75 Years of Transistor and Its Impact on Humanity
Birth and Evolution of Semiconductor Devices

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(Virtual Talk)

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OUTLINE

- **Electronics Evolution (devices)**
  - **Prior History and Birth of Transistor**
    - **Patents 755,840 ; 1,900,018 ; 2,524,035 ; 2,569,347**
  - **Concept to Reality - MOSFET - Birth of Modern Technology**
    - **Invention to Industry / Room at the Bottom**
  - **Fifty, Trillion & 0.0001 – and goes on**
- **Veracity in Device Progression**
  - **Challenges continues / What becomes Important**
- **Technology Impacts in Society and Humanity**
  - **Extended Research, Application**
  - **Transistors & Neurons – a number game**
  - **Advancements in Society and Human Interactions**

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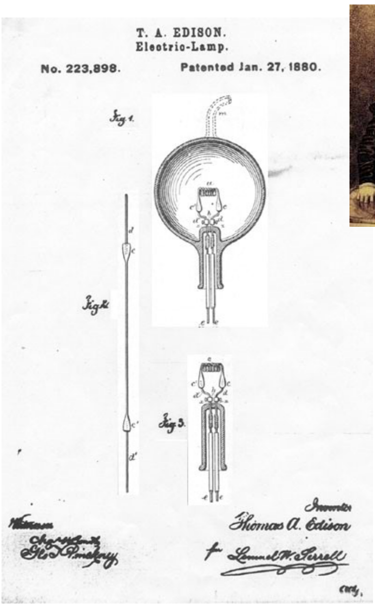
Electronics Evolution – the Beginning



William Gilbert (English Scientist)
in late 1500s coined the word
Electricity **from Greek word** ***ELEKTRON***
meaning ***like amber*.**
He showed static electricity from friction - occurs in materials

US Patent 223898 - Edison in 1878

Thomas Edison's first successful model of light bulb, used in public demonstration - December 1879
(https://en.wikipedia.org/wiki/Thomas_Edison)

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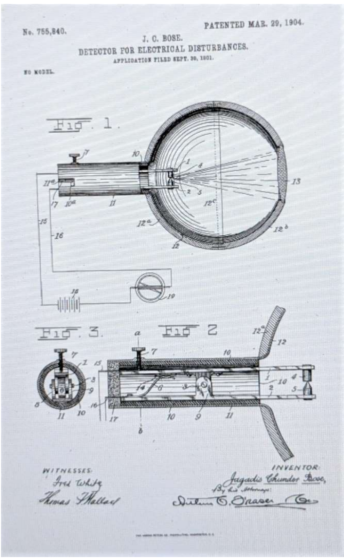
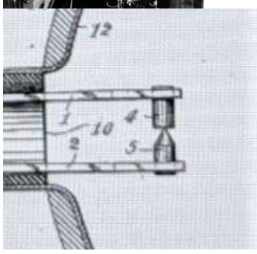
Electronics Evolution – Prior History

120 Years of Solid State Diode





First patent for solid-state diode (to receive electromagnetic waves)

J.C. Bose demonstrated his wireless millimetre wave (microwave) experiments at the Royal Institution, London in January 1897.

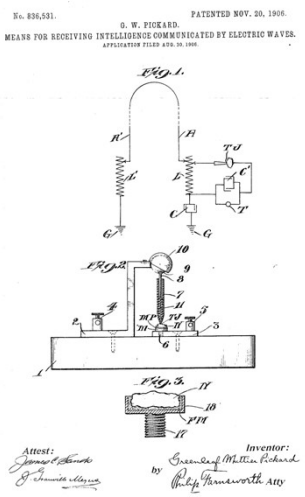
(This predates the wireless experiments at Salisbury Plain by Guglielmo Marconi in May 1897).

Bose was an authority with many pioneering works on reflection, refraction, polarization and absorption of millimeter waves and its application to wireless communication.

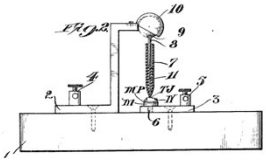
Based on his contributions
IEEE recognized JC Bose in 1997
as the Father of Radio Sciences.

"Detector for electrical disturbances,"
U. S. Patent 755,840 **- J.C. Bose,**
(**Filed September 30, 1901. Issued March 29. 1904**).

Electronics Evolution – Prior History (1901 to 1910)



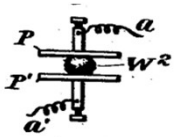
G W Pickard (1906)

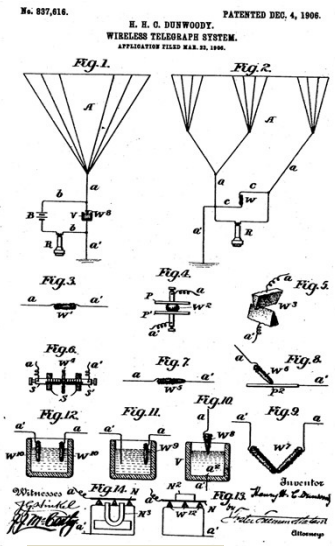


US Patent 836531

Detector for receiving Intelligence communicated by electric waves.

H H C Dunwoody (1906)

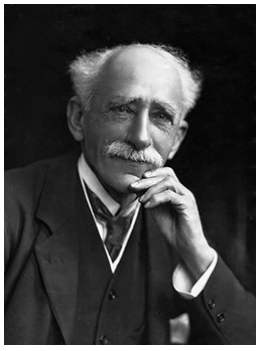




US Patent 837616

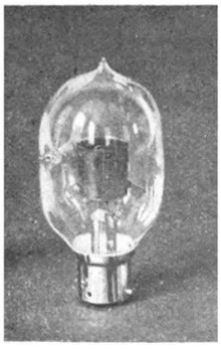
invented the carborundum radio detector.

Electronics Evolution – Prior History (1901 to 1910)

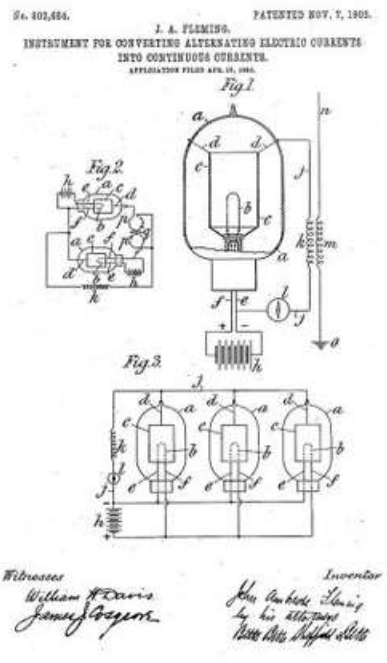


John Ambros Fleming – 1904 – Vacuum Diode
British Patent : 24850

John Ambrose Fleming invented the two-electrode vacuum tube rectifier



Fleming's valve

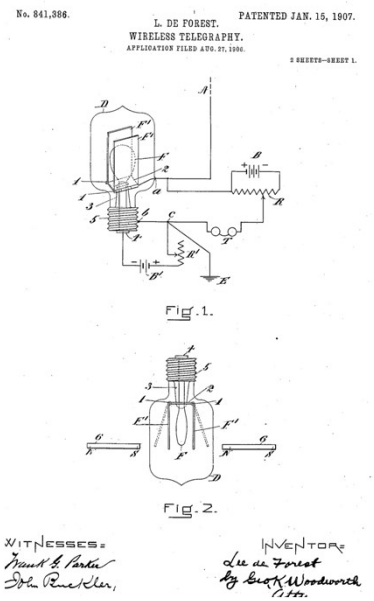


Electronics Evolution – Prior History (1901 to 1910)

Le De Forest

Vacuum Tube (Triode) -1906

(US Patent : 841,386 - Wireless Telegraphy)



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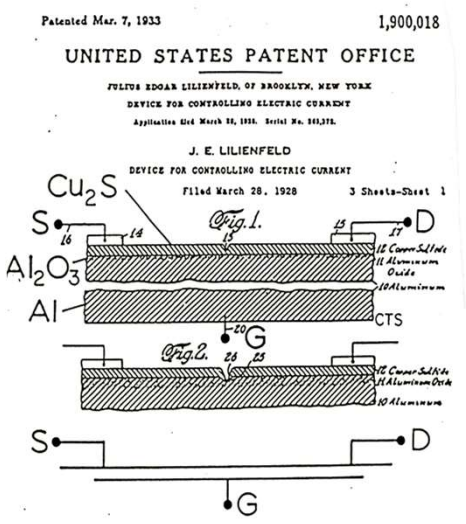
94 Years of MOSFET

