RFIC Design and Testing for Wireless Communications

A PragaTI (TI India Technical University) Course
July 18, 21, 22, 2008

Lecture 5: Semiconductor history, RF characteristics

By

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Course Objective

The boom of wireless and mobile networks has led to an ever-increasing demand for high performance, low power, and low cost RFIC design. Advances in silicon and silicon-germanium based technologies can now provide highly integrated system-on-chip (SOC). With WLAN and cellular standards operating in very different frequency bands, market leading wireless solutions have to offer multi-mode interoperability with transparent worldwide usage. The increasing demand for wireless multimedia applications such as video streaming keeps pushing future wireless systems to support higher data rates at higher link reliability and over greater distances. A multiple-input multiple-output (MIMO) wireless system in combination with space-time signal processing allows increased data rate, improved transmission range and link reliability without additional costs in bandwidth or power.

In spite of a significant motivation, the engineering education today lacks coverage of RFIC design and test techniques. Wireless networks provide plenty of design challenges with both academic and commercial values. This course provides information about fundamentals of wireless communication systems and building block designs of wireless transceivers. The course starts with a discussion on multi-com radios for multi-standard coexistence issues on RFIC designs. It then focuses on wireless transceiver IC designs such as low-noise-amplifier (LNA), mixer, and voltage-controlled oscillator (VCO) designs. The course presents essential topics in RFIC testing.

RFIC Design and Testing for Wireless Communications

References:

[1] J. Kelly and M. Engelhardt, *Advanced Production Testing of RF, SoC, and SiP Devices*, Boston: Artech House, 2007.

[2] B. Razavi, *RF Microelectronics*, Upper Saddle River, New Jersey: Prentice Hall PTR, 1998.

[3] J. Rogers, C. Plett and F. Dai, *Integrated Circuit Design for High-Speed Frequency Synthesis*, Boston: Artech House, 2006.

[4] K. B. Schaub and J. Kelly, *Production Testing of RF and System-on-a-chip Devices for Wireless Communications*, Boston: Artech House, 2004.

RFIC Design and Testing for Wireless Communications

Topics

Monday, July 21, 2008

9:00 – 10:30	Introduction – Semiconductor history, RF characteristics
11:00 – 12:30	Basic Concepts – Linearity, noise figure, dynamic range
2:00 – 3:30	RF front-end design – LNA, mixer
4:00 – 5:30	Frequency synthesizer design I (PLL)

Tuesday, July 22, 2008

9:00 – 10:30	Frequency synthesizer design II (VCO)
11:00 – 12:30	RFIC design for wireless communications
2:00 – 3:30	Analog and mixed signal testing

Schedule, July 18, 2008

09:00AM – 10:30AM	Lecture 1	Introduction	Agrawal
10:30AM – 11:00AM	Break		
11:00AM – 12:30PM	Lecture 2	Power & Gain	Agrawal
12:30PM – 01:30PM	Lunch		
01:30PM – 03:00PM	Lecture 3	Distortion	Agrawal
03:00PM – 03:30PM	Break		
03:30PM – 05:00PM	Lecture 4	Noise	Agrawal

Schedule, July 21, 2008

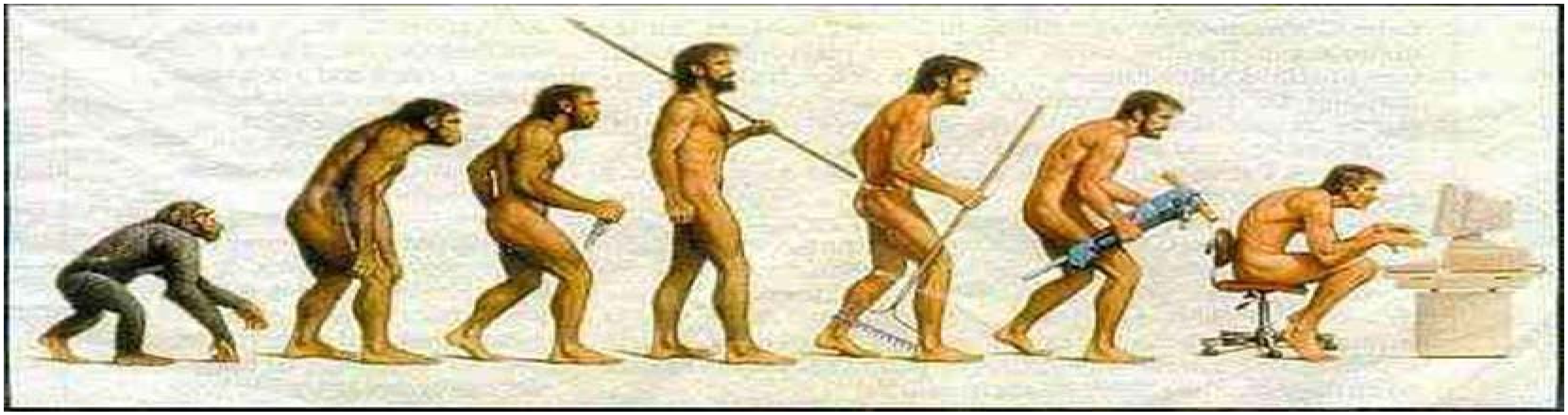
09:00AM – 10:30AM	Lecture 5	RF Design I	Dai
10:30AM – 11:00AM	Break		
11:00AM – 12:30PM	Lecture 6	RF Design II	Dai
12:30PM – 01:30PM	Lunch		
01:30PM – 03:00PM	Lecture 7	RF Design III	Dai
03:00PM – 03:30PM	Break		
03:30PM – 05:00PM	Lecture 8	RF Design IV	Dai

