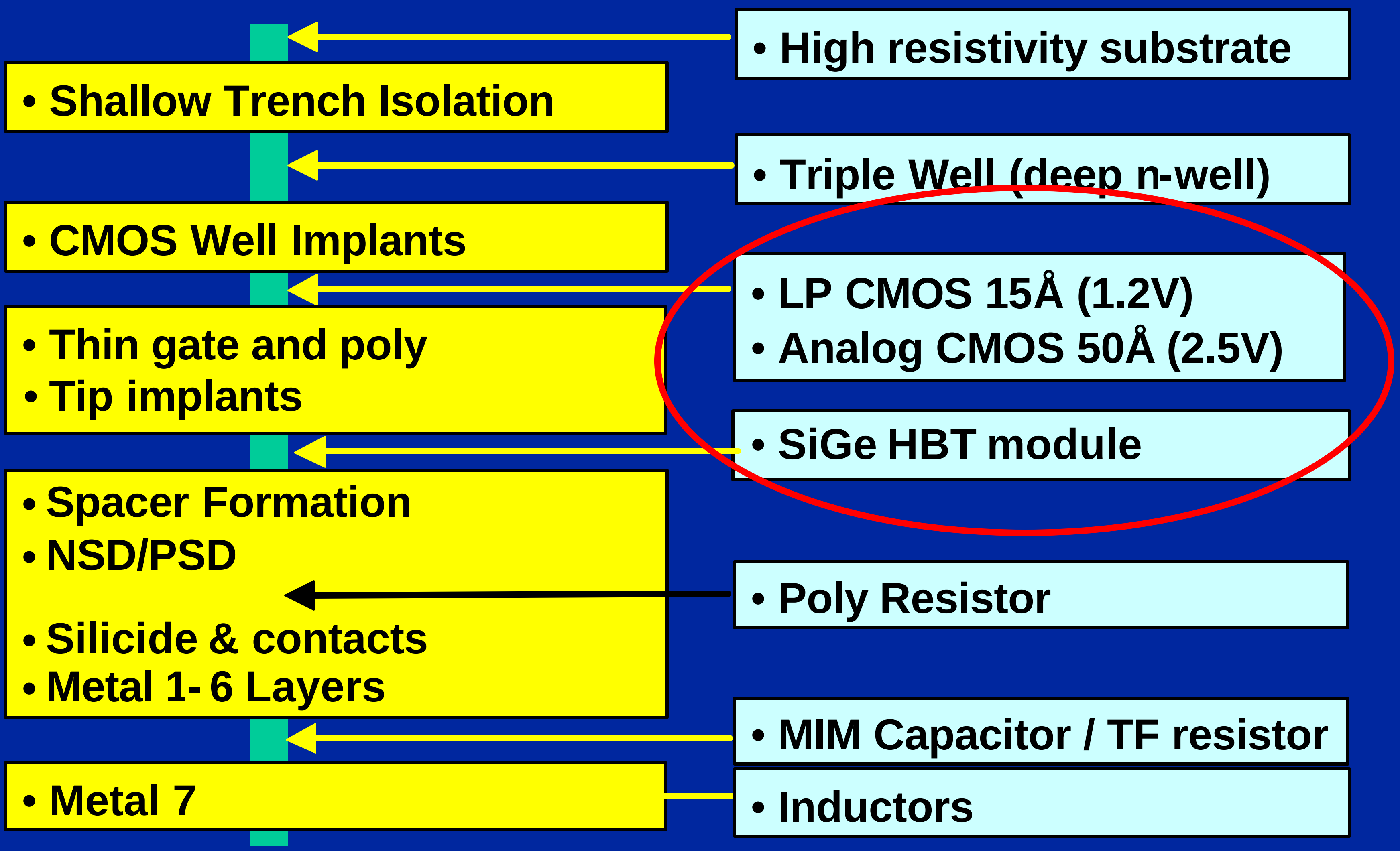

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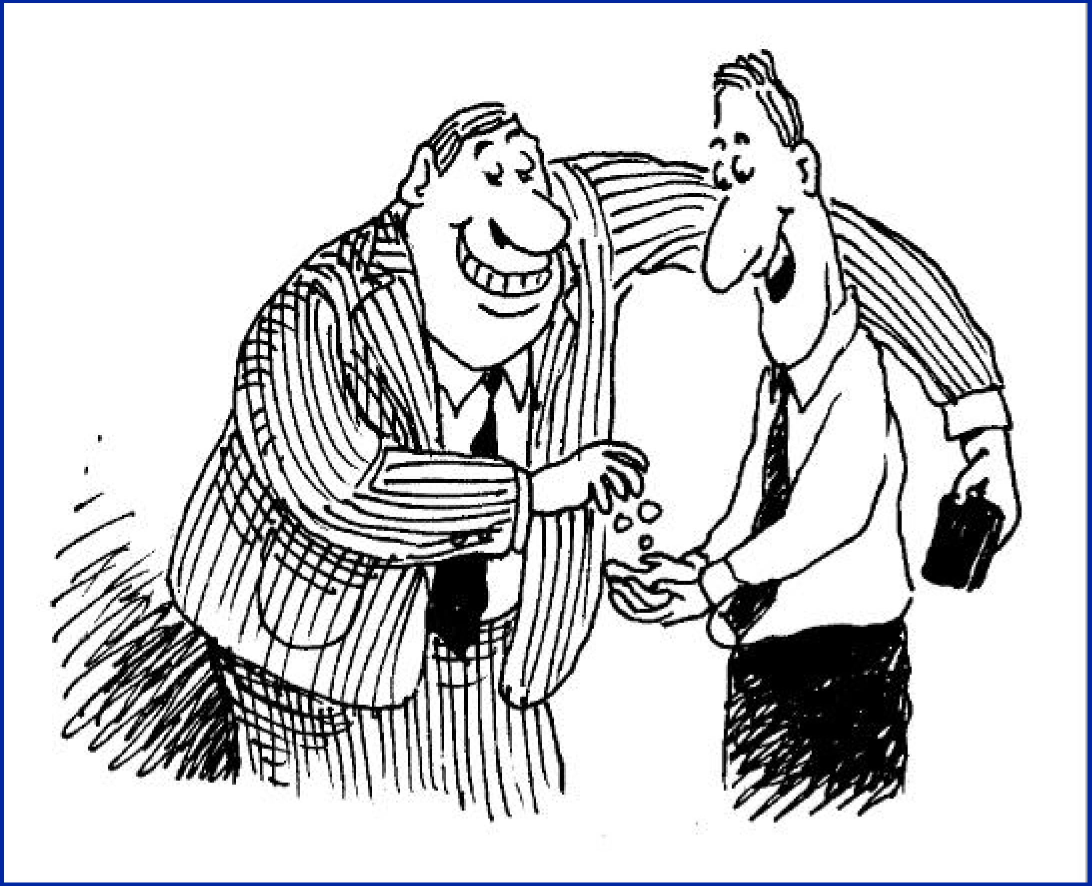
BJTs versus CMOS??



Key Performance Metrics

- *FREQUENCY*
- *NOISE*
- *MATCHING*
- g_m/ID_{SAT}
- *LINEARITY (IP3)*
- $V_A\ (g_{DS}, R_{OUT})$

Key Performance Metrics

- *FREQUENCY*
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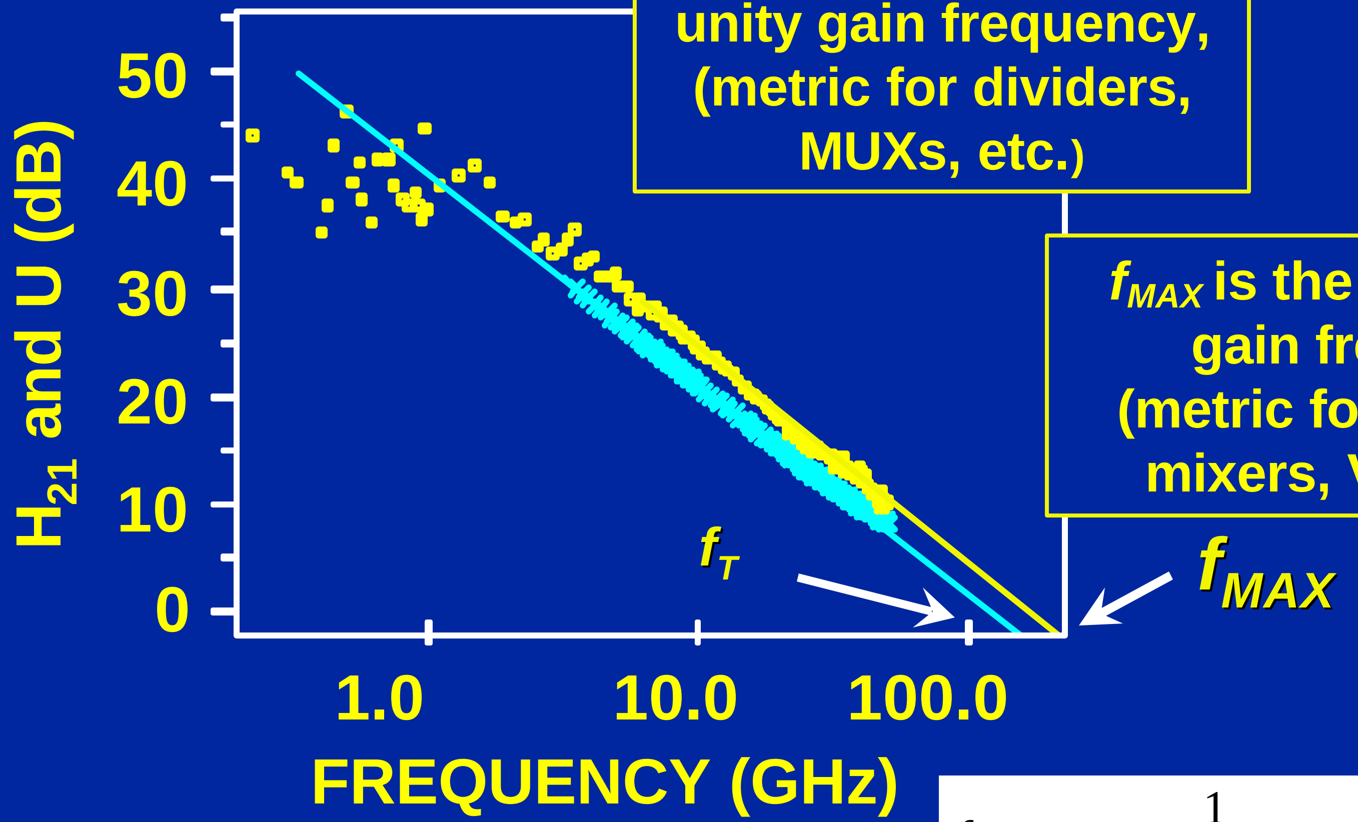
- *LINEARITY (IP3)*
- *V_A (g_{DS}, R_{OUT})*

Physics for MOSFET f_T and f_{MAX}



f_T is the short circuit unity gain frequency, (metric for dividers, MUXs, etc.)