MOSFET Patent - 1928

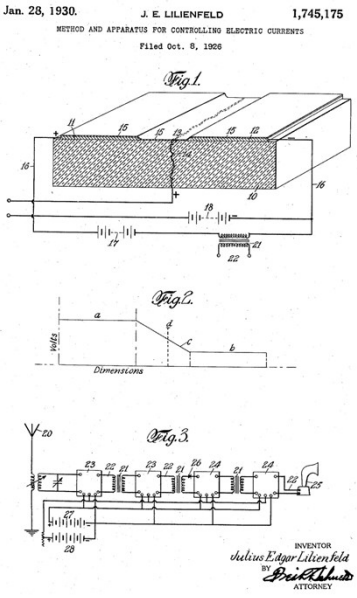


DEVICES FOR CONTROLLING ELECTRIC CURRENT

Patent filed on March 28, 1928

J. E. LILIENFELD

MESFET Patent - 1926



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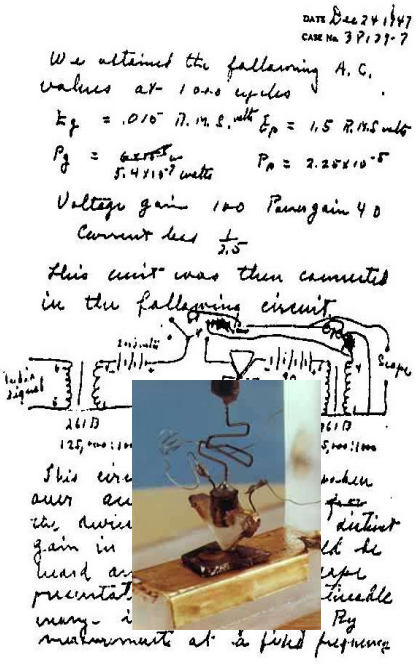
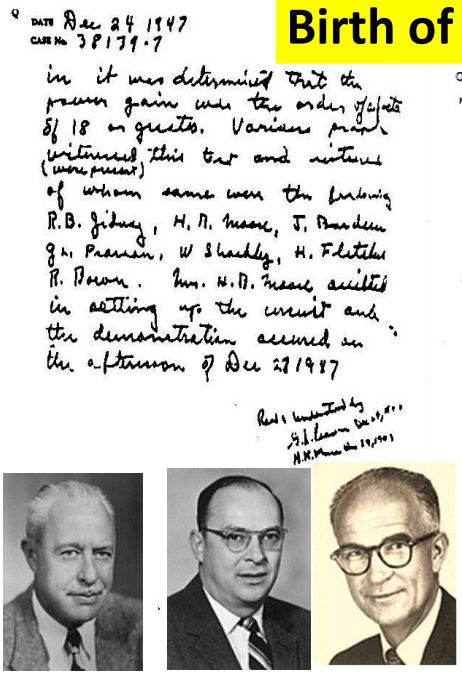
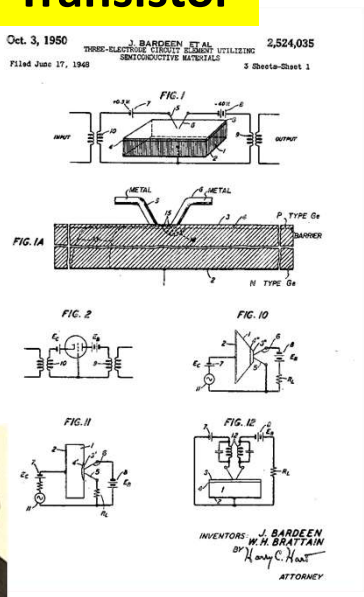
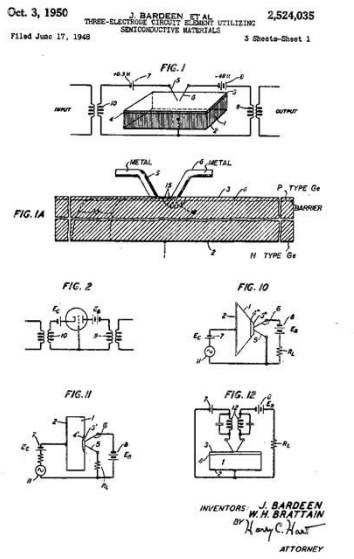
Birth of Transistor

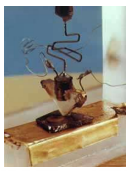




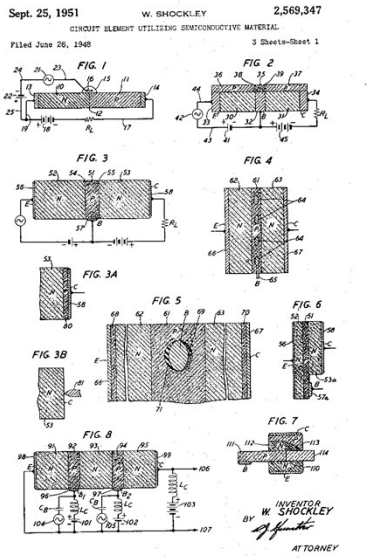


P-N Junction Transistor





William Shockley



Patent 2524035 filed June 17, 1948

Patent 2569347 filed June 26, 1948

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75 Years of Transistor

Birth Certificate of Our Era

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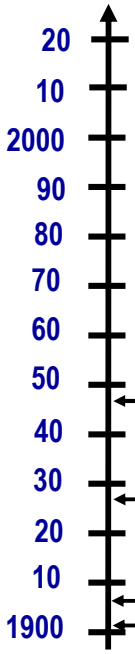
Devices Evolution



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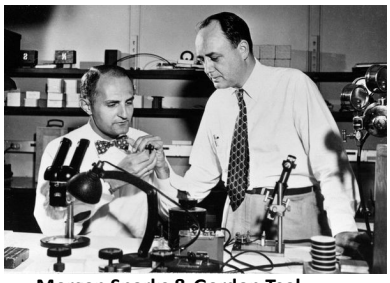
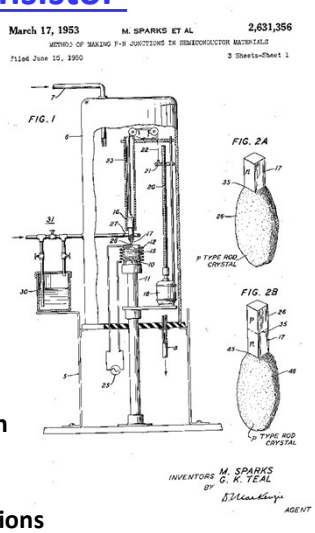
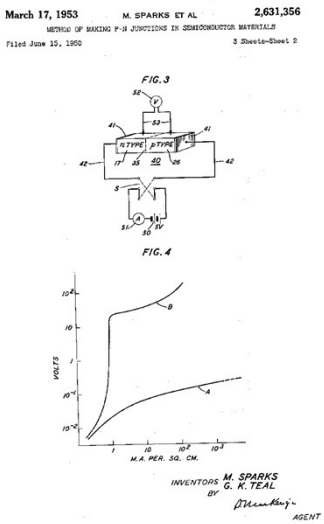
First grown Si Junction Transistor



Morgan Sparks & Gordon Teal

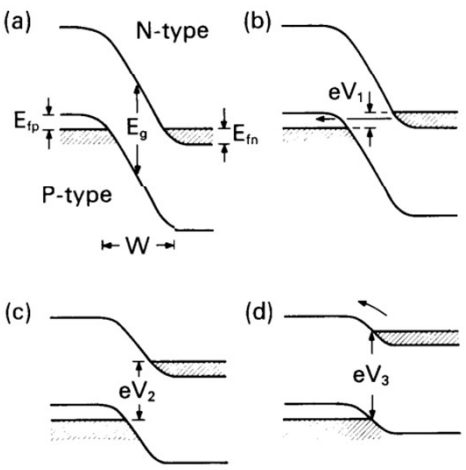
Czochralski grown semiconductor material used for making P-N junctions (1951-53)





First Grown Silicon Junction Transistor (1953)
(M Sparks & G Teal - US Patent : 2631356)

Tunneling phenomenon in Semiconductors



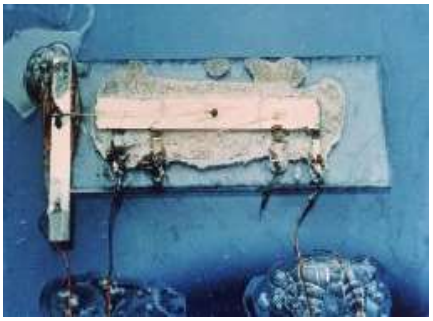
Energy band diagrams of heavily doped semiconductor P-N junctions at varied bias voltages depicting interband tunneling *(L. Esaki, Phys. Rev., 109, 1958)*

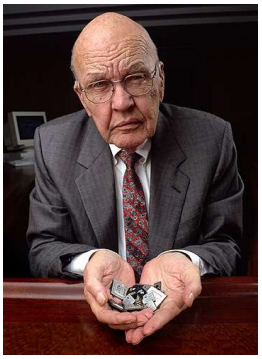
Leo Esaki (1973 Nobel Prize) demonstrated band-to-band Tunneling in semiconductors experimentally in 1958

I would like to point out that many high barriers exist in this world: Barriers between nations, races and creeds. Unfortunately, some barriers are thick and strong. But I hope, with determination, we will find a way to tunnel through these barriers easily and freely, to bring the world together so that everyone can share in the legacy of Alfred Nobel.