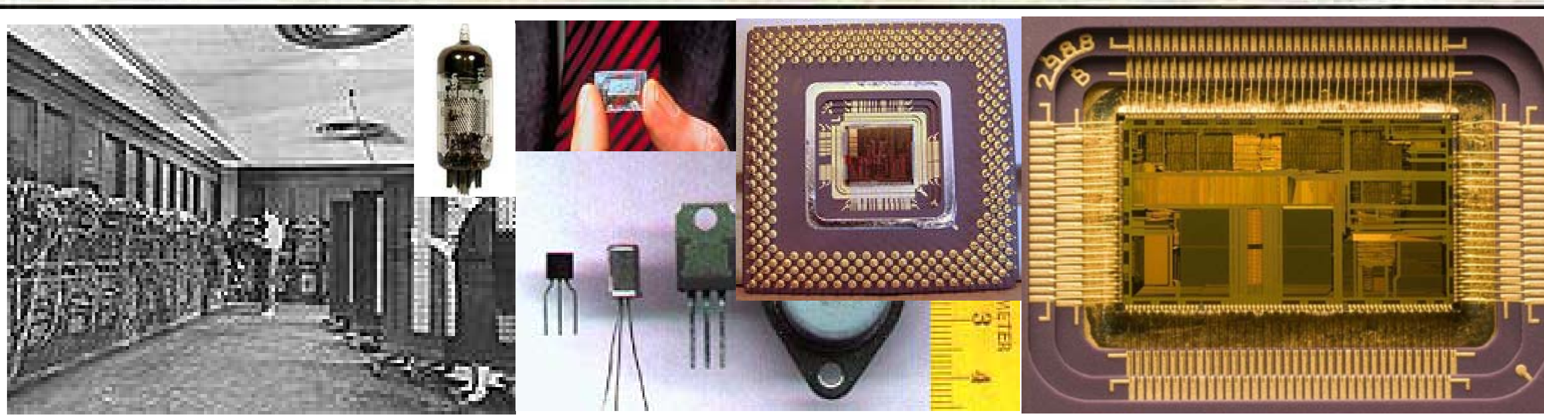
Schedule, July 22, 2008

09:00AM – 10:30AM	Lecture 9	RF Design V	Dai
10:30AM – 11:00AM	Break		
11:00AM – 12:30PM	Lecture 10	RF Design VI	Dai
12:30PM – 01:30PM	Lunch		
01:30PM – 03:00PM	Lecture 11	ATE & SOC Test	Agrawal
03:00PM – 03:30PM	Break		
03:30PM – 05:00PM	Lecture 12	BIST	Dai

The Evolution of Electronics

Computers had been built using vacuum tubes since 1950s. With the advent of the microchip in the 1960s, this could be done on a single chip using essentially a printing process.





Microelectronics Proliferation

- The integrated circuit was invented in 1958.
- World transistor production has more than doubled every year for the past twenty years.
- Every year, more transistors are produced than in all previous years combined.
- Approximately 10^{18} transistors were produced in a recent year.
- Roughly 10 transistors for every ant in the world.

*Source: Gordon Moore’s Plenary address at the 2003 International Solid State Circuits Conference.

A Few Astonishing Facts About ICs

- The aggregate number of transistors produced annually exceeds the number of ants on Earth. For each of an estimated 170dB ants, the IC industry fabricates about ten transistors each year, and that number is increasing exponentially.
- There were more transistors made annually than raindrops falling on California.
- The number of transistors produced annually exceeds the number of characters printed in all publications in the world!

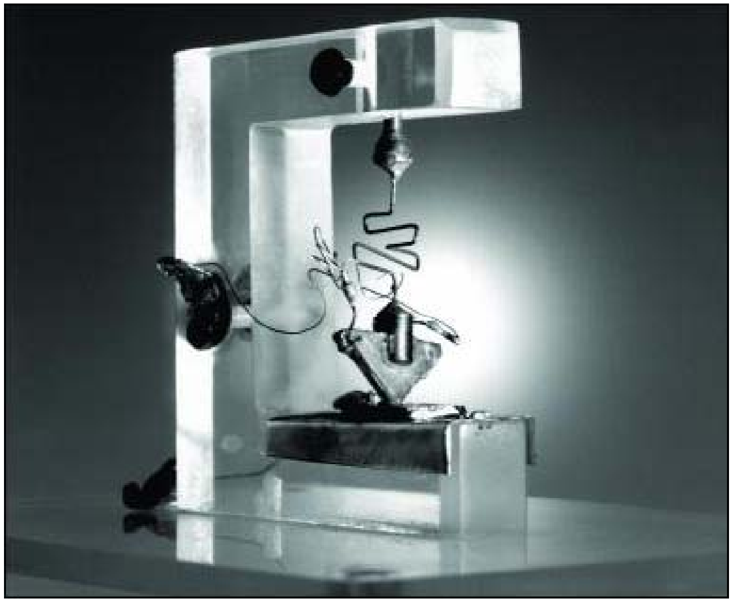
How did we get to this point?

How long can this continue?

And what comes next?

The Start of the Modern Electronics Era

Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.



The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world GDP.

The Birth of Silicon Valley

- By the mid-1950s, millions of radios, television sets and other electronic devices were produced every year by such giants of American industry as General Electric, RCA and Sylvania, but they came in large, cumbersome boxes powered by balky vacuum tubes.
- In 1952, Bell Lab made licenses for transistors available for a modest fee of $25K plus future royalty.
- In 1952 Gordon Teal left Bell Lab to work for Geophysical Services, Inc., which later became Texas Instrument. In 1954, TI began producing Ge junction transistors for a portable radio, which hit U.S. stores in Oct. at $49.95. TI abandoned this market, only to watch it be cornered by a little-known Japanese company that called itself SONY.
- Despite Shockley's numerous technical achievements, his inability to get along with many of his colleagues did not go unnoticed at the Labs. Shockley left Bell Labs in 1955 for his hometown of Palo Alto, California, where his aged mother still lived. He founded the very first semiconductor company Shockley Semiconductor Laboratory in San Francisco area.
- He assembled a remarkably talented founding group, but was unable to manage them well. On 18 September 1957, eight gifted employees (Traitorous Eight) jumped ship to start Fairchild Semiconductor Corp.
- Moore and Robert Noyce left Fairchild to found Intel in 1968. Ultimately, Shockley's company changed hands a couple of times, finally disappeared. Never having turned a profit, Shockley gave up his entrepreneurial ambitions and became a Stanford professor.

The Fairchild Traitorous Eight

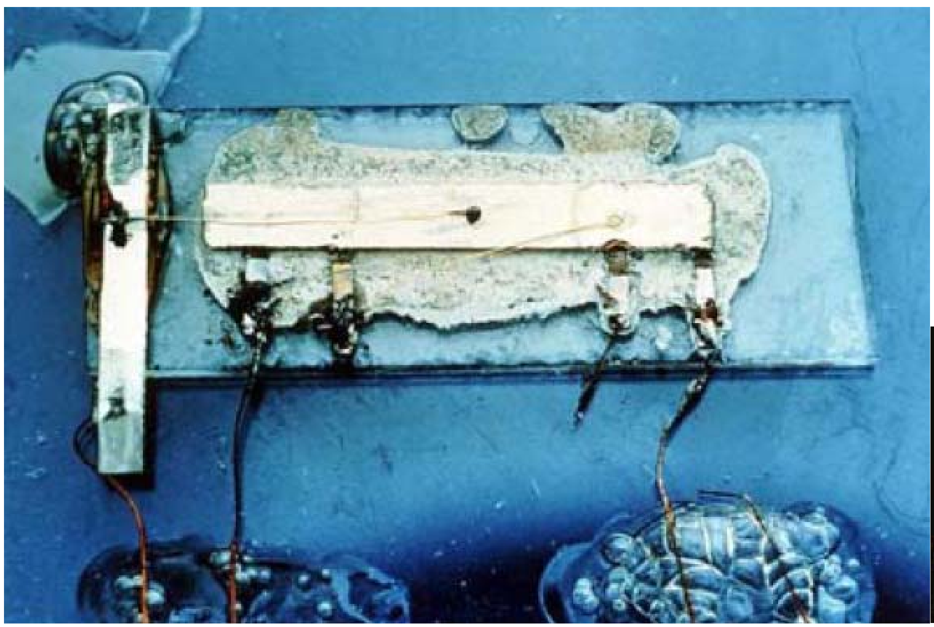
From left, Gordon Moore, Sheldon Roberts, Eugene Kleiner, Robert Noyce, Victor Grinich, Julius Blank, Jean Hoerni, and Jay Last.

