PLASMA PROCESSING FOR NANOELECTRONICS — HISTORY AND PROSPECTS

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Reference:

H. Abe, M. Yoneda and N. Fujiwara, Jpn. J. Appl. Phys. **47**, 1435 (2008)

Special thanks: John W. Coburn

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OUTLINE

- The nanoelectronics revolution
- History of plasma processing
- Future of plasma processing

THE NANOELECTRONICS REVOLUTION

- Transistors/chip doubling every $1\frac{1}{2}$–2 years since 1959
- 1,000,000-fold decrease in cost for the same performance in the last 30 years
- In 20 years one computer will be as powerful as all those in Silicon Valley today

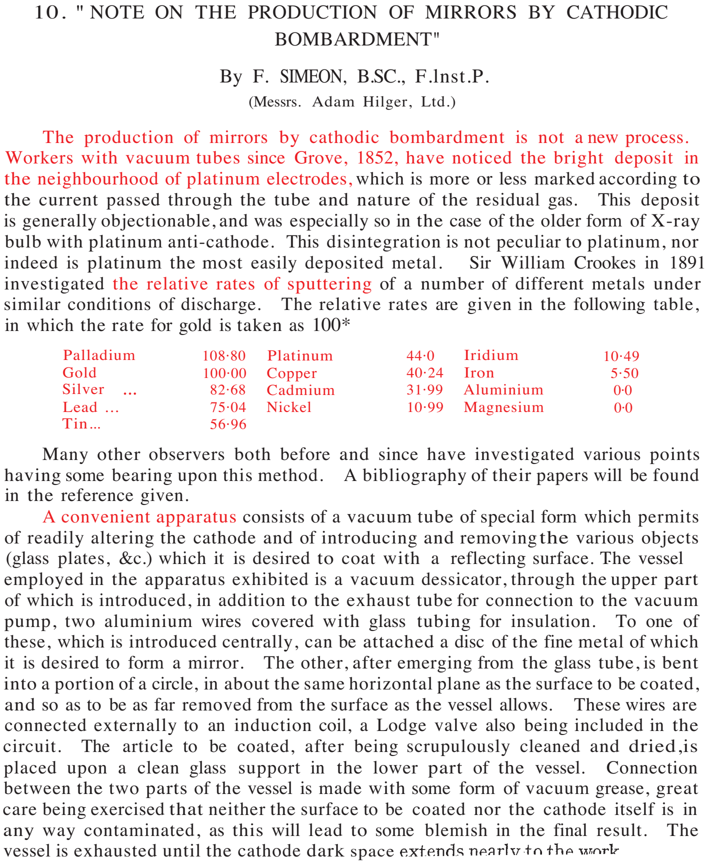
EQUIVALENT AUTOMOTIVE ADVANCE

- 60 million miles/hr
- 20 million miles/gal
- Throw away rather than pay parking fees
- 3 mm long × 1 mm wide
- Crash 3× a day

HISTORY OF PLASMA PROCESSING

HUMBLE BEGINNINGS — SILVERING MIRRORS

- Sputtering discovered by Sir William Grove in 1852
- Relative sputtering rates of various metals measured in 1890–1910
- Crude apparatus used to sputter-coat silver, platinum, etc on glass surfaces
- The mechanism of physical sputtering was not understood
- Discharge state-of-the-art in the 1920's was rudimentary



10. " NOTE ON THE PRODUCTION OF MIRRORS BY CATHODIC BOMBARDMENT"

By F. SIMEON, B.SC., F.Inst.P.

(Messrs. Adam Hilger, Ltd.)

The production of mirrors by cathodic bombardment is not a new process. Workers with vacuum tubes since Grove, 1852, have noticed the bright deposit in the neighbourhood of platinum electrodes, which is more or less marked according to the current passed through the tube and nature of the residual gas. This deposit is generally objectionable, and was especially so in the case of the older form of X-ray bulb with platinum anti-cathode. This disintegration is not peculiar to platinum, nor indeed is platinum the most easily deposited metal. Sir William Crookes in 1891 investigated the relative rates of sputtering of a number of different metals under similar conditions of discharge. The relative rates are given in the following table, in which the rate for gold is taken as 100*

Palladium	108·80	Platinum	44·0	Iridium	10·49
Gold	100·00	Copper	40·24	Iron	5·50
Silver ...	82·68	Cadmium	31·99	Aluminium	0·0
Lead ...	75·04	Nickel	10·99	Magnesium	0·0
Tin...	56·96				

Many other observers both before and since have investigated various points having some bearing upon this method. A bibliography of their papers will be found in the reference given.

