# U3A Science & Technology

Semiconductors and their early technology

# All about Semiconductors

Semiconductors and their early technology

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9th May 2012

# The first semiconducting device

- The Cat's Whisker detector
- Used to "detect" audio signals in a modulated radio wave
- Basically composed of a crystal of galena and a stout pointed wire of tunsten, molybdenum or similar metals
- The CWD is actually a Schottky Diode

# Why do we need a detector?

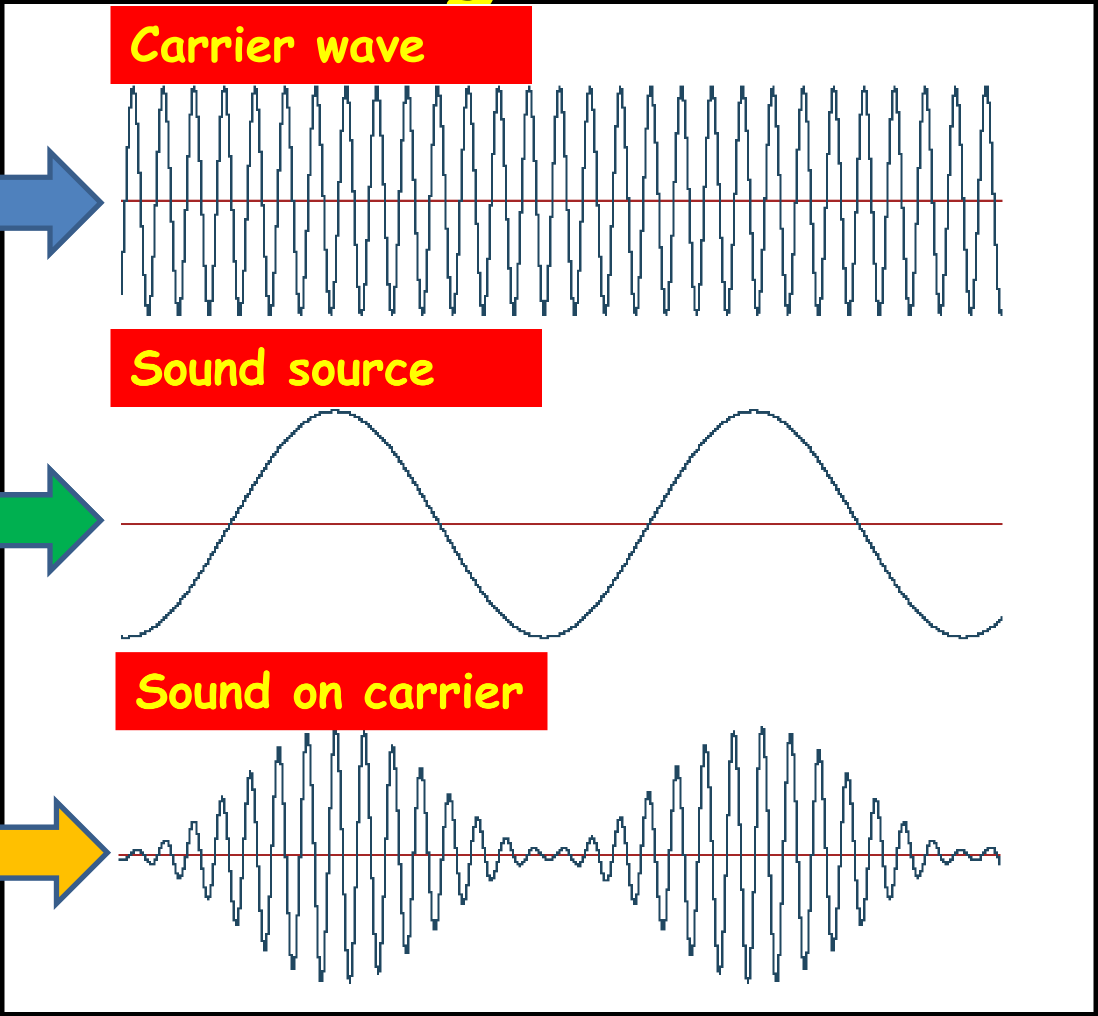
- The detector was used to remove the radio frequency element from the incoming radio frequency signal. Sounds very technical but the next slide will explain……