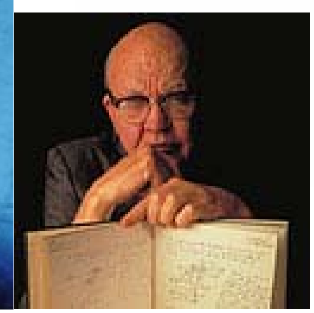
The Invention of Integrated Circuits

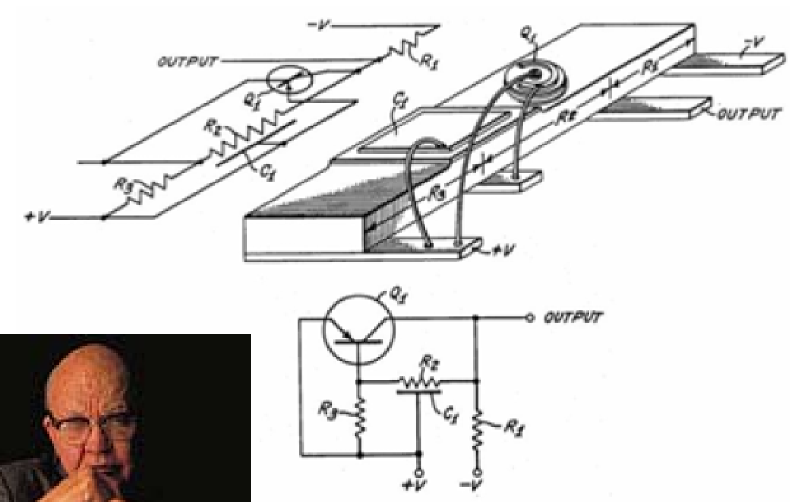
- Because of its initially poor reliability and far lower frequency response, Bell Labs did not pursue MOS technology further in 1961, and cast its lot initially with BJTs. This left the door wide open to RCA and Fairchild. By the time Bell Labs returned to MOS technology in the late 1960s, Fairchild researchers had solved its difficult problems, and had a commanding lead.
- It was Texas Instruments and Fairchild Semiconductor that took the next giant steps in the history of the semiconductor industry.
- Jack Kilby filed this patent for the integrated circuit nine years after John Bardeen and Walter Brattain were awarded the patent for the transistor. Using diffusion technology pioneered by Bell Labs, Jack Kilby figured out how to fabricate the world's first integrated circuit at Texas Instruments in 1958. Like Bardeen and Brattain's clumsy point-contact transistor, his first device was a delicate prototype; it used diffused junctions in a single chip of germanium.
- At Fairchild, Bob Noyce combined the planar process ideas invented by his colleague, Jean Hoerni, with his own ideas about photolithographically-defined interconnect and junction isolation. Fairchild was the first to describe a complete flow for building an IC. Fairchild first described their IC at the 1960 IRE-AIEE Conference on Transistor Circuits (later to become ISSCC).
- While Kilby's invention is more on devices, Noyce solved the interconnection and planar processing problems. Noyce and Kilby, the co-inventors of the integrated circuit, shared the Nobel Prize in Physics in 2000.

The First IC: Kilby’s 1.3MHz RC Oscillator

Jack Kilby joined TI in Dallas in 1958. During the summer of 1958, he conceived and built the first IC in which all of the components, both active and passive, were fabricated in a single piece of semiconductor material half the size of a paper clip. On 9/12/1958, Kilby successfully demonstrated a 1.3MHz integrated RC oscillator. Because TI had not yet mastered the art of diffusion in silicon, the first IC was built out of germanium bits. Bondwires interconnected the various components because Kilby had not solved that problem yet.







Electronics Milestones

1874 Braun invents the solid-state rectifier.

1906 DeForest invents triode vacuum tube.

1907-1927

First radio circuits developed from diodes and triodes.

1925 Lilienfeld field-effect device patent filed.

1947 Bardeen and Brattain at Bell Laboratories invent bipolar transistors.

1952 Commercial bipolar transistor production at Texas Instruments.

1956 Bardeen, Brattain, and Shockley receive Nobel prize.

1958 Integrated circuits developed by Kilby and Noyce

1961 First commercial IC from Fairchild Semiconductor

1963 IEEE formed from merger of IRE and AIEE

1968 First commercial IC opamp

1970 One transistor DRAM cell invented by Dennard at IBM.

1971 4004 Intel microprocessor introduced.

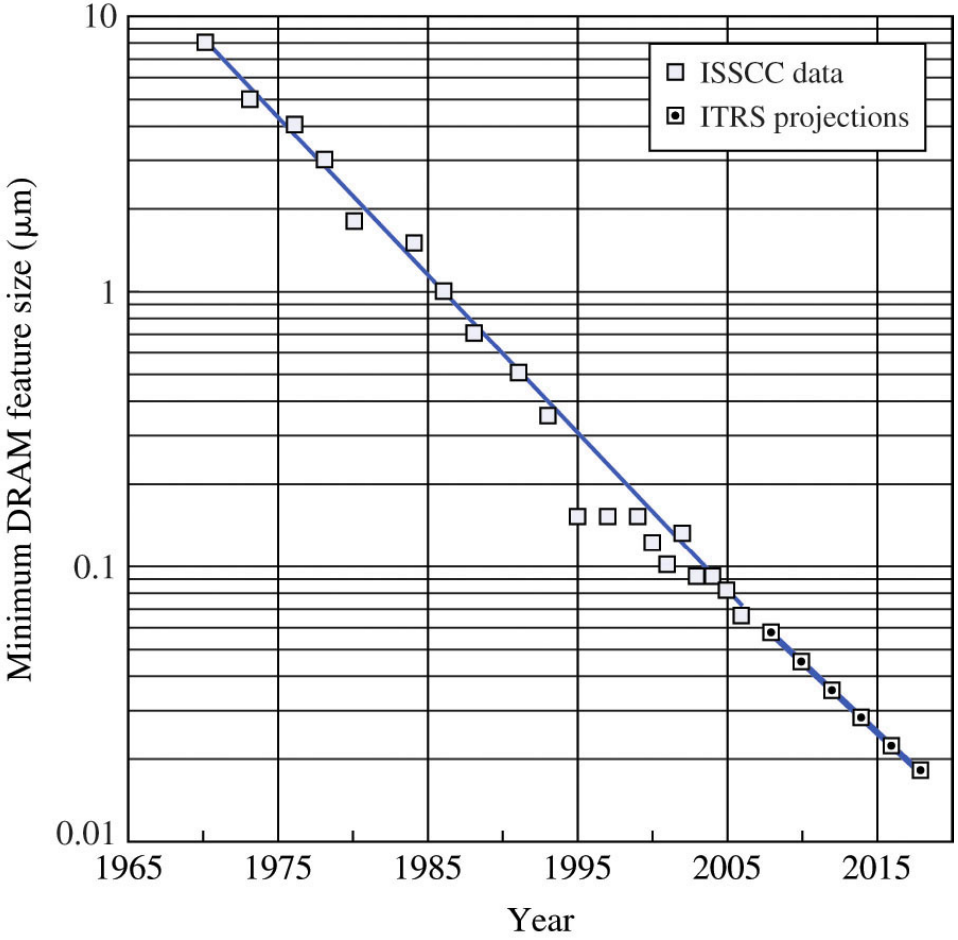
1978 First commercial 1-kilobit memory.