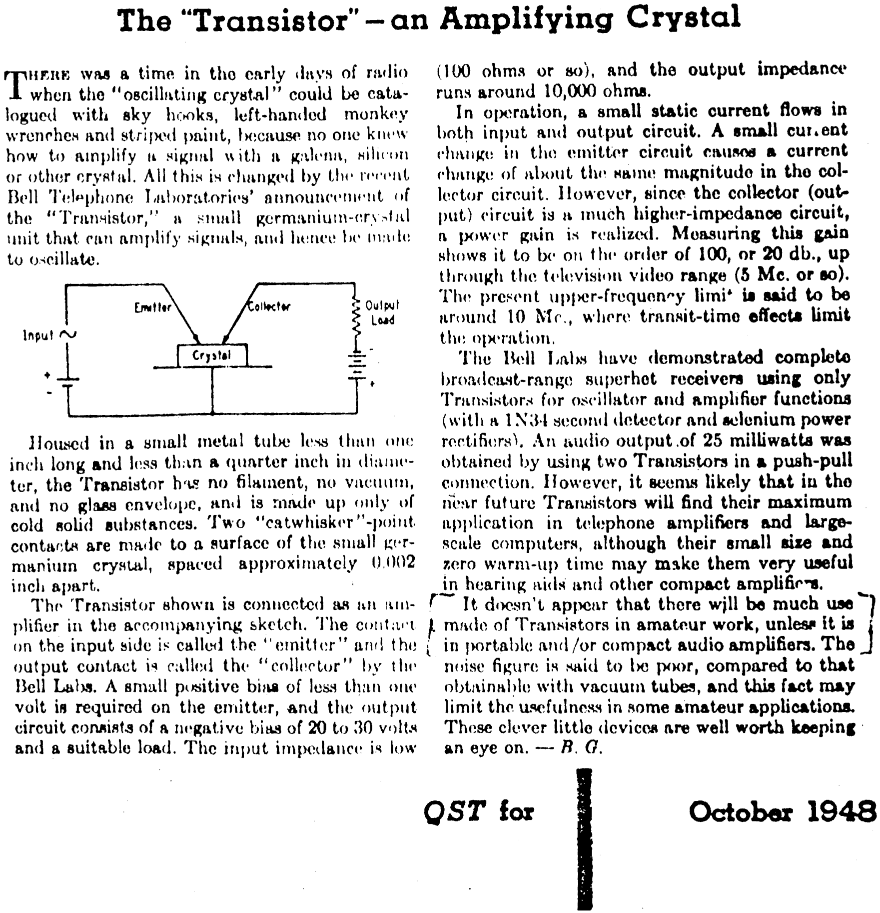
A convenient apparatus consists of a vacuum tube of special form which permits of readily altering the cathode and of introducing and removing the various objects (glass plates, &c.) which it is desired to coat with a reflecting surface. The vessel employed in the apparatus exhibited is a vacuum dessicator, through the upper part of which is introduced, in addition to the exhaust tube for connection to the vacuum pump, two aluminium wires covered with glass tubing for insulation. To one of these, which is introduced centrally, can be attached a disc of the fine metal of which it is desired to form a mirror. The other, after emerging from the glass tube, is bent into a portion of a circle, in about the same horizontal plane as the surface to be coated, and so as to be as far removed from the surface as the vessel allows. These wires are connected externally to an induction coil, a Lodge valve also being included in the circuit. The article to be coated, after being scrupulously cleaned and dried, is placed upon a clean glass support in the lower part of the vessel. Connection between the two parts of the vessel is made with some form of vacuum grease, great care being exercised that neither the surface to be coated nor the cathode itself is in any way contaminated, as this will lead to some blemish in the final result. The vessel is exhausted until the cathode dark space extends nearly to the work