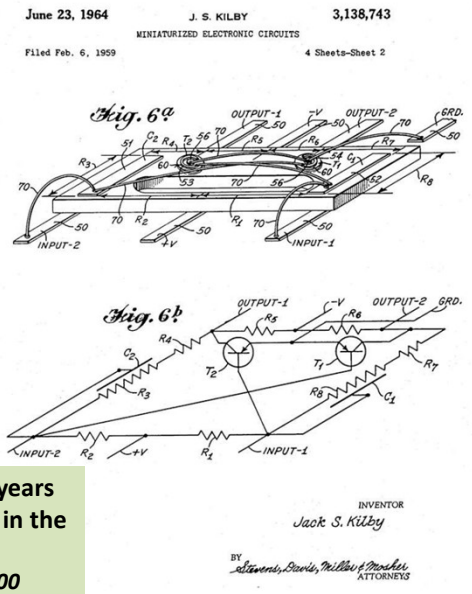
(from *Leo Esaki, Nobel Lecture, 1973)*

1958: 1st Integrated Circuit





Jack S. Kilby



US Patent 3138743

"The innovation and development that has followed in the past 40 years has been remarkable and far more rapid than all the developments in the prior 400 years after William Gilbert coined the term 'electricity'"

- from Jack Kilby's Nobel Lecture 2000

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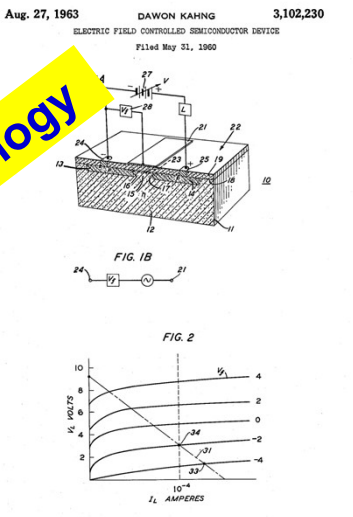
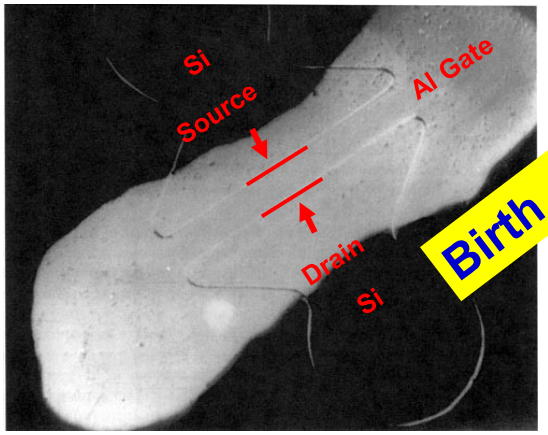
32 Years for Concept to Reality

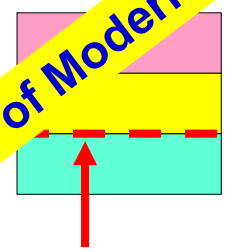
1960: First MOSFET by D. Kahng and M. Atalla



Top View



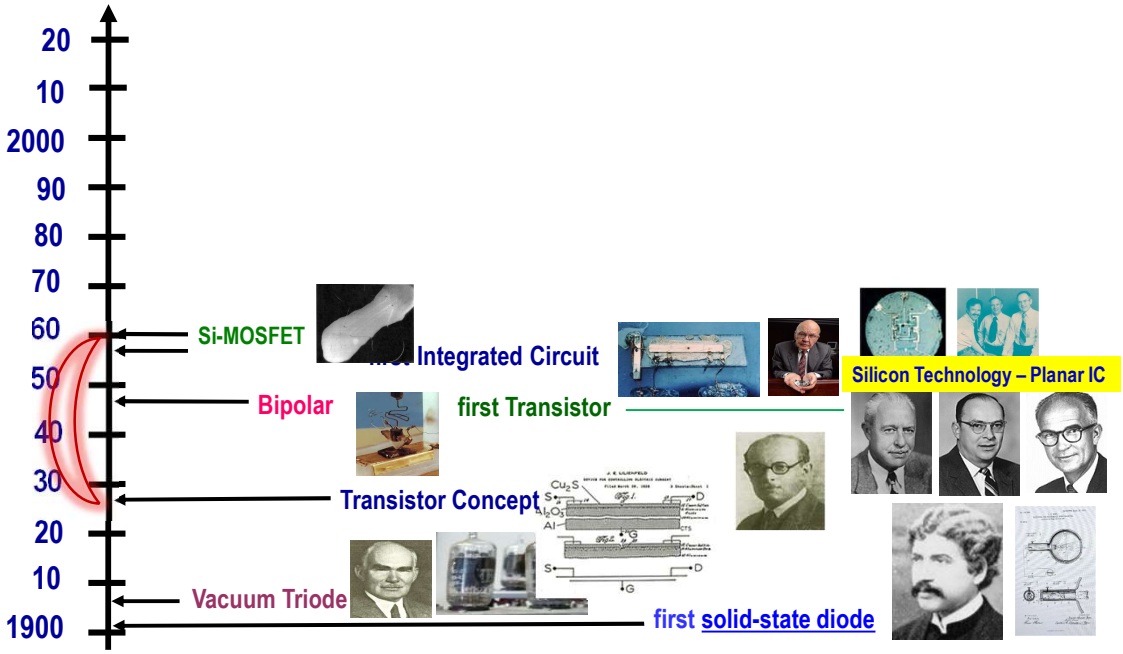
Cross-sec



Exceptionally good interface!

Birth of Modern Technology

Devices Evolution



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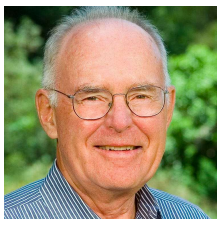
Integrated Circuits – Invention to Industry

First Semiconductor company

FAIRCHILD SEMICONDUCTOR® **in 1957 in San Jose, CA**

by a team including

Robert Noyce and Gordon Moore



Gordon Moore, Robert Noyce & Andrew Grove

Both Noyce and Moore left Fairchild in 1968 and started a company **NM Electronics** which later changed the name to **Intel**

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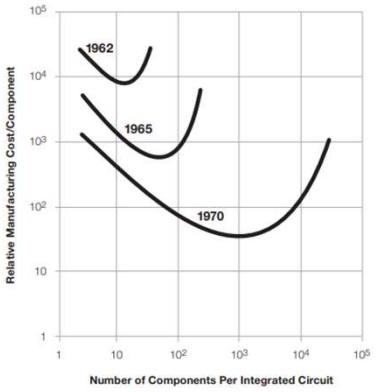
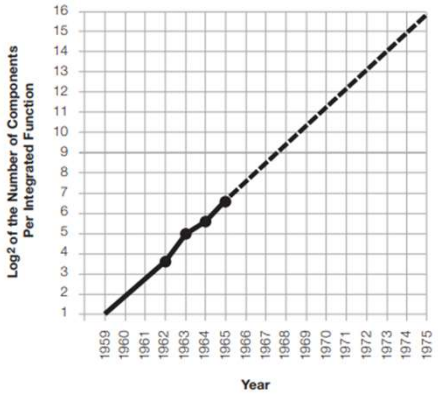
Invention to Industry – Moore's Law

Gordon Moore, "Cramming more components onto integrated circuits" Electronics, Vol 38, Number 8, April 19, 1965





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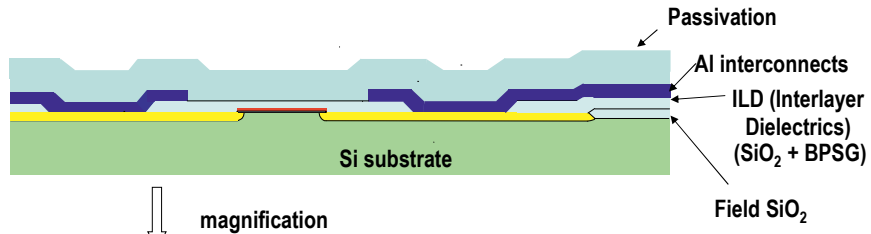
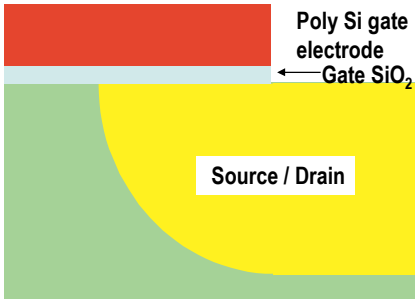
NMOS LSI in Early 1970s



magnification



Layers

- Si substrate
- Field oxide
- Gate oxide
- Poly Si gate electrode
- Source/Drain diffusion
- Interlayer dielectrics
- Aluminum interconnects
- Passivation

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Device Evolution LSI to VLSI

Major Stages in Process

1970 - 10-12 um device (1971 – Intel 4004)

1979 - Polycide Gate

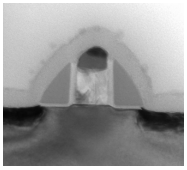
1981 - Salicide Process

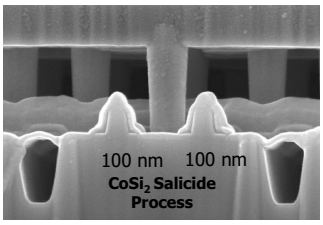
1995 - Shallow Trench Isolation (STI)

