The History and Future of RF CMOS:
From Oxymoron to Mainstream

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What experts were saying not so long ago

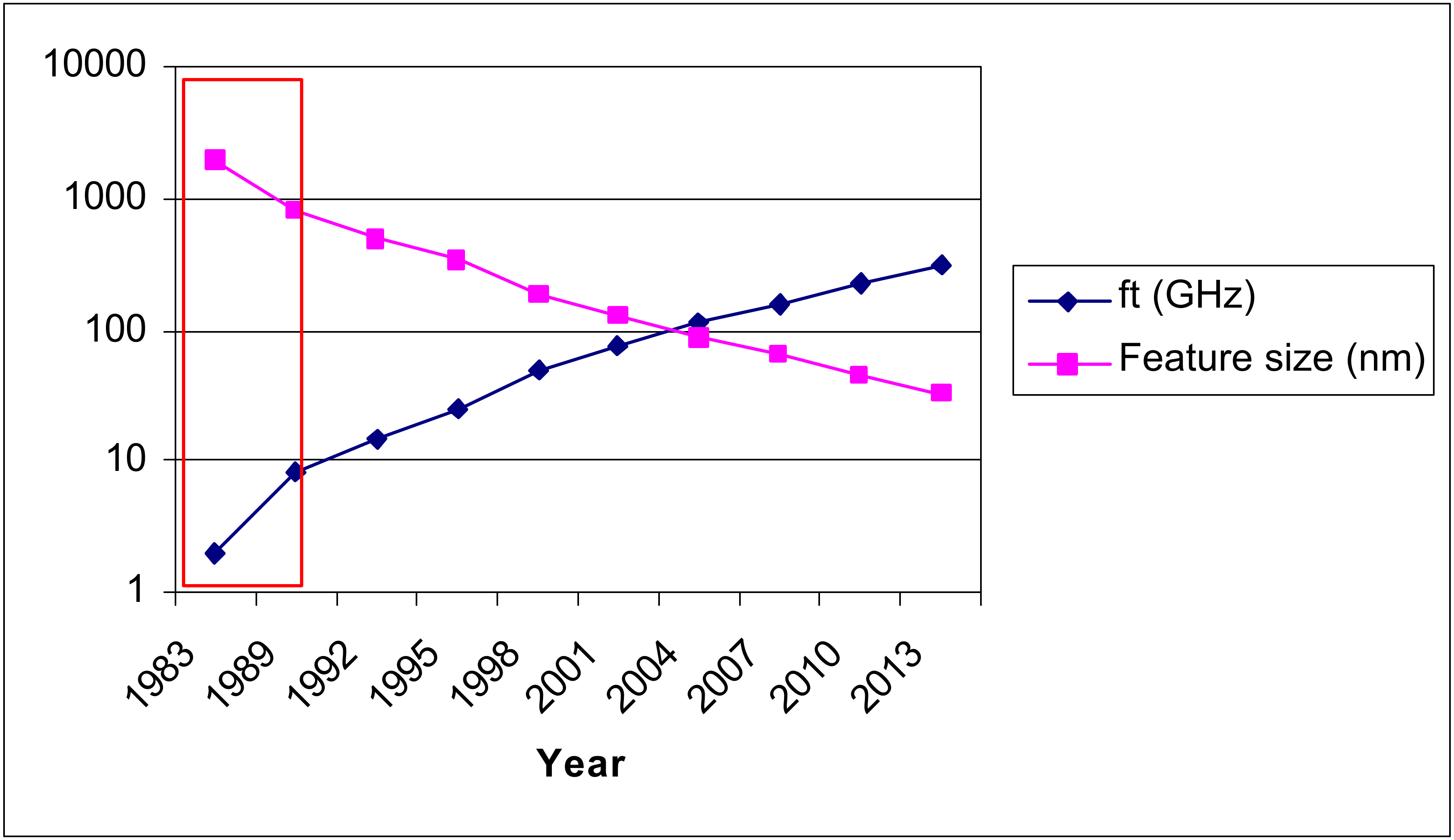
- "The total market for cellular telephones will saturate at about 900,000 subscribers in the year 2000."
  - Paraphrase of McKinsey & Co. report commissioned by AT&T in 1982.

- "RF is a solved problem. And using an inferior technology like CMOS to solve it yet again is stupid-squared."
  - Unnamed MIT professor, c. 1986.

RF CMOS today

- **Worldwide, two thousand cell phones are sold each minute, three million each day, a billion each year.**
  - **Most of the semiconductor value in cell phones is derived from CMOS.**
- **WiFi, Bluetooth, Zigbee, RF ID are now almost exclusively CMOS.**
- **Microprocessors and other digital components operate at speeds once thought of as the domain of RF.**
- **CMOS is in fact now the dominant RF IC technology. *How did this happen?***

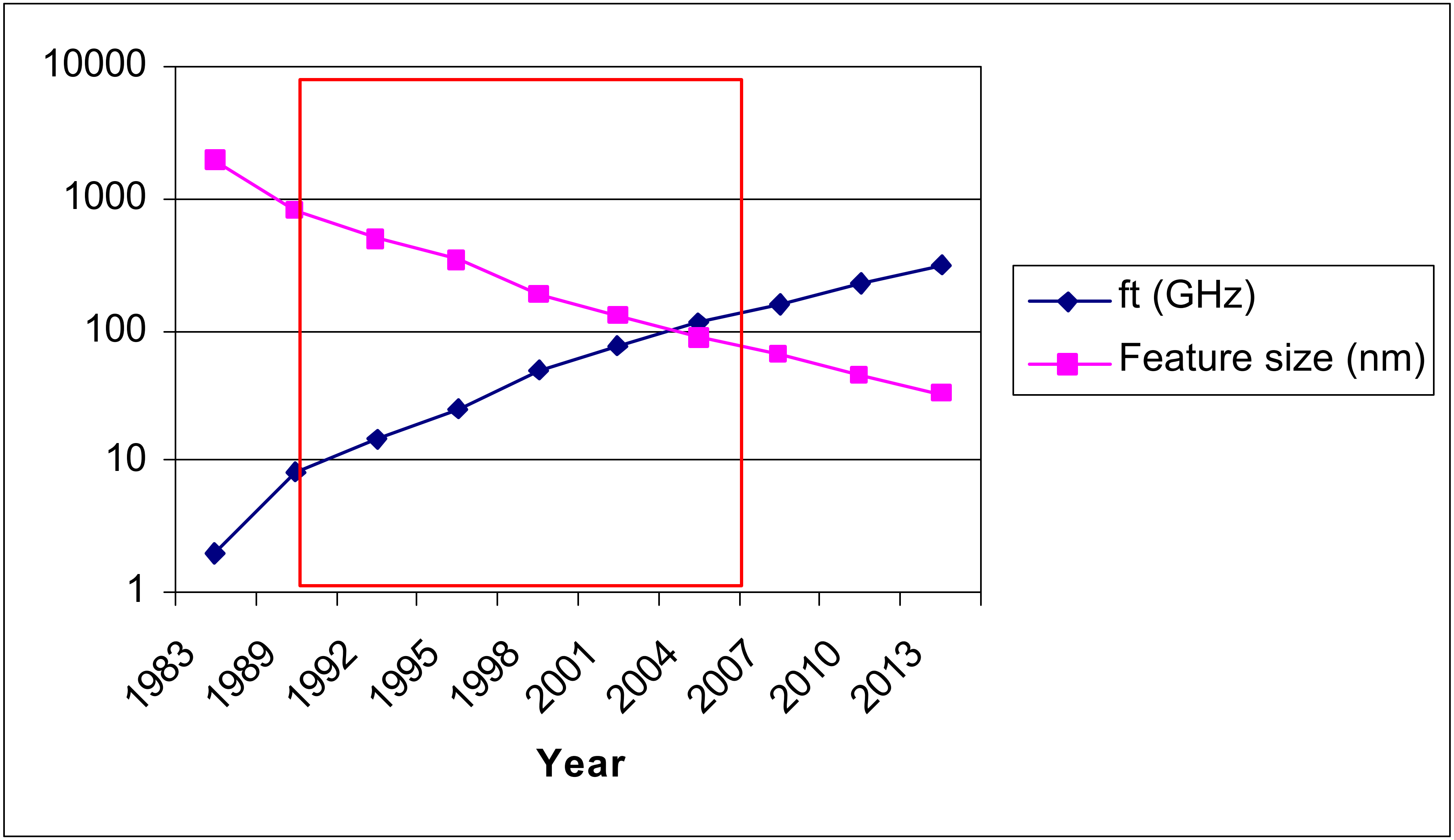
How we got here: Scaling in the '80s



RF CMOS in the 1980s

- Peak NMOS ft values in the ~1GHz range (2μm technology).
  - Allows marginally usable circuits in the ~100-200MHz range.
- First CMOS FM radio IC reported in 1989 (2μm technology).
  - Paper rejected by ISSCC in 1990.
- RF CMOS not yet ready for prime time.
  - But underestimating the power of Moore’s law is foolish.

Scaling from the '90s to today



RF CMOS in the 1990s

- CMOS ft grows to multi-GHz values. *Very* crude approximation for peak NMOS ft is 10THz-nm/Lmin.

- Serious efforts to study and develop RF CMOS begin in earnest at a few schools.
  - UCB, UCLA, KU Leuven, Stanford among them.

- Foundations laid for designing RF circuits and realizing acceptable passive components in CMOS.

- Transition from demonstrating individual building blocks, to demonstrating receivers and transmitters.

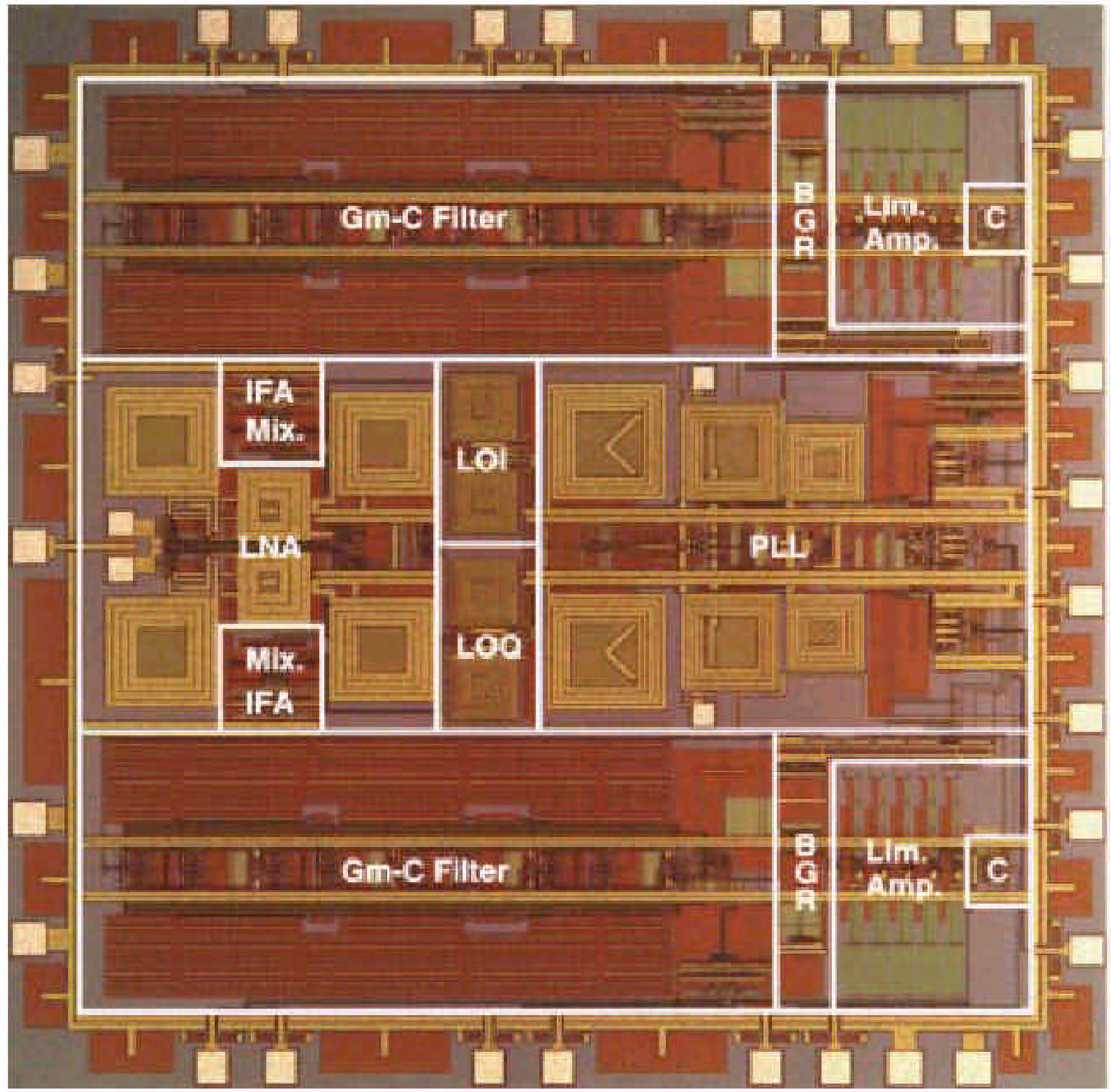
- Because linewidths keep shrinking throughout the mid-’90s, “CMOS is too slow” morphs into “CMOS is too noisy” (then to “phase noise will be too high,” then to “substrate will eat all the energy,” to…)