(From "The Making of Reflecting Surfaces", Phys. Soc., London, 26 Nov 1920)

INVENTION OF THE TRANSISTOR — 1948

W.B. Shockley,
J. Bardeen,
W.H. Brattain

Nobel Prize in Physics (1956)



The "Transistor" – an Amplifying Crystal

There was a time in the early days of radio when the "oscillating crystal" could be catalogued with sky hooks, left-handed monkey wrenches and striped paint, because no one knew how to amplify a signal with a galena, silicon or other crystal. All this is changed by the recent Bell Telephone Laboratories' announcement of the "Transistor," a small germanium-crystal unit that can amplify signals, and hence be made to oscillate.

Housed in a small metal tube less than one inch long and less than a quarter inch in diameter, the Transistor has no filament, no vacuum, and no glass envelope, and is made up only of cold solid substances. Two "catwhisker"-point contacts are made to a surface of the small germanium crystal, spaced approximately 0.002 inch apart.

The Transistor shown is connected as an amplifier in the accompanying sketch. The contact on the input side is called the "emitter" and the output contact is called the "collector" by the Bell Labs. A small positive bias of less than one volt is required on the emitter, and the output circuit consists of a negative bias of 20 to 30 volts and a suitable load. The input impedance is low (100 ohms or so), and the output impedance runs around 10,000 ohms.

In operation, a small static current flows in both input and output circuit. A small current change in the emitter circuit causes a current change of about the same magnitude in the collector circuit. However, since the collector (output) circuit is a much higher-impedance circuit, a power gain is realized. Measuring this gain shows it to be on the order of 100, or 20 db., up through the television video range (5 Mc. or so). The present upper-frequency limit is said to be around 10 Mc., where transit-time effects limit the operation.

The Bell Labs have demonstrated complete broadcast-range superhet receivers using only Transistors for oscillator and amplifier functions (with a 1N34 second detector and selenium power rectifiers). An audio output of 25 milliwatts was obtained by using two Transistors in a push-pull connection. However, it seems likely that in the near future Transistors will find their maximum application in telephone amplifiers and large-scale computers, although their small size and zero warm-up time may make them very useful in hearing aids and other compact amplifiers.

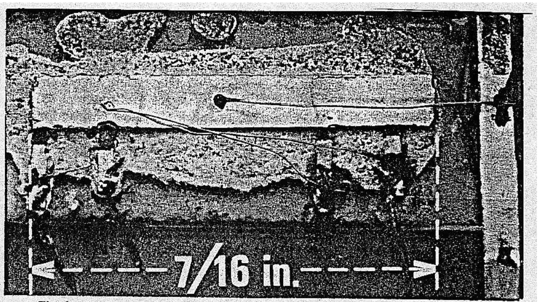
It doesn't appear that there will be much use made of Transistors in amateur work, unless it is in portable and/or compact audio amplifiers. The noise figure is said to be poor, compared to that obtainable with vacuum tubes, and this fact may limit the usefulness in some amateur applications. These clever little devices are well worth keeping an eye on. — *B. G.*

QST for October 1948

FIRST INTEGRATED CIRCUIT AND MICROPROCESSOR

Jack Kilby (1958)

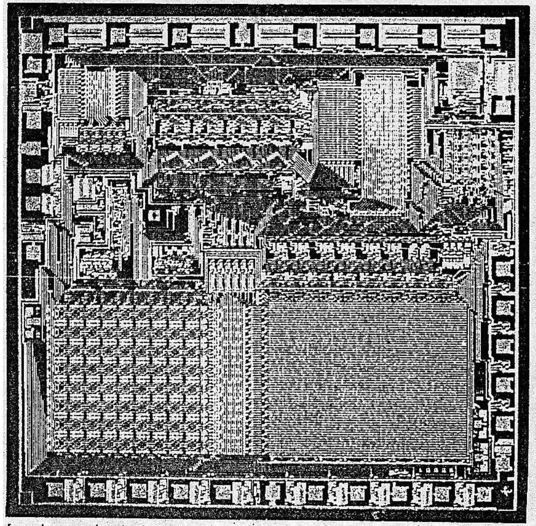
Nobel Prize in Physics (2000)



The first integrated circuit was made in 1958 by Jack Kilby of Texas Instruments.

