# Toward a real system integration
# -- A direction of IC technology --

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# Motivation

**Interconnection peoples may worry about the future of digital LSI.**
**There are many serious problems;**
**such as large wire-delay, weak reliability.**
**Recently, mixed signal and RF technology becomes important.**
**Are there any wants or some jobs for these interconnection peoples?**

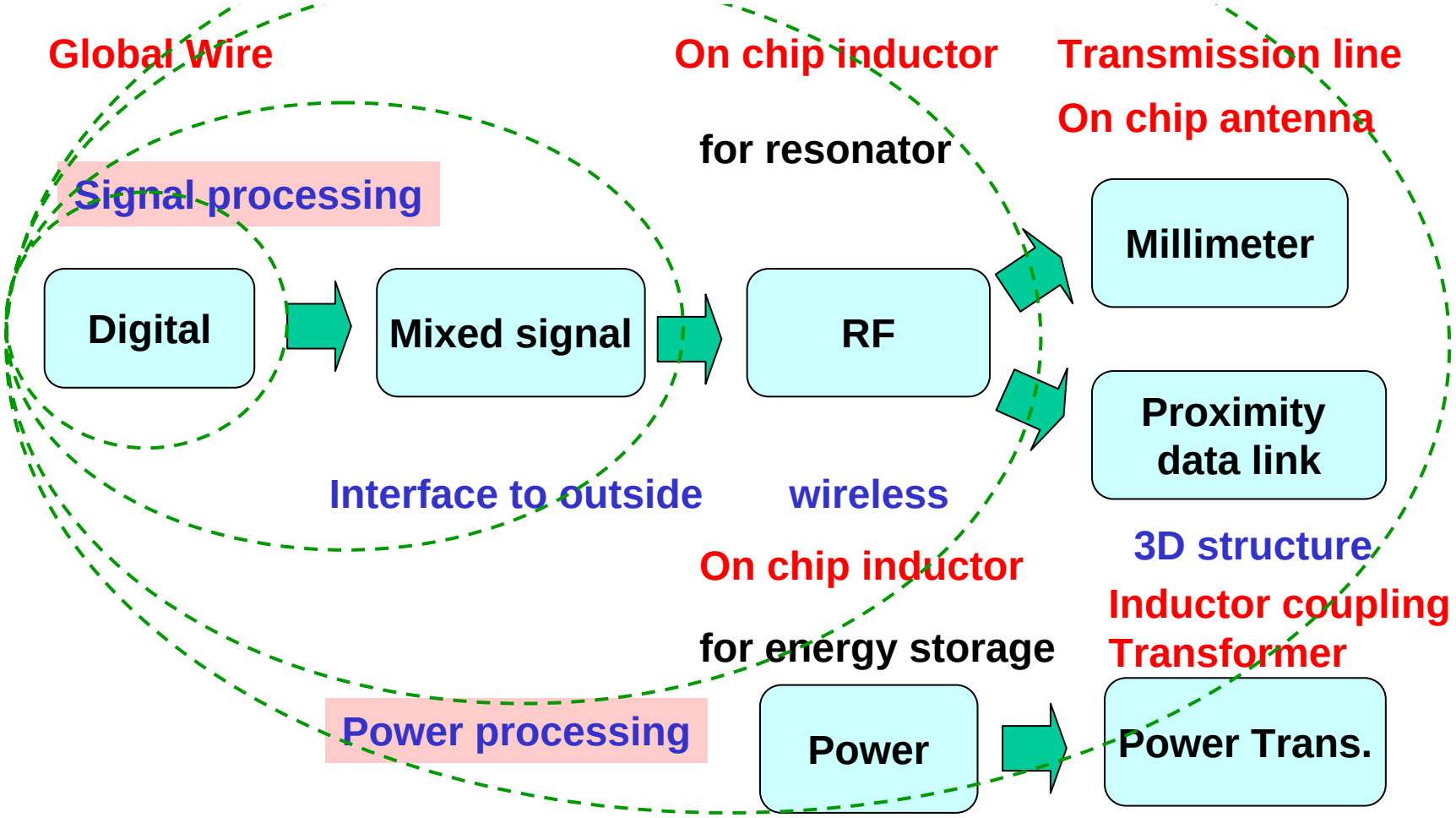
**I will show the trend of mixed and RF technology**
**and discuss the role of interconnection and metallization technology.**

# Contents

- **Mixed signal technology**
- **RF CMOS Technology**
- **mm wave SoC**
- **Proximity high speed data link**
- **Micro power systems**

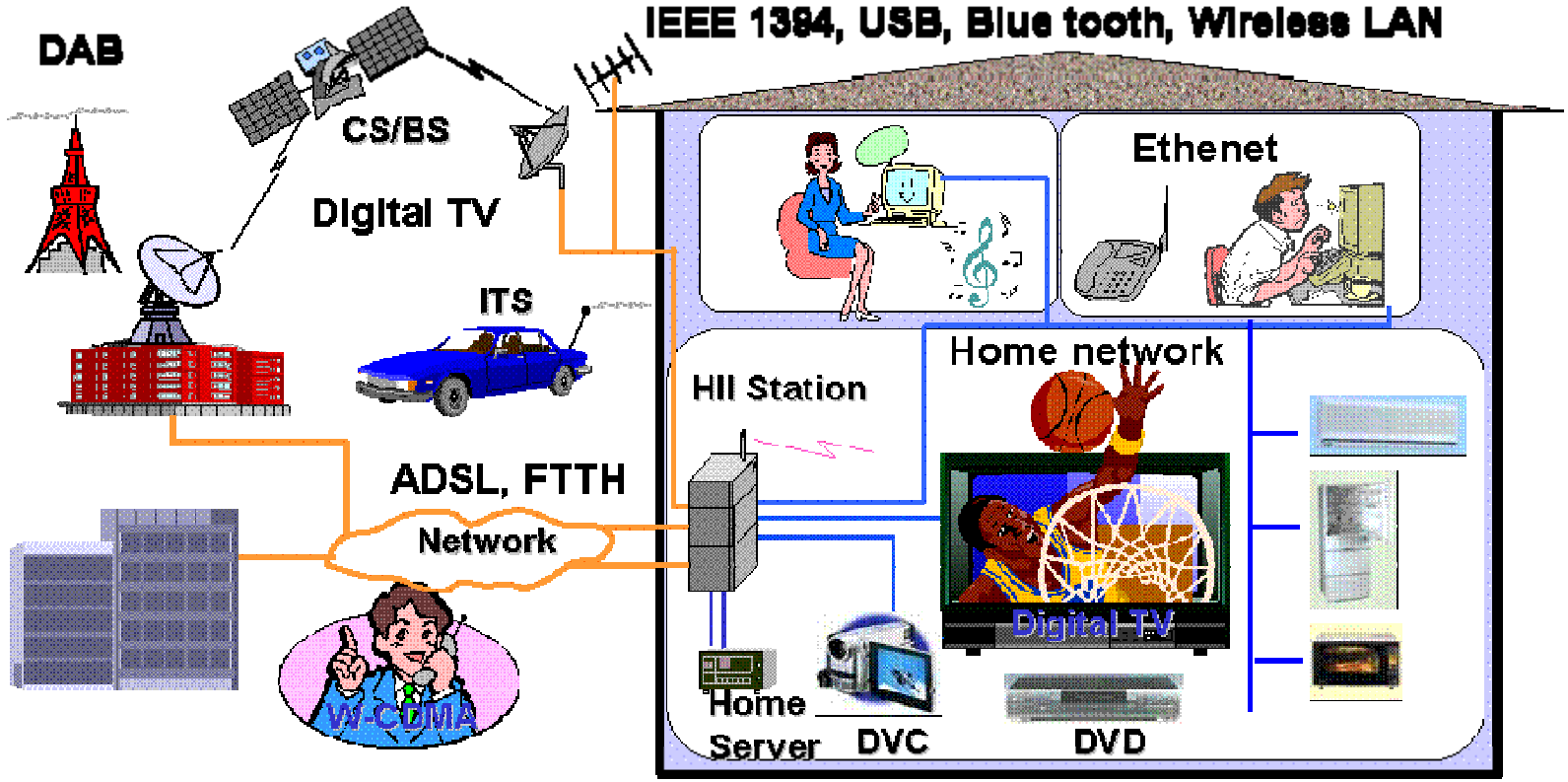
# Toward a real system integration

**A real system needs not only digital technology but also analog, RF , and power technology.**
**Interconnection technology plays an important role for the real system integration.**