CMOS and RF noise

- **Aldert van der Ziel published basically correct MOSFET RF noise model in the 1960s [*IEEE Proc*. March 1963; updated in 1986]. First to discuss *induced gate noise* in detail.**
  - **Largely ignored and forgotten (theory arrived too far in advance of when needed).**
- **Resuscitated in the mid-1990s, and used as basis for CMOS low-noise amplifier design theory [Shaeffer et al, *JSSC* May 1997].**
- **Executive summary: Noise is not a big problem. Minimum practical spot NF is (*very* crudely) 10log(1+3f/ft).**
  - **In 2007: < 1dB @ 1GHz; < 2dB NF @ 7.5-15GHz; < 5dB NF @ 15-30GHz.**
  - **In 2019: < 2dB NF @ 30-60GHz; < 5dB NF @ 60-120GHz.**

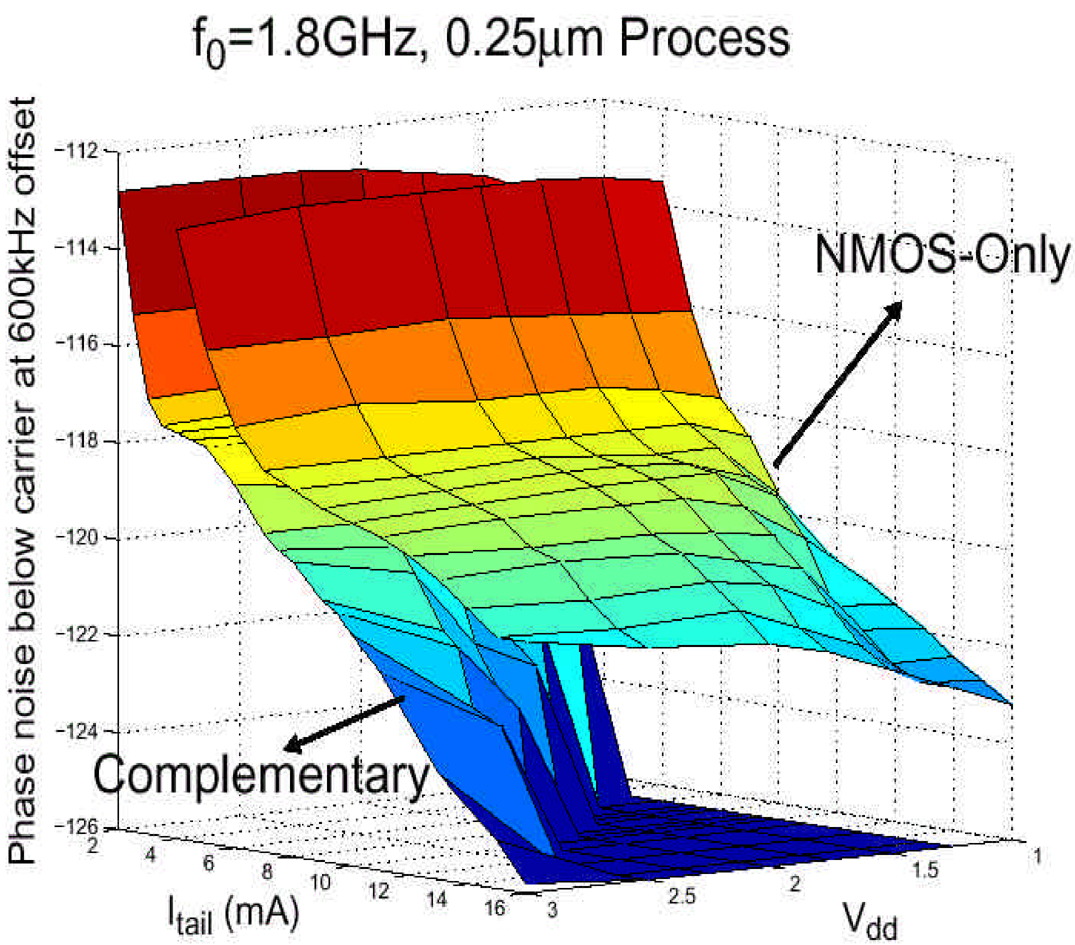
CMOS and RF noise: Some proof

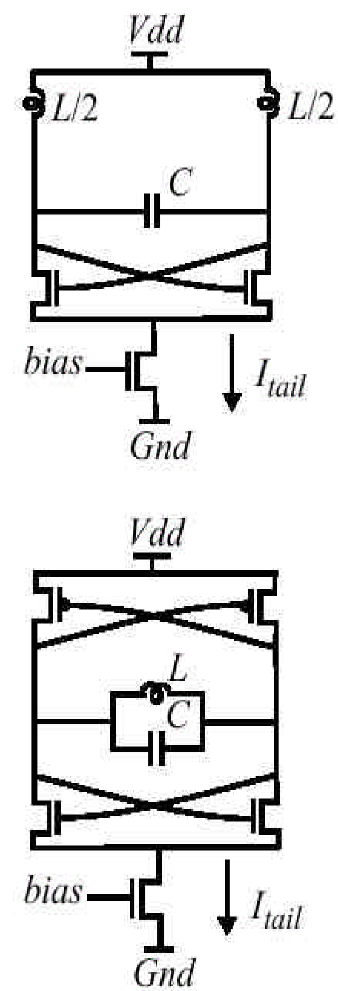
- **Early example of low noise CMOS RF IC: GPS receiver built in a 0.5mm process (1997).**
- **NF: 2.2dB@1.6GHz.**
  - **Comparable to contemporary non-CMOS receivers**



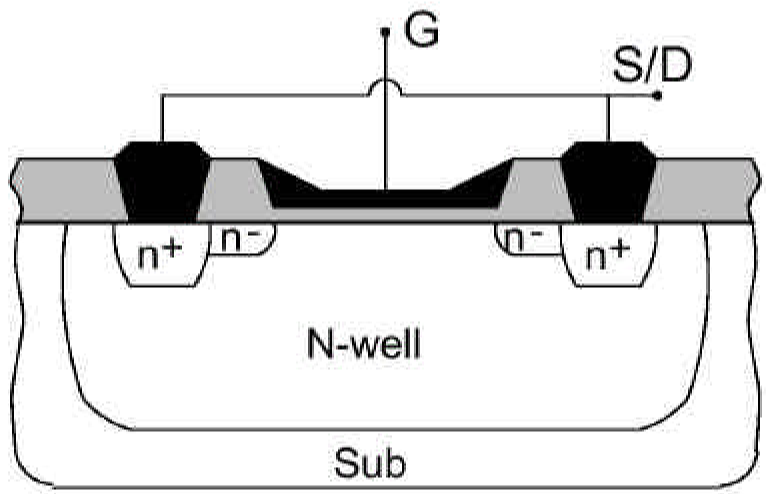
CMOS and RF noise: Some proof

- **LTV phase noise theory shows how to make good oscillators with crummy CMOS (Hajimiri et al., 1997-98).**

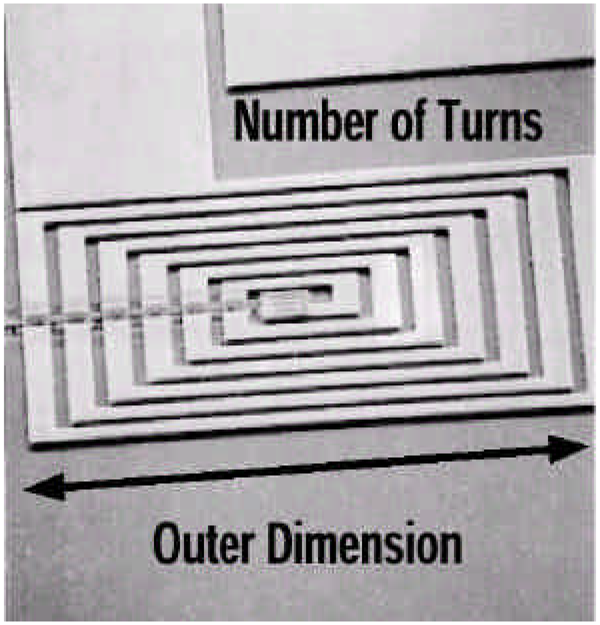




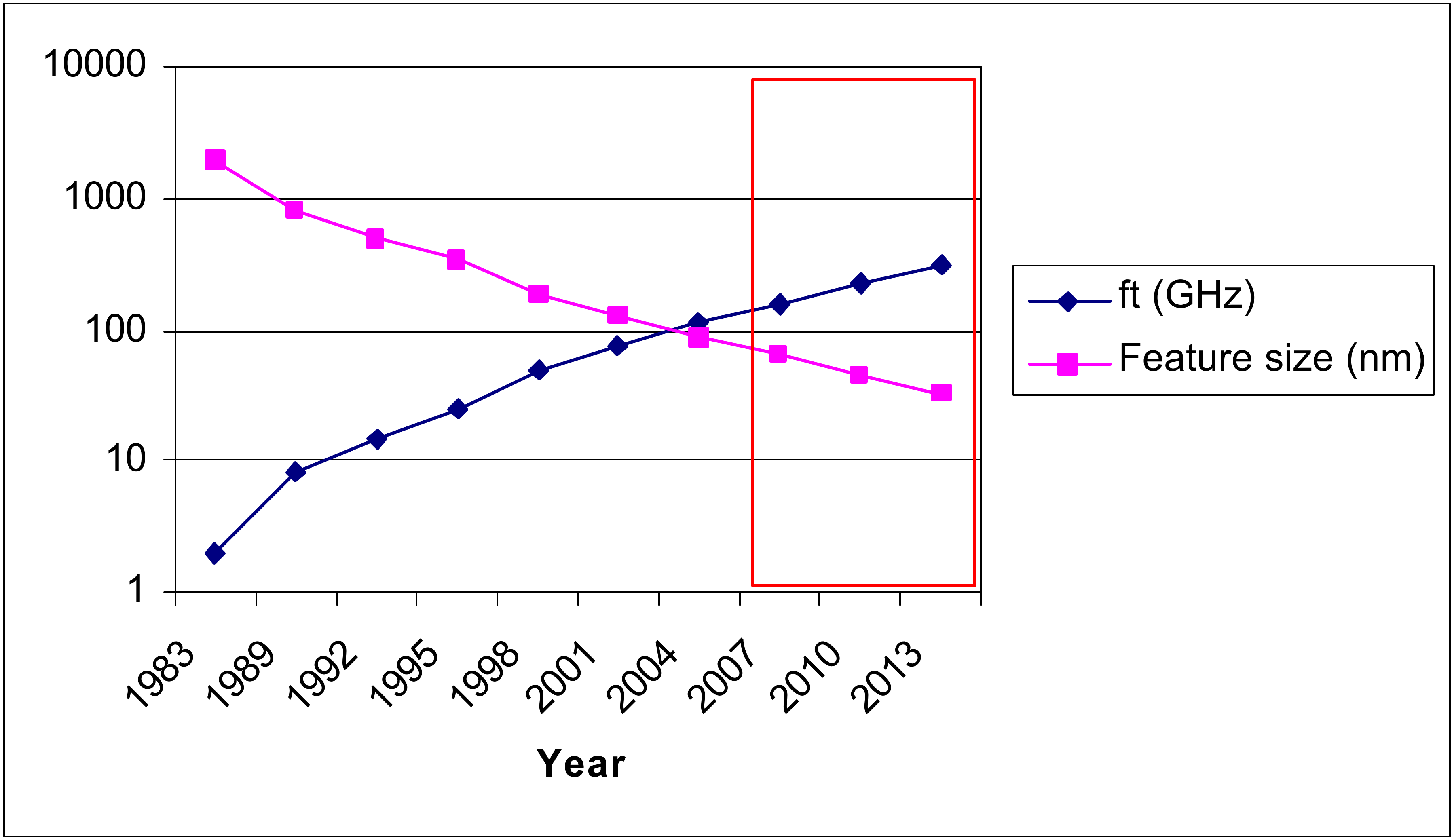
CMOS: Parts is parts



- **Sophistication of modern CMOS permits implementation of many useful passives.**
  - **Junction varactors.**
  - **High-Q accumulation-mode MOS varactors (upper right).**
  - **Spiral inductors and transformers (lower right).**
  - **Transmission lines.**
  - **Metal-metal capacitors (parallel-plate and lateral flux).**



Scaling: Present and future



CMOS scaling: Observations

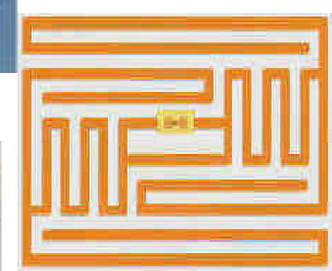
- Constant advances in process technology eventually give us fast enough devices for any sensible terrestrial wireless application.
  - Unique among RF technologies, advances in CMOS are paid for by someone else – the digital community.