1974 8080 microprocessor introduced.

1984 Megabit memory chip introduced.

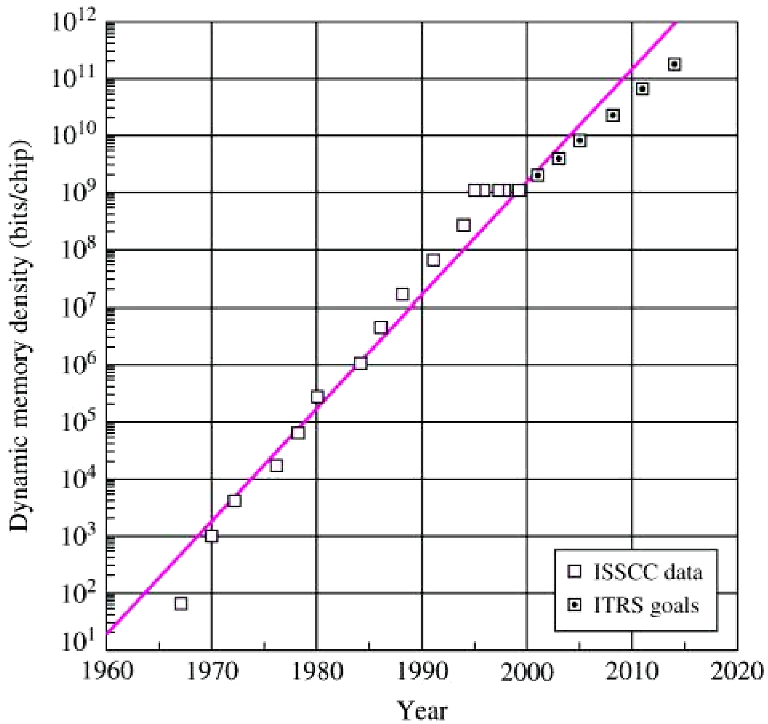
2000 Alferov, Kilby, and Kromer share Nobel prize

Device Feature Size

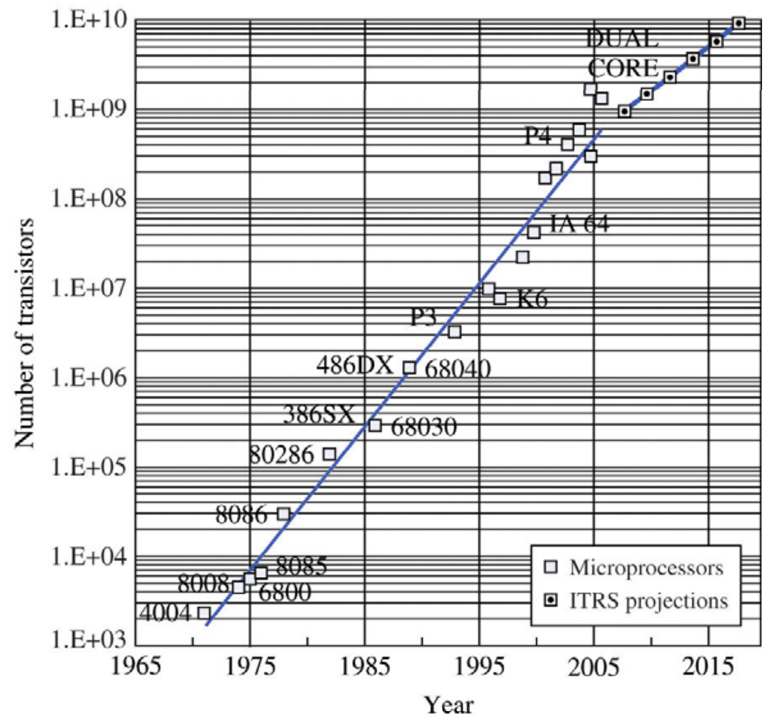


- Feature size reductions enabled by process innovations.
- Smaller features lead to more transistors per unit area and therefore higher density.
- 0.13um and 90nm CMOS become the main frame processes right now.