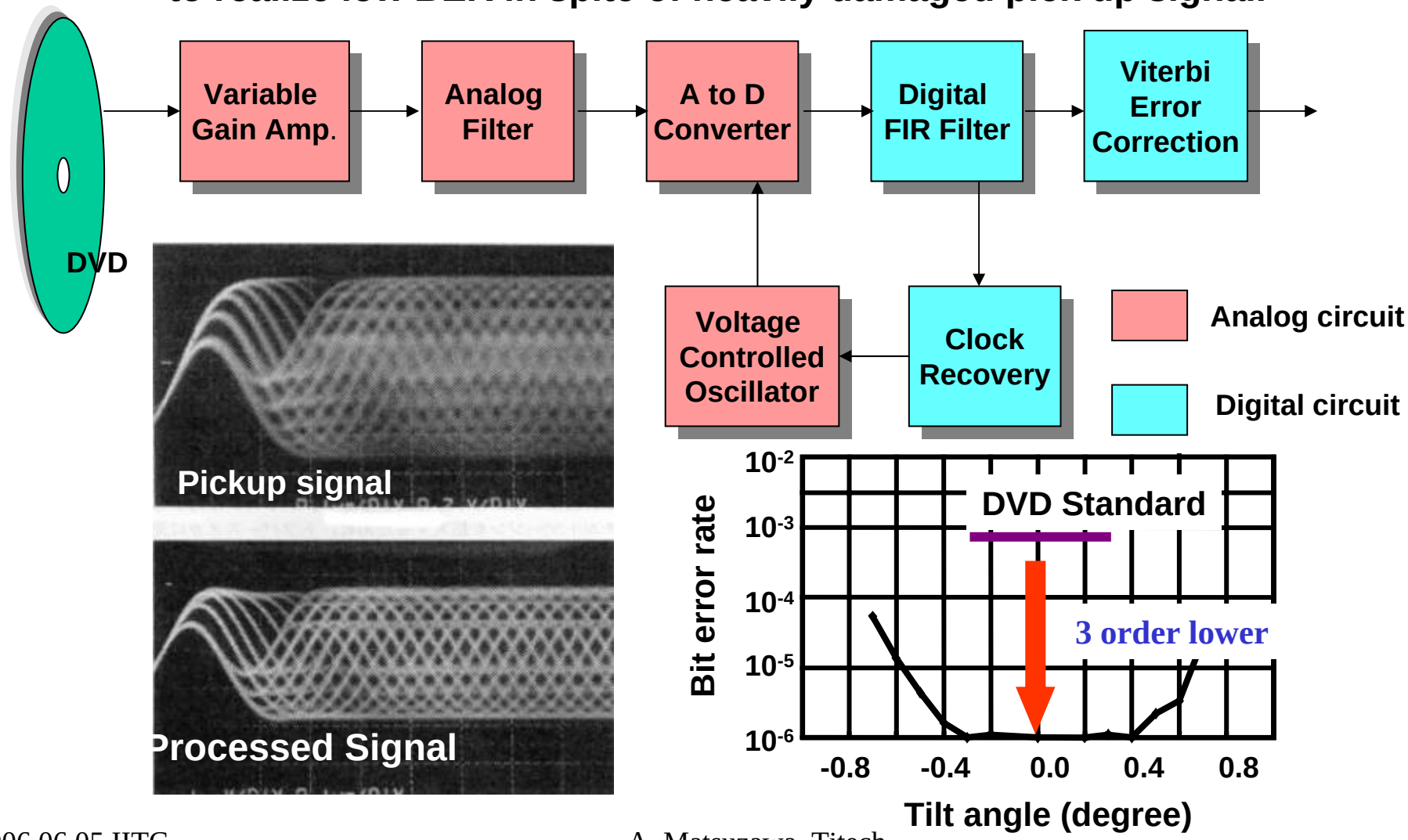
# Digital network society

**The digital network era has emerged. All digital consumer systems will connect each other through the networks.**
**Mixed signal and RF technology play the important roles.**



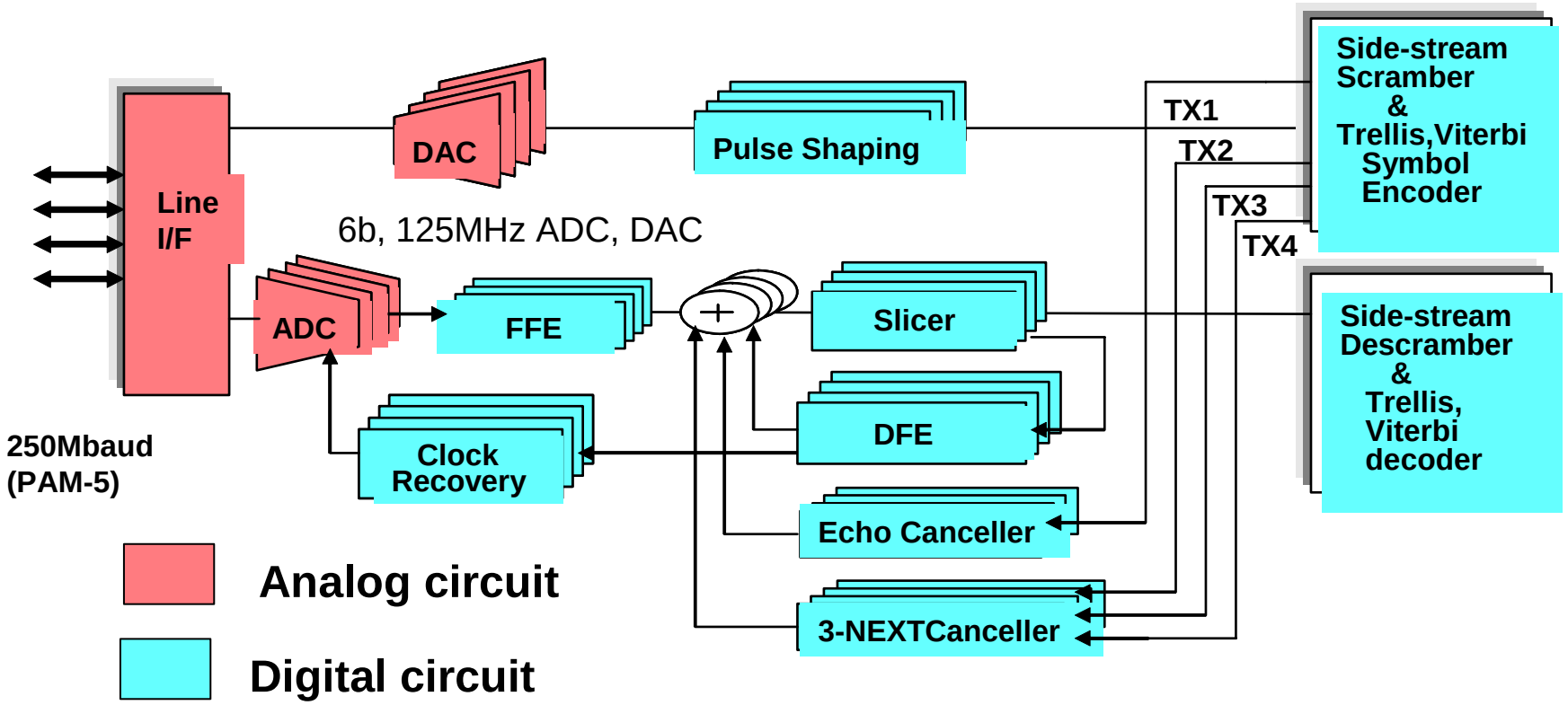
# Mixed signal Tech. for digital recording

**Current digital recording needs mixed signal processing to realize low BER in spite of heavily damaged pick up signal.**



# Mixed signal Tech. for digital networking

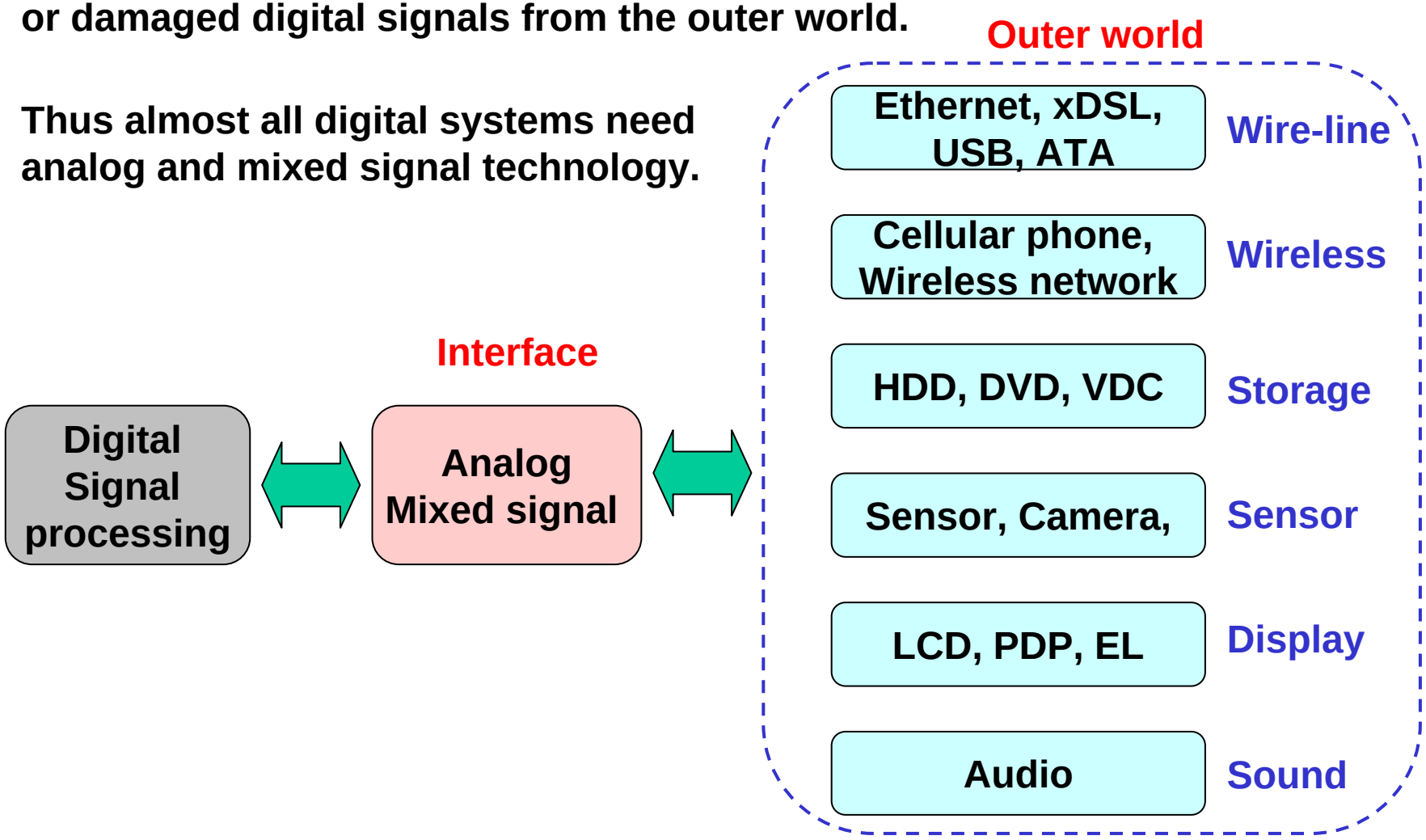
**Digital networking systems need mixed signal technology for the same reason of digital recording; recover the signal from the damage by signal transmission.**