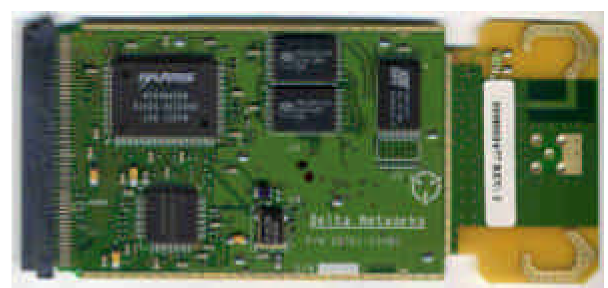
- Peak NMOS ft (~peak fmax) is already 150GHz today.
  - 300GHz in 2013
  - 600GHz (maybe) in 2019.

- To consider what we could do with this bounty, let's look at the whole history of RF, not just the age of CMOS.

RF through the ages

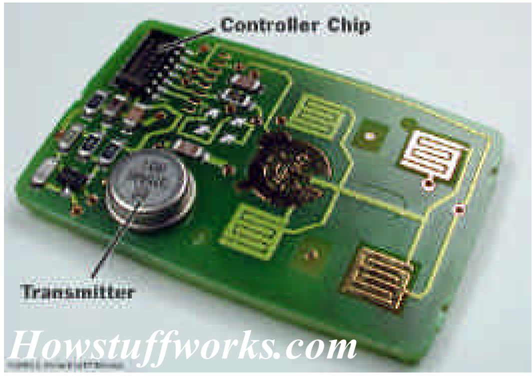
- *First Age (1890-1920s)*: Station-to-station telegraphy.
- *Second Age (1920s-today)*: Station-to-people broadcasting.
- *Third Age (1980-today)*: People-to-people.
- *Fourth Age (now)*: Things-to-things.

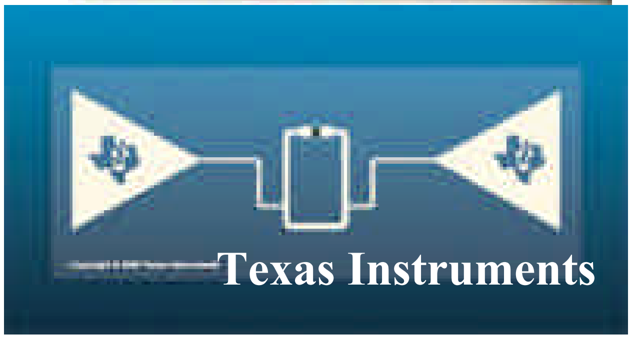




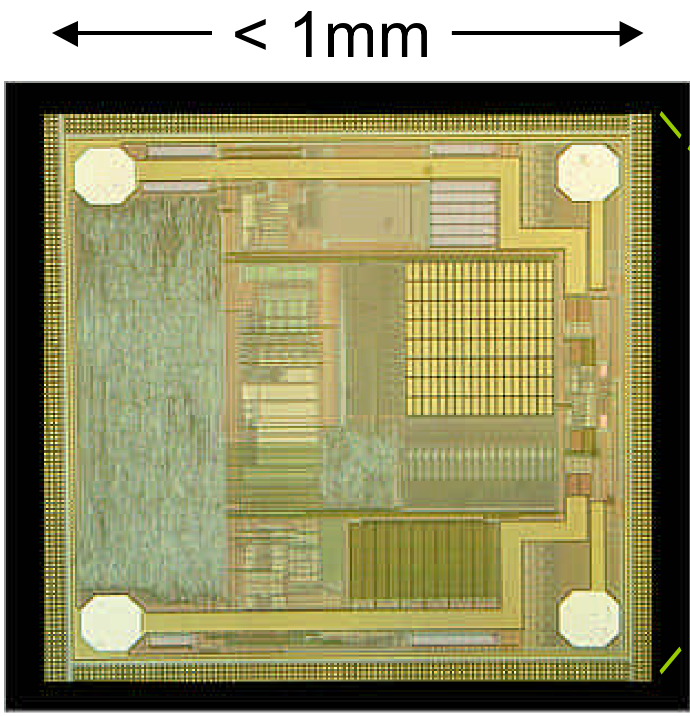
Sampling of fourth-age devices

- **Remote entry key fobs (40Mu in 2006).**
- **Contactless smart cards (1Bu in China alone over 5yrs).**
  - **etickets (~100Mu in 2006).**
- **Drive-through electronic toll collection.**
- **Passive asset tracking devices (<1-10m).**
  - **EPC (< $300M in 2005).**
- **Active asset tracking devices (>10m).**
  - **WiFi et al.**

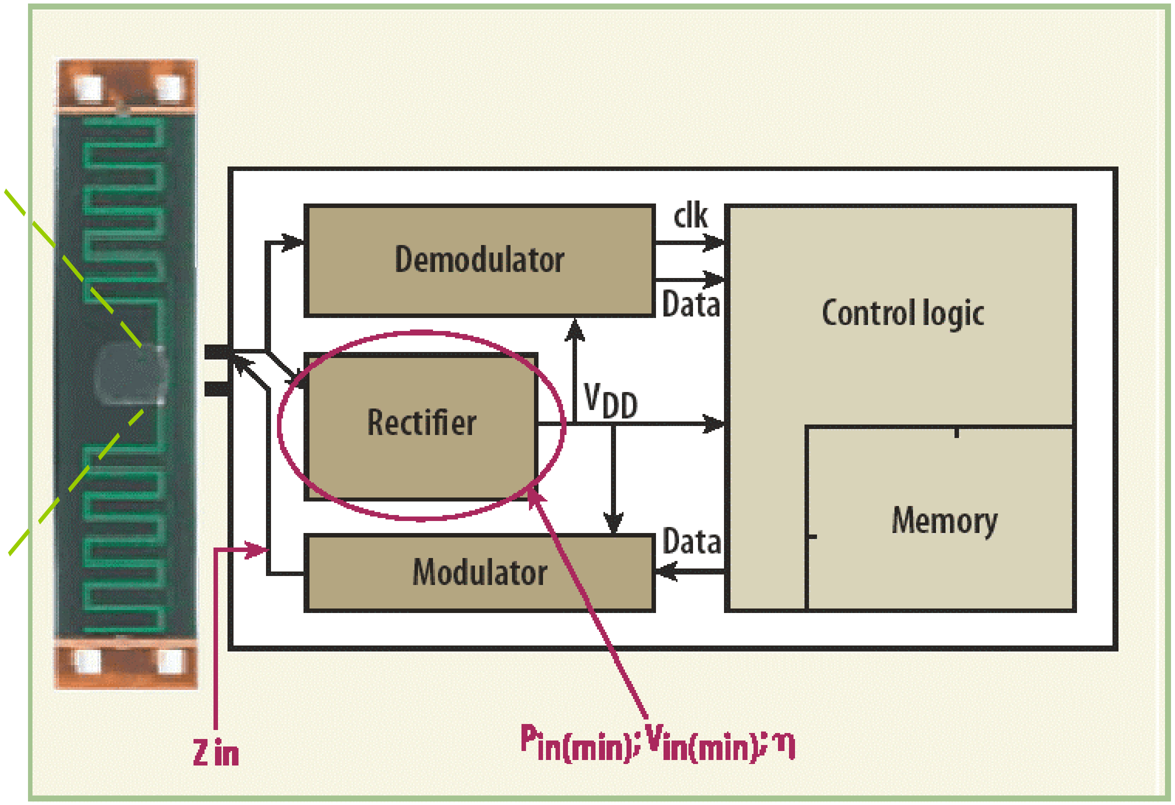




RF CMOS today: At the low end

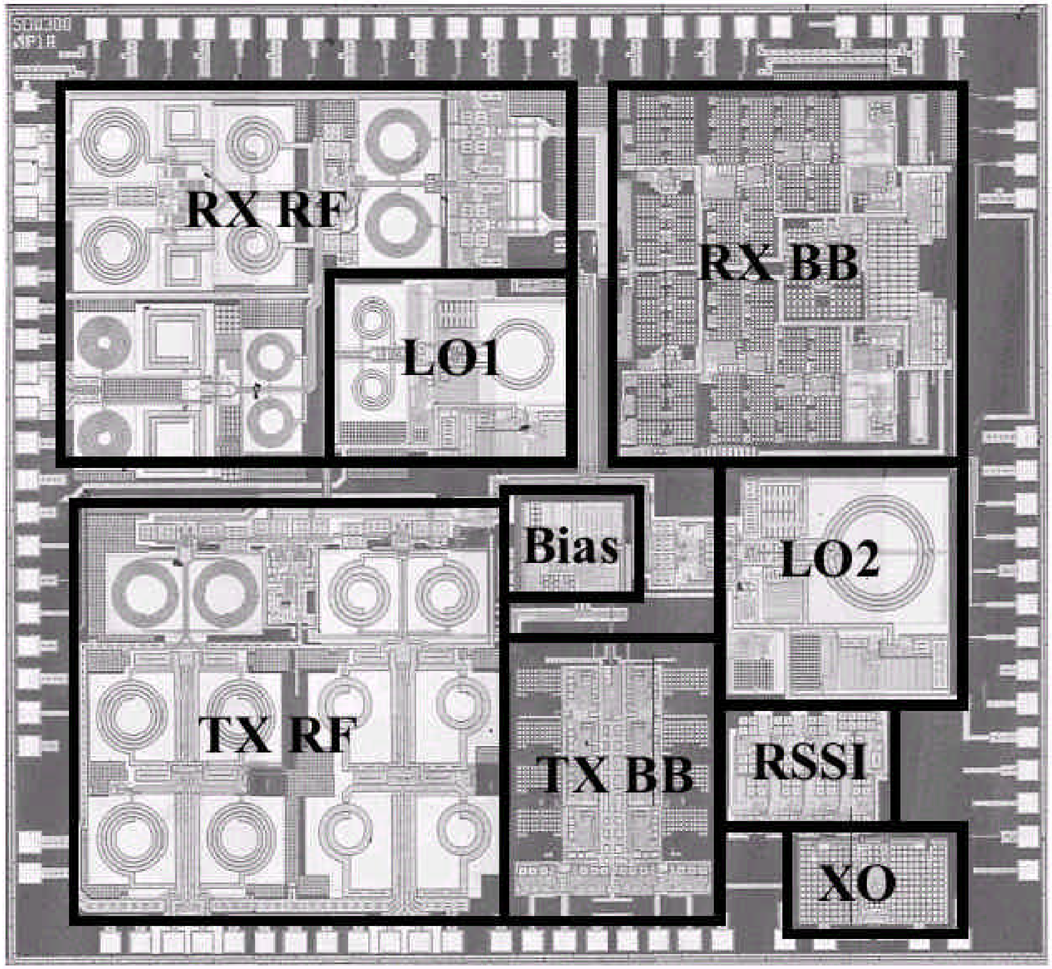


RFID chip (*Impinj*)



RFID tag block diagram (*Faisal et al.*, MWRF Sept. 2006)