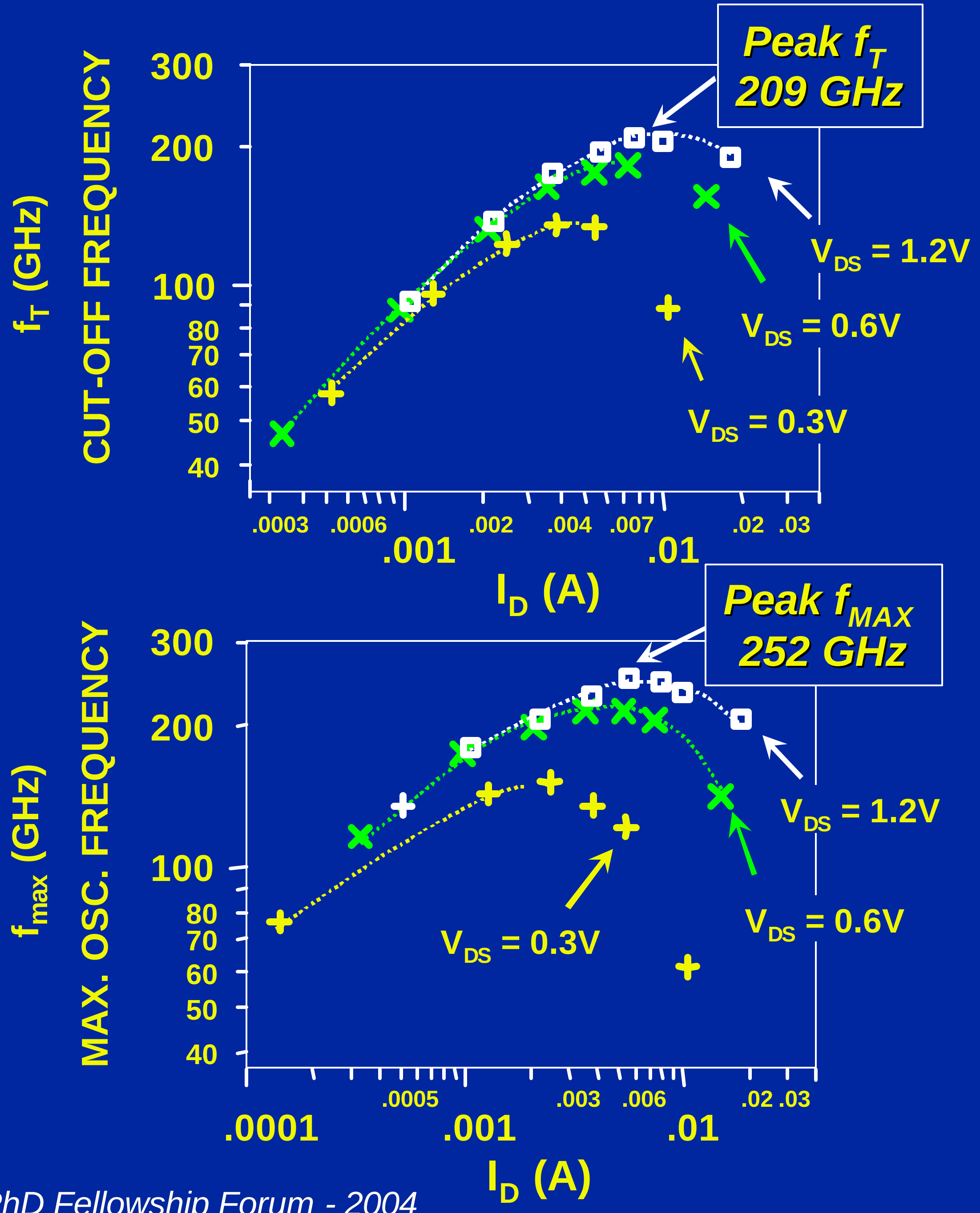
f_{MAX} is the unity power gain frequency, (metric for amplifiers, mixers, VCOs, etc.)

$$f_{\max} = \frac{f_T}{2\sqrt{\left(g_{sd}\left(R_G + R_S\right) + 2\pi f_T R_G C_{gd}\right)}}$$

$$f_T = g_m \cdot \frac{1}{2\pi C_{ox} \cdot ZL} = \frac{\mu\left(V_{GS} - V_T\right)}{2\pi \alpha L^2} \propto \frac{1}{L^2}$$

$$f_T = g_m \cdot \frac{1}{2\pi C_{ox} \cdot ZL} = \frac{\left|v_{d\,\max}\right|}{2\pi L} \propto \frac{1}{L} \quad (vel.sat.)$$