# Current role of analog technology

**Current role of analog and mixed signal technology is interfacing between digital signal processing and signals from sensors or damaged digital signals from the outer world.**

**Thus almost all digital systems need analog and mixed signal technology.**

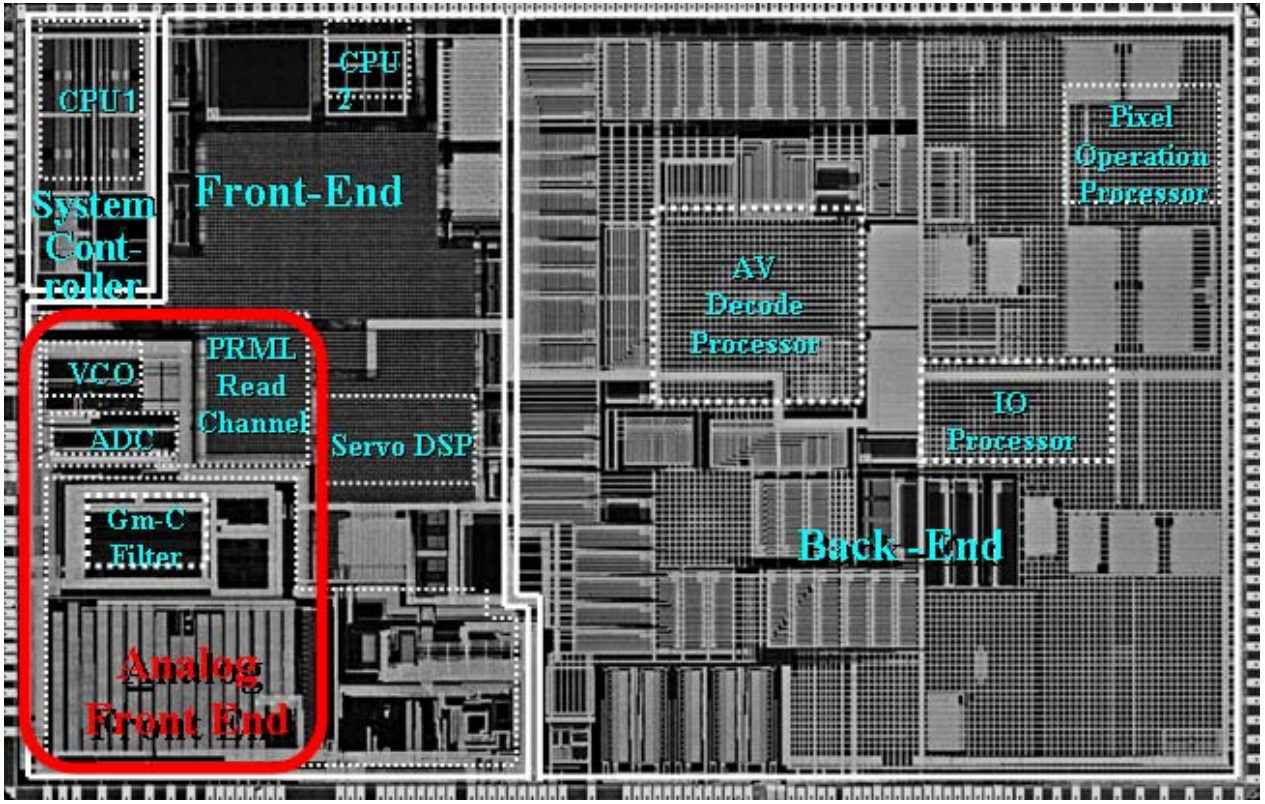


# Mixed signal SoC

**Mixed signal SoC technology has realized one chip DVD SoC.**

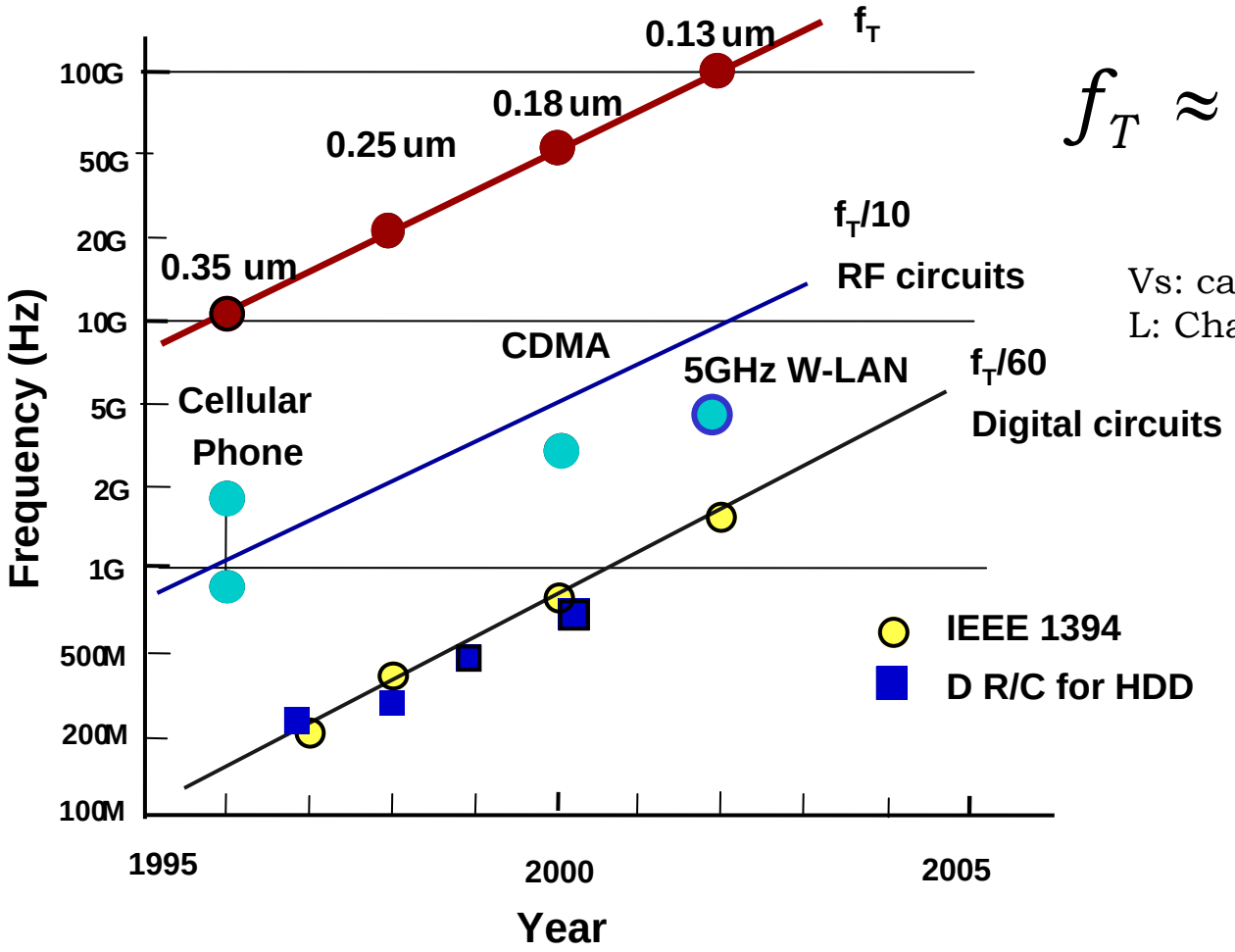
**0.13um, Cu 6Layer, 24MTr**

Okamoto, et al., ISSCC 2003



# CMOS RF technology

**Technology scaling increases operating frequency of CMOS circuits.**
**Now CMOS technology is widely used for many wireless systems.**



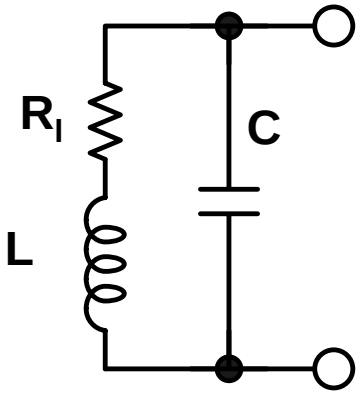

$$f_T \approx \frac{v_s}{2\pi L}$$

Vs: carrier velocity
L: Channel length

# Inductor for RF circuits

**Inductor is the key for RF circuits to form the resonator**
**Low parasitic resistor is required to realize high Q circuits**