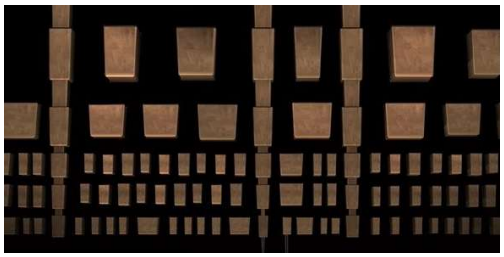
1997 Cu Metallization / Low K ILD

SiON / High K Gate Dielectrics

2007 Metal gate Structures







Gate Length – from 10um to 65-45nm

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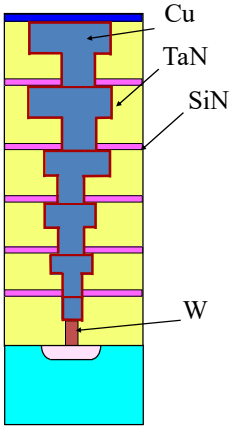
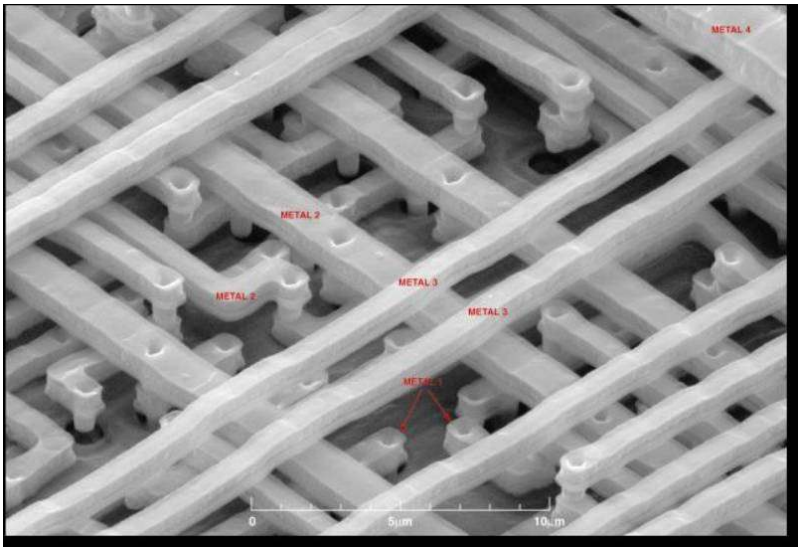
Device Evolution - Interconnects





(Courtsey : Jeff Gambino, IBM)

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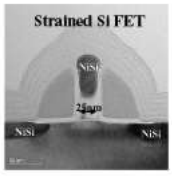
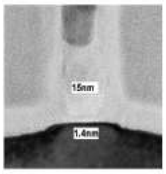
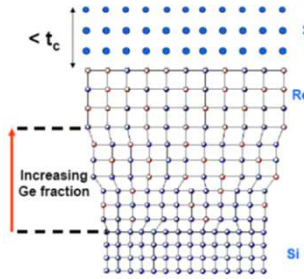
Device Evolution - Technology nodes





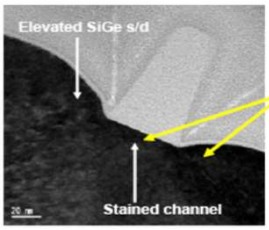
(Courtesy : H Iwai, Tokyo Institute of Technology)

Si bandstructure perturbed by forcing a tensile strain

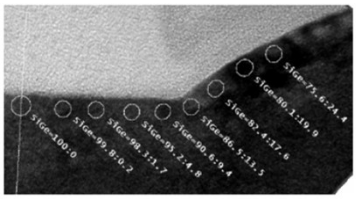


Strain field splits 6 conduction band valleys into 4 & 2, enhancing the electron mobility

Strain field increases the light hole contribution enhancing the hole mobility



To know Lattice strain & details of Band structure



(Ref : MK Radhakrishnan & CH Tung, IEEE IPFA 2007)

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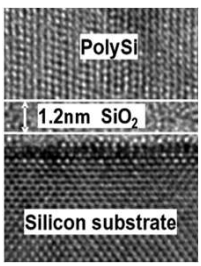
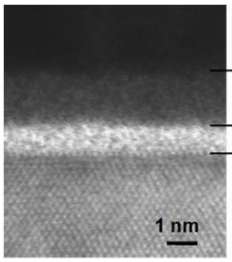
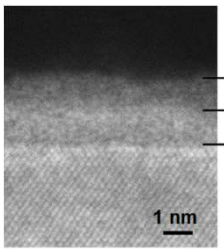
Device Evolution - Gate Structures







(Source : Robert Chau, Intel & Hiroshi Iwai, Tokyo Institute of Technology)

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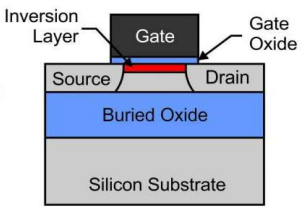
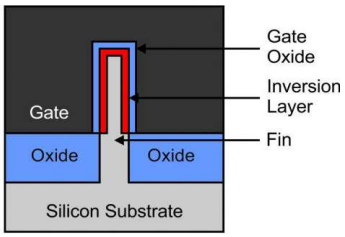
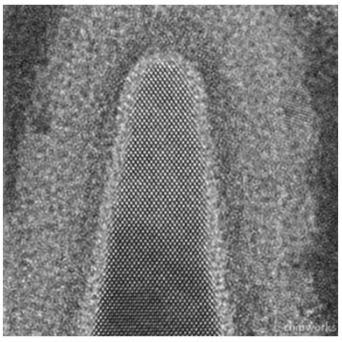
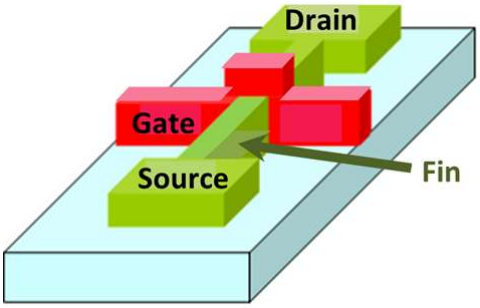


Floating body eliminated
- fully depeleted
FDSOI



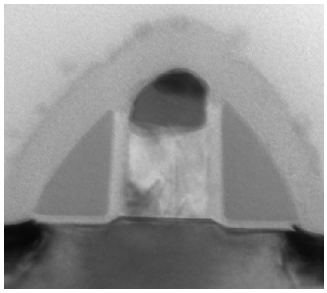
Gate on three side
- fully depleted



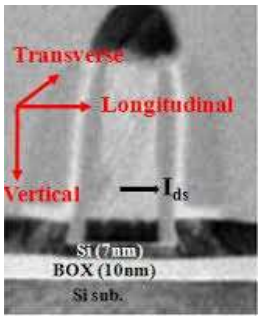


1998 - FinFET
UC Berkley, TSMC

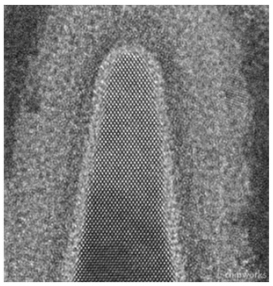
25



Gate Stack



SOI



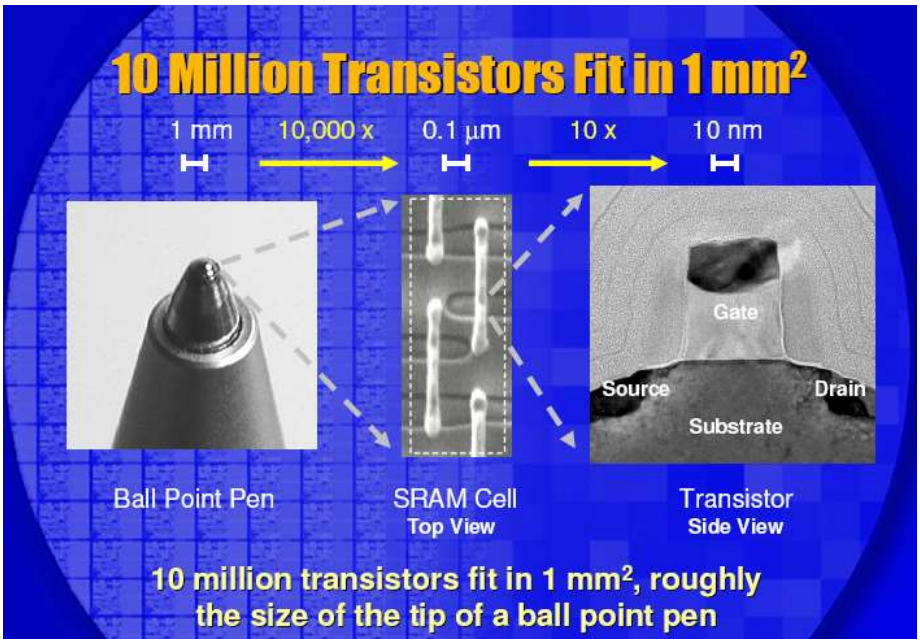
Fin / Tri Gate

Richard Feynman
1959

" Why cannot we write the entire 24 volumes of Encyclopedia Britannica on the head of a pin "

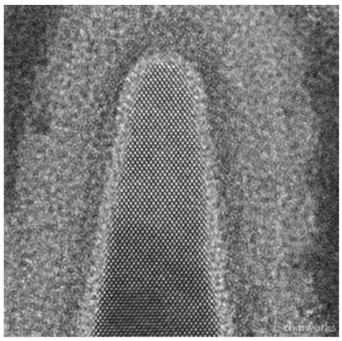
"There is plenty of room at the bottom"