f_T/f_{MAX} at 70 nm vs bias

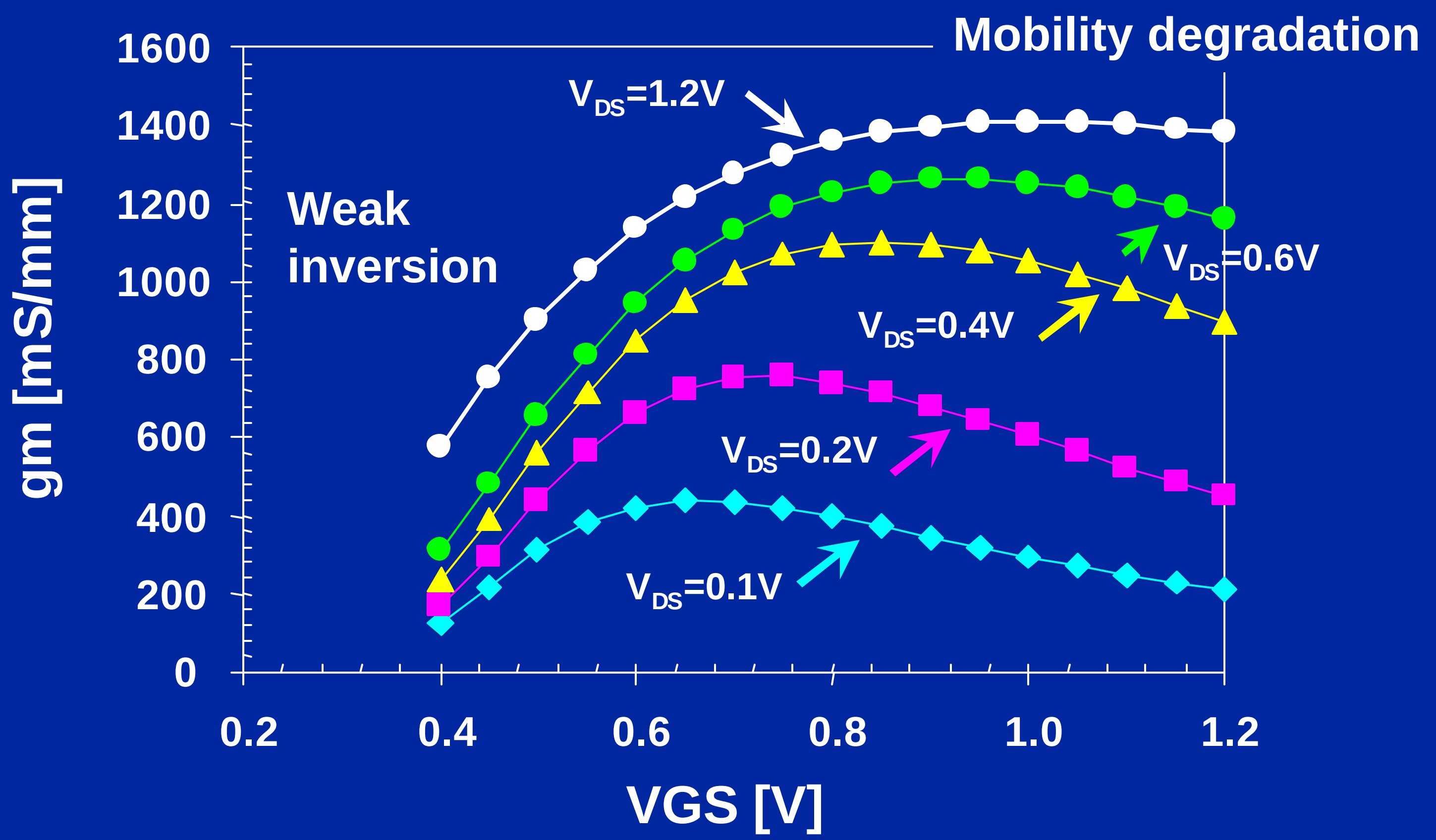


70 nm x 2.5 μm x 6
Peak f_T at 0.7 V_{GS}:
209 GHz

70 nm x 2.5 μm x 6
Peak f_{MAX} at 0.6 V_{GS}:
252 GHz

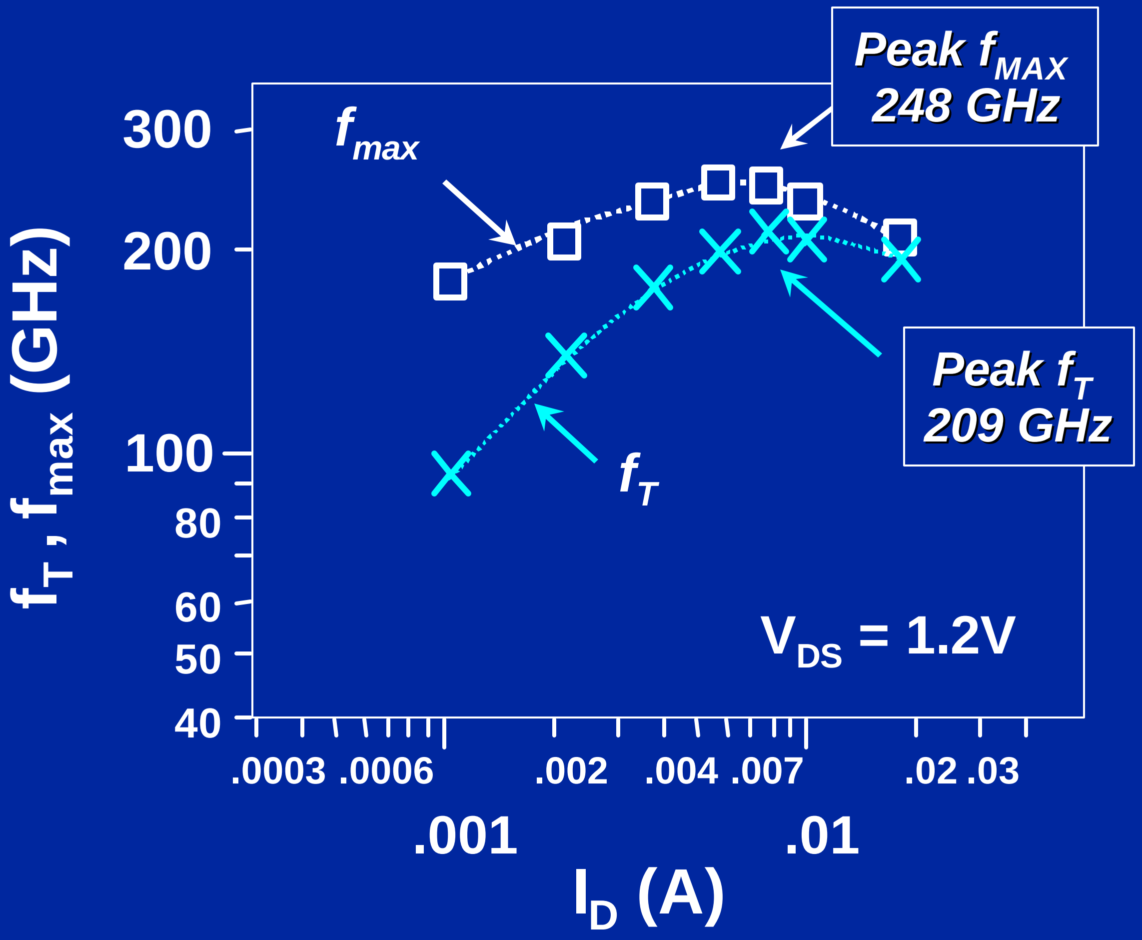
Bias behavior is due to f_T (g_m)

Simulation of g_m vs V_{GS} and V_{DS}



In a MOSFET *g_m* is low for low values of *V_{GS}* (weak inversion), increases with *V_{GS}* to a maximum, and then reduces at higher *V_{GS}* (carrier mobility degradation)

Simultaneous f_T/f_{MAX} at 70 nm at V_{DS} = 1.2V



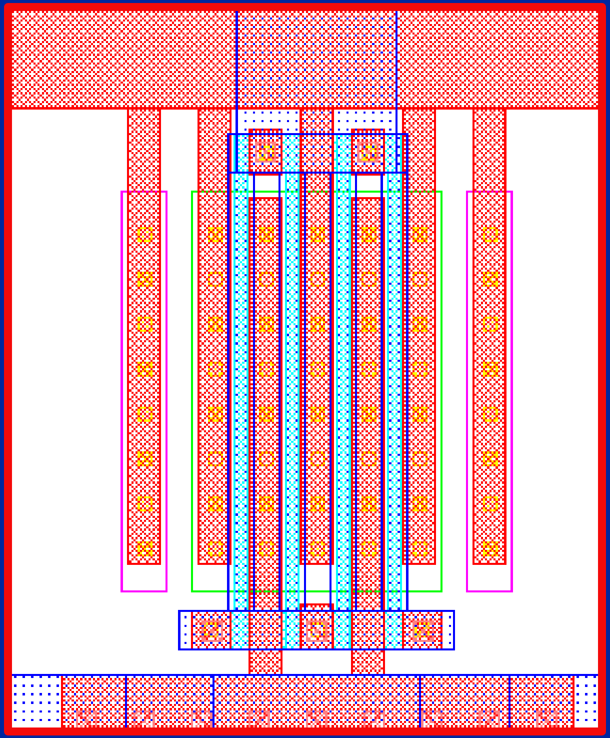
Peak f_{MAX} 248 GHz

Peak f_T 209 GHz

Simultaneous peak f_T and f_{MAX} at V_{GS} = 0.7V and V_{DS} = 1.2V
70 nm x 2.5μm x 6 device.

f_{MAX} at longer channel lengths

$$f_{\max} = \frac{f_T}{2\sqrt{\left(g_{sd}\left(R_G + R_S\right) + 2\pi f_T R_G C_{gd}\right)}}$$

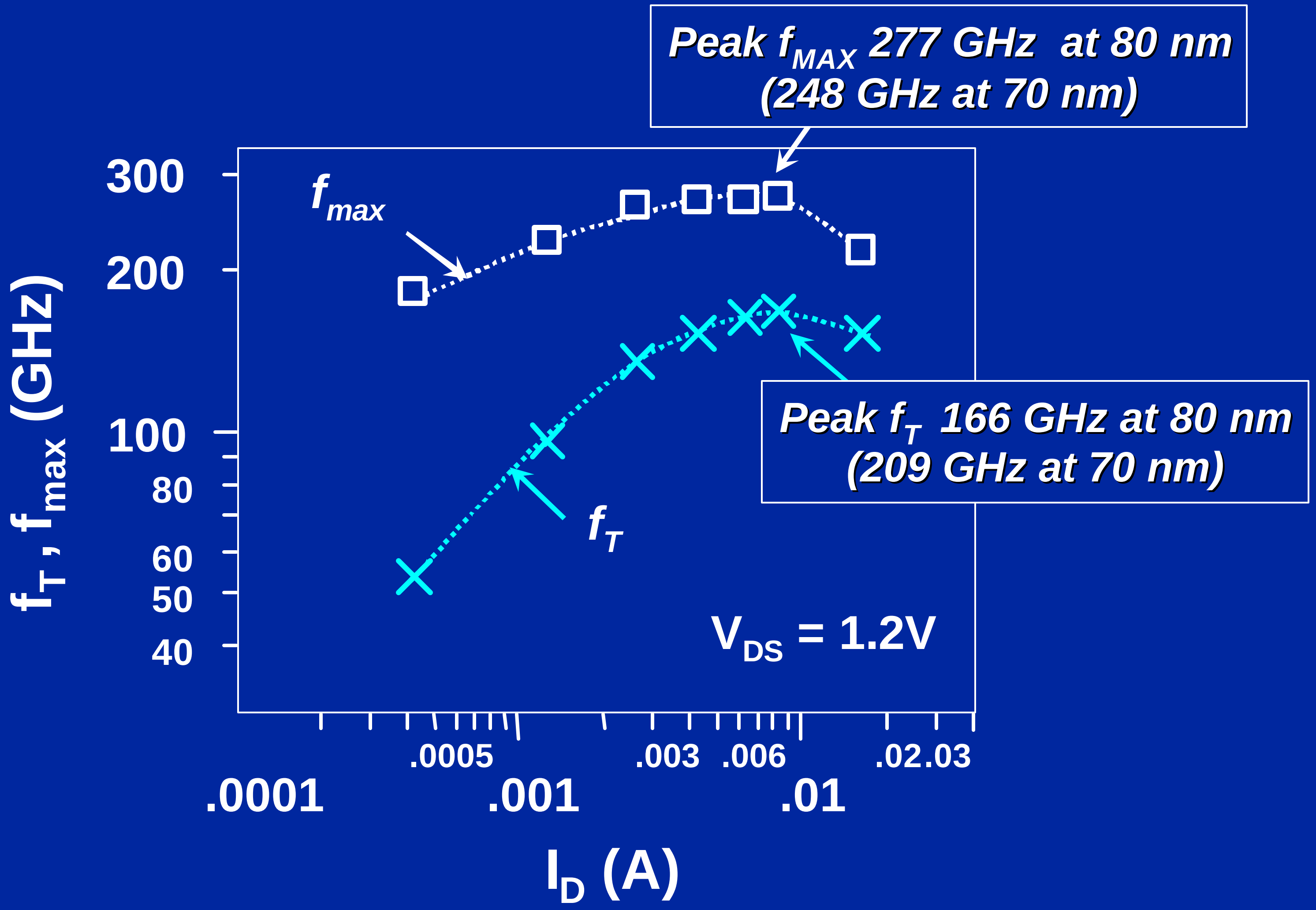


f_{max} is a function of the output conductance (g_{sd}) and the gate resistance (R_G).

R_G and g_{sd} increase significantly as the gate length approaches the minimum gate length of the technology.

→ Devices slightly greater in length than minimum will frequently deliver higher f_{max} (g_{sd} and R_G improvement compensating for f_T reduction)