**High Q inductor reduces phase noise and power consumption of oscillator.**

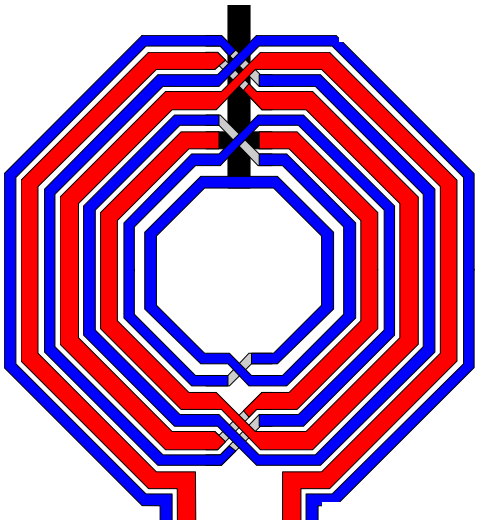



**Resonator**

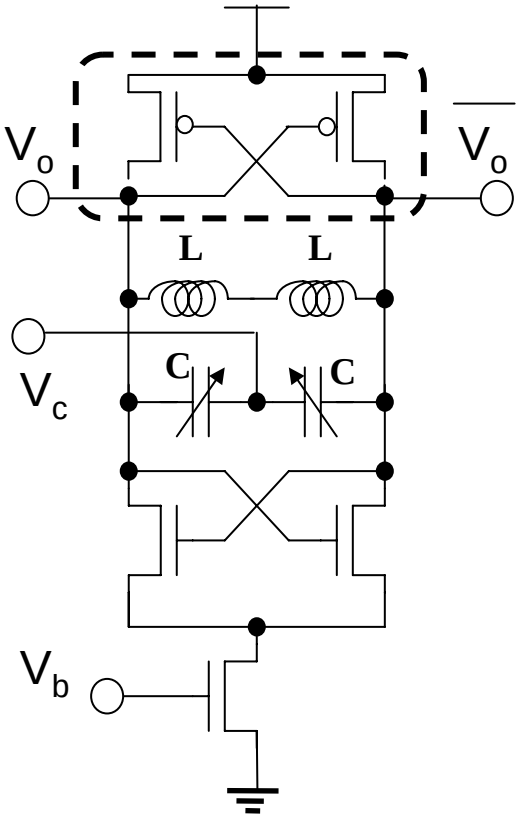
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{\omega L}{R_l}$$

$$Q(\omega) = \frac{1}{2\pi} \cdot \frac{E_{magnetic} - E_{electric}}{E_{loss/cycle}}$$



**On chip inductor**




**Phase noise**

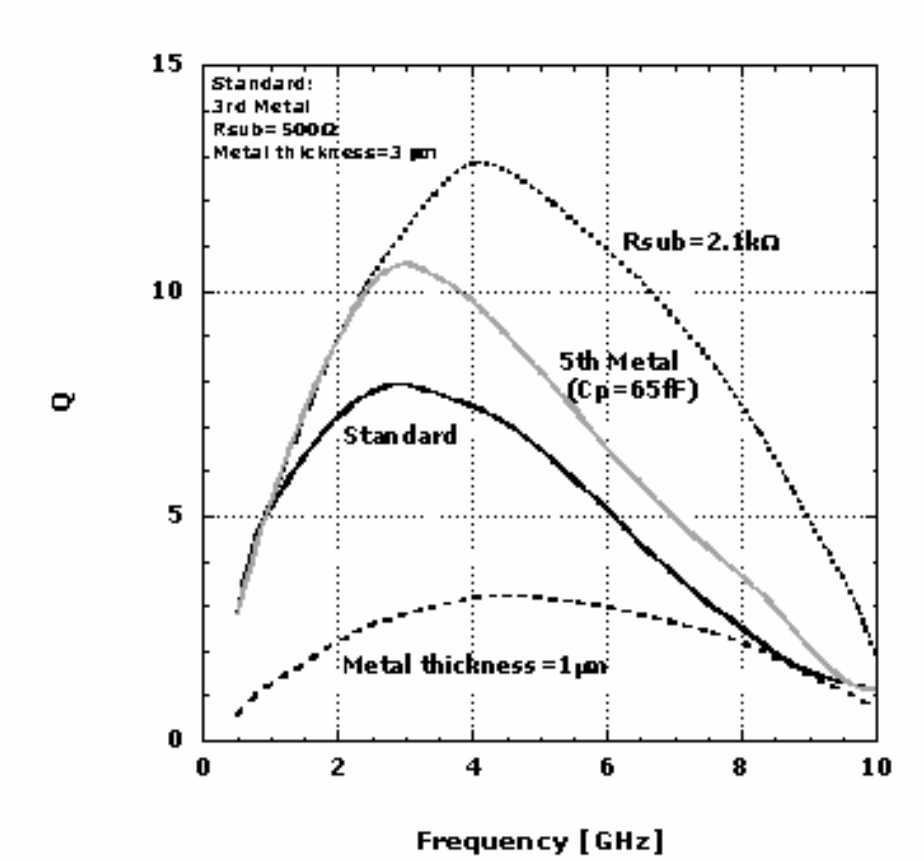
$$S_\phi \propto \frac{1}{Q^2}$$

**Current**

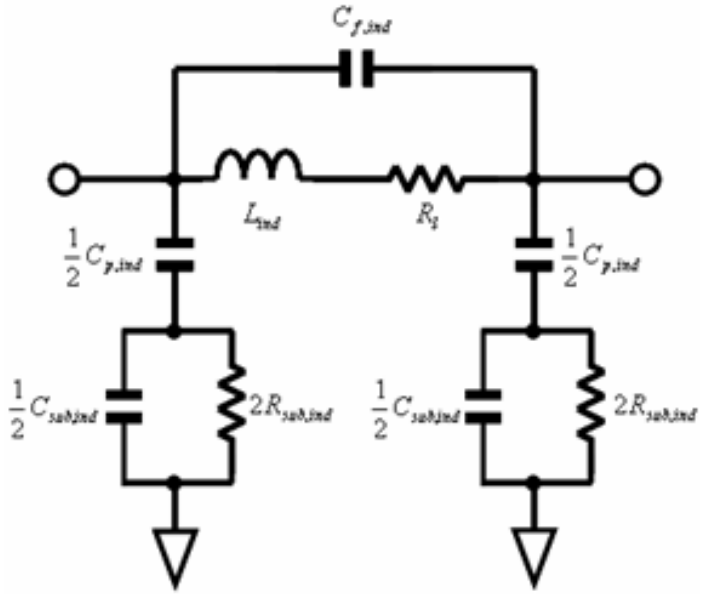
$$I \propto \frac{1}{Q}$$

# Requirement for an inductor

**Low parasitic resistance and low parasitic capacitance are required to realize high Q circuit for radio frequency applications.**
**Thicker top metal with high resistance substrate is suitable.**

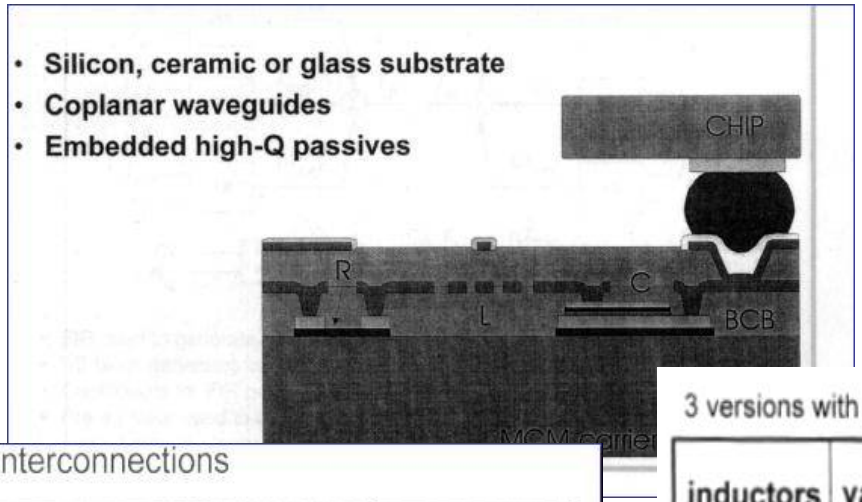


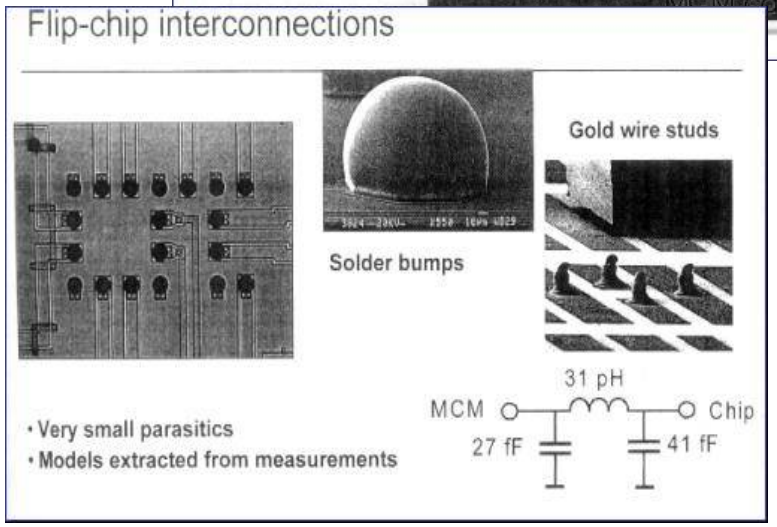

**High L/R and L/C ratio is needed**



# High Q inductor

**The inductor formed above chip can attain extreme high Q factor.**




$Q_{max}$=63 @9.2GHz

3 versions with constant output power: -7 dBm (single-ended)