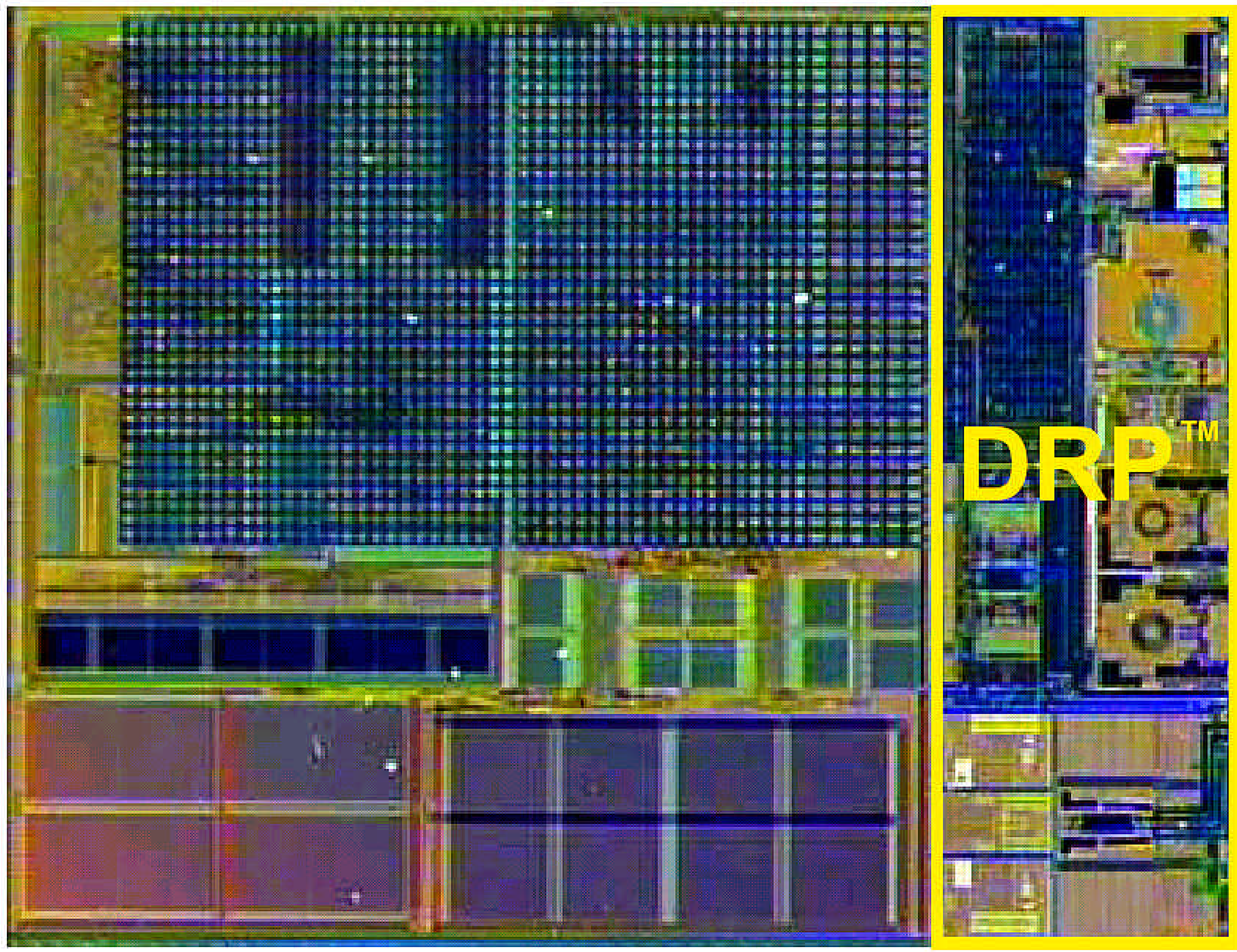
RF CMOS today: At the high end



802.11a/b/g (*Ahola et al.*, ISSCC Feb. 2004)

Trends: Strong digital, weak analog

- **TI "DRP" (digital radio processor) example.**
  - **All-digital LO, all-digital TX, discrete-time RX**
  - **One approach to multi-standard radio.**

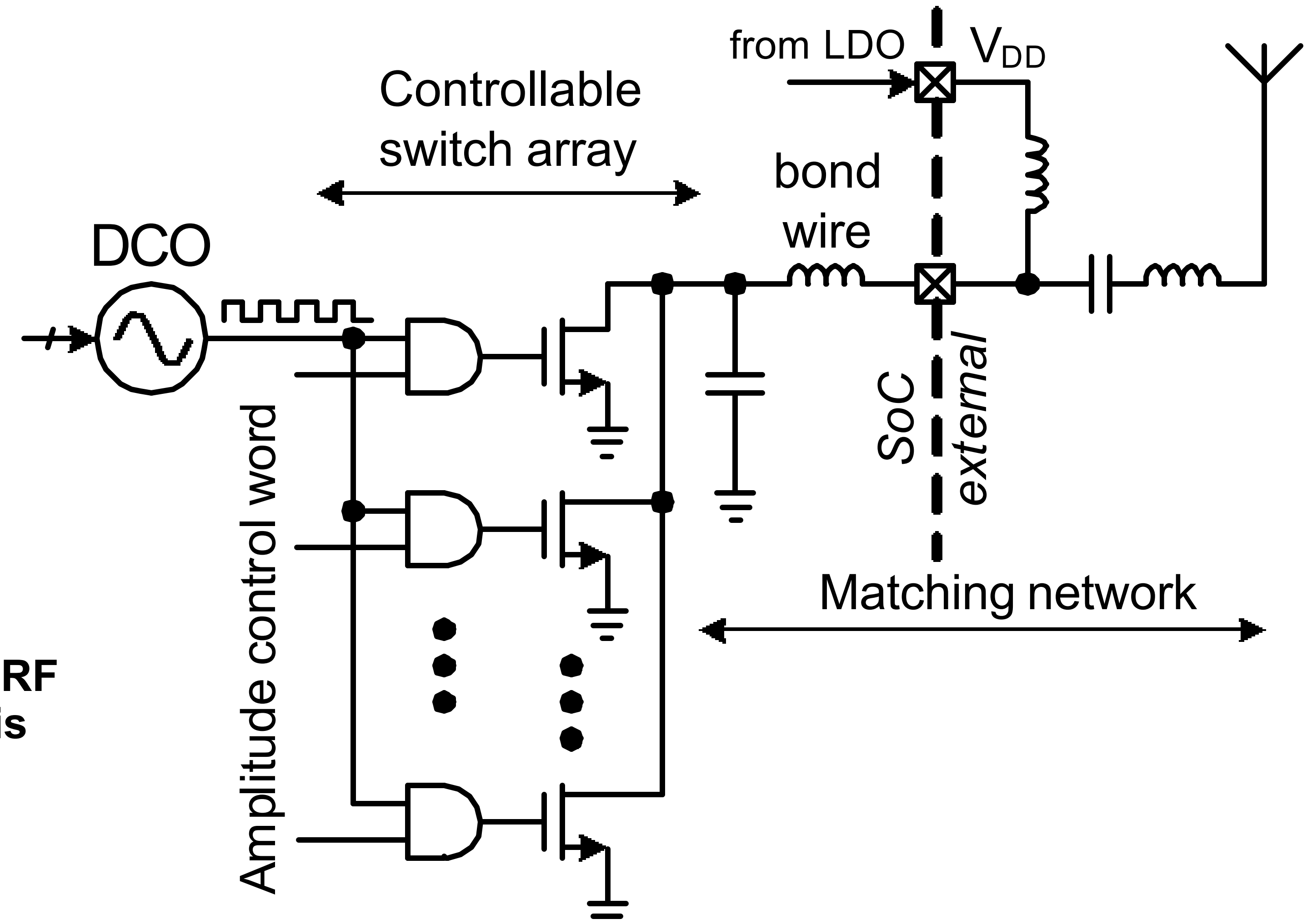


Krenik et al., TI

Example: Digitally-Controlled PA

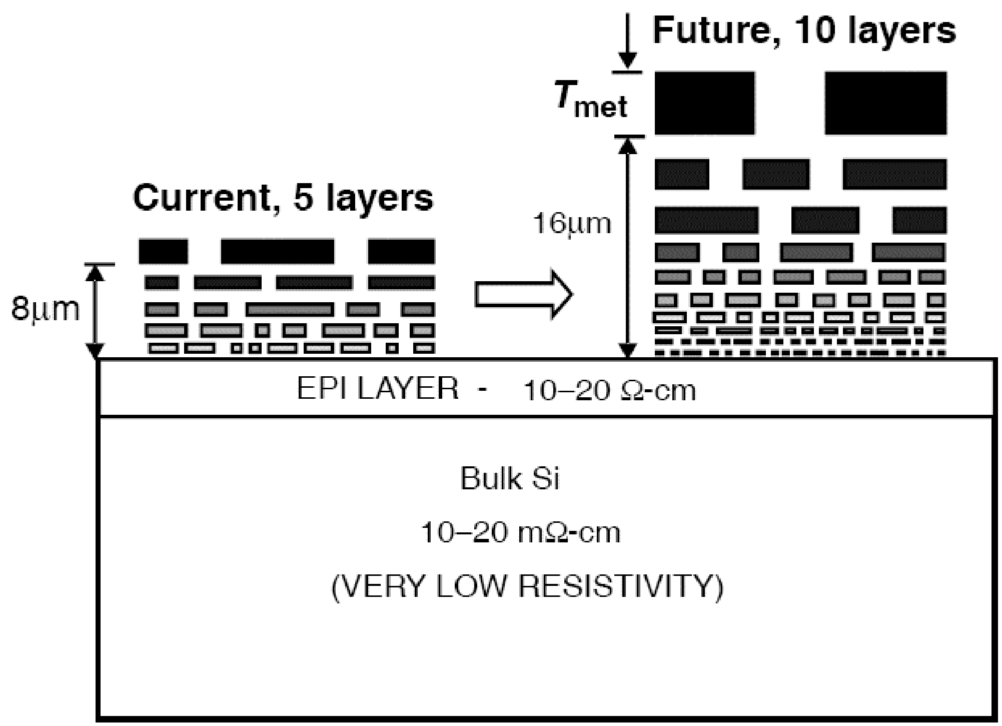
B. Staszewski, TI

- **Array of unit-weighted MOS switches**
- **Each switch contributes a conductance**
- **Near class-E operation**
- **Fine amplitude through ΣΔ modulation**
- **The DPA can be thought of as an RF DAC, where "A" is RF "amplitude"**

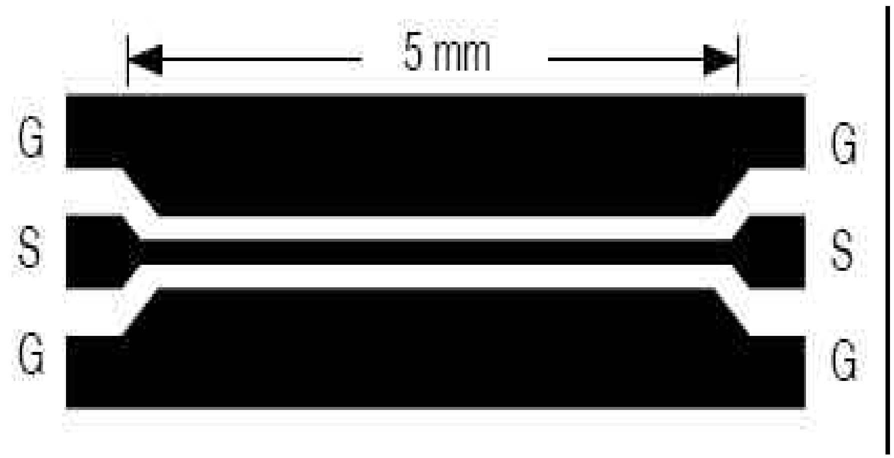


CMOS as a microwave technology

- **Six to eight metal layers readily available.**
- **Use coplanar metal lines with small spacing to keep energy out of lossy Si substrate. Can achieve 0.3dB/mm loss at 50GHz [*Kleveland et al*, 1998].**