# A BBC Radio 4 Long Wave amplitude modulated radio signal

This is the radio frequency signal 198 KHz

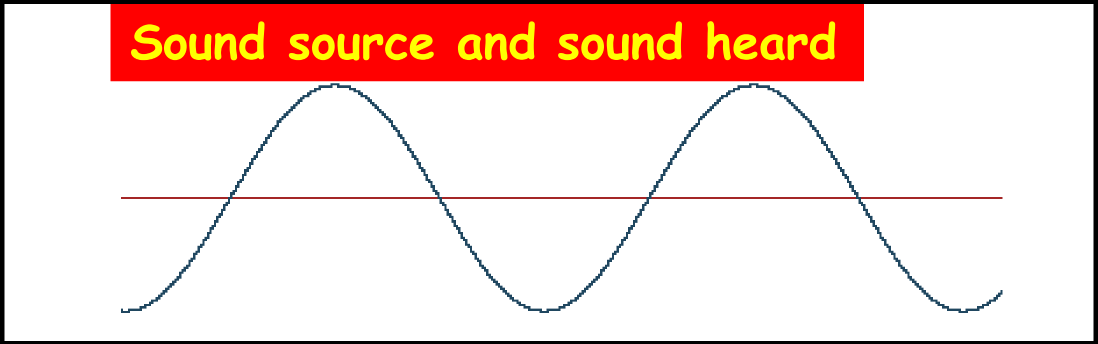
This is the audio (sound) signal 20-20,000 Hz