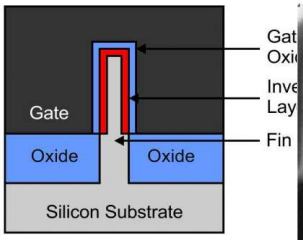
26



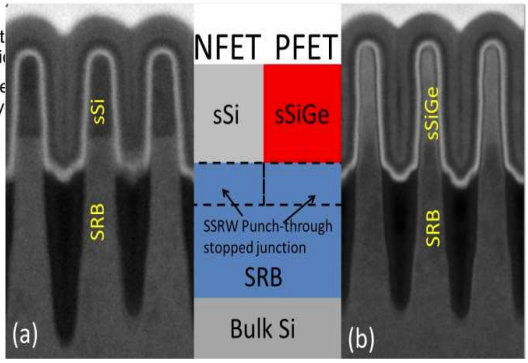
(Source : Intel Developer's Forum)

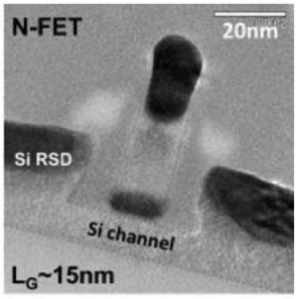
27

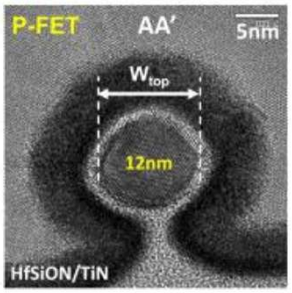




Gate on three side
- fully depleted







(P. Nguyen et al,, IEDM 2014)

SiGe FETs – different approaches

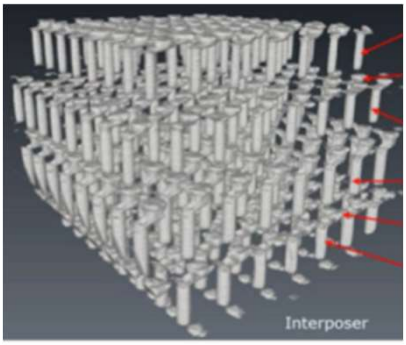
7 nm FinFET : Dual-stressed channel materials on the strain-relaxed buffer (SRB) with a super-steep retrograde well (SSRW)
(a) TEM image of tensile strained silicon fin
(b) TEM image of compressively strained SiGe fin on a common SRB

(source : IBM/Globalfoundries/Samsung – 2016)

28

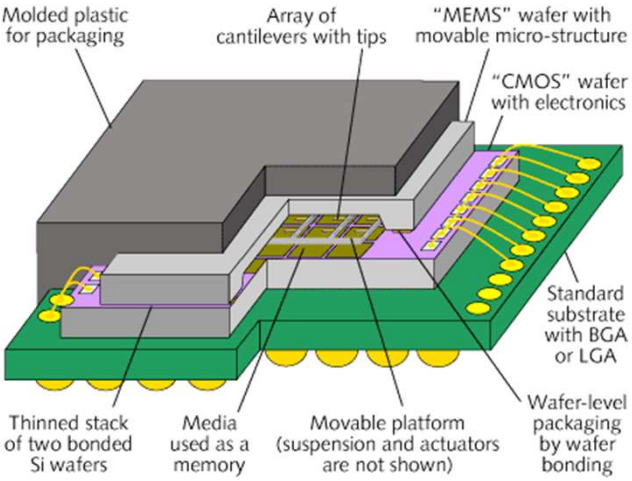
3D Integration and Super Chips

3D hetero-integration technology opens up the possibility to assemble various functional blocks - processors, memory, sensors, logic, analog, photonic, and power ICs into one stacked chip



X-ray CT scan image measured from TSV array areas in the 4-layer stacked 3-D multicore processor chip

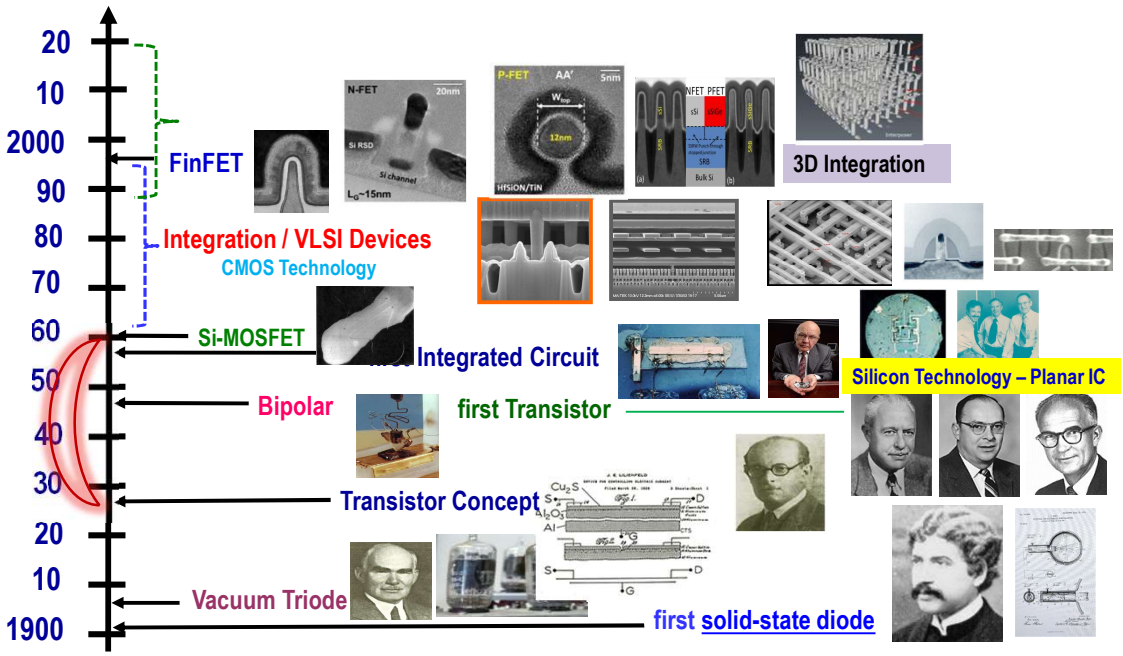
(K.-W. Lee et al, IEDM 2014)