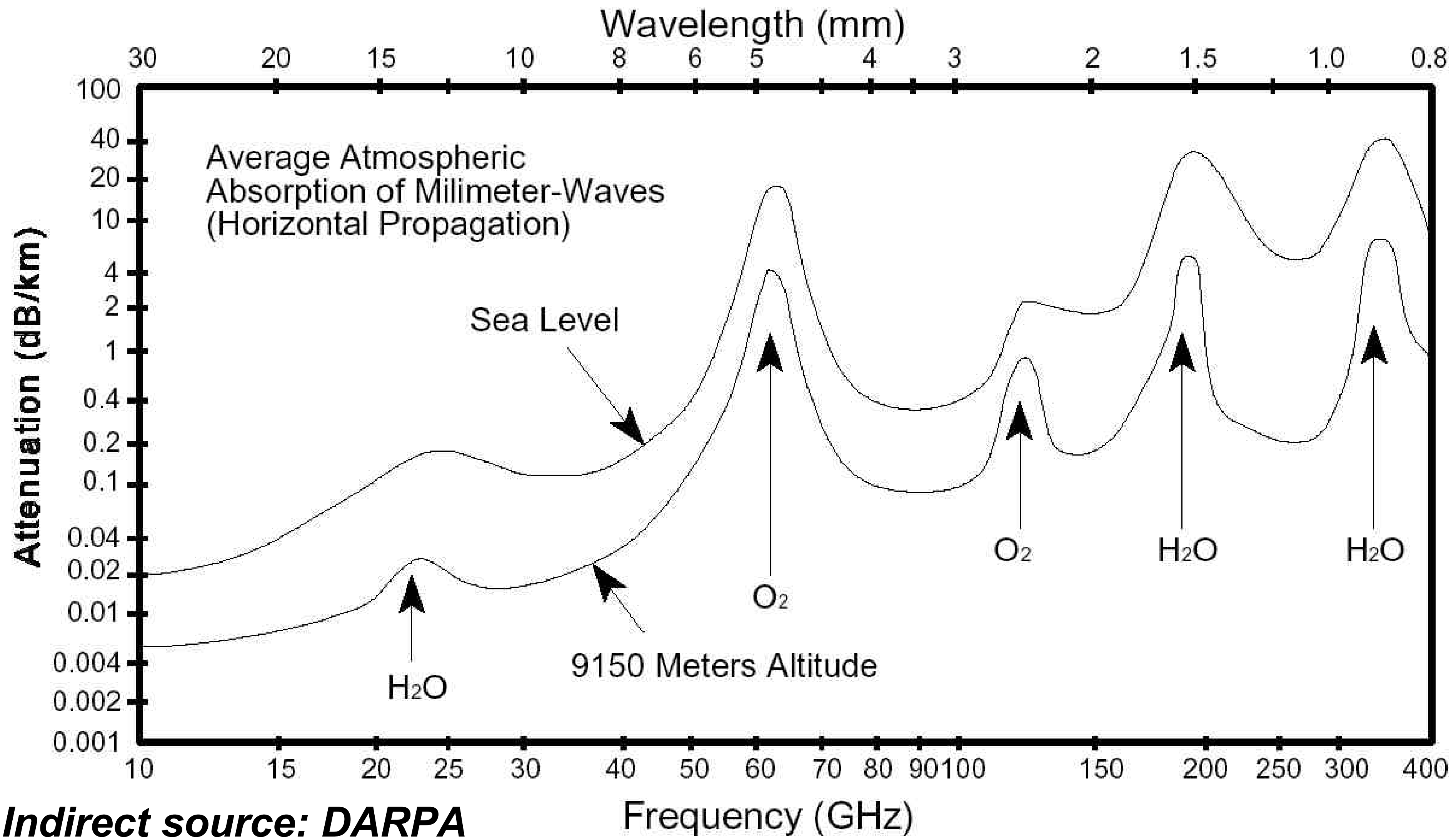


Cross-section



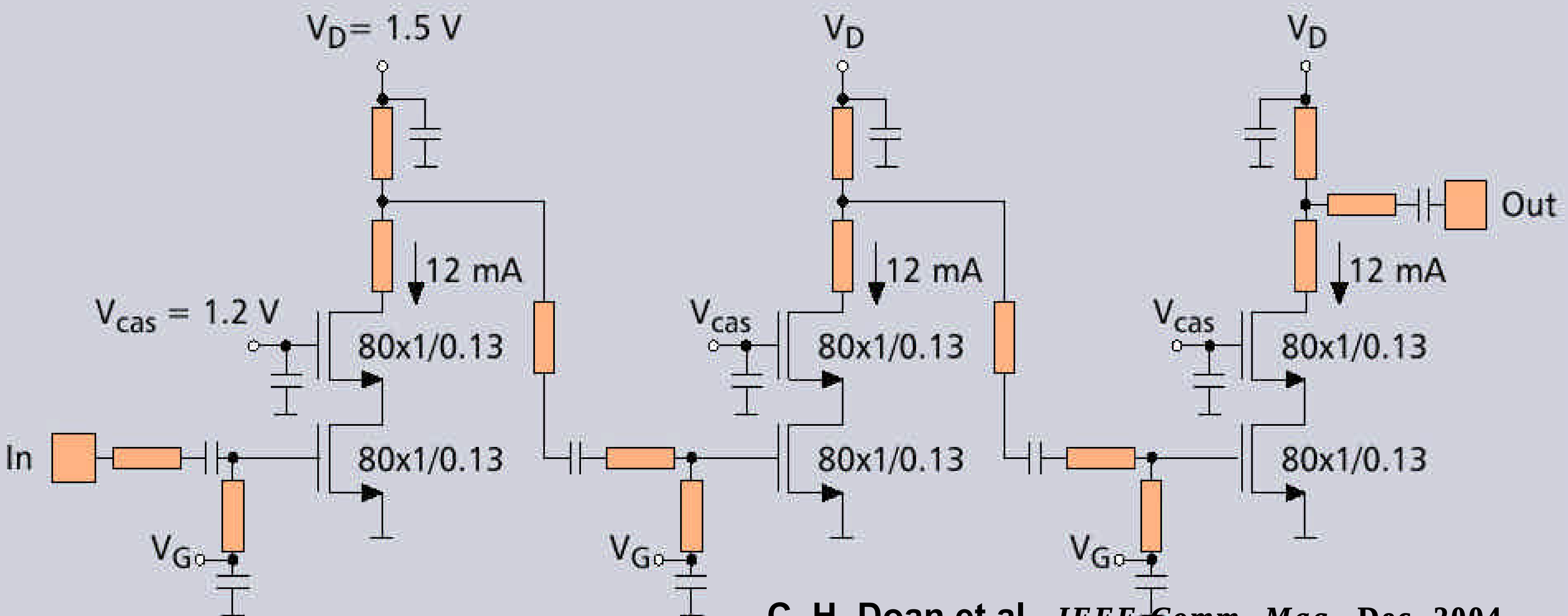
Top view: Coplanar line

Atmospheric attenuation



Indirect source: DARPA

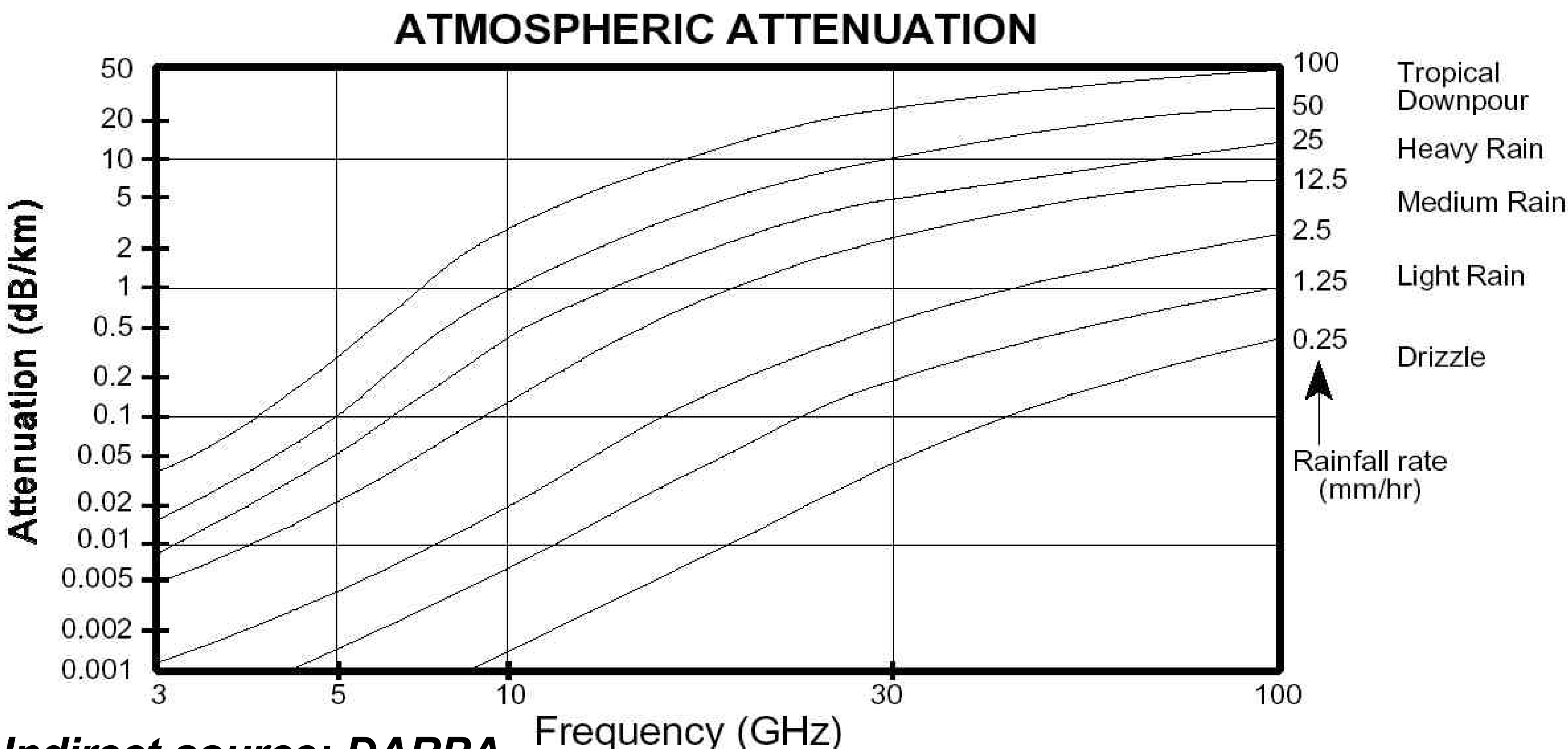
60GHz amplifier in 0.13μm CMOS



C. H. Doan et al., *IEEE Comm. Mag.*, Dec. 2004

- 11dB gain, 8.8dB NF, 15GHz bandwidth

Atmospheric attenuation in rain



Indirect source: DARPA

Onward and upward?

- Atmospheric attenuation in dry weather allows free-space operation well into the millimeter bands.
  - Progressively worse diffraction and scattering effects limit operation to line-of-sight as frequency increases.
- Can now imagine pushing CMOS into near-THz operation.
  - Is it possible?
  - Would anyone care?

Why the THz band is interesting

X-rays penetrate, but ionize

THz penetrates but does not ionize (Teraview, 2003)

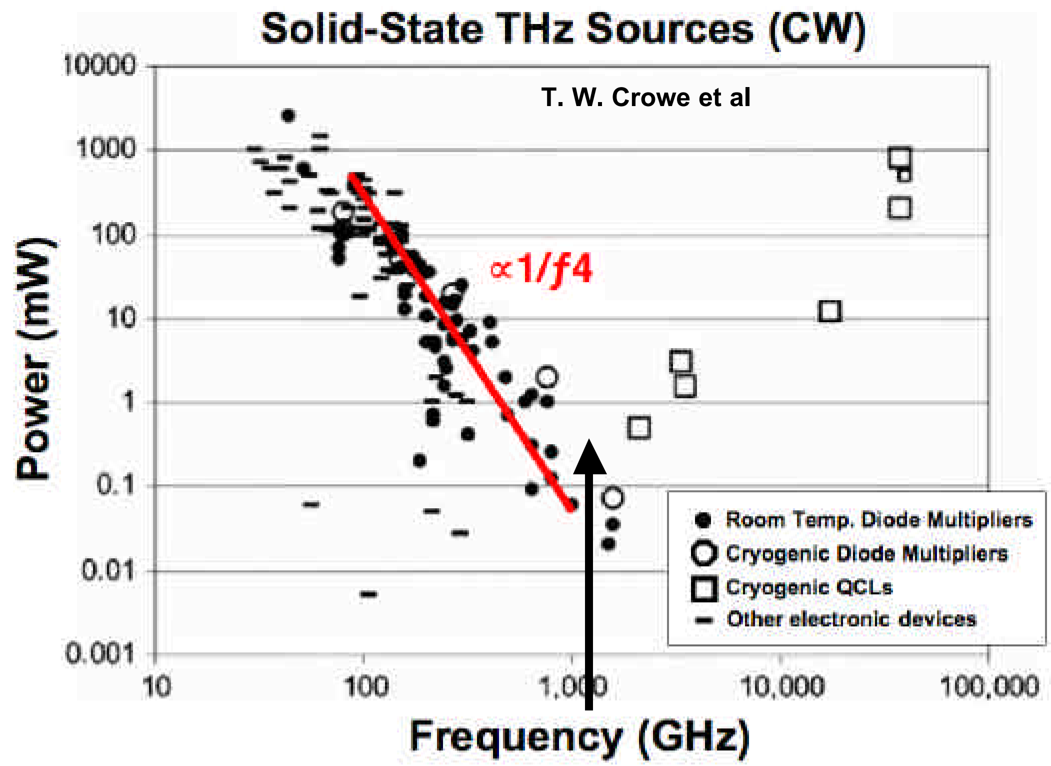
Through-clothing imaging

Concealed gun (Teraview, 2003)