Simultaneous f_T/f_{MAX} at 80 nm at V_{DS} = 1.2V

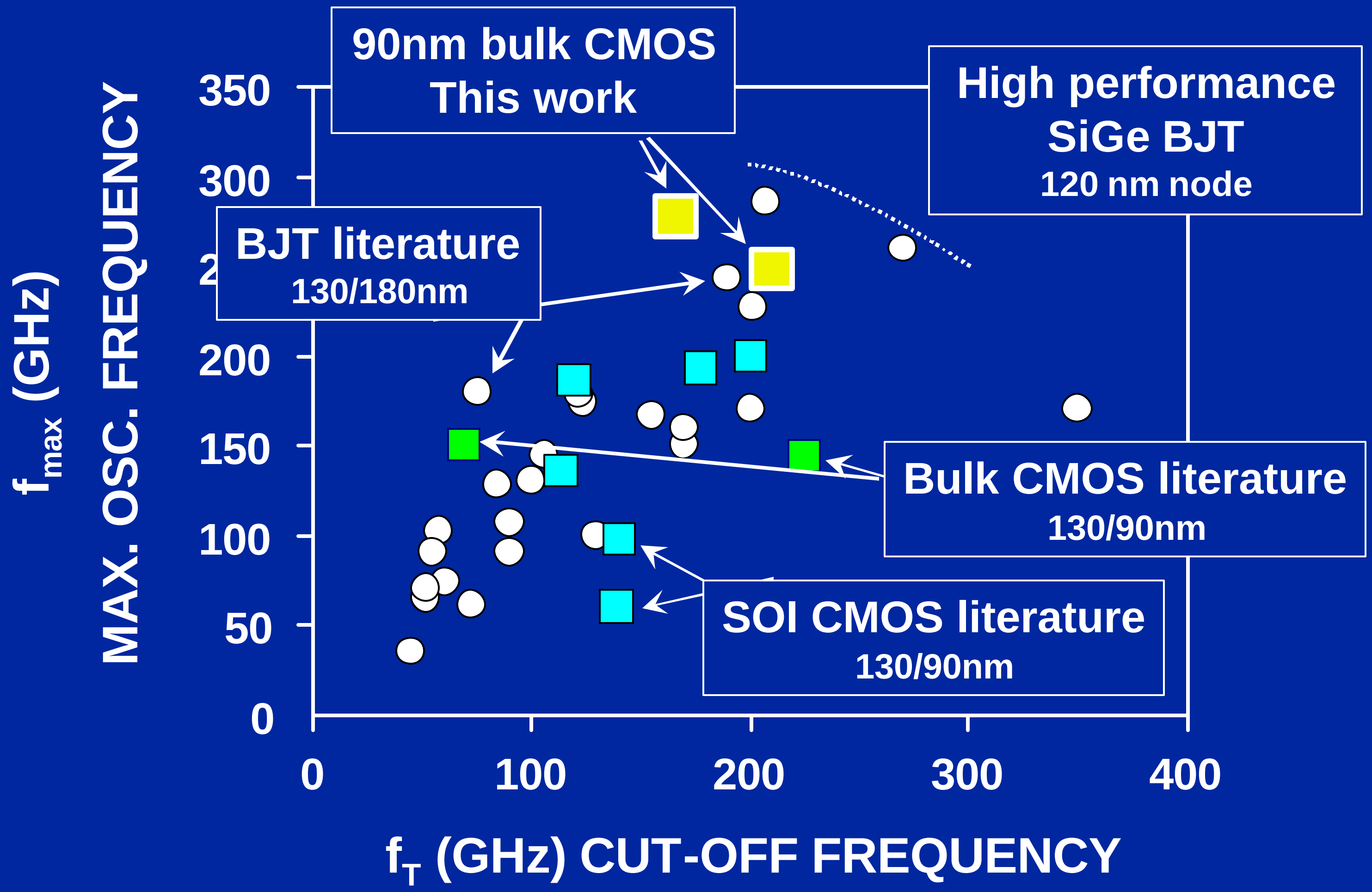


Peak f_{MAX} 277 GHz at 80 nm (248 GHz at 70 nm)

Peak f_T 166 GHz at 80 nm (209 GHz at 70 nm)

Simultaneous peak f_T and f_{MAX} at V_{GS} = 0.8V and V_{DS} = 1.2V
70 nm x 2.5μm x 6 device.

f_T and f_{MAX}: CMOS vs BJT



Key Performance Metrics

- *FREQUENCY*
- *NOISE*
- *MATCHING*
- *g_m/ID_{SAT}*
- *LINEARITY (IP3)*
- *V_A (g_{DS}, R_{OUT})*

Broadband Noise

Noise Figure

$$F = F_{\min} + \frac{4r_n\,|\Gamma_s - \Gamma_{opt}|^2}{(1-|\Gamma_s|^2)\,|1+\Gamma_{opt}|^2}$$

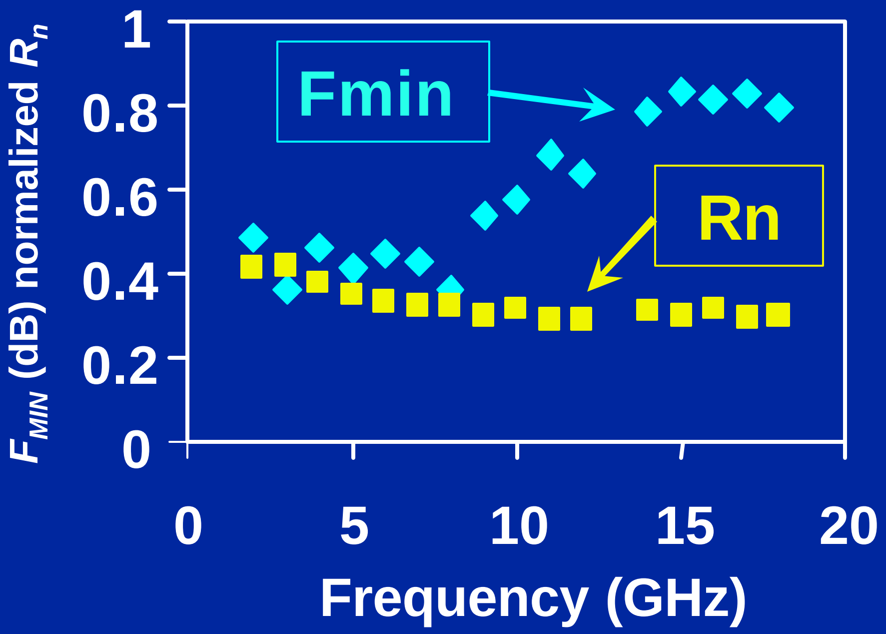
Minimum Noise Figure

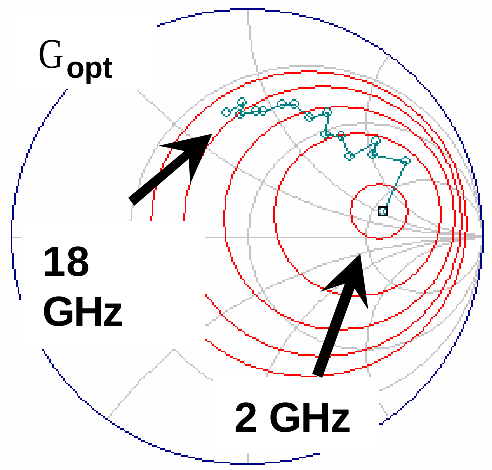
(Fukai equation)