A vision of Super Chips *(Source : Solid State Technology)*

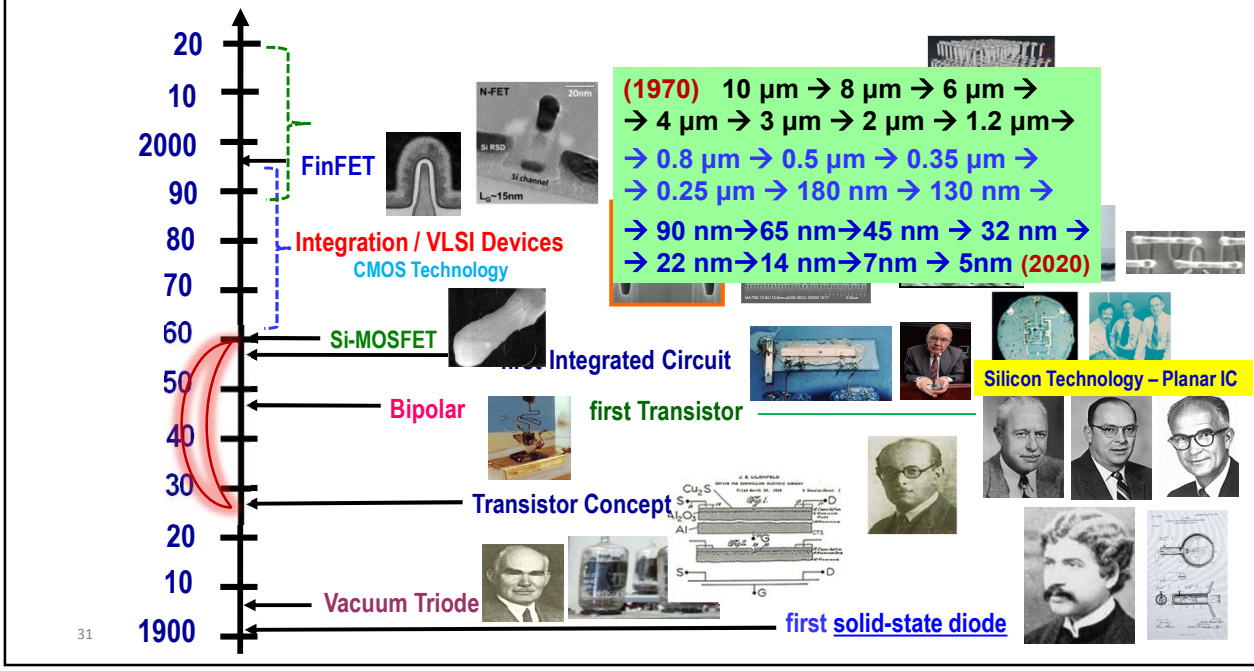
29

Devices Evolution

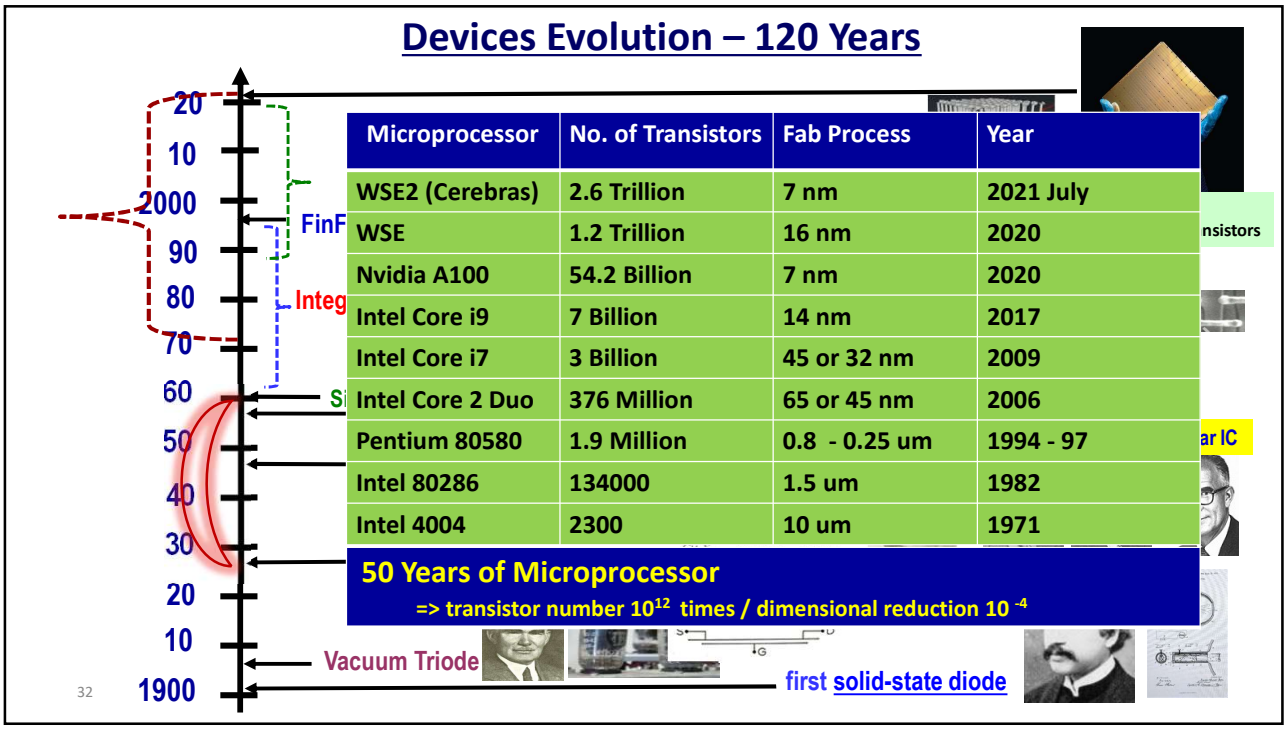


30

Devices Evolution – 120 Years

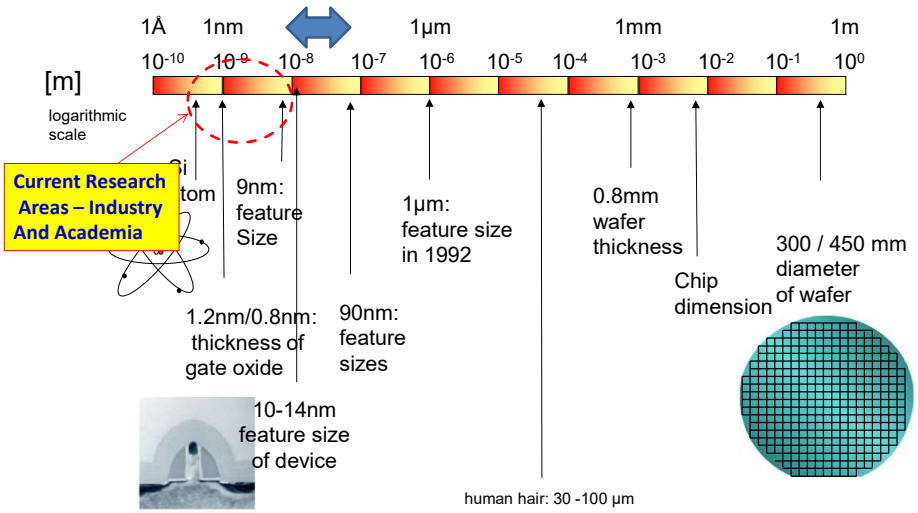


Devices Evolution – 120 Years



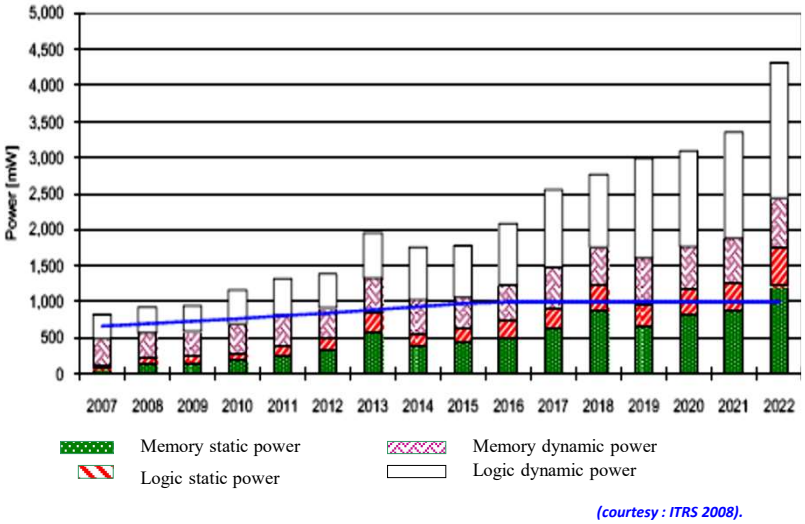
Microprocessor	No. of Transistors	Fab Process	Year
WSE2 (Cerebras)	2.6 Trillion	7 nm	2021 July
WSE	1.2 Trillion	16 nm	2020
Nvidia A100	54.2 Billion	7 nm	2020
Intel Core i9	7 Billion	14 nm	2017
Intel Core i7	3 Billion	45 or 32 nm	2009
Intel Core 2 Duo	376 Million	65 or 45 nm	2006
Pentium 80580	1.9 Million	0.8 - 0.25 um	1994 - 97
Intel 80286	134000	1.5 um	1982
Intel 4004	2300	10 um	1971

Present Day Semiconductor (Si) Status



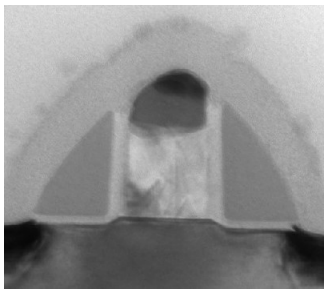
33

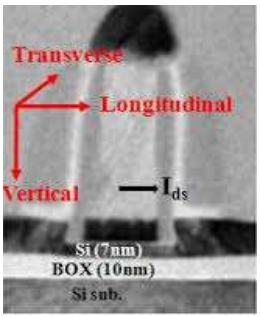
Power Consumption Trends

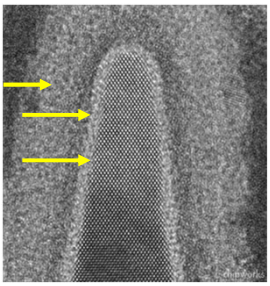


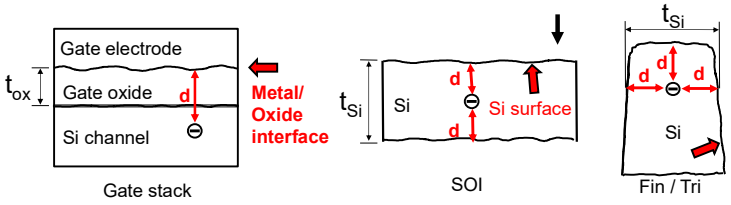
(courtesy : ITRS 2008).

34





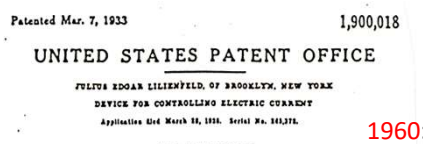




Interaction between the channel carriers and interfaces The interaction becomes stronger as d becomes smaller with decrease in t_{ox} and t_{Si}.

What becomes Important ?