Problem: The “terahertz gap”

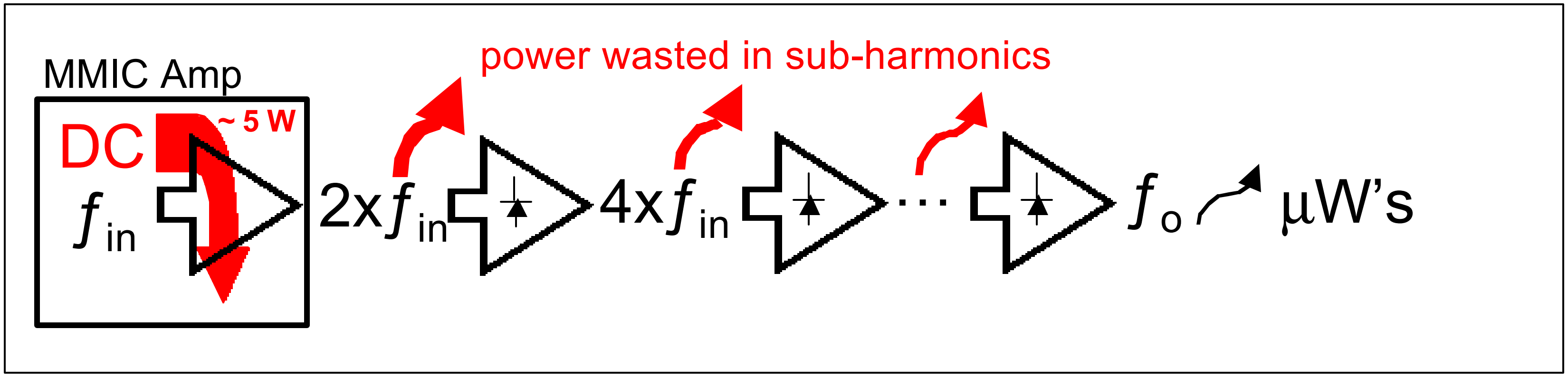
Two major non-CMOS sources:

- Diode multipliers
  - Proven to work beyond 1THz
  - Poor efficiency (~.01%)
- Quantum cascade lasers
  - Work best above 10THz at room temperature.
  - Cryogenic operation needed to achieve coherent emission at single-digit THz frequencies.
  - Room temperature thermal energy corresponds to ~10µm peak blackbody wavelength, frustrating coherent emission below about 15-30THz.

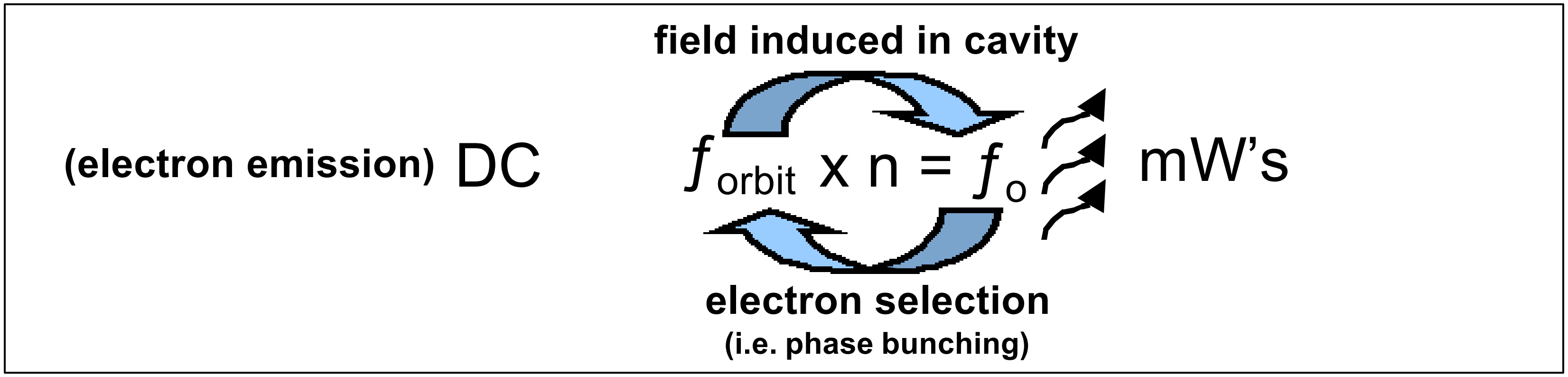


DC-to-THz Conversion

Diode multiplier chain dissipates power at sub-harmonic frequencies:



Alternate idea:



Out of the box: How to do better

- **Forcing carriers to bash their way through a solid is antithetical to high-speed performance.**
- **Scaling trends are driving us inexorably toward the ballistic realm anyway.**
  - **Might as well think about exploiting ballistic transport directly, rather than simply regarding it as an incidental artifact of scaling.**

Ballistic transport can overcome many problems.

Ballistic (“empty state”) devices

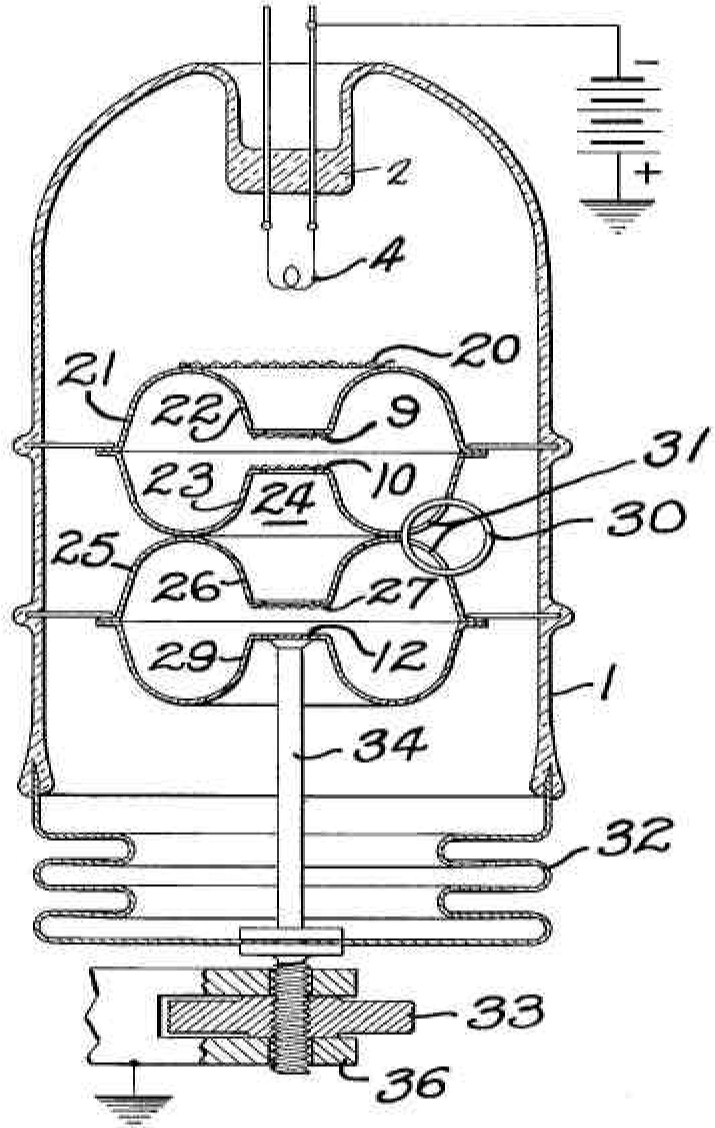
- **Ballistic transport is best in its purest form: *Through free space*.**
- **Semiconductor becomes less important electrically.**
  - **Scaling laws change, hopefully for the better in at least some critical areas.**

Ballistic Transport

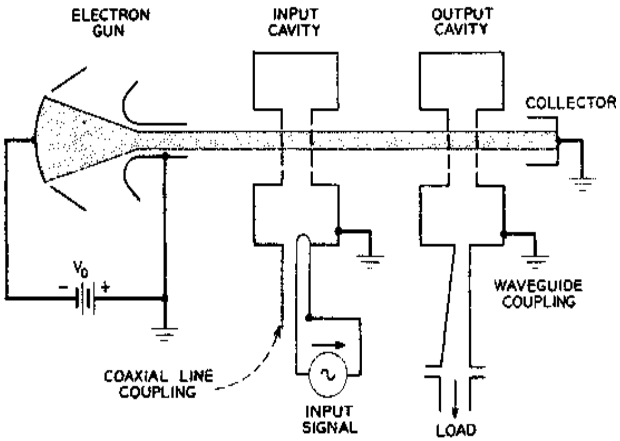
- **Important distinction between vacuum-state and solid-state devices is in scattering time constant … no scattering in an ideal vacuum.**
  - **Neglect space charge effect for now.**

- **Without scattering, transit-time limitations need not constrain performance.**

- **1937: Varian brothers at Stanford realized that transit-time could be *exploited* to achieve gain. They named their idea the “klystron” [after êëõó, referring to the action of waves breaking against a shore].**



The Klystron - A Linear Beam Tube

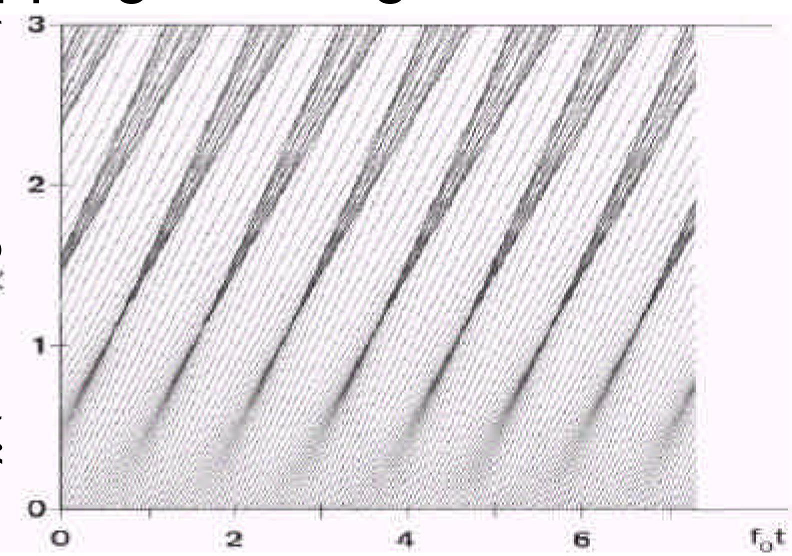


Bunching parameter:

$$\chi = 1/2 \frac{z}{v_o} \frac{V}{V_o}$$

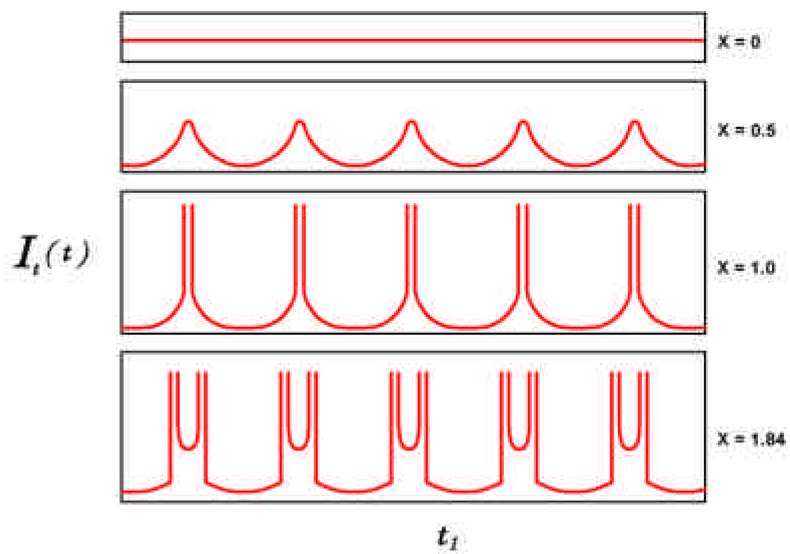
“Applegate” Diagram:

χ (Bunching Parameter)



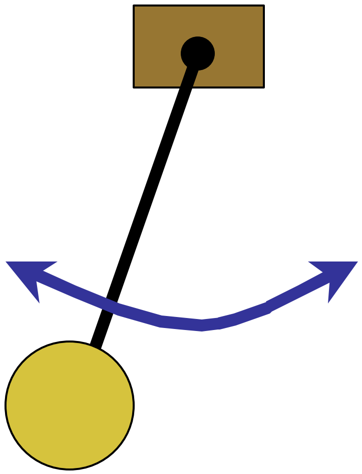
time

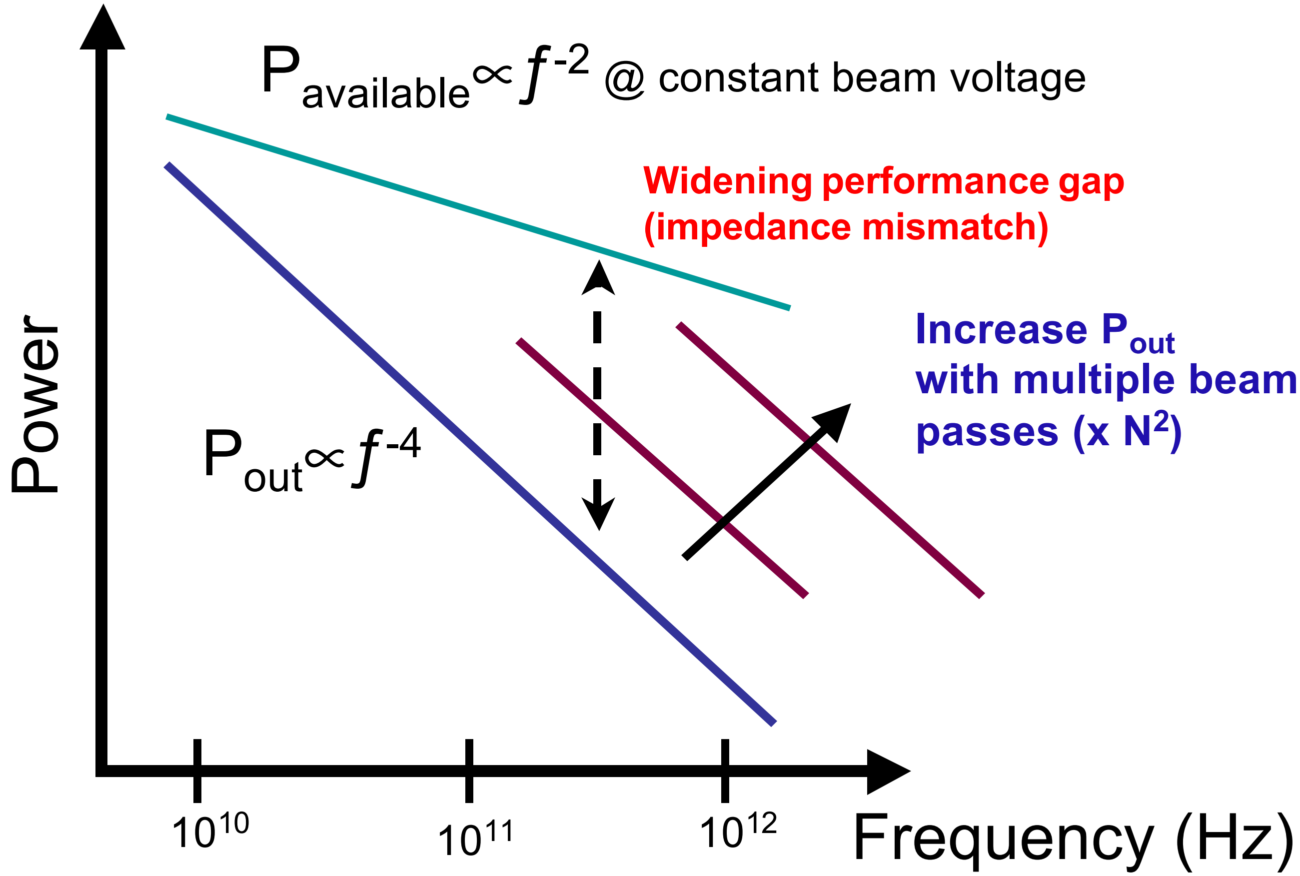
Current bunching:



Why ballistic transport?

- **Ballistic transport can help overcome impedance mismatch between electron source and load at high frequencies. Can extract energy from a ballistic electron beam through multiple passes, as with a pendulum.**

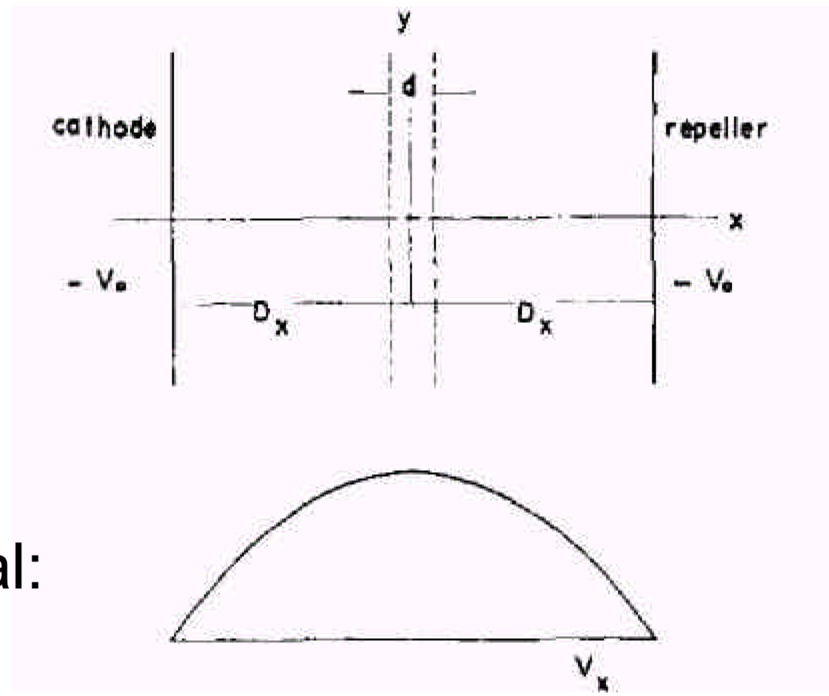




An Electron Pendulum: How

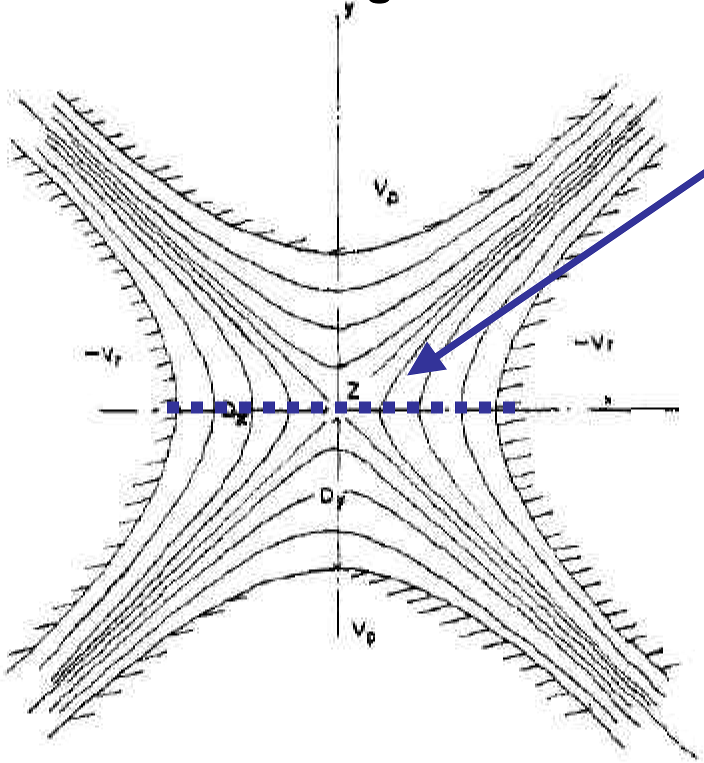
- Want electrons to be able to pass through a cavity multiple times.
- As the electrons give up their energy to the field, we want them to remain in phase with the field.
- A pendulum is the classic example of a system where the frequency (and therefore phasing) remains constant with time.

Desire a parabolic potential:

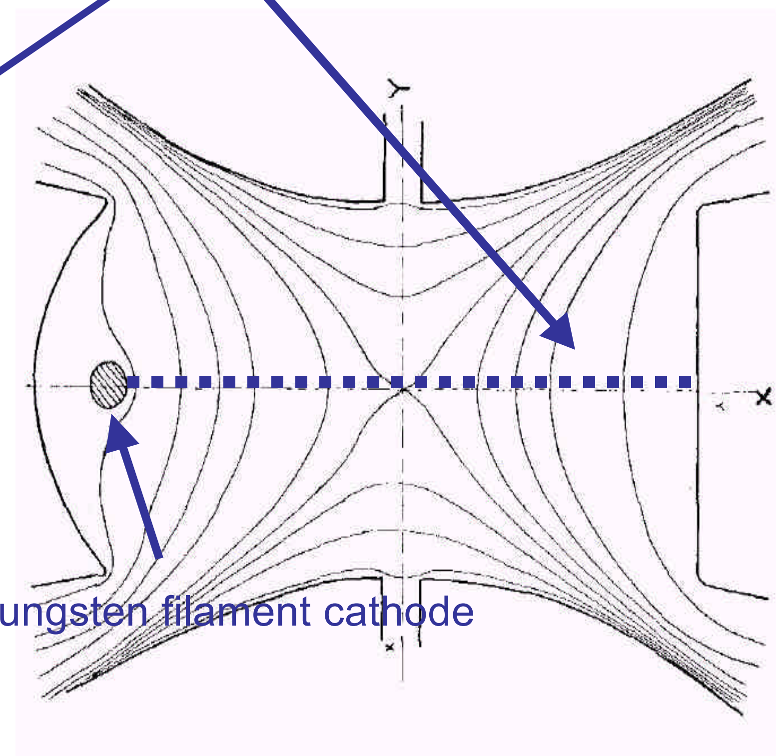


Parabolic Potential Well

- **To generate a parabolic potential along the beam path, use a quadrupole electrode arrangement:**



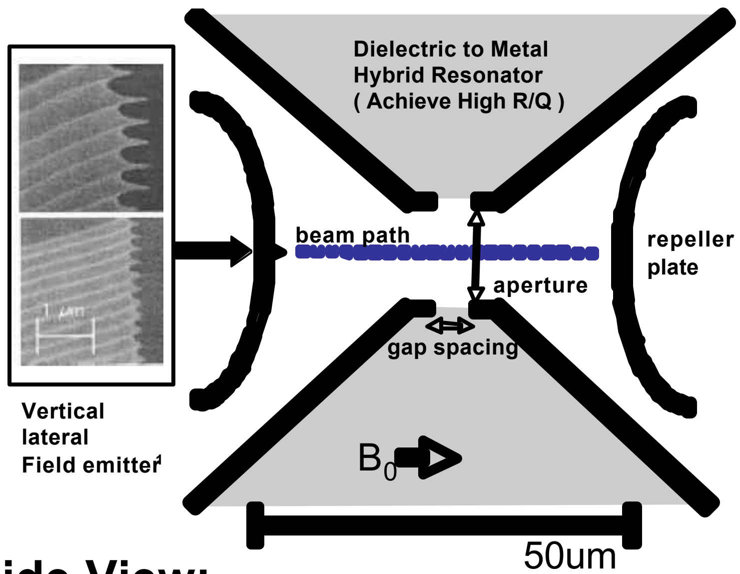
Ideal quadrupole field



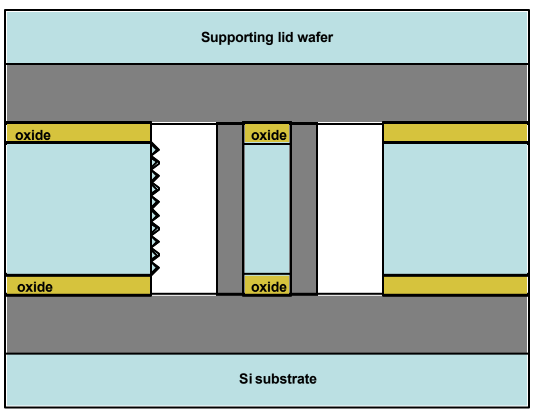
1958 Implementation
(Uenohara et al.)