$$F_{\min} = 1 + K\frac{f}{f_t}\sqrt{g_m(R_G + R_S)}$$

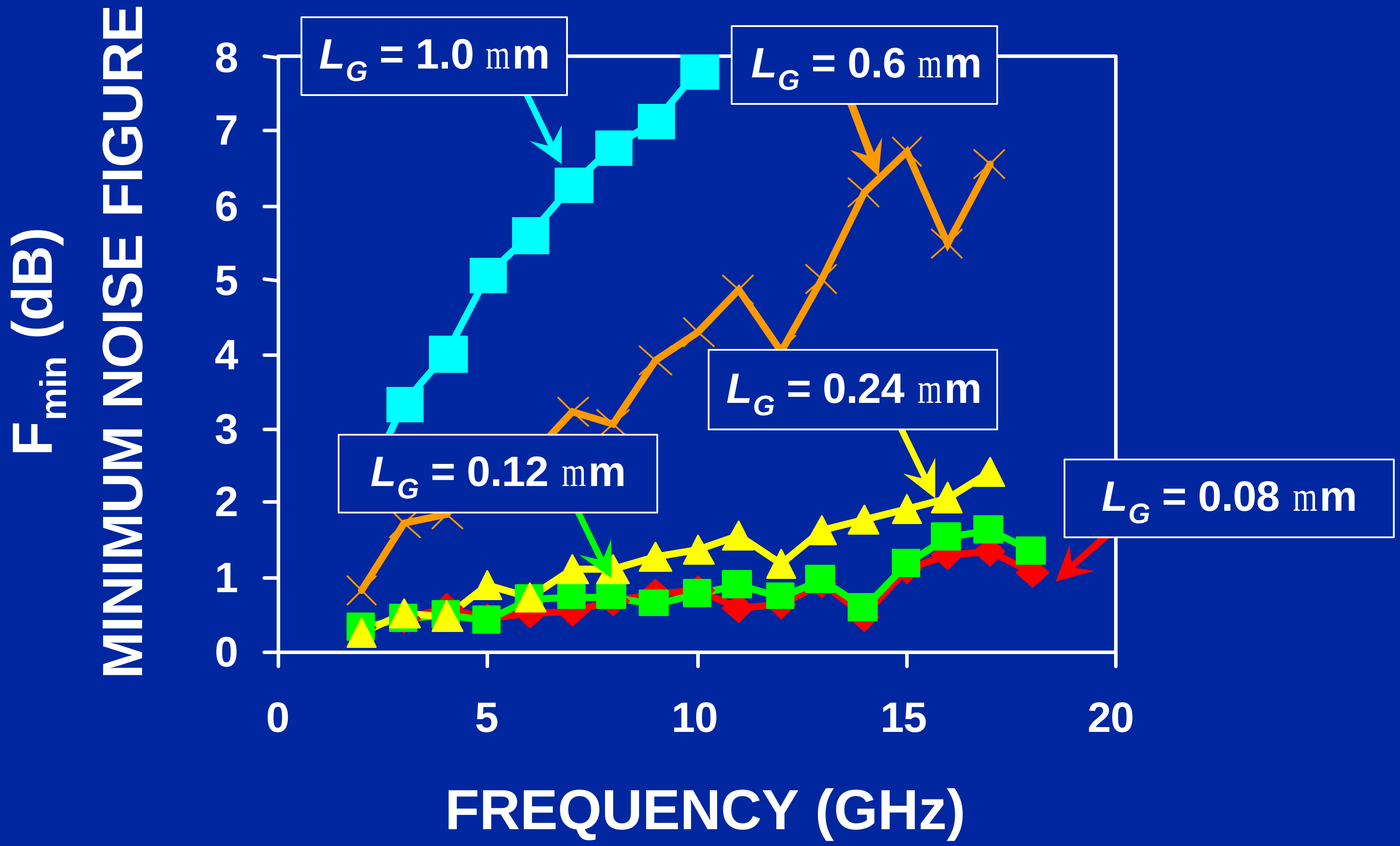
Minimum Noise Figure for a MOSFET

$$F_{\min} = 1 + K\frac{2pfmC_{ox}ZL}{\sqrt{g_m}}\sqrt{R_G + R_S}$$

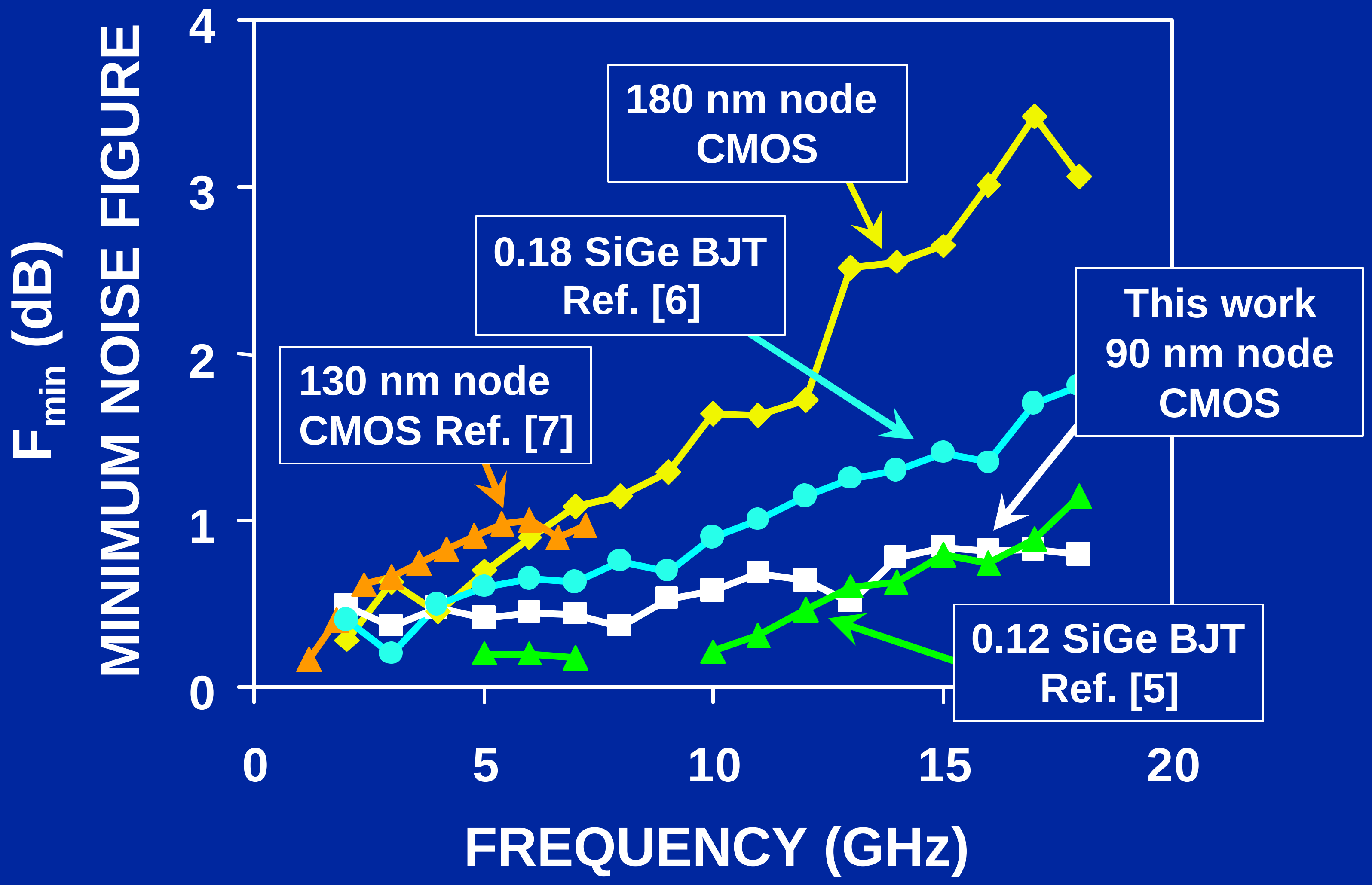




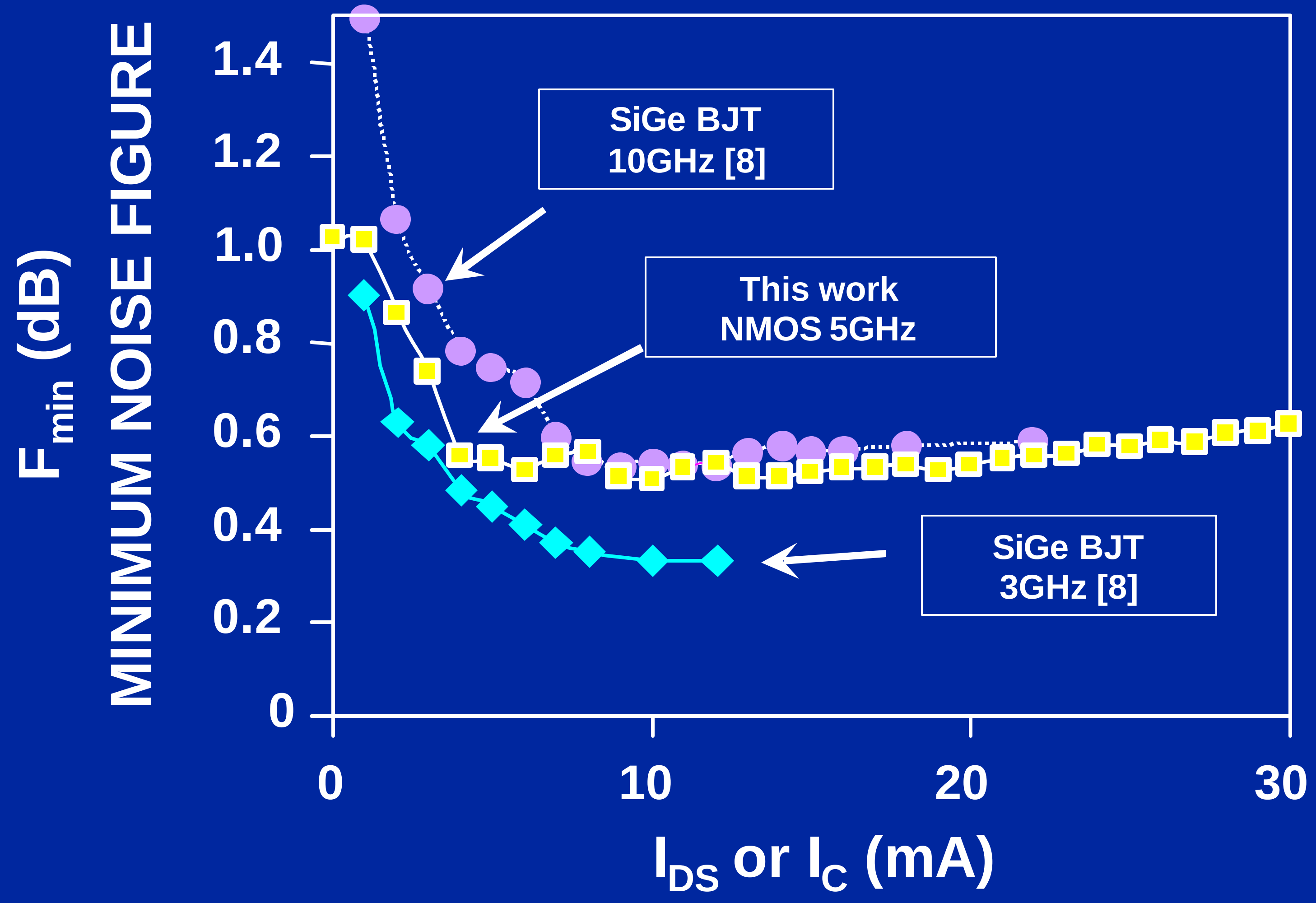
Minimum Noise Figure vs L_G



Minimum Noise Figure: CMOS vs BJT



Minimum Noise Figure: CMOS vs BJT

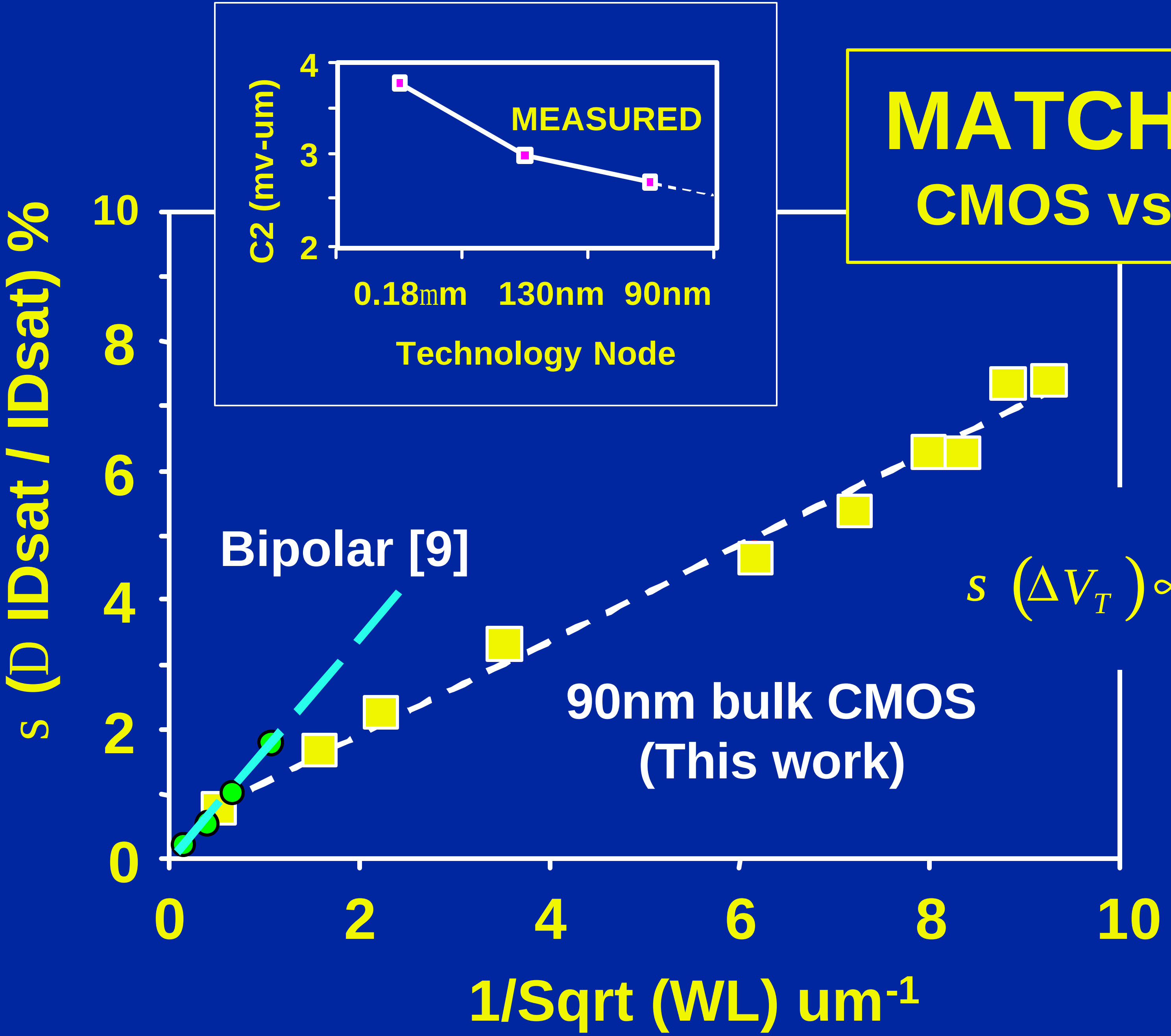


Key Performance Metrics

- *FREQUENCY*
- *NOISE*
- ***MATCHING***
- g_m/ID_{SAT}
- *LINEARITY (IP3)*
- V_A (g_{DS}, R_{OUT})