1928 – J E Lilienfeld



Patented Mar. 7, 1933 1,900,018

UNITED STATES PATENT OFFICE

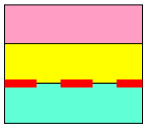
JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

DEVICE FOR CONTROLLING ELECTRIC CURRENT

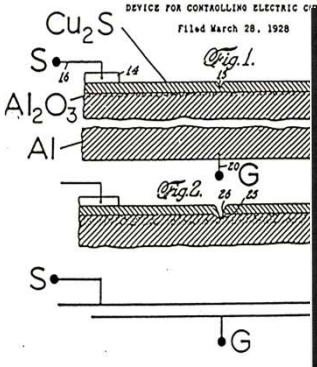
J. E. LILIENFELD

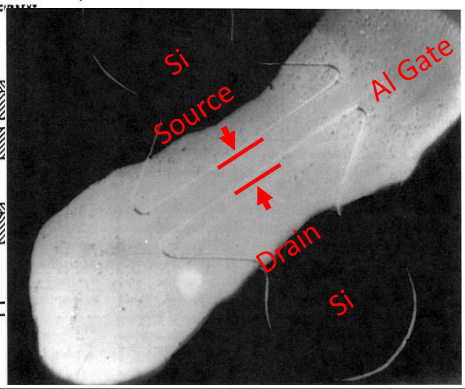
Filed March 28, 1928

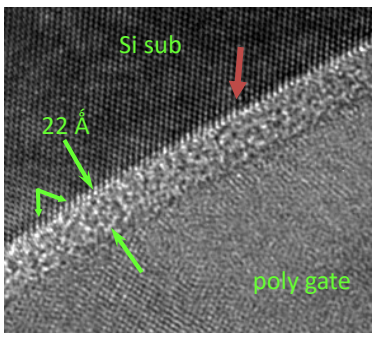
Exceptionally good interface!



1960: D. Kahng and M. Atalla

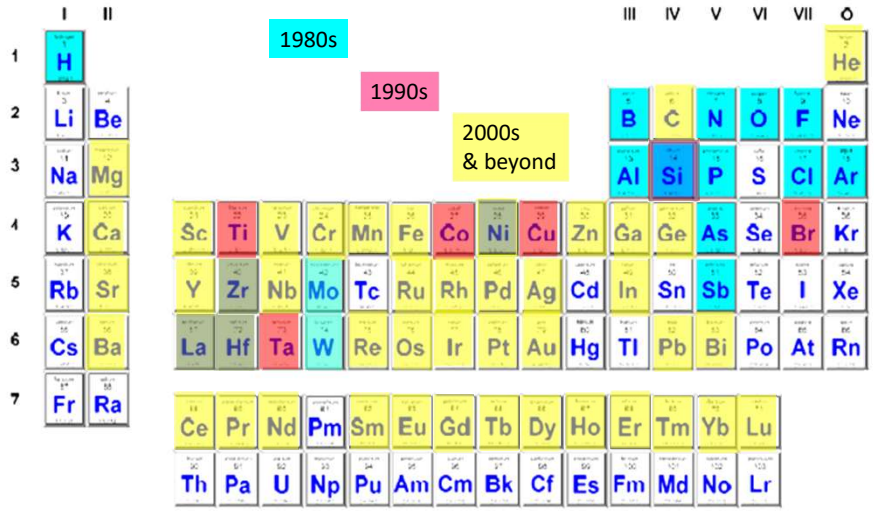






(Ref : C.H. Tung & M.K. Radhakrishnan, IEEE IPFA, 2002)

Materials for Devices



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Si Devices : Reliability Challenges - in decades

- ***Major Efforts - Reliability Physics Studies (1980 – 1990)***
  - **Models for *EM / SM / TDDB / HC*** ***(µm devices)***
  - **ESD Protection & Corrosion and Related Issues**
- ***Major Efforts - Process/Device Engineering(1990 - 2000)***
  - **Approaches based on WLR / DFR , etc** ***(sub-µm devices)***
  - **SPC, 6-Sigma, etc – in process lines**
- ***New Material Challenges (2000 – 2010)***
  - **High-K gate dielectrics / Cu & lowK)** ***(sub-100nm devices)***
  - **Material Interactions / new structures**
- ***Interface Physics / Tools Limitations (2010 onwards)***
  - **Interfaces & new failure mechanisms** ***(nano devices)***
  - **Physical analysis challenges & tools**

OUTLINE

- **Electronics Evolution (devices)**
  - Prior History and Birth of Transistor
    - Patents 755,840 ; 1,900,018 ; 2,524,035 ; 2,569,347
  - Concept to Reality - MOSFET - Birth of Technology
    - Invention to Industry / Room at the Bottom
  - Fifty, Trillion & 0.0001 – and goes on
- **Veracity in Device Progression**
  - Challenges continues / What becomes Important
- **Technology Impacts in Society and Humanity**
  - Extended Research, Application
  - Transistors & Neurons – a number game
  - Advancements in Society and Human Interactions

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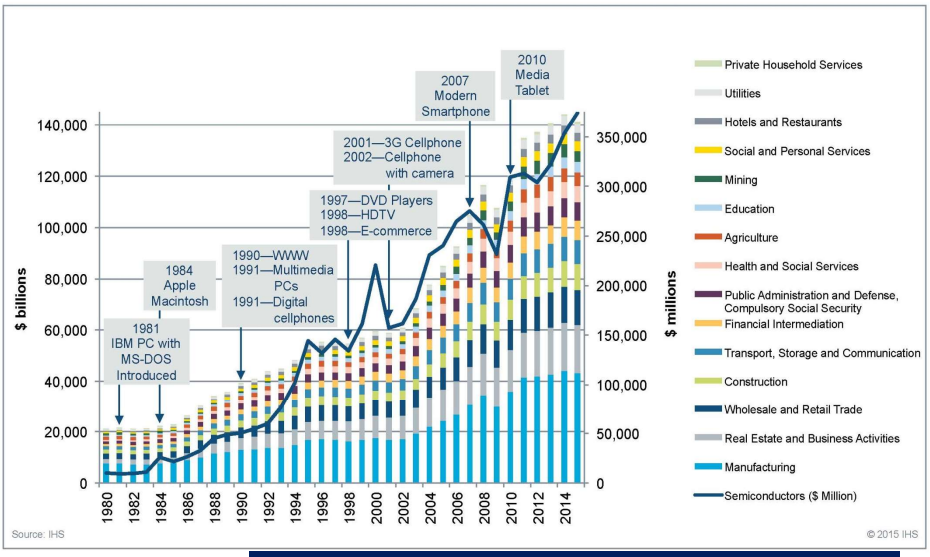
Moore and Impact of Devices

Semiconductor growth tracks global output
Worldwide gross output by industry ($ in billions, left axis) and semiconductor sales ($ in millions, right axis)



(Source : Solid State Technology, June 2015 : 50 Years of Moore's Law)

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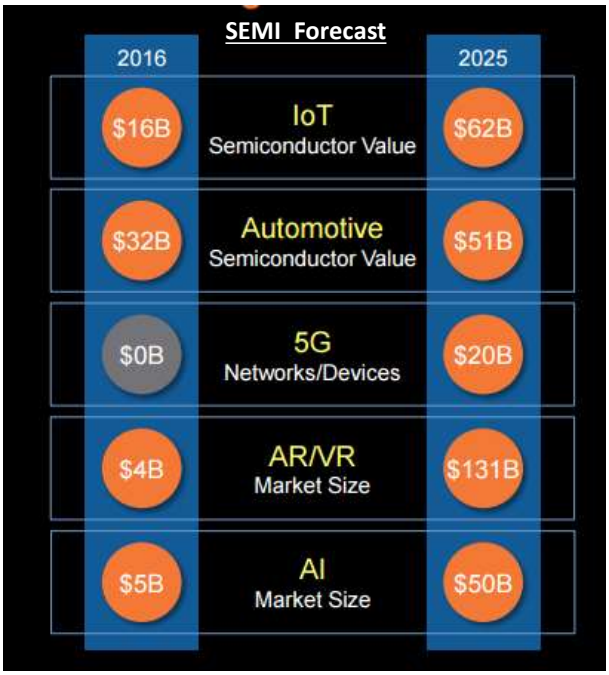

(Ref : D McGuirk, SST, January, 2017)