μ Barkhausen-Kurz THz Oscillator

Top View:



Side View:



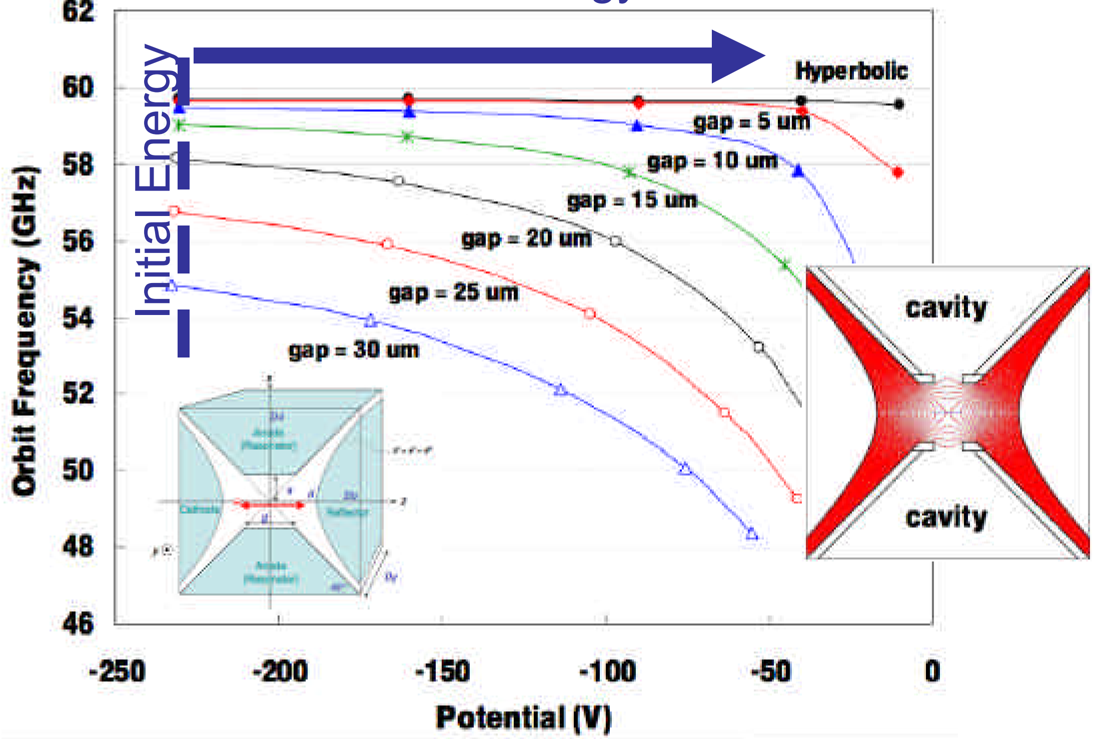
- Intuitively, operates like an electronic pendulum with electrons oscillating inside a parabolic potential well.
- Tunable over octaves by variation of electrode potential.
- Possible to achieve very high efficiency, like a magnetron (another crossed-field vacuum device).
- Can create a serrated knife-edge field emitter by enhancing the natural scalloping caused by DRIE.

[1] V. Milanovic, L. Doherty, D. Teasdale, S. Parsa, and K. Pister, "Micromachining technology for lateral field emission devices," IEEE Transactions on Electron Devices, vol. 48, no. 1, pp. 166-173, 2001.

Engineering a Parabolic Well

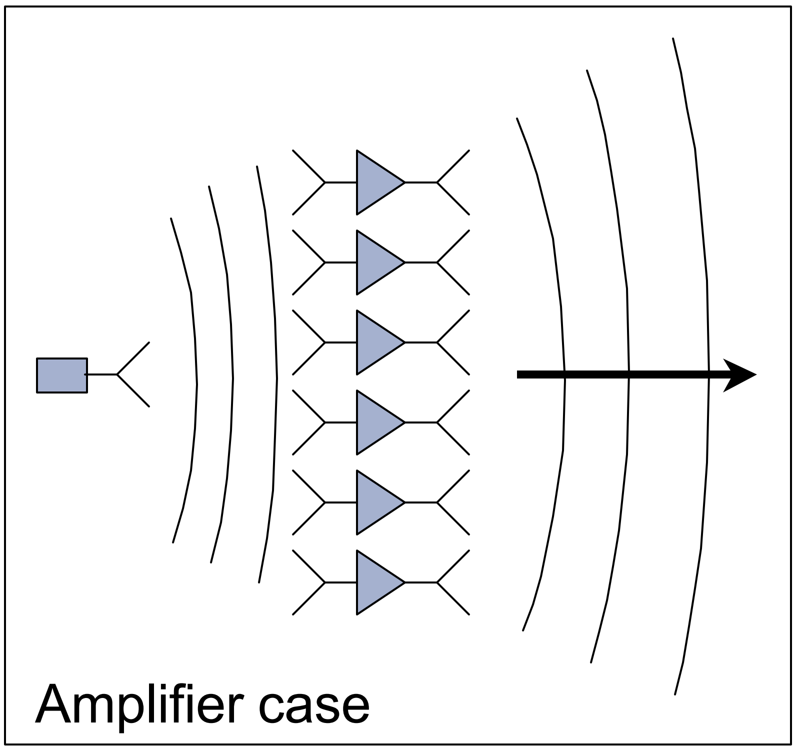
- **A precise parabolic potential well allows for true simple harmonic oscillation of electrons**
- **Careful modeling of non-idealities is required**
  - **Effect of finite electrode extent**
  - **Cavity aperture**
  - **Space charge of electron stream**
- **This modeling was too computationally expensive in 1958!**

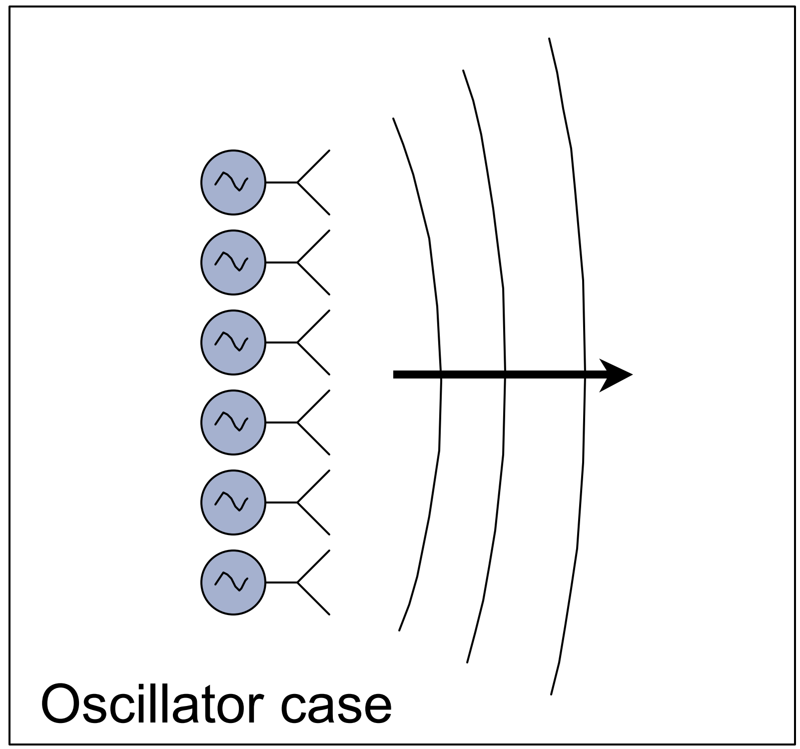
Oscillation frequency shifts as electrons lose energy in the well.



Spatial Power Combining

- **Use spatial combining to achieve watts of THz power with high efficiency at room temperature.**

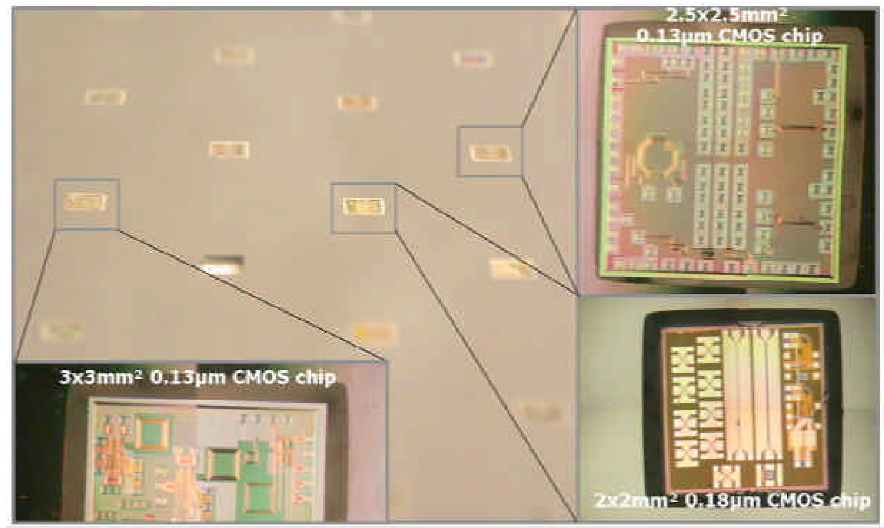




J. Harvey, E. R. Brown, D. B Rutledge and R. A. York, "Spatial Power Combining for High-Power Transmitters.", IEEE Microwave Mag. Pp. 48-59, Dec. 2000

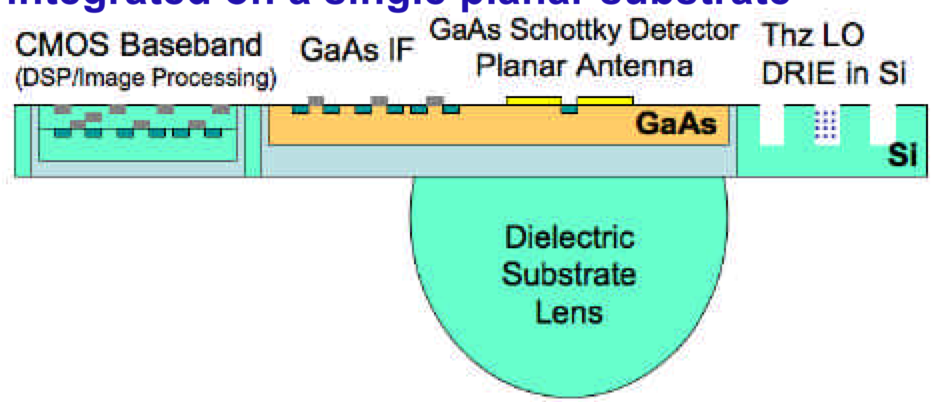
MEMS Heterogeneous Integration

- Integrate multiple *incompatible* processes onto single substrate utilizing MEMS technologies
- Terahertz integrated modules (TIMs) will use best processes for each sub-block.
  - Example of larger trend towards heterogeneous microsystems
- Wideband interconnects can be patterned onto planar surface
- Possible to utilize cheaper substrates than even silicon
  - Advantageous for large FPAs (Pixel spacing µ l x F#)



E. P. Quevy, R. T. Howe, and T.-J. King

GOAL: THz Heterodyne pixels fully integrated on a single planar substrate



Summary

- RF CMOS will continue to evolve as long as there is economic incentive to do so.
- Many compelling applications at low and high data rates, low and high carrier frequencies, and at low and high levels of complexity.
  - Terahertz CMOS is on its way.
- “Strong digital” means that one can implement sophisticated systems, including RF built-in self-test (RF BIST) engines.
  - Facilitates testing at wafer, die, package, and in the field.
- “Strong digital” also confers flexibility and reconfigurability.
  - Offers credible (TI says best) roadmap to the fabled software-defined radio.
- Moore’s law will continue on its historical trajectory for about another decade or so.
  - That’s long enough to enable fantastic achievements.

In closing…

- Market is nowhere near saturation: US consumers spend $50B annually on diet products alone. That is about double the global revenue for analog and RF CMOS ICs.

- For RF CMOS, “the future’s so bright, I gotta wear shades.”