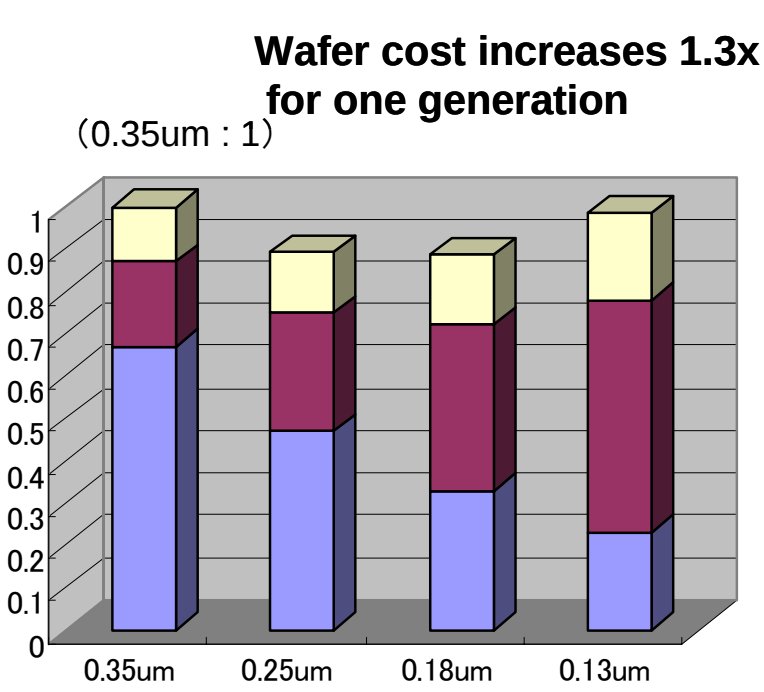
| inductors | varactors | phase noise (dBc/Hz @ 100 kHz) | Power (mW) | FOM |
|---|---|---|---|---|
| on-chip Q=5.5 | on-chip Q=17 | -86 | 17.8 | 167 |
| MCM Q=50 | on-chip Q=17 | -90 | 9.5 | 173.7 |
| MCM Q=50 | off-chip Q=40 | -92 | 7.9 | 176.5 |

(simulated results)

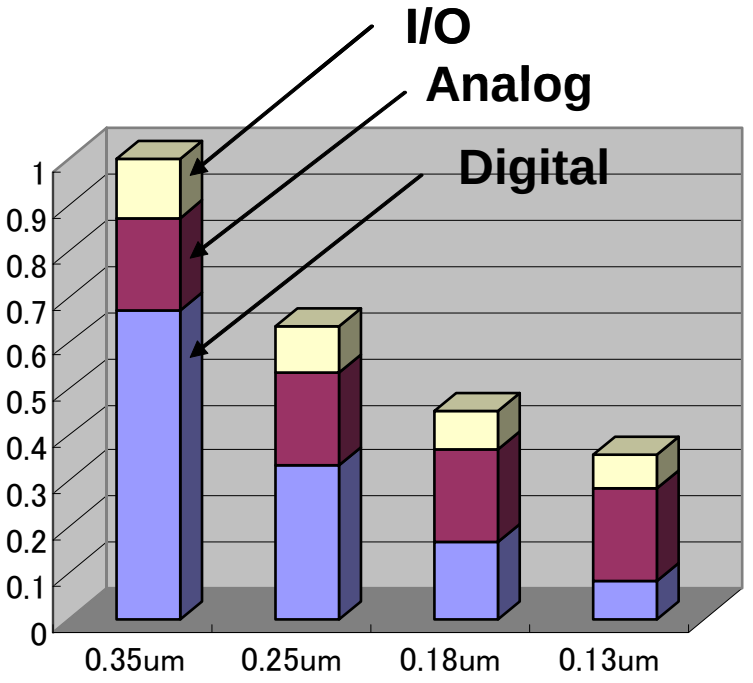
W.P.Donnay, et al., ISSCC 2000, WA 19.1

# Cost issue of mixed signal LSI

**It is difficult to reduce occupied area for analog/RF circuits,**
**in particular for passive components.**
**This results in increase of chip cost when using highly scaled CMOS technology.**




**Chip cost**

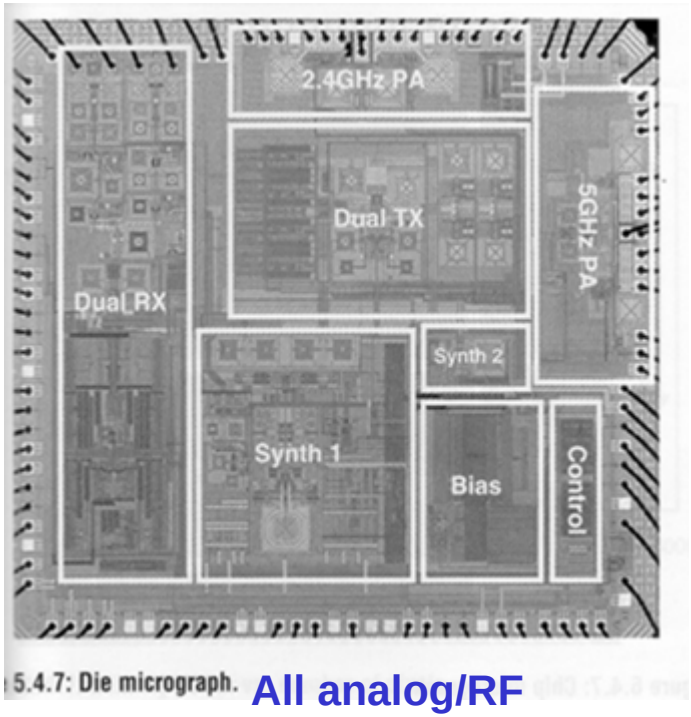



**Chip area**

# Trend: Less inductors

**Inductors occupies large area and results in increase of chip cost.**
**Recent RF chips minimize the number of inductors.**

**Wireless LAN, 802.11 a/b/g**
0.25um, 2.5V, 23mm$^2$, 5GHz

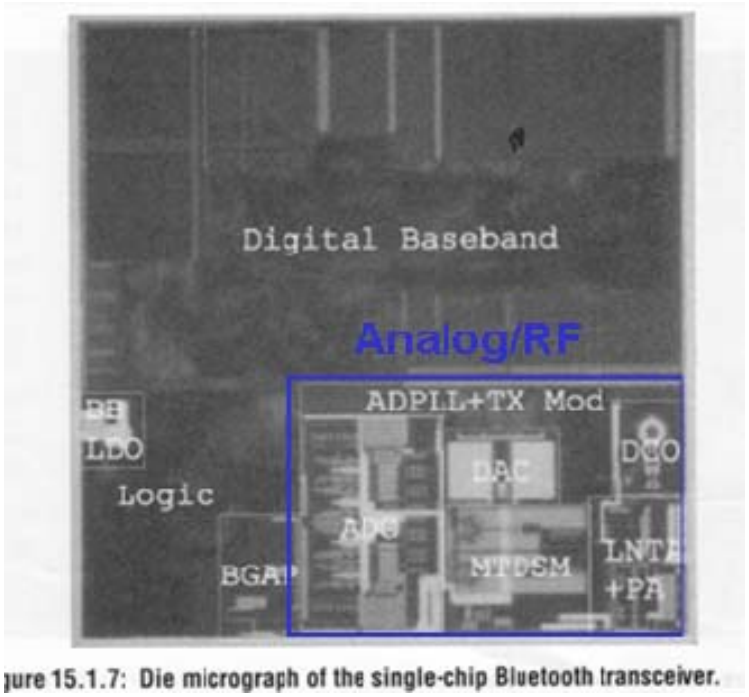



5.4.7: Die micrograph. **All analog/RF**

M. Zargari (Atheros), et al., ISSCC 2004, pp.96

**SoC**

**Discrete-time Bluetooth**
0.13um, 1.5V, 2.4GHz



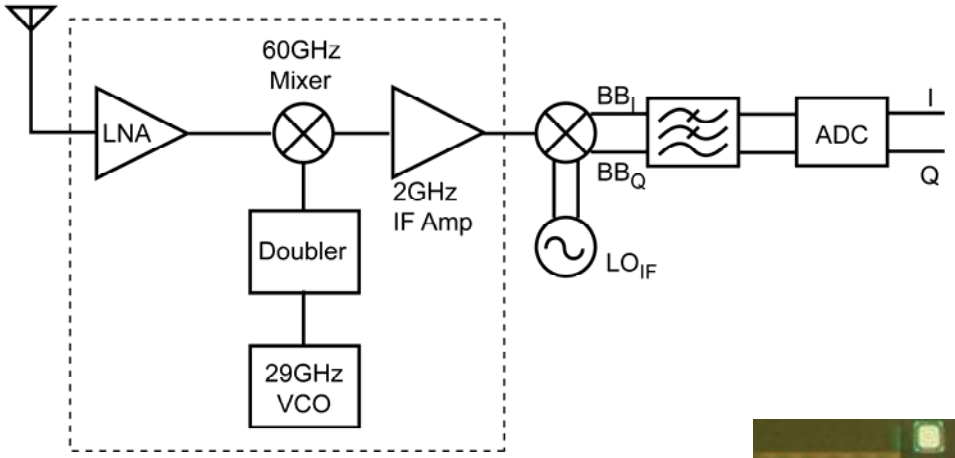

ure 15.1.7: Die micrograph of the single-chip Bluetooth transceiver.