MATCHING

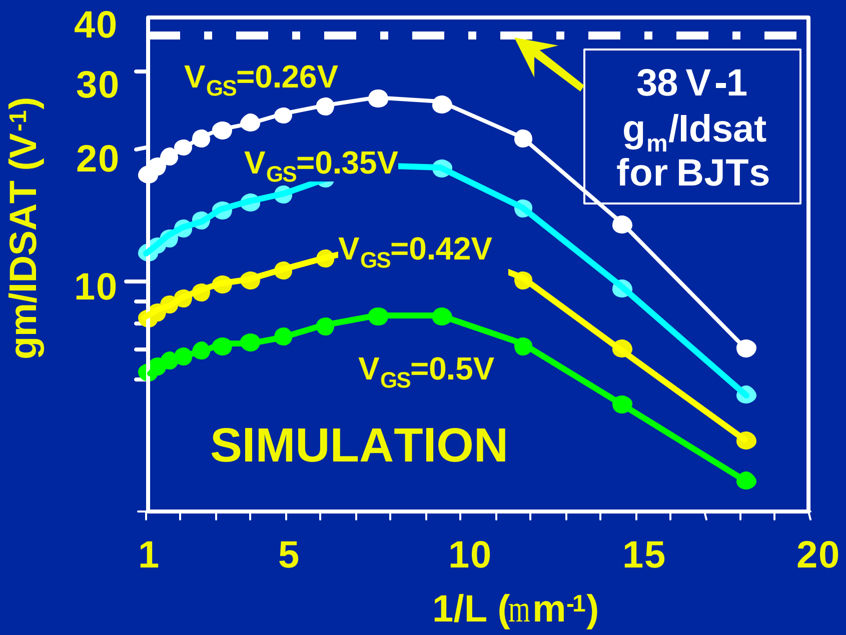
CMOS vs BJT

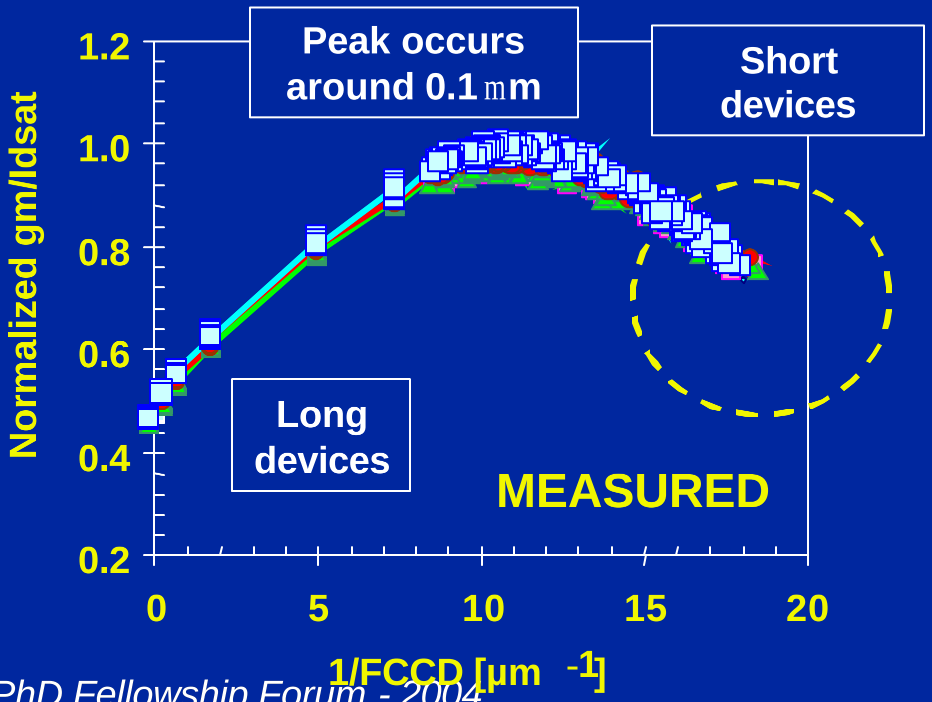


$$\sigma(\Delta V_T) \propto \frac{T_{OX}\sqrt[4]{N}}{\sqrt{W \times L}}$$

Key Performance Metrics

- *FREQUENCY*
- *NOISE*
- *MATCHING*
- g_m/ID_{SAT}
- *LINEARITY (IP3)*
- V_A (g_{DS}, R_{OUT})





g_m/ID_{SAT}

Simulated and measured

→ In 1973, Johnson demonstrated that the maximum (g_m/I_X) for a diffusion current limited device is q/kT.

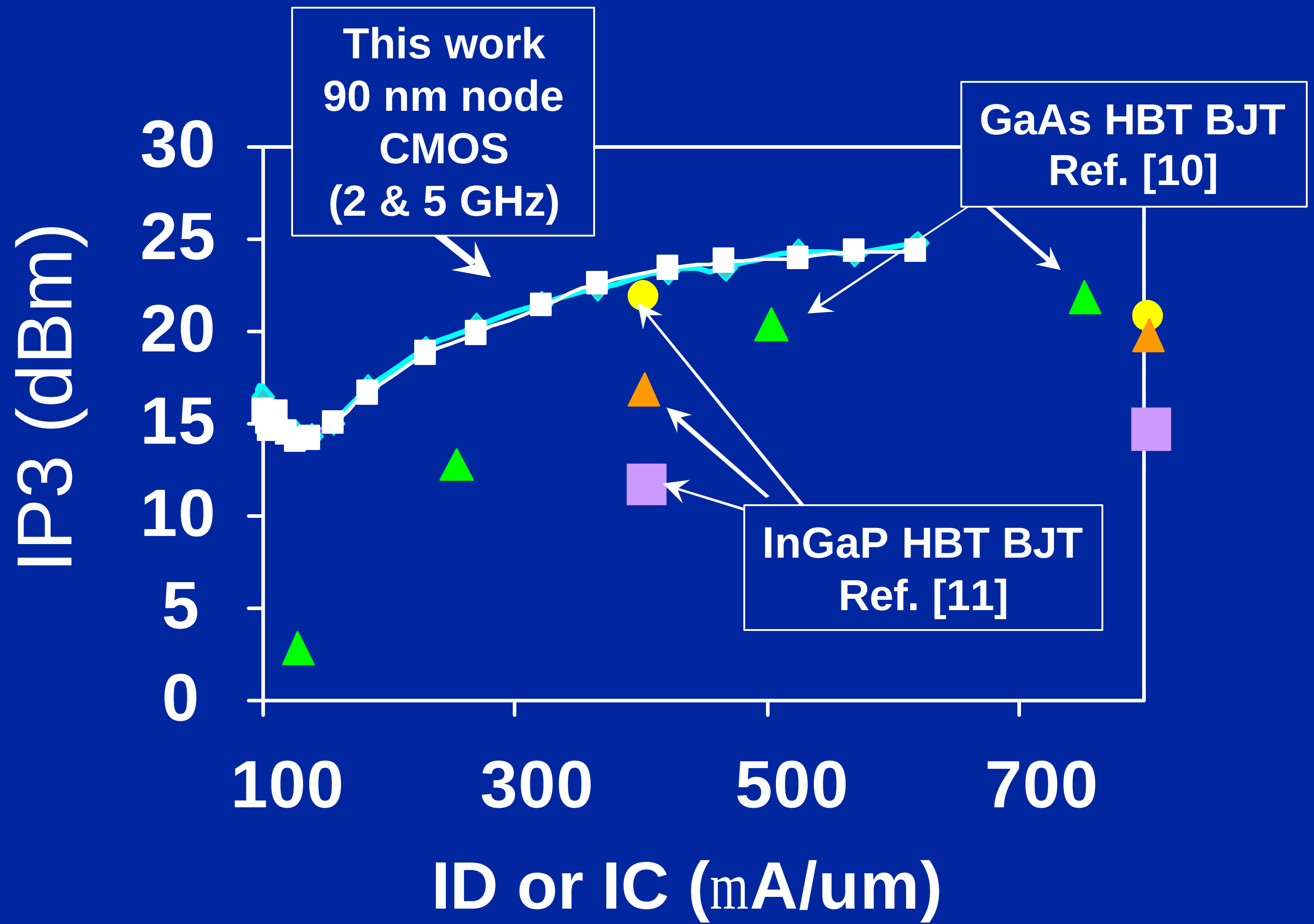
→ g_m/I_{DS} for NMOS devices approaches, but does not yet equal the BJT q/kT=38V^{-1}

→ Note that the optimal g_m/I_{DS} is not at the minimum channel length.

Key Performance Metrics

- *FREQUENCY*
- *NOISE*
- *MATCHING*
- *g_m/ID_{SAT}*
- *LINEARITY (IP3)*
- *V_A (g_{DS}, R_{OUT})*

Linearity (IP3): CMOS vs BJT



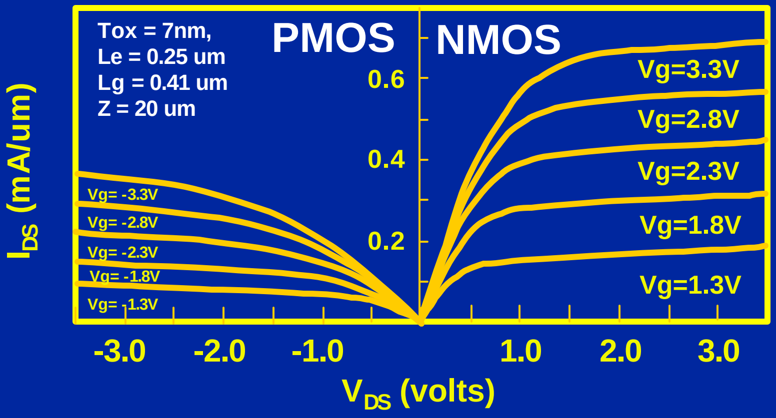
Recall that input IP3 is the input amplitude at which the first and third output harmonics are matched. Output IP3 is the same thing, referenced to the output.