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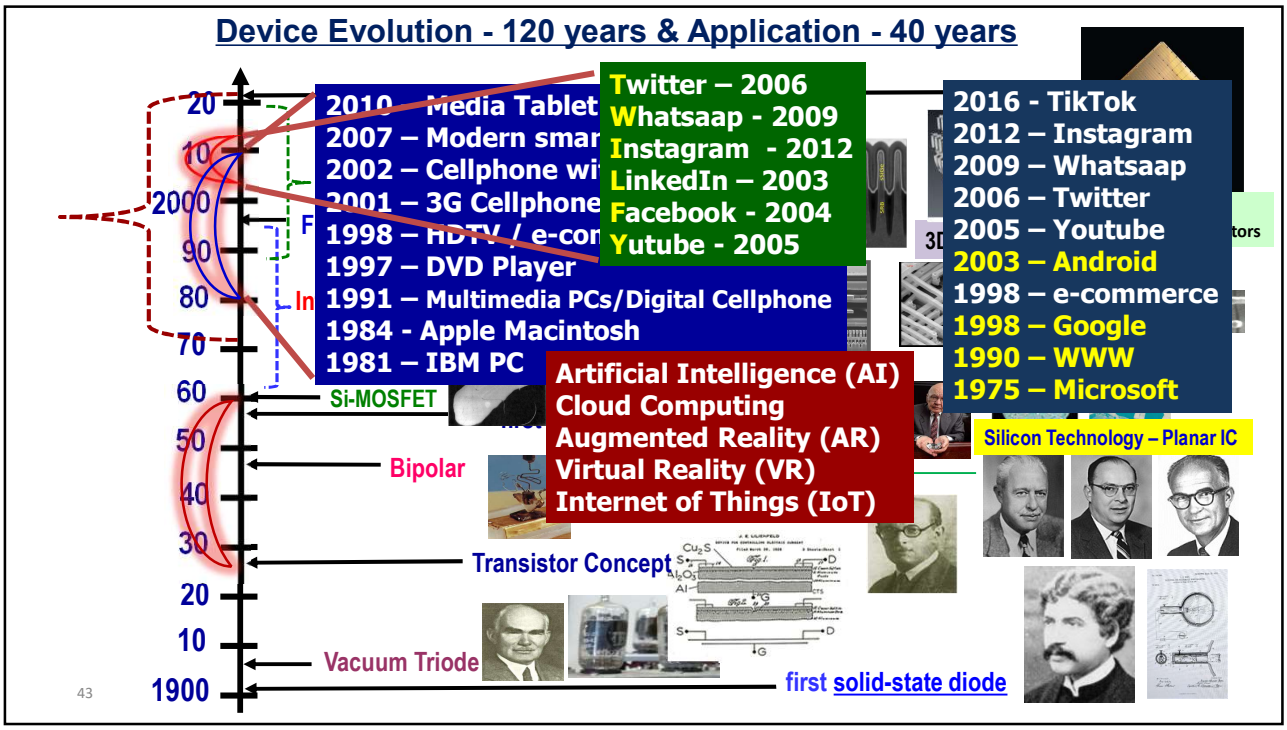
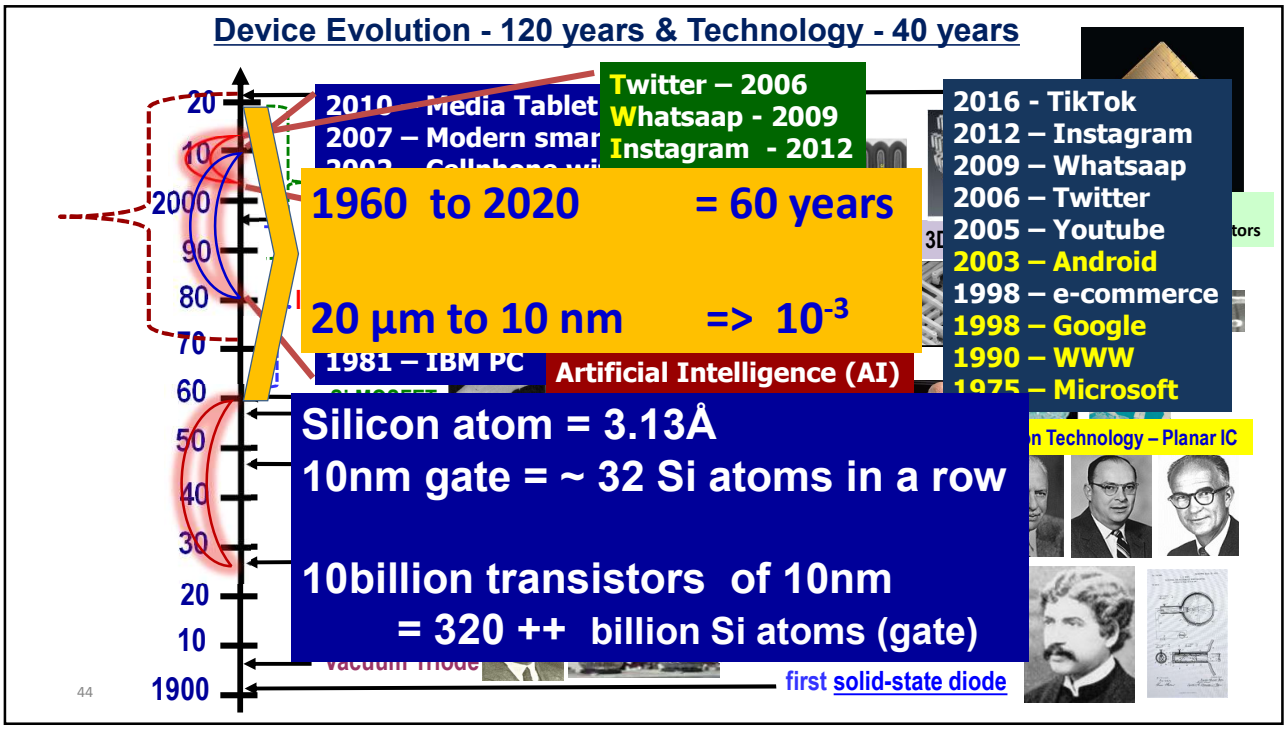
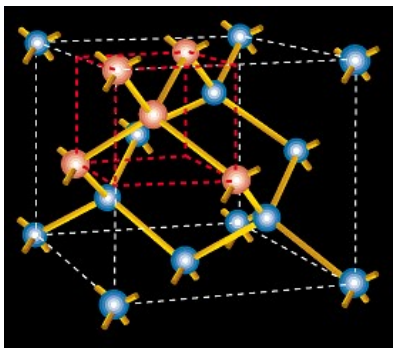
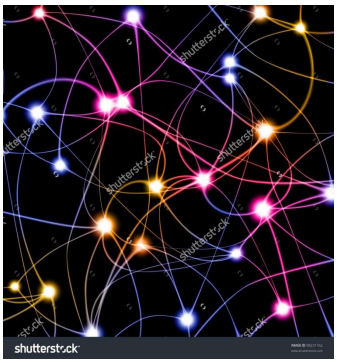

Device Evolution - 120 years & Application - 40 years
20
10
2000
90
80
70
60
50
40
30
20
10
1900
2010 – Media Tablet
2007 – Modern smar
2002 – Cellphone wi
2001 – 3G Cellphone
1998 – HDTV / e-cor
1997 – DVD Player
1991 – Multimedia PCs/Digital Cellphone
1984 - Apple Macintosh
1981 – IBM PC
Twitter – 2006
Whatsaap - 2009
Instagram - 2012
LinkedIn – 2003
Facebook - 2004
Yutube - 2005
2016 - TikTok
2012 – Instagram
2009 – Whatsaap
2006 – Twitter
2005 – Youtube
2003 – Android
1998 – e-commerce
1998 – Google
1990 – WWW
1975 – Microsoft
Artificial Intelligence (AI)
Cloud Computing
Augmented Reality (AR)
Virtual Reality (VR)
Internet of Things (IoT)
Si-MOSFET
Bipolar
Transistor Concept
Vacuum Triode
Silicon Technology – Planar IC
first solid-state diode
43


Device Evolution - 120 years & Technology - 40 years
20
10
2000
90
80
70
60
50
40
30
20
10
1900
2010 – Media Tablet
2007 – Modern smar
Twitter – 2006
Whatsaap - 2009
Instagram - 2012
2016 - TikTok
2012 – Instagram
2009 – Whatsaap
2006 – Twitter
2005 – Youtube
2003 – Android
1998 – e-commerce
1998 – Google
1990 – WWW
1975 – Microsoft
1960 to 2020 = 60 years
20 µm to 10 nm => 10-3
1981 – IBM PC
Artificial Intelligence (AI)
Silicon atom = 3.13Å
10nm gate = ~ 32 Si atoms in a row
10billion transistors of 10nm
= 320 ++ billion Si atoms (gate)
Technology – Planar IC
first solid-state diode
44



Si Lattice structure
Lattice Constant = 5.431Å
Silicon Atom - 3.13Å



Digital illustration of neuron
(Courtsy : http://www.123rf.com/photo_14580711_digital-illustration-of-neuron.html)

Human brain has about 100 billion neurons
10nm gate IC with 10 billion transistors

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How Effectively the Technology is being Utilized ?

Technology advancements = > Progress

(Advancements in living conditions)

- Environment
- Empathy – towards fellow beings
- Expansion of knowledge
- Equity in living
- Excellence

Are we really owe all these ?

Technology advancements also led us *(human beings)*

- In dwindling the power of "observation" & "Awareness"
- Gradual alteration from a *Social Being*
- Decline in social responsibility = = > *Selfish*

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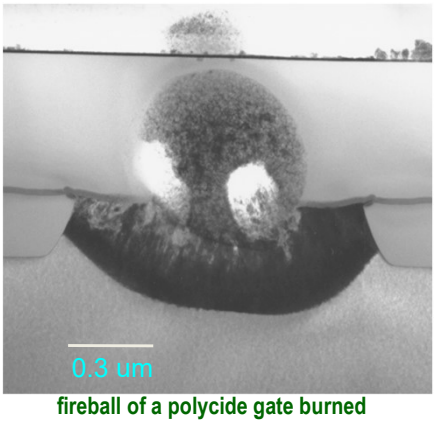
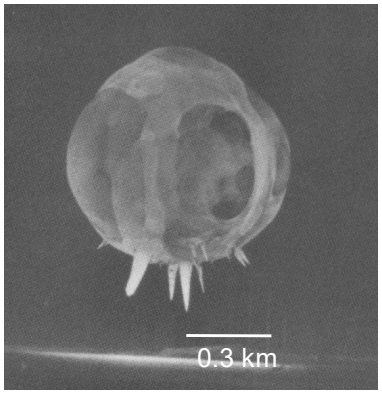
Nature has its own game – whether Micro or Macro



fireball of a polycide gate burned
(a few days after explosion)
(C H Tung & MK Radhakrishnan, 2000)



fireball of a 2nd generation A-bomb
(0.006 sec after explosion)
(Courtsey ; US Defence)

An exploding polygate burnt out location due to ESD, strikingly resembles to an atomic bomb exploding fireball.

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Thank You for Attending