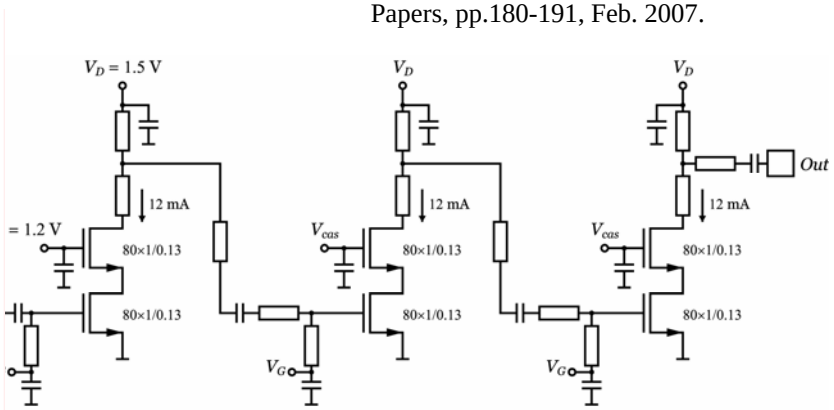
K. Muhammad (TI), et al., ISSCC2004, pp.268

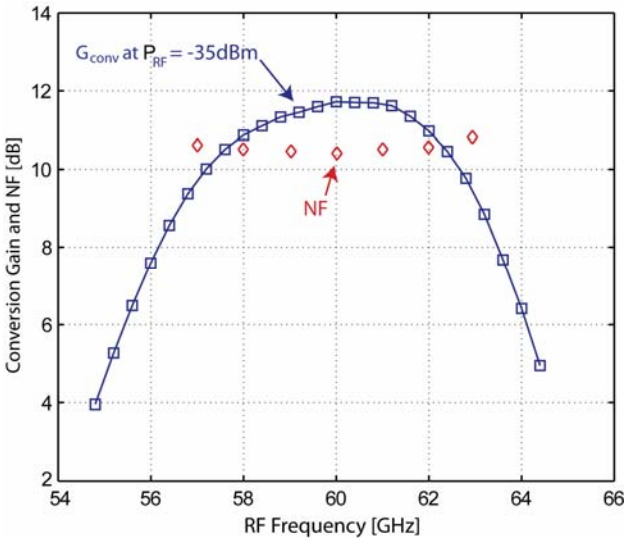
# Millimeter wave applications

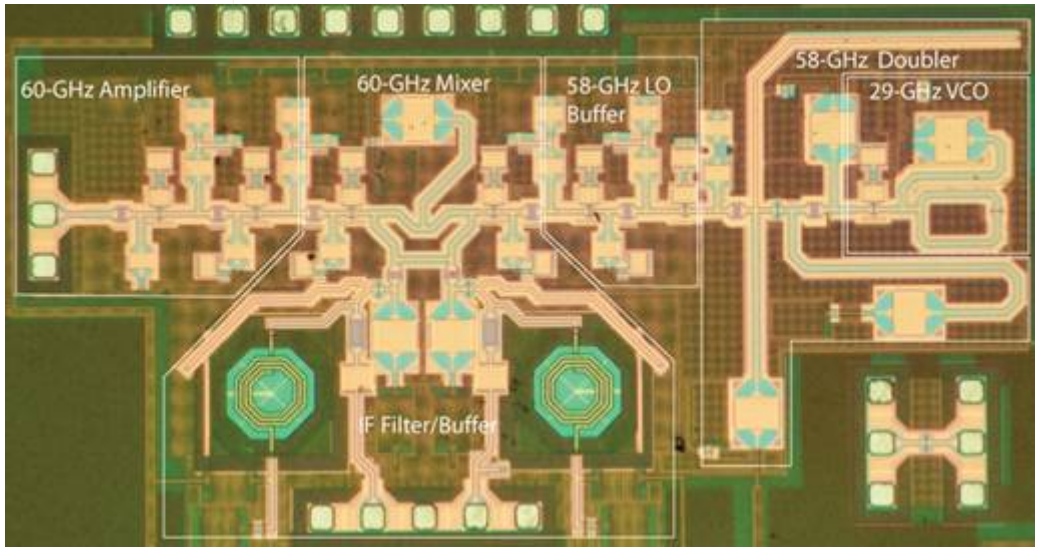
**Technology scaling has enabled 60 GHz application by CMOS technology to realize several Gbps data transfer.**

S. Emami, C. H. Doan, A. M. Niknejad, R. W. Broderson, "A Highly Integrated 60GHz CMOS Front-End Receiver," IEEE ISSCC 20007, Dig. of Tech. Papers, pp.180-191, Feb. 2007.



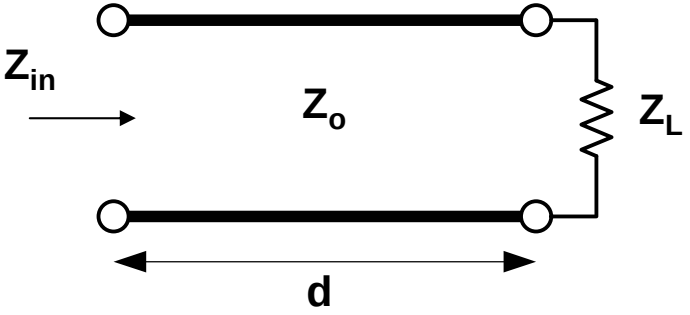



# Transmission line for mm wave applications

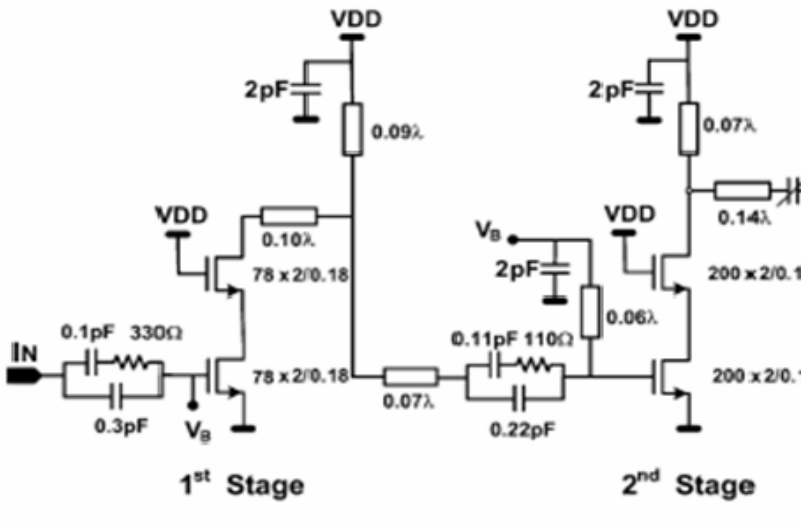
**Coplanar transmission line with substrate shield is used for signal lines of mm wave applications to reduce signal power loss.**
**This structure can realize an impedance transfer and a resonator.**

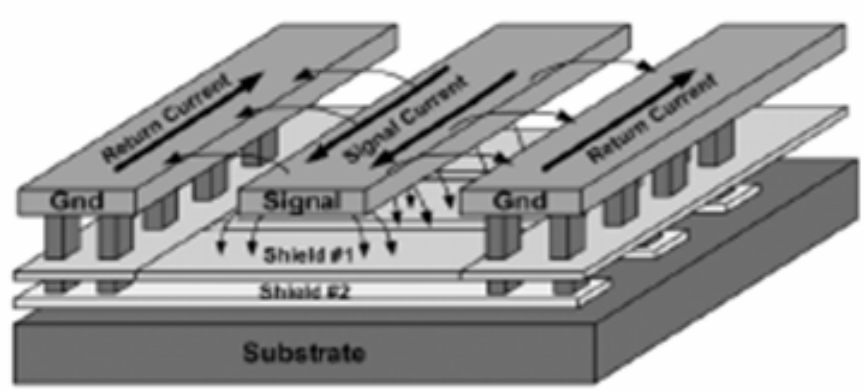



$$Z_{in} = Z_0 \frac{Z_l + jZ_0 \tan\beta d}{Z_0 + jZ_l \tan\beta d}$$

resonator

$$Z_{in}\left(\frac{\lambda}{4}\right) = \frac{Z_0^2}{Z_l} \qquad Z_{in}\left(\frac{\lambda}{4}\right) = \infty \ when\ Z_l = 0$$