Texas Instruments TMS 1000

USP 3,757,306 (1973)



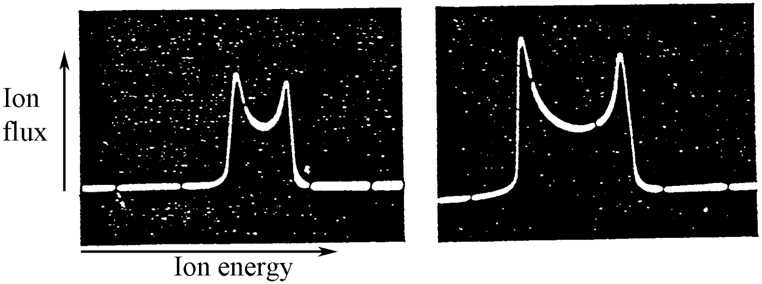
Less than two decades later, engineers put a complete microcomputer on a chip. [Source: *Texas Instruments, Inc.*]

SPUTTER DISCHARGE STATE-OF-THE-ART — 1960's

- Parallel plate capacitively coupled rf discharges that generated energetic ions were widely used for sputter-etching and sputter-deposition
- Formation of the ion energy distribution on substrate surface
- Role of blocking capacitor and formation of self-bias voltage
- Influence of electrode area ratio on dc plasma potential
- Optical emission spectroscopy for etch end-point detection
- Reactive sputter deposition
- Basic theory of physical sputtering

EXAMPLES

- Earliest measurement of ion energy distribution (J. Erö, 1958)



- Blocking capacitor and self-bias voltage (Butler and Kino, 1963)

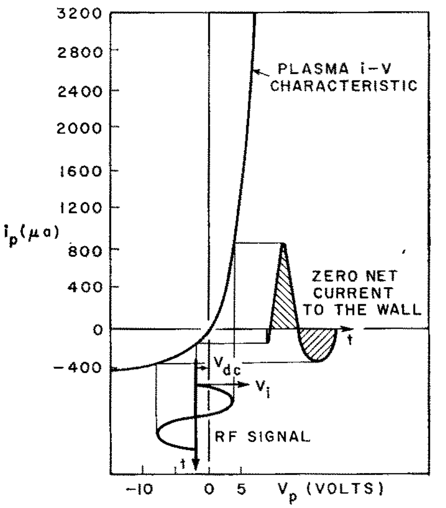


FIG. 2. Pictorial representation of mechanism by which a positive ion sheath is formed as a result of applying an rf voltage outside the plasma.

PLASMA ETCH STATE-OF-THE-ART — 1970's

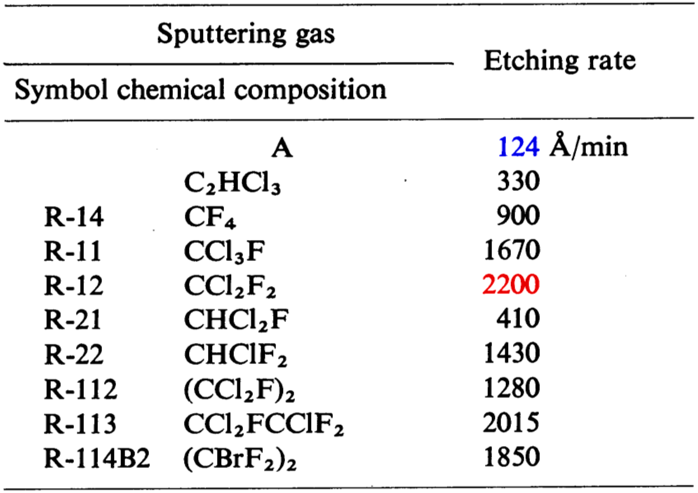
- Etch was isotropic
- Capacitively-powered "barrel" etchers were used
- High pressures (~ 1 Torr)
- An important application was photoresist strip
- Isotropic etching of Si, W, Ta, Ti, Si_3N_4 was demonstrated
- Need for volatile etch products was recognized
- No mention of energetic ion bombardment