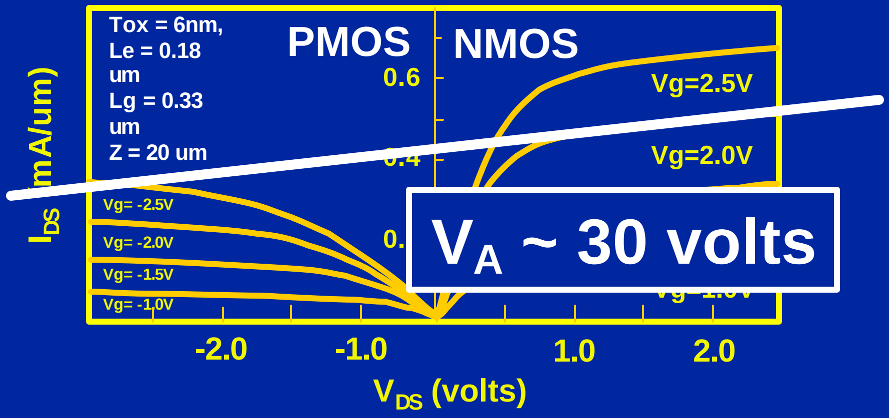
Key Performance Metrics

- *FREQUENCY*
- *NOISE*
- *MATCHING*
- *g_m/ID_{SAT}*
- *LINEARITY (IP3)*
- *V_A (g_{DS}, R_{OUT})*

CMOS Early Voltage, the impact of scaling

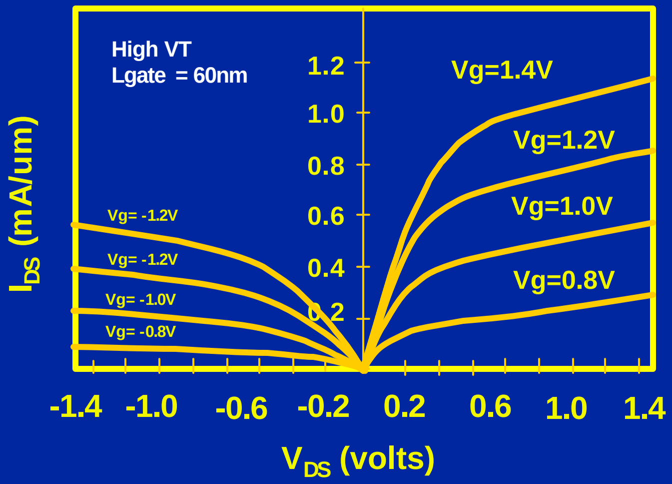
50A gate

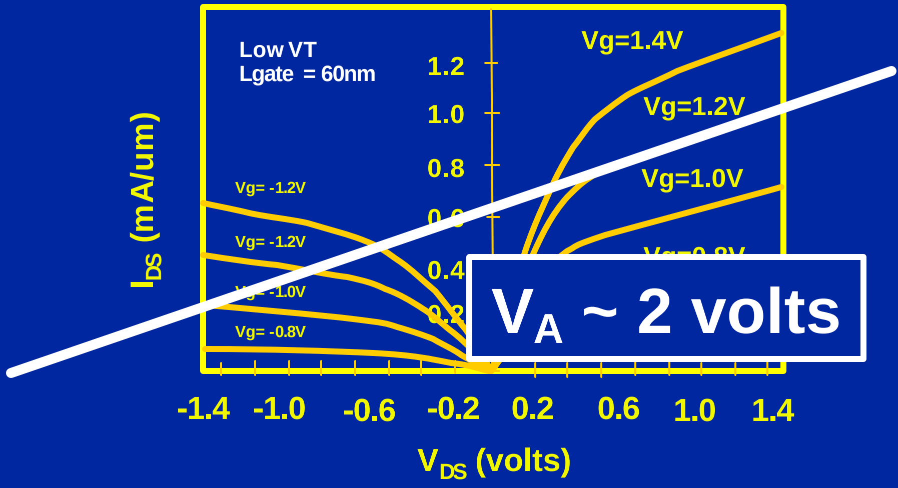




V_A ~ 30 volts

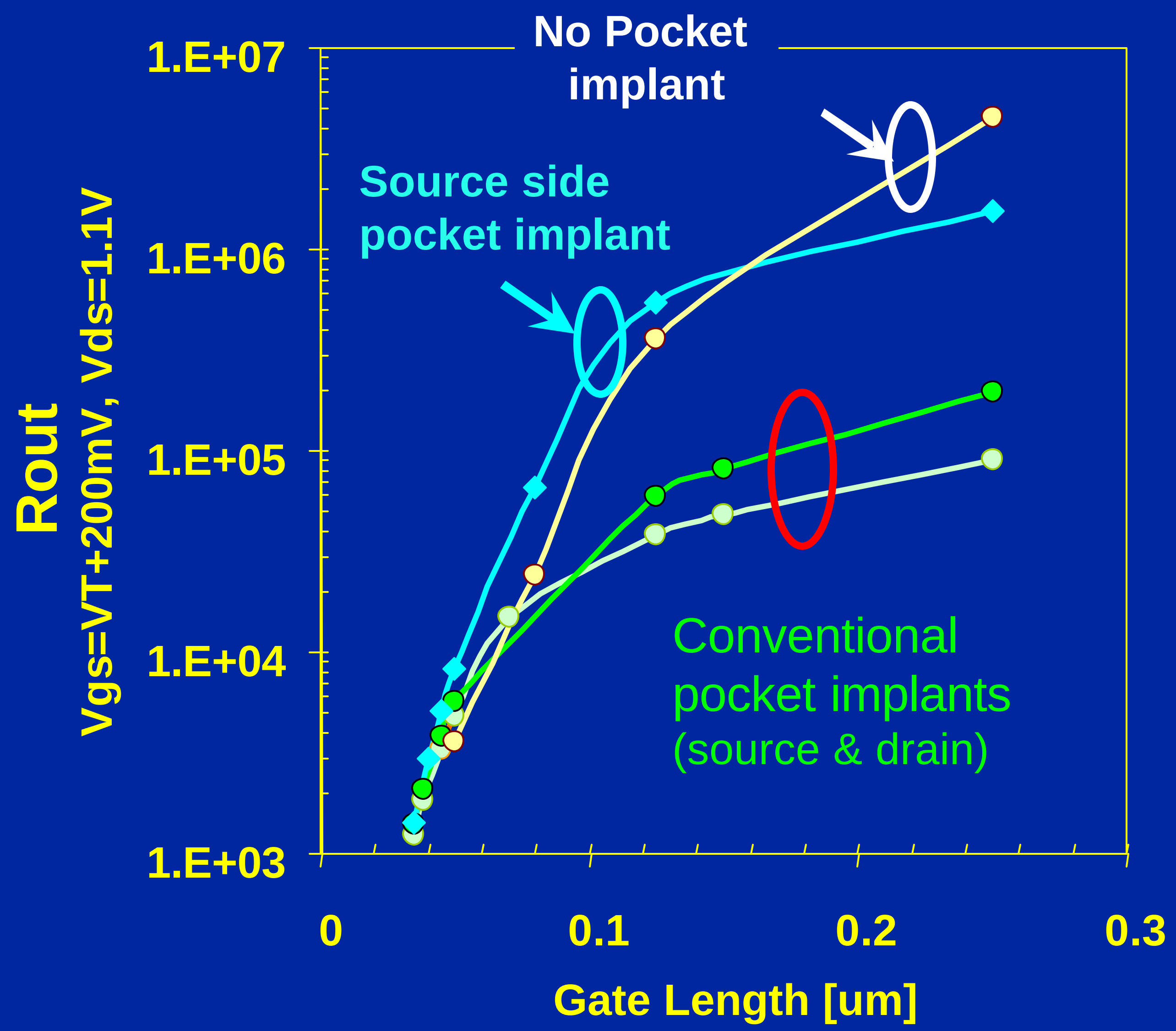
15A gate

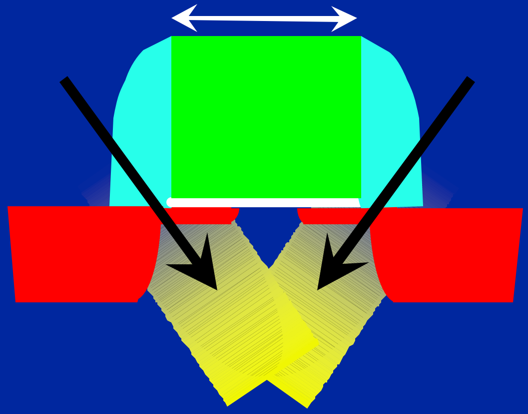




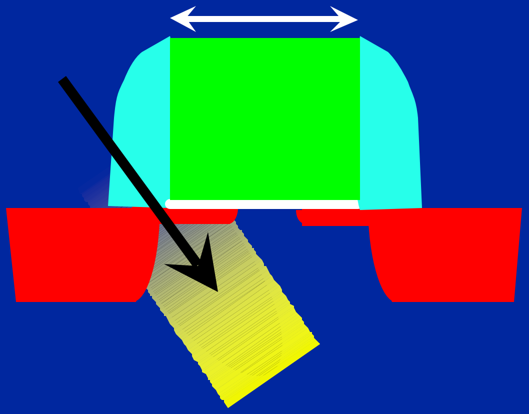
V_A ~ 2 volts

Thompson, S.; et al.; IEDM '02.
Bohr, M.; et al; IEDM ‘94.





Pocket implants for improvement of short channel effects (SCE)



Source side only, Improvement SCE + improvement Rout

SUMMARY

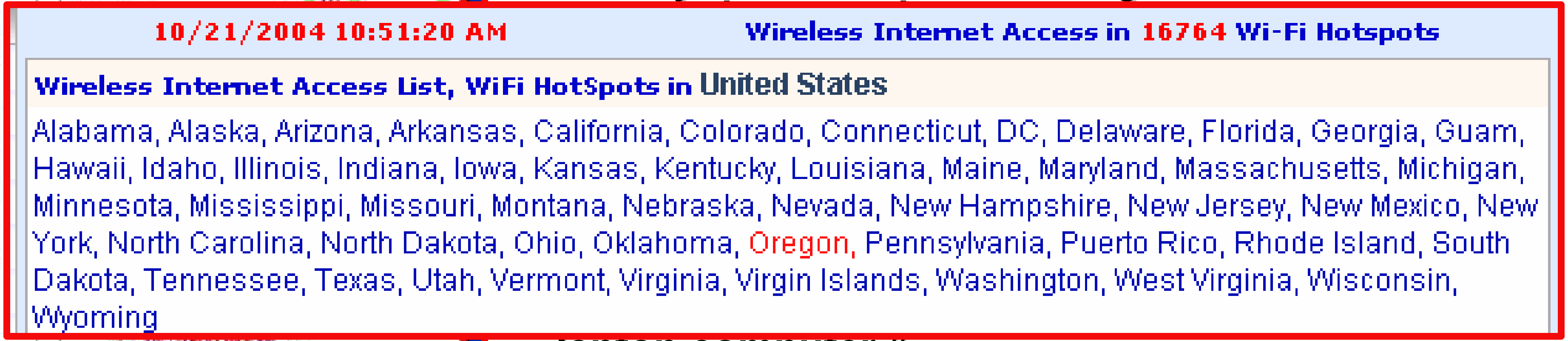
- ***FREQUENCY***
  - **Demonstrated RF NMOS devices at 209/252 GHz f_T/f_{MAX}**
  - **Demonstrated RF NMOS f_{MAX} at 277 GHz at increased Lgate**
  - **Comparable to all but the very highest performance SiGe BJT**
- ***NOISE***
  - **Demonstrated <1dB**
  - **Comparable to SiGe BJTs**
- ***MATCHING***
  - **Equivalent/better to SiGe BJTs**
- **g_m/ID_{SAT}**
  - **Less than BJT's ideal *q/KT***
  - **Can be optimized by proper device targeting**
- ***LINEARITY (IP3)***
  - **Equivalent/better to HBT BJTs**
- **V_A (g_{DS}, R_{OUT})**
  - **Short channel effects prevent equivalent performance to BJTs**
  - **Can be optimized by process changes**