**Coplanar transmission line**

# On chip antenna for mm wave SoC

**An on-chip antenna is available for mm wave applications.**
**A real RF system  on a chip can be realized.**

**Electrical beam forming is also possible by phased array antenna technology.**

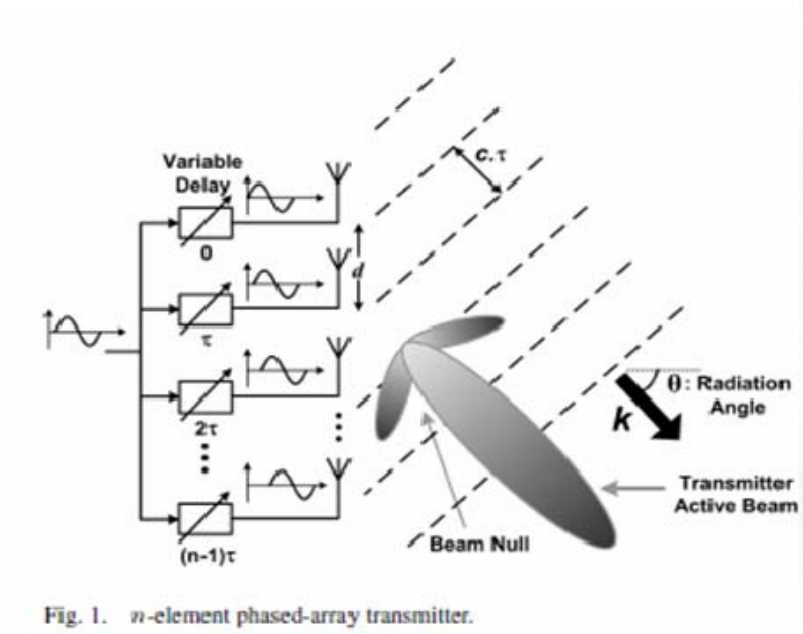
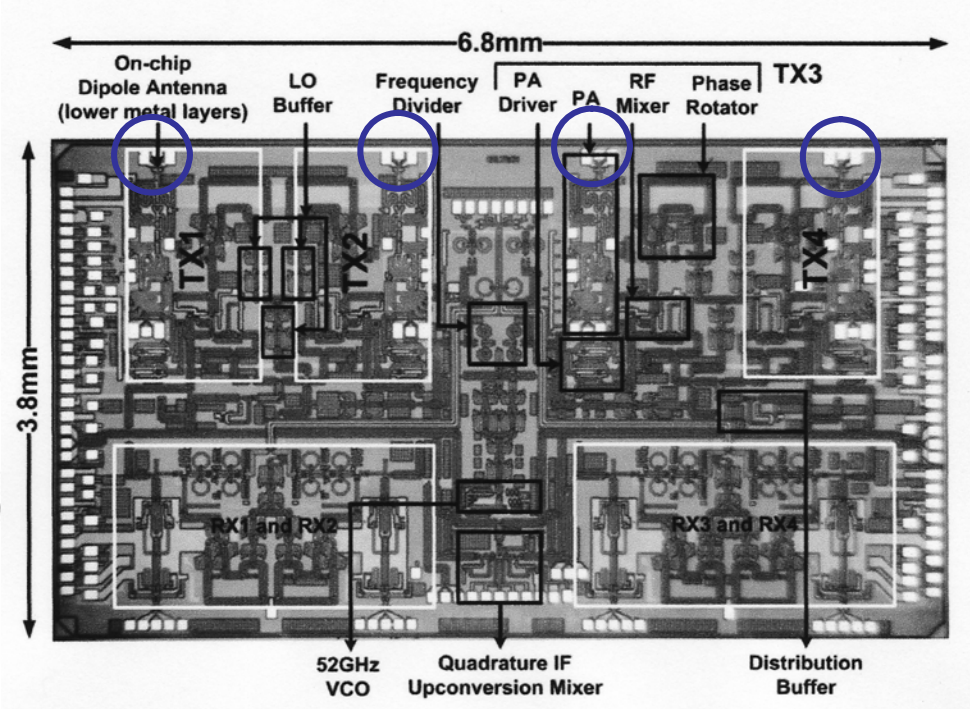


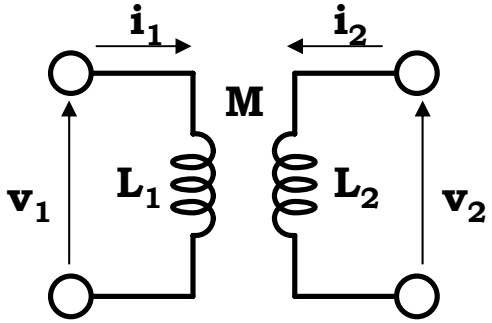

Fig. 1. *n*-element phased-array transmitter.




A. Natarajan, et. al., IEEE, Journal of Solid-State Circuits, Vol. 40, No. 12, pp. 2502-2514, Dec. 2005.
A. Natarajan, et. al., IEEE, Journal of Solid-State Circuits, Vol. 41, No. 12, pp. 2807-2819, Dec. 2006.

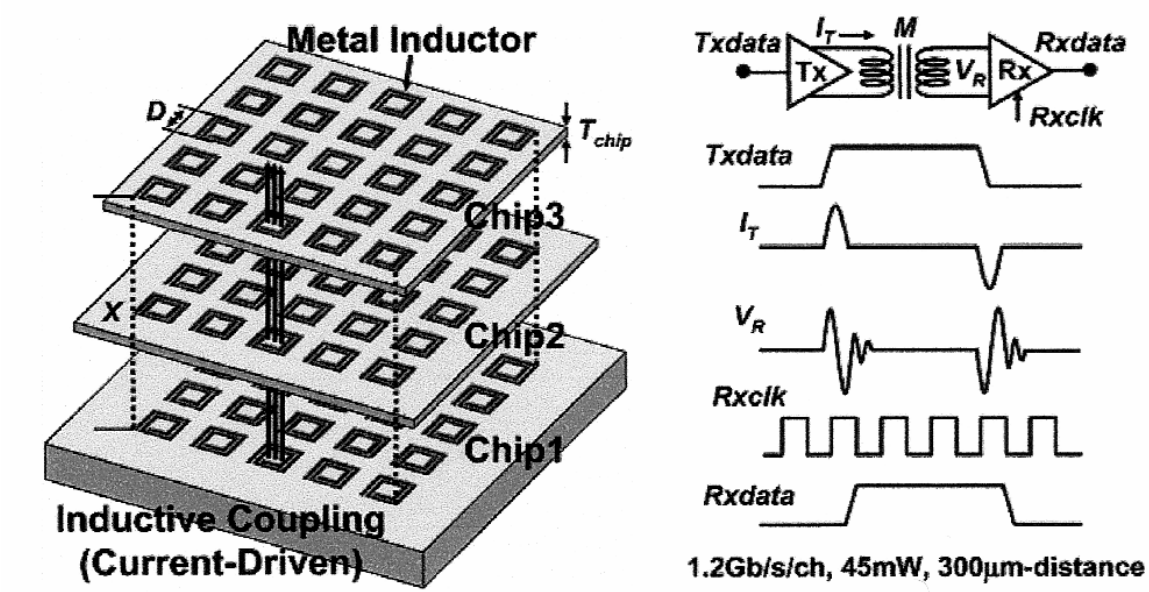
# Proximity magnetic coupling

**Magnetic coupling is useful for proximity high speed data transfer between stacked chips.**




$$v_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \qquad v_2 = M \frac{di_1}{dt}$$

$$v_2 = M \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \qquad M \propto \frac{\sqrt{L_1 L_2}}{x^3}$$

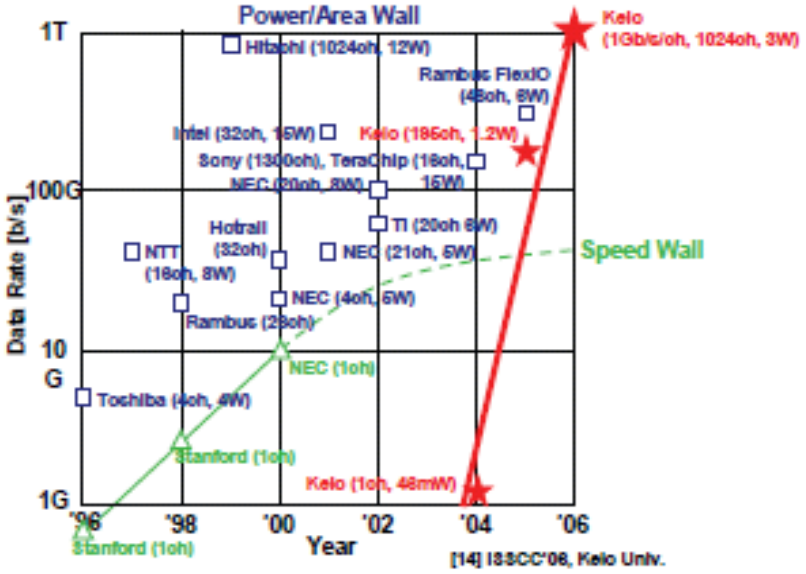


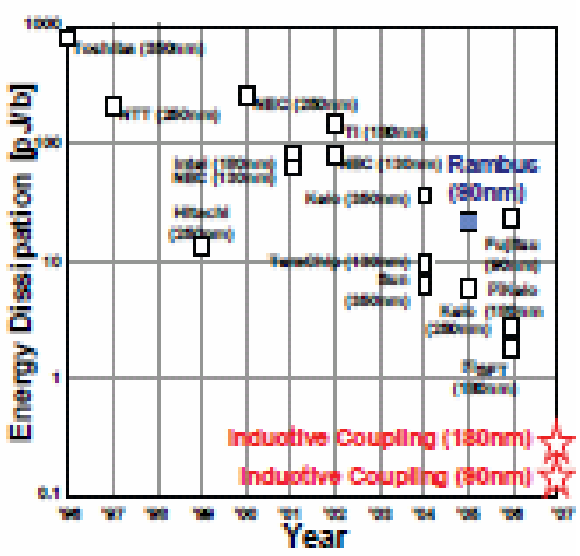

N. Miura, et. al., IEEE, Journal of Solid-State Circuits, Vol. 41, No. 1, pp. 23-34, Jan. 2006.

# Proximity high speed data link

**Magnetic coupling realized sufficiently high speed data rate of 1Gbps/ch with very low energy consumption.**
**No ESD and no need to adjust bias voltages.**
**Suitable for interconnection between stacked chips.**