This is the modulated radio frequency signal

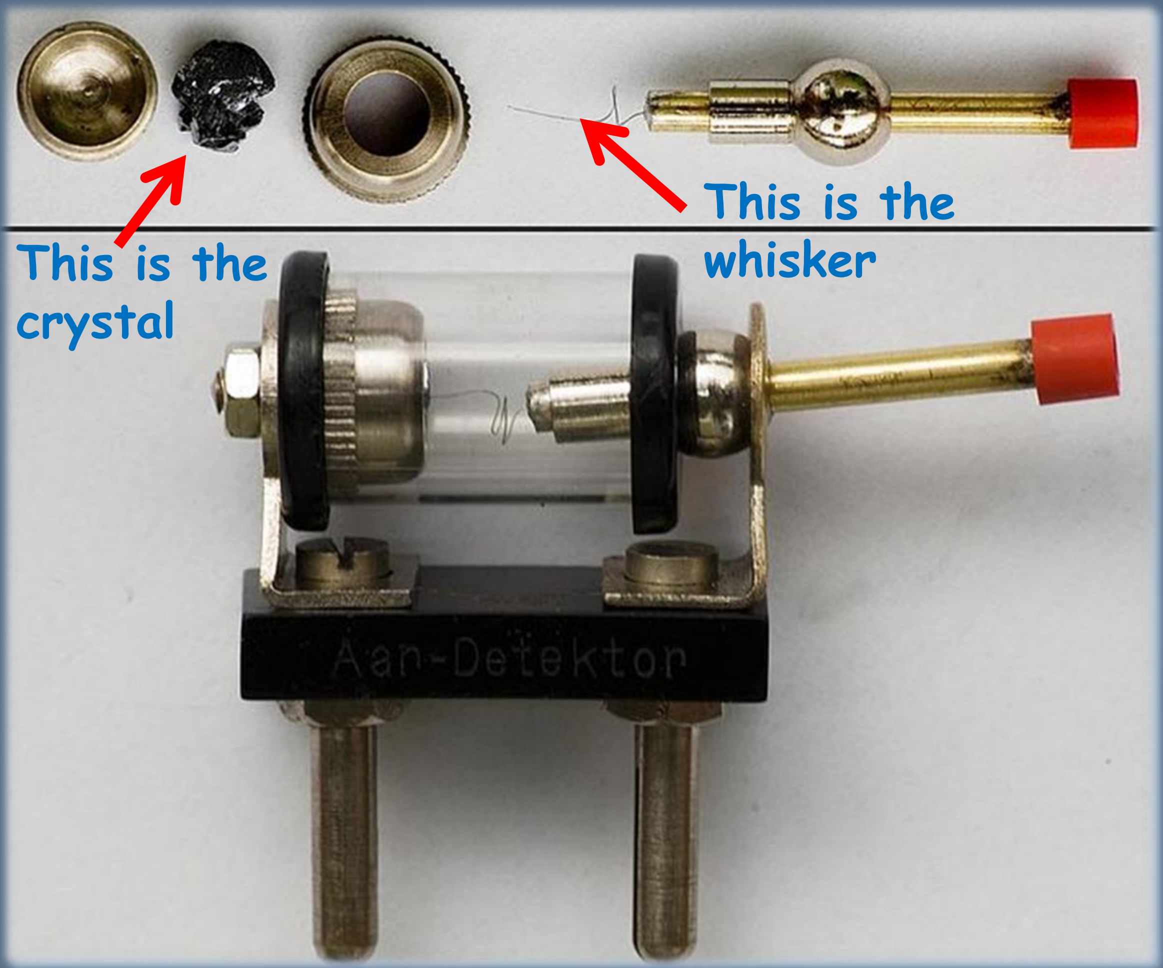


# What you hear is what was said

This is the audio (sound) signal as impressed onto the carrier wave and as heard after it has been "detected"



# The Cat's Whisker



# The Cat's Whisker dies
# Or "This is an ex-cat"

- Cat's Whisker detectors were very unreliable
- They relied on a point contact Schottky diode being formed through the pressure of the whisker on the Galena crystal
- Performance was highly variable
- Highly susceptible to vibration
- The real advantages of the point contact diode over the thermionic valve were that
    - ✓ The life was indefinite
    - ✓ There was nothing to wear out
    - ✓ No power consumption

# Thermionic diodes

Fleming diode

Mullard EA50

Mullard EB91
(Double diode)

# Apologies

There will now be a short intermission and a small digression into the interesting subject of

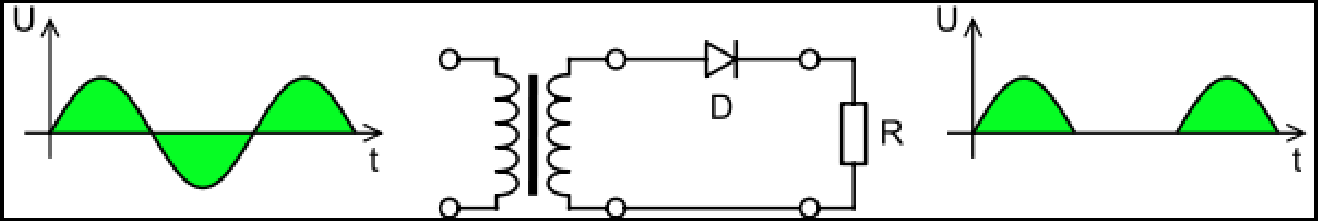
## AC-DC

# Rectification – converting AC to DC

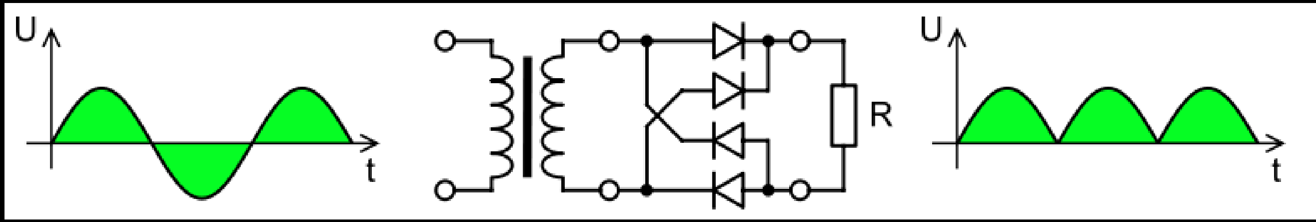
- The most effective way of generating and transmitting electricity is as Alternating Current – or AC
- All mains operated electronic equipment – starting with the humble fireside radio – needed Direct Current – or DC
- The process of converting AC to DC inside the radiio s called RECTIFICATION
- High power thermionic diode valves were commonly used to undertake this task
- They were even used to provide DC for the London Underground