ION-ENHANCED PLASMA ETCHING

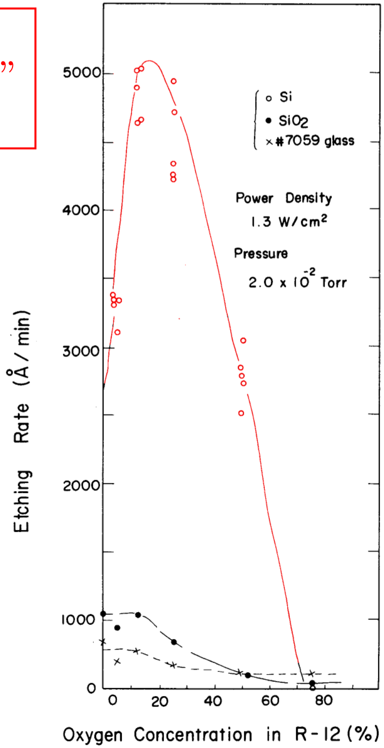
- Sputtering — involatile products and high ion energies
- Plasma etching — volatile products and low ion energies

Who first combined volatile products with high ion energies?

N. Hosokawa, R. Matsuzake and T. Asamaki
“RF Sputter-Etching by Fluoro-Chloro-Hydrocarbon Gases”
Jpn. J. Appl. Phys. Suppl. 2, Pt. 1, 435 (1974)



Sputtering gas		Etching rate
Symbol	chemical composition	
	A	124 Å/min
	C_2HCl_3	330
R-14	CF_4	900
R-11	CCl_3F	1670
R-12	CCl_2F_2	2200
R-21	$CHCl_2F$	410
R-22	$CHClF_2$	1430
R-112	$(CCl_2F)_2$	1280
R-113	CCl_2FCClF_2	2015
R-114B2	$(CBrF_2)_2$	1850



IMPLICATIONS OF HOSOGAWA'S DISCOVERY

(From discussions with John W. Coburn)

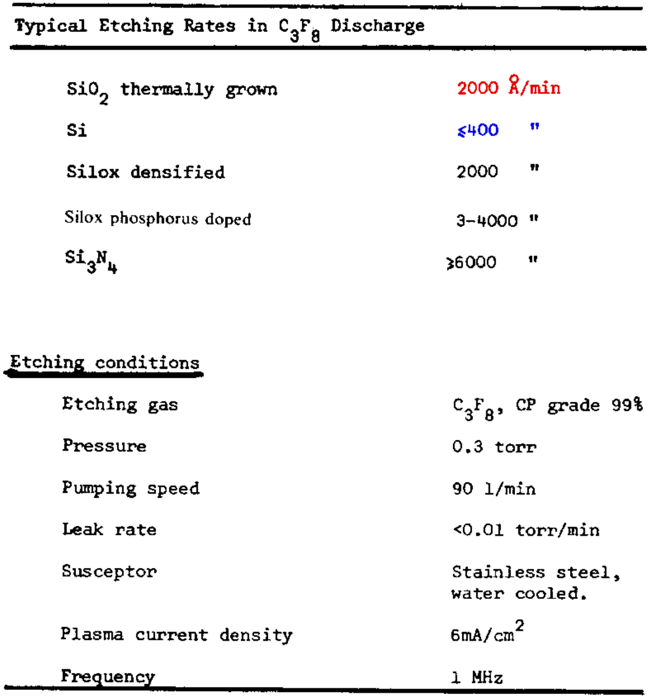
- The work was first presented at the Sixth International Vacuum Congress, Kyoto, Japan, 25-29 March 1974
- Hosokawa's main interest was to etch faster
- He may not have recognized the importance of his discovery for pattern transfer
- But there were many pattern transfer engineers in the audience
- In 1975, there were around a dozen "reactive ion etching" (RIE) patents filed worldwide

ANISOTROPIC PLASMA ETCHING WAS BORN

SILICON DIOXIDE AND ALUMINUM ETCHING

- Anisotropic etching of SiO_2 with high selectivity over Si

R.A.H. Heinecke, “Control of Relative Etch Rates of SiO_2 and Si in Plasma Etching,” Solid State Electronics **18**, 1146 (1975)