Rapid Increase in Density of Microelectronics

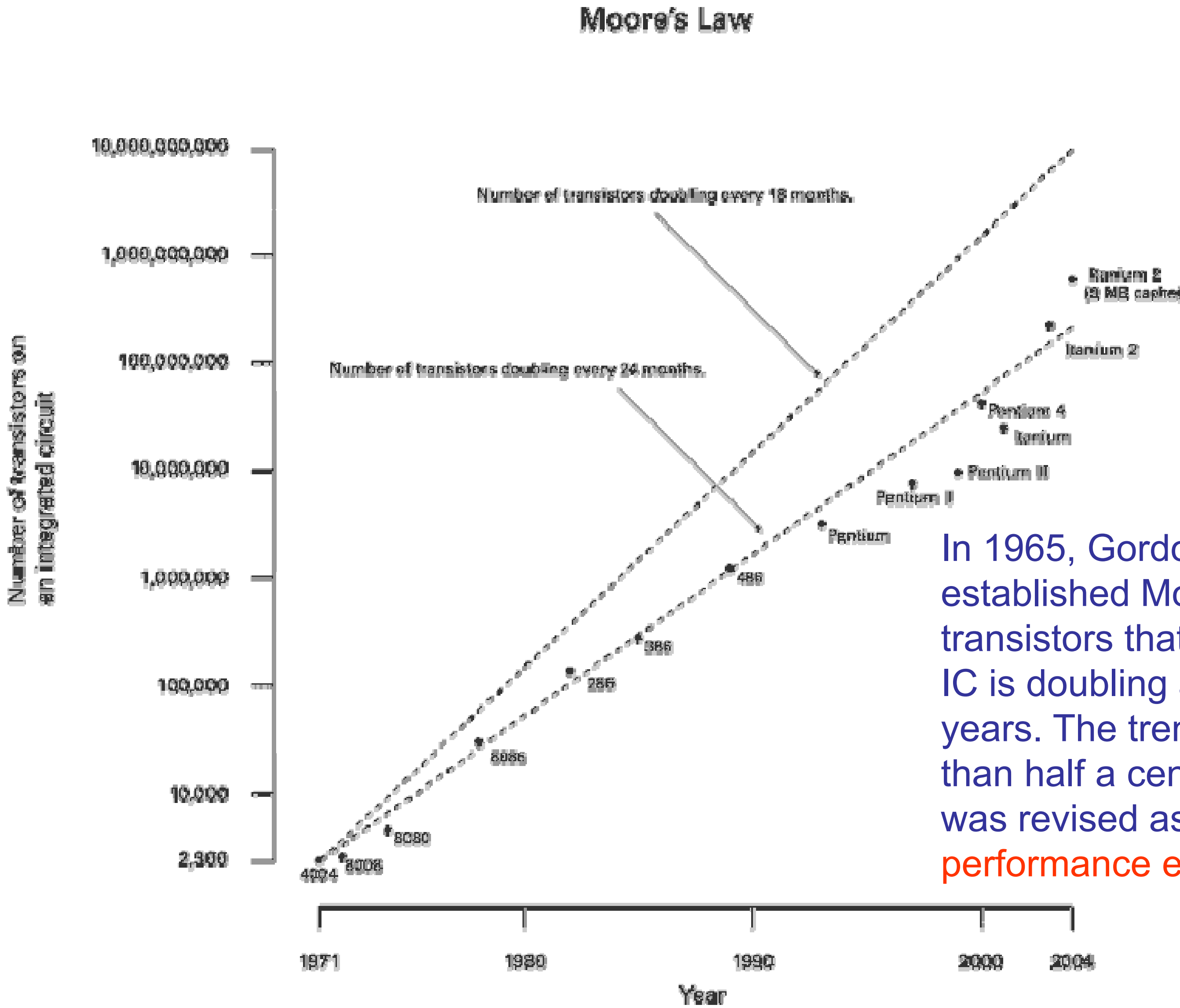


Memory chip density
versus time.



Microprocessor complexity
versus time.

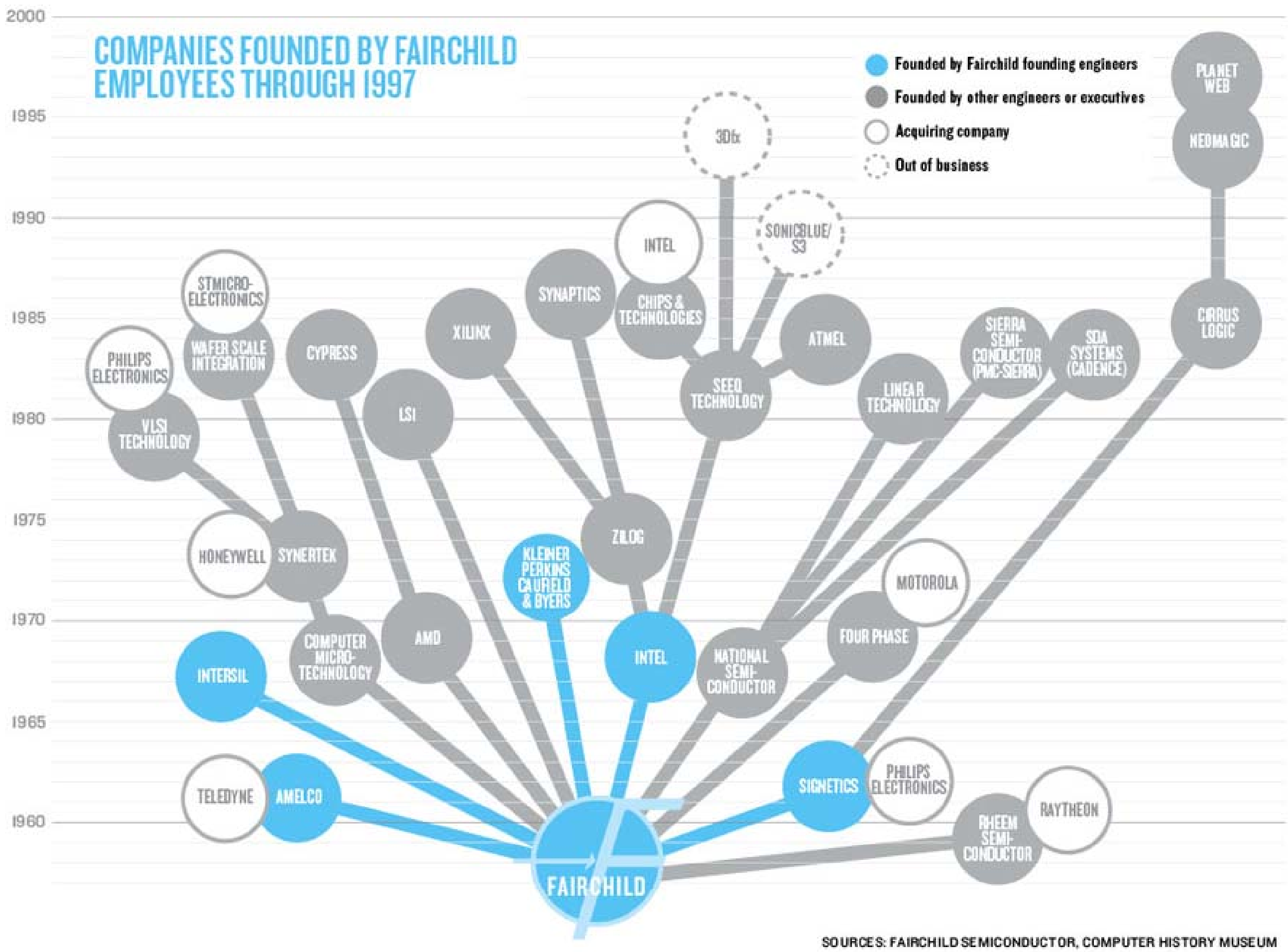
Moore’s Law and The Booming of IC Industry



In 1965, Gordon E. Moore at Fairchild established Moore’s law: the number of transistors that can be integrated on an IC is doubling approximately every two years. The trend has continued for more than half a century. In 1975, the rule was revised as IC would double in performance every 18 months.

Children of Fairchild

In the past 50 year, executives and engineers from Fairchild founded many of the most influential technology firms in Silicon Valley, including Intel, AMD, Xilinx, and one of the best-known venture capital firms, Kleiner Perkins Caufield & Byers. Fairchild itself was purchased by National Semiconductor in 1987. 10 years later it was spun out as an independent company, focused on power-related chips.



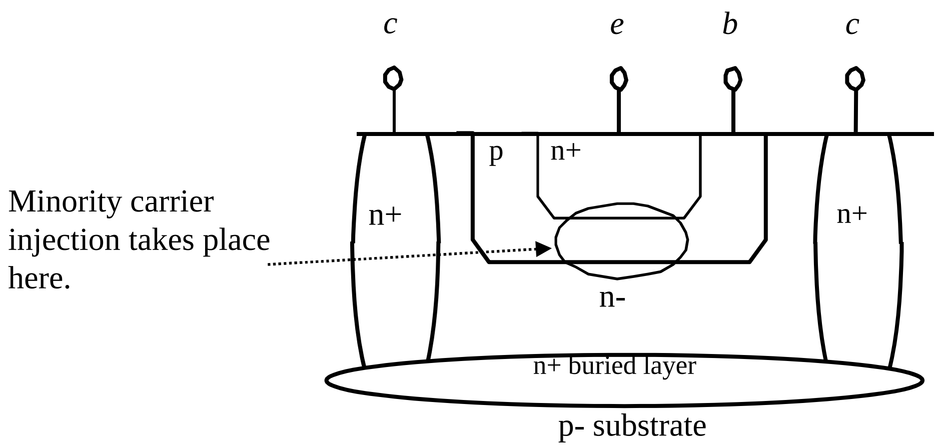
Is The Game Over?