# Rectification - schematic

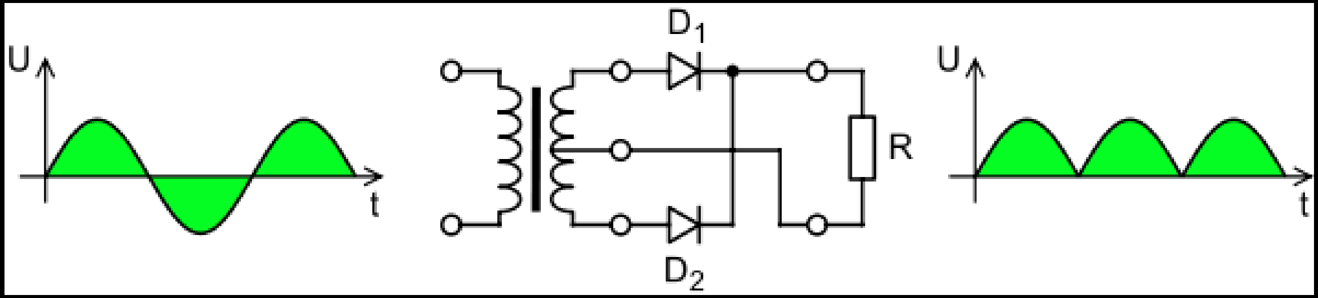
## Half wave rectification



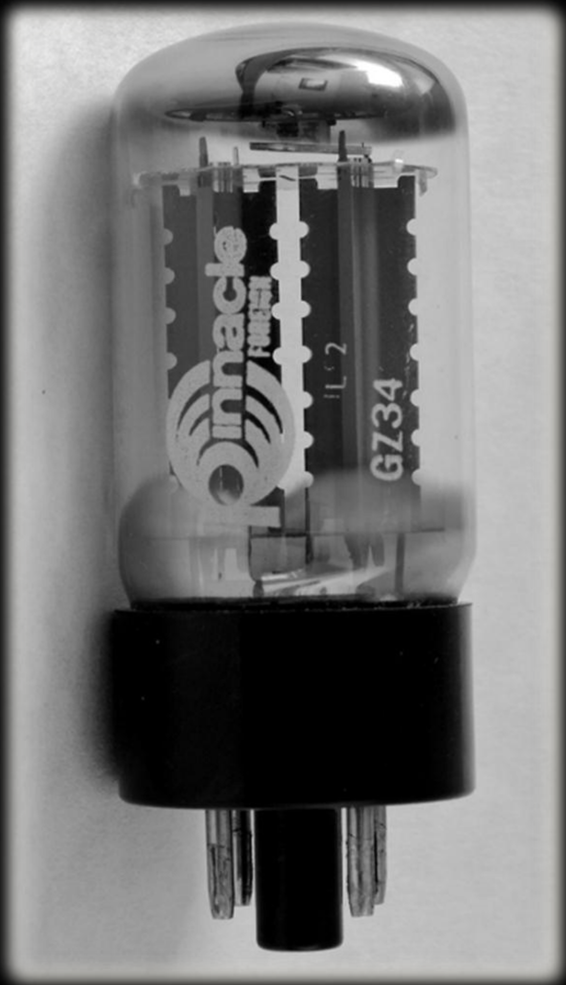

## Full wave rectification - I




## Full wave rectification - II



# Low power diode rectifier




- A typical double diode valve rectifier
- Used in domestic radio equipment
- Typically converts mains AC to DC at around 250-300 volts and less than 150mA current