Typical Etching Rates in C_3F_8 Discharge

SiO_2 thermally grown	2000 Å/min
Si	≤400 "
Silox densified	2000 "
Silox phosphorus doped	3-4000 "
Si_3N_4	≥6000 "

Etching conditions

Etching gas	C_3F_8, CP grade 99%
Pressure	0.3 torr
Pumping speed	90 l/min
Leak rate	<0.01 torr/min
Susceptor	Stainless steel, water cooled.
Plasma current density	$6 mA/cm^2$
Frequency	1 MHz

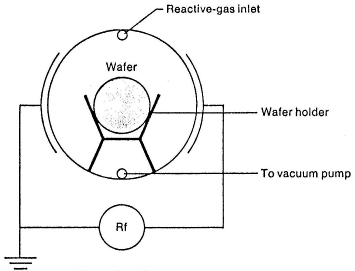
- Anisotropic etching of Al with native Al_2O_3 etch

S.I.J. Ingrey, H.J. Nentwich, and R.G. Poulsen
“Gaseous Plasma Etching of Al and Al_2O_3”
USP 4,030,967 (filed 1976)

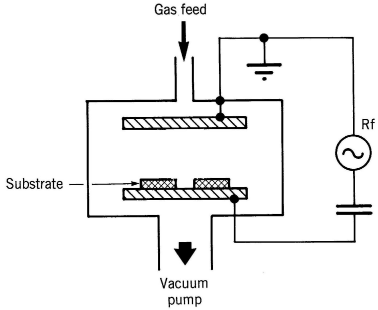
EVOLUTION OF ETCHING DISCHARGES

FIRST GENERATION

(1 source, multi-wafer, low density)



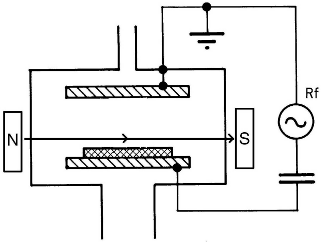
Barrel etcher
(Isotropic etch)



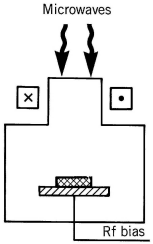
Capacitive
(Anisotropic etch)

SECOND GENERATION

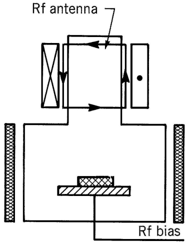
(2 sources, single wafer, high density)



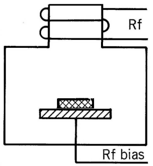
Magnetically enhanced
capacitive discharge



ECR



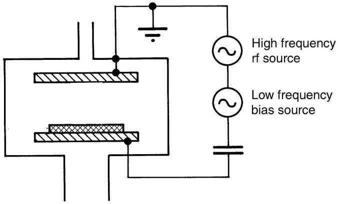
Helicon



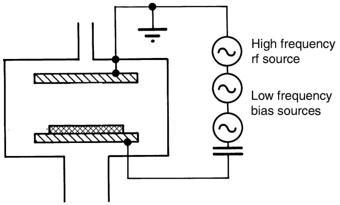
Inductive

THIRD GENERATION

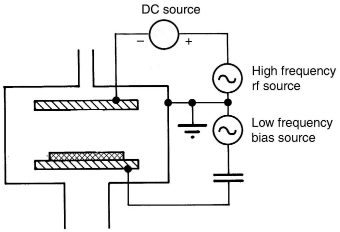
(multi-source, single wafer, moderate density)



Dual frequency
capacitive discharge



Triple frequency
capacitive discharge



DC/dual frequency
capacitive discharge

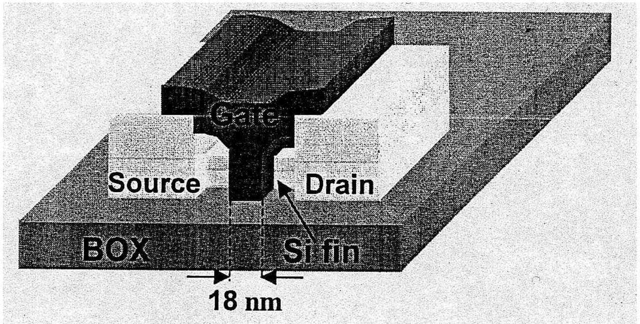
FUTURE OF PLASMA PROCESSING

THE EXPERTS SPEAK[†]