- In 1949 Shockley called the "nerve cell" of the electronic computers that were just then emerging. Today, almost no electronic equipment can be made without transistors. Are all the good stuff has already been invented?

- There is a big gap of performance between carbon and silicon:
- Leading-edge microprocessors today consume on the order of 100 watts, but have yet to compose anything like Beethoven's Symposium.
- The human brain consumes about 20-25 watts, and is capable of performing all kinds of things that a computer cannot do.
- Despite the apparent performance deficit at the device level, comparing the picosecond-level switching speeds of electronics to the microsecond speeds of cells, biology wins by an enormous margin even without going digital.
- As rocket scientist Wernher von Braun famously noted, "Man is the only computer that can be mass-produced by unskilled labor."

- Nature has thus provided ample evidence that we have only scratched the surface. There is still plenty of room to grow and plenty of game to play!

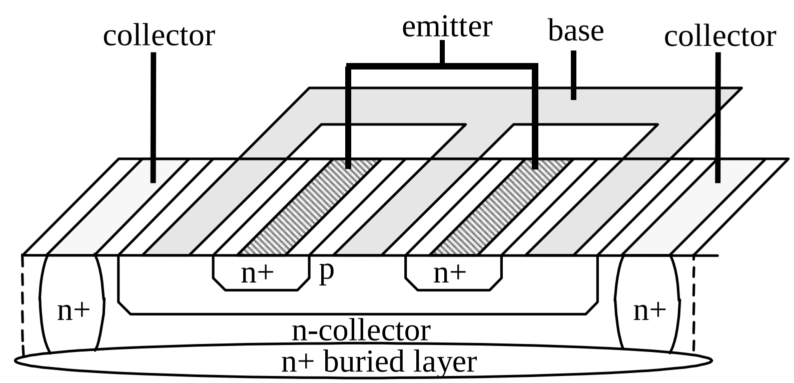
NPN Bipolar Transistor



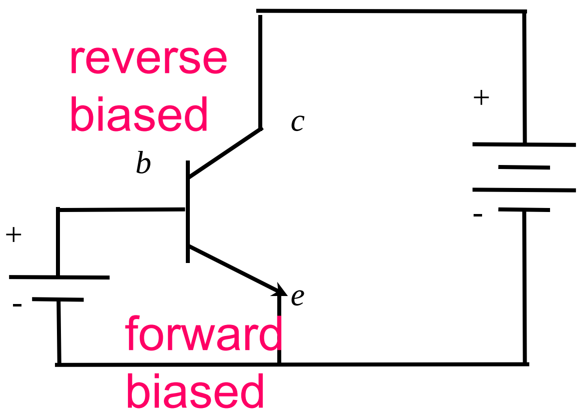
e = emitter

b = base

c = collector



$$i_c + i_b = i_c$$



- Biasing:
- Normal Operation: V_{BE}>V_{th}, V_{CB} > 0
- Soft saturation: V_{BE}>V_{th}, V_{CB} > -0.3V

BJT Small-Signal Parameters

- Forward current gain

$$\beta = \underbrace{\frac{i_c}{i_b}}_{small-signal} = \underbrace{\frac{\Delta I_C}{\Delta I_B}}_{\Delta large-signal}$$

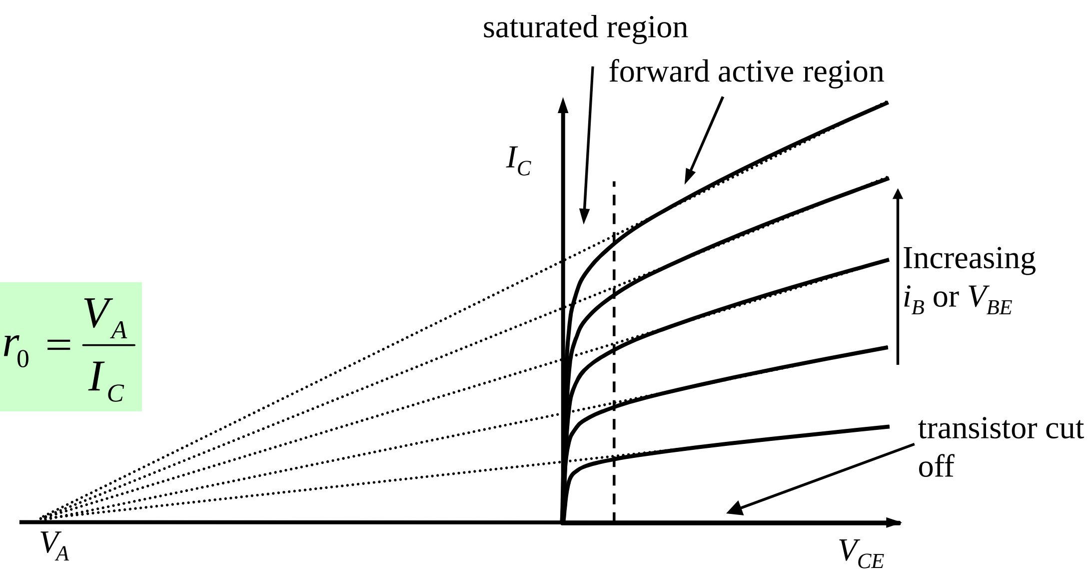
$$\beta = g_m r_\pi$$

- Trans-conductance

$$g_m = \frac{i_c}{v_\pi} = \frac{I_C}{v_T} = \frac{I_c q}{kT} \qquad v_T = \frac{kT}{q}$$

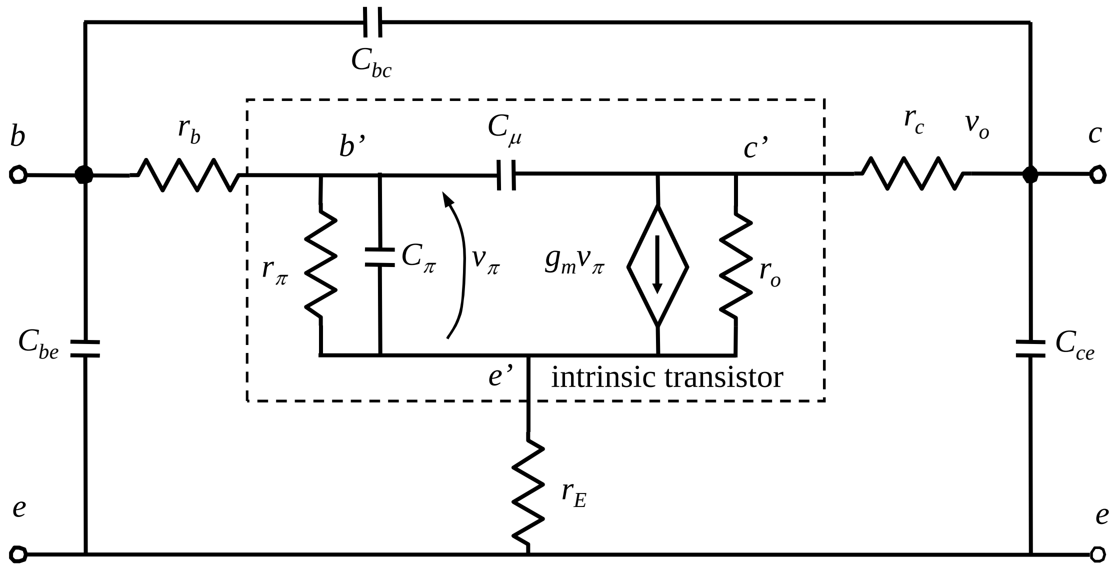
$$i_c = \beta i_b = g_m v_\pi = g_m i_b r_\pi$$