OVERVIEW

- Context
  - What do people want to buy?
- Elements
  - What pieces do we need?
- Integration
  - How do we fit the pieces together?
- **Summary**

- Wi-Fi is like the Internet itself, reenacting the bottoms-up process that surprised people so much -- *Nicholas Negroponte (Professor, MIT)*
- [We need to] “take Wi-Fi from a wireless rogue activity to an industrial-strength solution that

laptop computer.”
-- *Heather Green, Business Week*

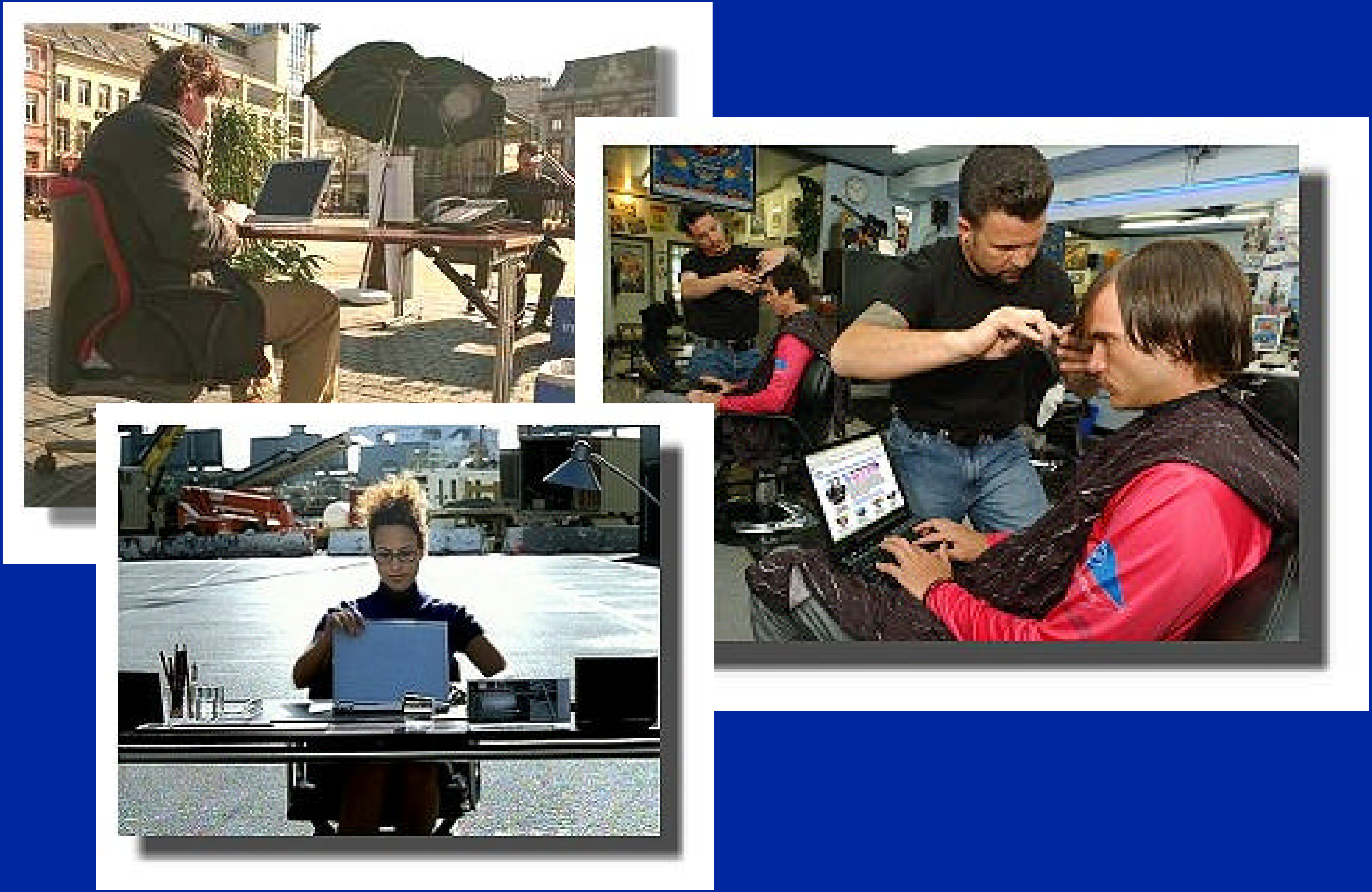


10/21/2004 10:51:20 AM Wireless Internet Access in 16764 Wi-Fi Hotspots

Wireless Internet Access List, WiFi HotSpots in United States

Alabama, Alaska, Arizona, Arkansas, California, Colorado, Connecticut, DC, Delaware, Florida, Georgia, Guam, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, Puerto Rico, Rhode Island, South Dakota, Tennessee, Texas, Utah, Vermont, Virginia, Virgin Islands, Washington, West Virginia, Wisconsin, Wyoming

- Wi-Fi looks obvious now, but there were other competing technologies before. We invested in all of them. As soon as we saw Wi-Fi was winning, our resources shifted. But I think Wi-Fi is going to win long term, too, [in laptops and PDAs]
– *Jim Johnson, general manager for the wireless networking group at Intel)*



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- Sort Test Technology Development
- Quality and Reliability Engineering
- Technology Computer Aided Design

QUESTIONS?

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- So what IS Wi-FI anyway? Short for *wireless fidelity* and is meant to be used generically when referring of any type of 802.11 network, whether 802.11b, 802.11a, dual-band, etc. The term is promulgated by the Wi-Fi Alliance. This group was formerly known as the *Wireless Ethernet Compatibility Alliance* (WECA) but changed its name in October 2002 to better reflect the Wi-Fi brand it wants to build.
- WiMAX from 802.16 is a standards-based wireless technology that provides high-throughput broadband connections over long distances. WiMAX can be used for a number of applications, including "last mile" broadband connections, hotspot and cellular backhaul, and high-speed enterprise connectivity for businesses. Unlike WiFi's 150-foot range, WiMax has a reach of one to 10 miles, offering a way to bring the Internet to entire communities without having to invest billions of dollars to install phone or cable networks. An implementation of the IEEE 802.16 standard, WiMAX provides metropolitan area network connectivity at speeds of up to 75 Mb/sec. WiMAX systems can be used to transmit signal as far as 30 miles. However, on the average a WiMAX base-station installation will likely cover between three to five miles.
- Formerly, the term "Wi-Fi" was used only in place of the 2.4GHz 802.11b standard, in the same way that "Ethernet" is used in place of IEEE 802.3. The Alliance expanded the generic use of the term in an attempt to stop confusion about wireless LAN interoperability.

- In its infancy, long before Wi-Fi took shape, the radio technology belonged to businesses. The year was 1985. The Federal Communications Commission had opened up slivers of the radio spectrum for experimentation. Researchers at a vanguard of companies, including NCR (NCR), Symbol Technologies (SBL), and Apple Computer (AAPL), started building wireless networks. Their goal was to link everything from cash registers to auto assembly lines. But momentum slowed in the late '80s as the companies developed systems that didn't work together.

  An NCR Corp. scientist named Vic Hayes stepped into the mess in 1990. Hayes led the movement toward a standard. It was a long and combative process, but in 1997, it led to the release of 802.11b, now known as Wi-Fi, or Wireless Fidelity. Two years later, Apple kick-started the market by adding Wi-Fi to its iBook portables for the then-stunningly low price of $99.

  The race was on. In cities worldwide, tech geeks began setting up wireless networks. Led by pioneers such as Rob Flickenger in San Francisco and Anthony Townsend in New York, these techies jerry-built Linux-based hot spots and cheap alternatives to expensive gear. Famously, they improvised antennas using empty Pringles cans. And in the 21st century equivalent of barn-raisings, they united to link neighbors to the growing community networks. Says Townsend, who co-founded NYCwireless in 2000 with Terry Schmidt: "Our model of Wi-Fi is if you charge people to use it, it's not useful." Now the pair runs a business that builds community networks.

- Any products tested and approved as "Wi-Fi Certified" (a registered trademark) by the Wi-Fi Alliance are certified as interoperable with each other, even if they are from different manufacturers. A user with a "Wi-Fi Certified" product can use any brand of access point with any other brand of client hardware that also is certified. Typically, however, any Wi-Fi product using the same radio frequency (for example, 2.4GHz for 802.11b or 11g, 5GHz for 802.11a) will work with any other, even if not "Wi-Fi Certified." While all 802.11a/b/g products are called Wi-Fi, only products that have passed the Wi-Fi Alliance testing are allowed to refer to their products as "Wi-Fi Certified" (a registered trademark). Products that pass are required to carry an identifying seal on their packaging that states "Wi-Fi Certified" and indicates the radio frequency band used (2.5GHz for 802.11b or 11g, 5GHz for 802.11a)

- While Wi-Fi Nation was taking shape in the streets, a smattering of businesses were adapting the new networks to their own needs. In 2000, At CareGroup Inc. hospitals in Massachusetts, engineers installed wireless systems to connect more than 2,000 doctors and nurses to the corporate system. This way, whether they were in emergency rooms or intensive-care units, they could access patient records, add observations to the database, and check on medicines. "It's cost-effective, and the doctors love it," says Chief Information Officer John D. Halamka, who estimates that the system helps reduce costly medical errors by 50%.

  Early on, entrepreneurs saw opportunity in the burgeoning Wi-Fi community. Sky Dayton, founder of Internet service Earthlink Inc., believed that if anyone could unite the ragtag collection of hot spots and network communities into a secure nationwide network, there was a fortune to be made. In 2001, he founded Boingo Wireless Inc. The idea was to certify networks everywhere as Boingo providers. Then, when subscribers paying up to $50 a month turned on their laptops and saw a Boingo connection, they'd log in. Boingo, based in Santa Monica, Calif., and local providers would split the take.