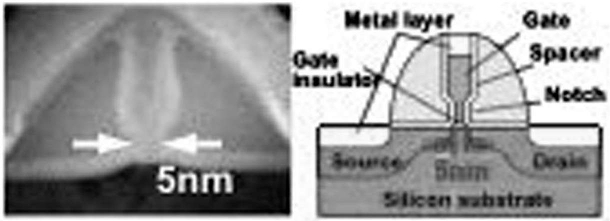
- “There is not the slightest indication that [nuclear] energy will ever be obtained” — *Albert Einstein, 1932*
- “Anyone who expects a source of power from the transformation of these atoms is talking moonshine.” — *Ernest Rutherford, 1933*
- “A few decades hence, [when controlled fusion is achieved], energy will be free — just like the unmetered air.” — *John von Neumann, 1956*
- “Radio has no future.” — *Lord Kelvin, 1897*
- “I think there is a world market for about five computers.” — *Thomas J. Watson, 1943*
- Where a calculator like ENIAC is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and perhaps only weigh $1\frac{1}{2}$ tons.” — *Popular Mechanics, March 1949*
- “640k ought to be enough for anybody.” — *Bill Gates, 1981*

[†] C. Cerf and V. Navasky, Villard, New York, 1998

DOUBLE/TRI GATE TRANSISTORS



FinFET (UC Berkeley)



NEC 5 nm Gate

- Vertical structures can be built with current fabrication techniques
- CMOS can be scaled another 15 years
- State of the art (2010):
  - In manufacture:
    32 nm (130 atoms) gate length
  - Smallest fabricated CMOS transistor (NEC):
    5 nm (20 atoms) gate length
  - Limiting gate length from simulations (desktop ic):
    4 nm (16 atoms) gate length

INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS (ITRS 2009)

Year	2009	2012	2015	2018	2021	2024
Half-pitch (nm)	52	36	25	18	13	9
Gate length (nm)	29	22	17	13	10	7

- Below limits imposed by thermodynamics and quantum mechanics
- Major issues are transistor physics, materials limitations, and power dissipation
  - Doping profiles, silicon-on-insulator, FinFET's, tri-gate structures
  - High-κ gate dielectrics, metal gates, strained Si, Si-Ge, low-κ interconnect dielectrics
  - Power limitation of around 200 W/cm^2
- Formidable manufacturing issues remain; eg, lithography, metrology

> "You can scale CMOS down another 10–15 years; nothing touches the economics of it." — Intel CEO Craig Barrett

BEYOND 2025

- Moore's law (miniaturization) ends, but products improve for decades
- MOS-FET's continue for fast switches

  Vertical/Segmented/Etc CMOS transistors → silicon/carbon nanowires/nanotubes?
- Copper/low-κ dielectric layers continue for interconnects

  Copper → carbon nanotubes? Optical interconnects?
- CMOS memory → magnetic memory/phase change memory

  Magnetic → electron spin; phase change → crystal/amorph
- Flash (slow, non-volatile) migrates first

  ⇒ EverSpin MRAM (16 Mb, 35 ns) in 2010
  Samsung PRAM (512 Mb, 65 nm) in 2010

PIE IN THE SKY[†]

- "3D chips" (heat removal limit of 200 W/cm^2)
- "Single-molecule transistors" (not much smaller than CMOS transistors)
- "Single-electron transistors" (need very low temperatures)
- "Cross-bar computing" (replace reliable CMOS switches with defect-prone nanowire switches)
- "Self-assembled, DNA-based computers" (we each own one already)
- "Quantum computing using qubits" (exponentially faster computation for niche applications)

[†] From a Joe Hill union song, *The Preacher and the Slave*, 1911

SUMMARY

- CMOS scales to 30-atom gate lengths in 2024
- CMOS product improvements continue decades beyond 2024
- Plasma reactor research and development will intensify to meet these needs
- Displacing CMOS beyond 2024 is unlikely; instead, other technologies will be integrated into the CMOS platform

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