$$r_0 = \frac{V_A}{I_C}$$



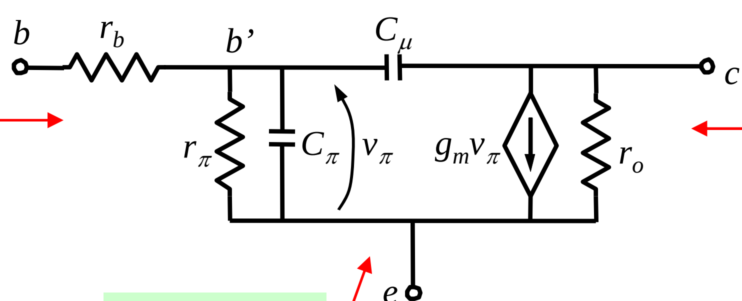
$$I_C = I_S\left(1 + \frac{V_{CE}}{V_A}\right)e^{(V_{BE}/v_T)}$$

BJT Small-Signal Model



$r_\pi, C_\pi, C_\mu, g_m, r_e, r_0$ depend on bias

Simplified Model



$$Z_{in} \approx r_b + r_\pi // C_\pi // C_\mu$$
$$\approx r_b + r_\pi // C_\pi$$
$$\approx r_\pi = \frac{\beta_0}{g_m} (\text{low freq})$$

$$Z_o \approx \frac{V_A}{I_C} = \frac{V_A}{g_m V_T}$$

$$Z_E \approx r_e = \frac{V_T}{g_m}$$

BJT High-Frequency Effects -- f_T

$$\beta(\omega) = \frac{\beta_o}{1 + j\,\omega/\omega_\beta}$$

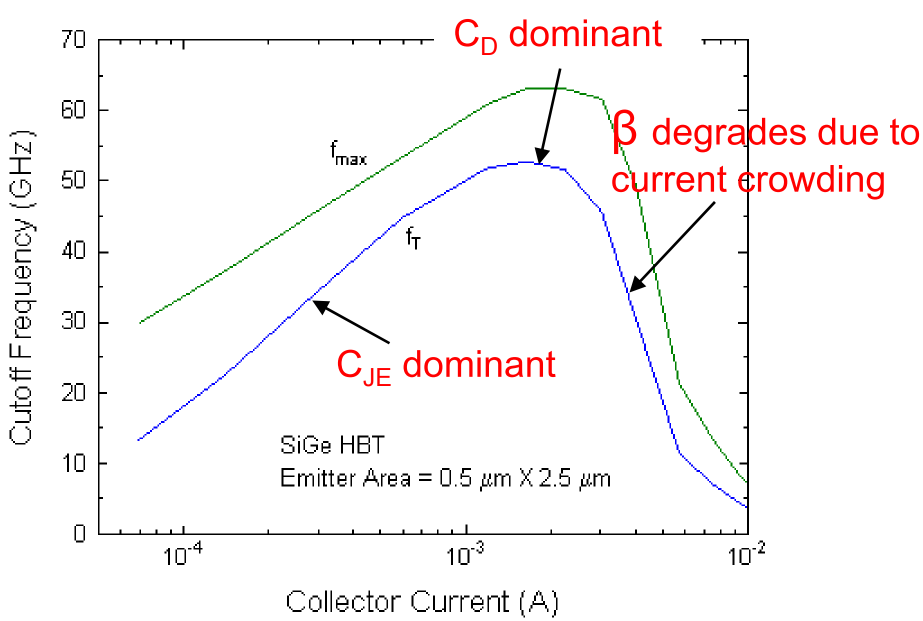
3-dB corner frequency

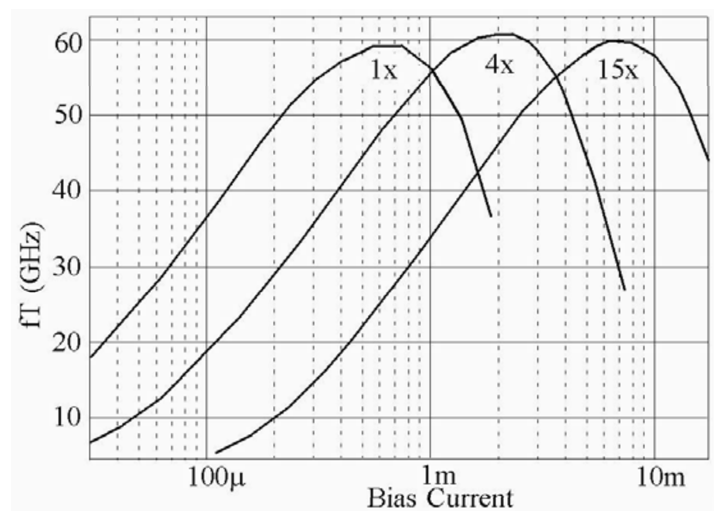
$$f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)} = \frac{1}{2\pi r_\pi C_\pi}$$

- f_T is the frequency at which the short-circuit current gain β is equal to 1 → unity current gain-bandwidth product. Useful to specify the maximum switching frequency for CML circuits and gain/bandwidth of an amplifier.

$$f_T = \beta f_\beta = \frac{g_m}{2\pi (C_\pi + C_\mu)} \approx \frac{g_m}{2\pi C_\pi} = \frac{I_C}{2\pi C_\pi V_T}$$

Emitter-base junction capacitance proportional to A_E → scaling peak f_T current by scaling emitter length





BJT High-Frequency Effects -- f_{MAX}

- f_{max} is the frequency at which maximum available power gain $G_{A,max}$ is equal to 1 →unity power gain-bandwidth product. Useful to specify the maximum oscillation frequency.