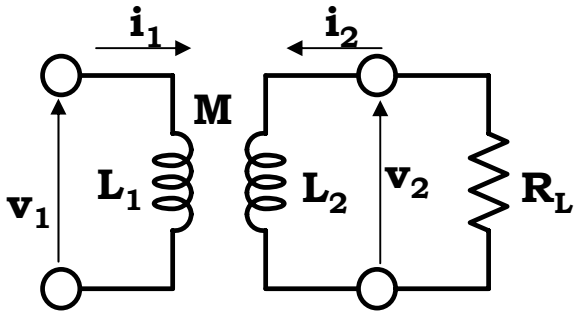
**Data rate: 1Gbps/ch**
**Energy consumption:140fJ/b**



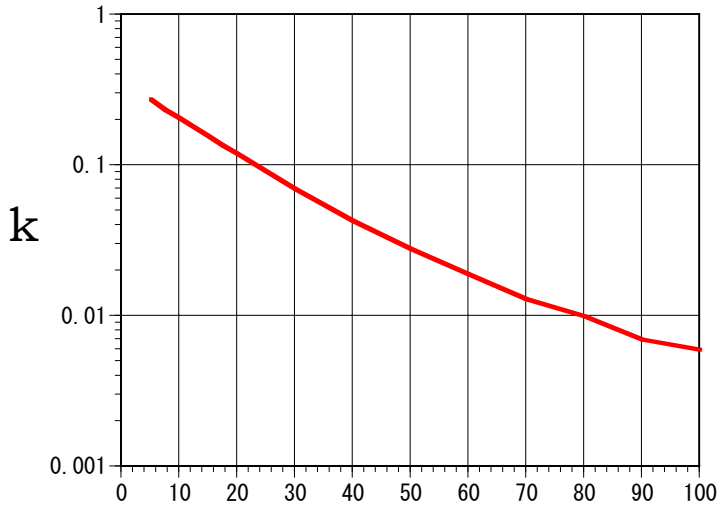
# Data and power transfer by magnetic coupling

**Magnetic coupling can transfer electrical power as well as data.**
**It will be used for sensor telemetry systems, for example in-vivo chips.**

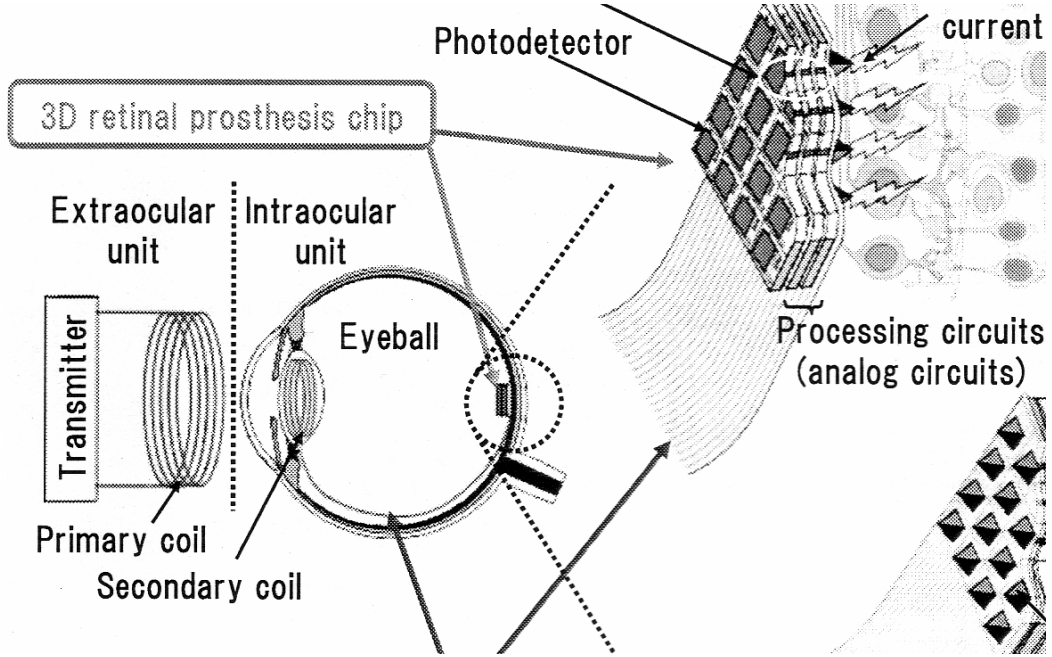



$$P_L = k^2 \frac{L_1}{L_2} I_1^2 R_L \qquad k = \frac{M}{\sqrt{L_1 L_2}} \propto \frac{1}{d^3}$$

K decreases rapidly with increase of distance



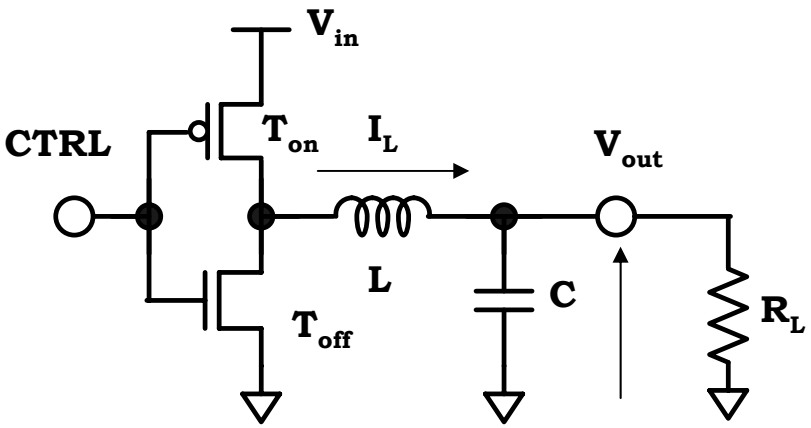

4 turns 85.6mm x 54 mm



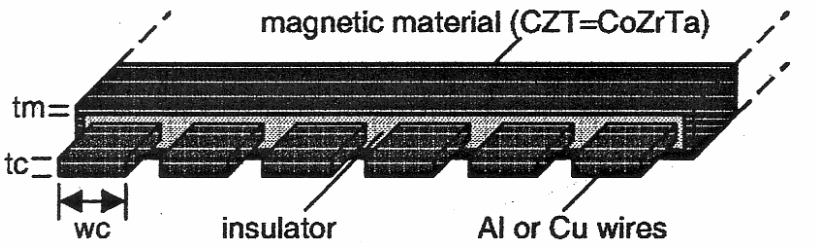

T. Tanaka, et. al., Tech. Dig. of Int. 3D S I Conference, 6-1, 2007

# Micro power systems

**Micro power system will be needed for distributed voltage regulators over a chip.**
**High Q (L/R) inductor is the key, as well as RF applications.**
**Higher frequency operation realizes higher efficiency even though using small on-chip inductors.**

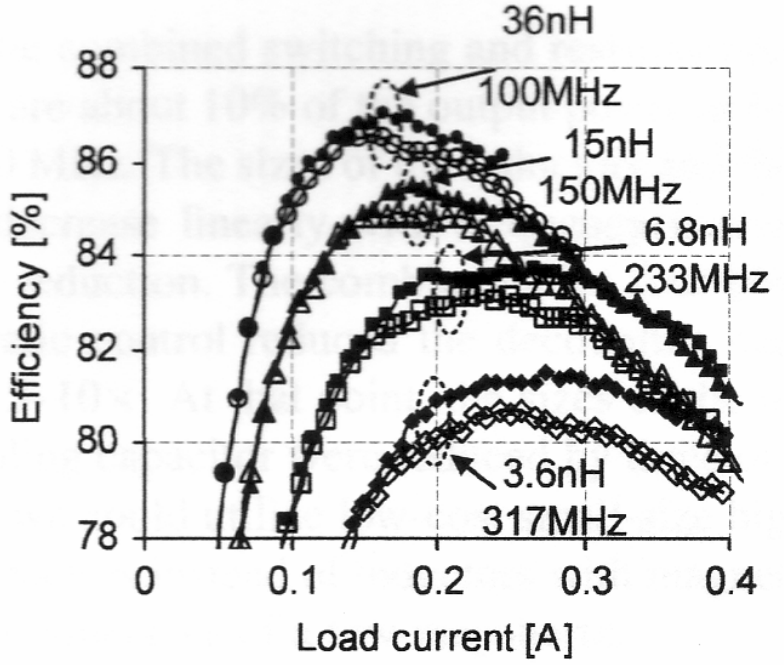



$$\mu_r = 900,\ \frac{L}{R} = 50ns$$




$$V_{out} = \frac{T_{on}}{T_{on} + T_{off}} V_{in} \quad \Delta I_L \propto \frac{1}{Lf} \qquad Q = 2\pi \frac{fL}{R}$$

$$E_L = \frac{1}{2} LI^2, \quad P_L = \frac{f}{2} LI^2$$




G. Schrom, et. al., Proc. ISLPED'04, pp. 263-268, 2004.

# Summary

- **Real systems need mixed signal, RF, and power technology, as well as digital technology.**
- **Mixed signal technology is vital for interfacing outer analog and digital signals.**
- **RF technology needs high Q inductor, however an issue is large occupied area.**
- **Millimeter wave applications have been emerged and need high Q transmission line and on-chip antenna.**
- **Magnetic coupling is useful for proximity high speed data transfer and power transfer.**
- **Micro power system must be needed. High Q and large inductor is vital.**

# Many works !

**There are many works for interconnection and metallization peoples.**