- The output power P_0
- and power gain:

$$P_0 = \frac{i_c^2 \Re\{z_0\}}{4} = \frac{g_m v_b^2}{4 r_b^2 \omega^2 k^2 C_\pi C_\mu}$$

$$\frac{P_0}{P_i} = \frac{g_m}{4 r_b \omega^2 k^2 C_\pi C_\mu}$$

- Set equal to 1, one can solve for *fmax:*

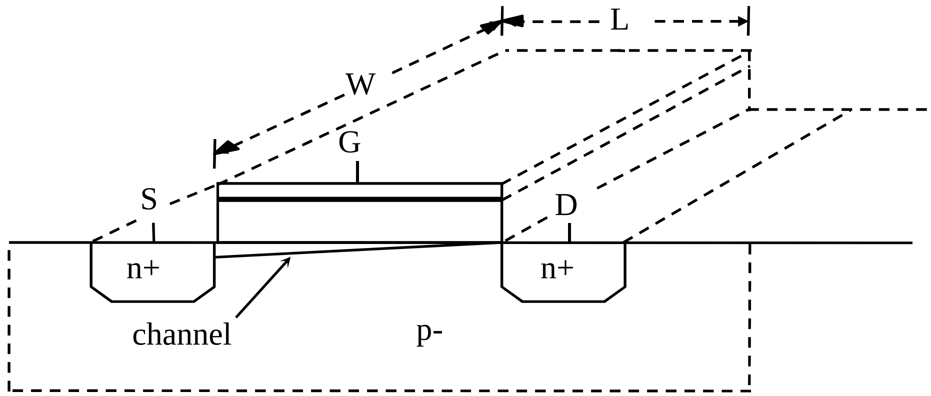
$$f_{\max} = \frac{1}{2\pi}\sqrt{\frac{g_m}{4 r_b \omega^2 k^2 C_\pi C_\mu}} = \sqrt{\frac{f_T}{8\pi r_b k^2 C_\mu}} = \frac{1}{4\pi r_{bb}}\sqrt{\frac{\beta}{k^2 C_\pi C_\mu}}$$

where r_{bb} is the total base resistance given by k=3/2 due to Miller multiplication.

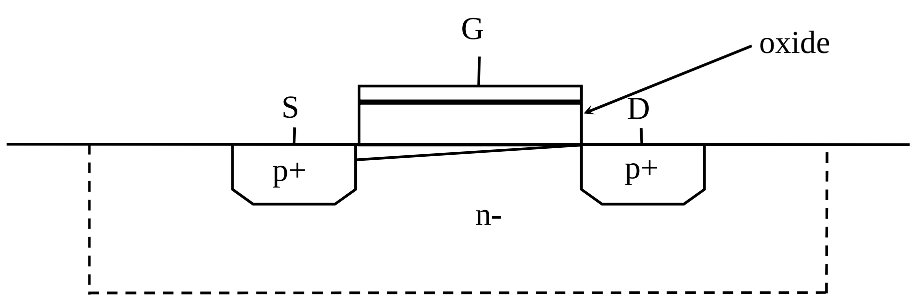
$$r_{bb} = \sqrt{r_b r_\pi}$$

CMOS Transistors

- CMOS is necessary to implement baseband digital or DSP functions. For low cost applications, CMOS-only process is desired to implement both digital and RF functions on the same chip – system on chip (SOC).



NMOS



PMOS

CMOS Transistor Parameters

- In saturation region: $i_{DS}^{sat} = \frac{\mu C_{ox}}{2}\left(\frac{W}{L}\right)\frac{(v_{GS}-V_T)^2}{1+\alpha(v_{GS}-V_T)}(1+\lambda v_{DS}) \approx \frac{\mu C_{ox}}{2}\left(\frac{W}{L}\right)(v_{GS}-V_T)^2$

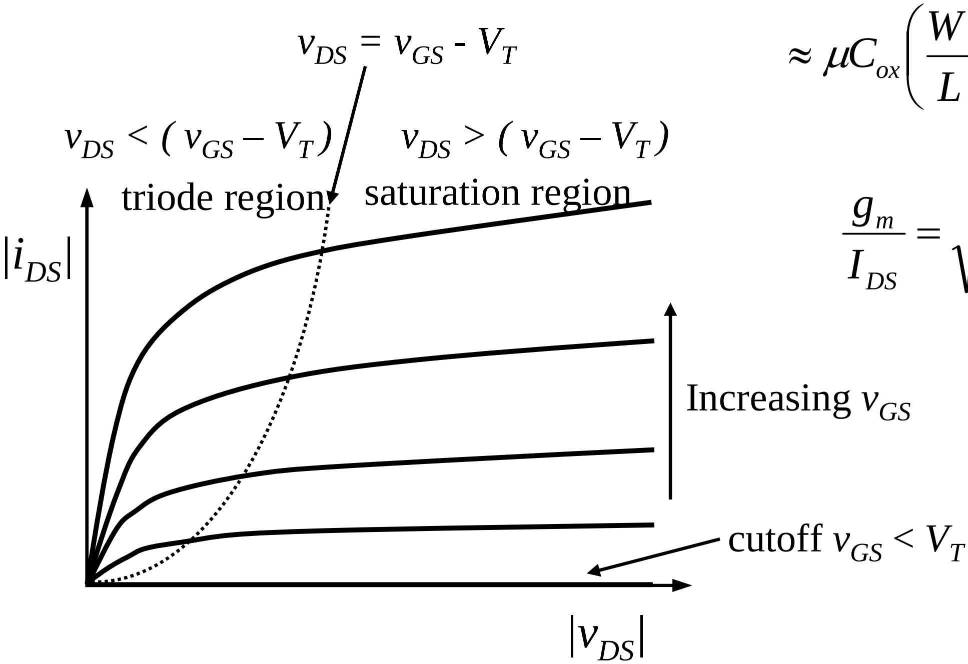
$\alpha = \theta + \frac{\mu_0}{2nv_{sat}L}$ models the mobility degradation and velocity saturation effects.

- Transconductance:

$$g_m = \frac{di_{DS}}{dv_{DS}} = \mu C_{ox}\left(\frac{W}{L}\right)(v_{GS}-V_T)(1+\lambda v_{DS})$$

$$\approx \mu C_{ox}\left(\frac{W}{L}\right)(v_{GS}-V_T) = \sqrt{2\mu C_{ox}\left(\frac{W}{L}\right)I_{DS}} \propto \sqrt{I_{DS}}$$

$$\frac{g_m}{I_{DS}} = \sqrt{2\mu C_{ox}\left(\frac{W}{L}\right)\frac{1}{I_{DS}}} = \frac{2}{V_{GS}-V_t} = \frac{2}{V_{ot}}$$



- In triode region:

$$i_{DS}^{triode} = \mu C_{ox}\left(\frac{W}{L}\right)\left(v_{GS}-V_T-\frac{v_{DS}}{2}\right)v_{DS}(1+\lambda v_{DS})$$

CMOS, BJT, and SiGe HBT

- CMOS: low quiescent power dissipation, good complementary transistors, low cost; low speed and large noise, challenging to model CMOS for RFIC.
- Bipolar transistors: high speed (npn), high g_m, low noise; slow pnp, high power consumption.
- SiGe HBT: high speed, low noise, good linearity and low power consumption comparing to BJT, cost dropped to almost RF CMOS cost.