# High power mercury arc rectifier

- Possibly the most powerful rectifier of its type ever built
- This installation in Manitoba typically converted AC to DC at 450 kV with a combined rating of 1 GW
- Mercury is a persistent heavy metal in the environment and a severe health hazard
- Silicon becomes the replacement

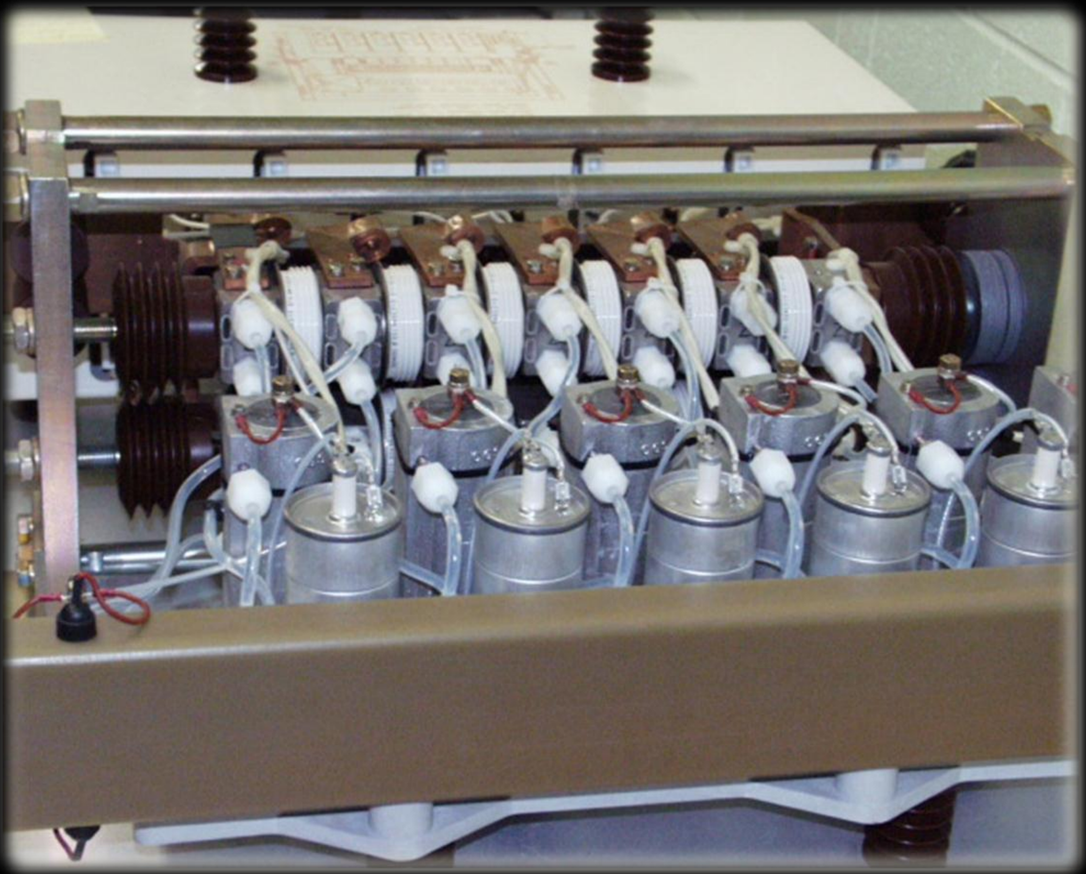
# Silicon rules the World today

- Manitoba replaced their mercury arc rectifier system with a semiconductor system
- This is a Thyristor or Silicon Controlled Rectifier (SCR)
- No mercury pollution risk
- Nothing to wear out
- SCRs are used extensively throughout the world to undertake high power control operations

# The Silicon Controlled Rectifier


- A single 100 amp 1200 volt SCR mounted on a heat sink
- Note the two diminutive control wires!

# The Silicon Controlled Rectifier



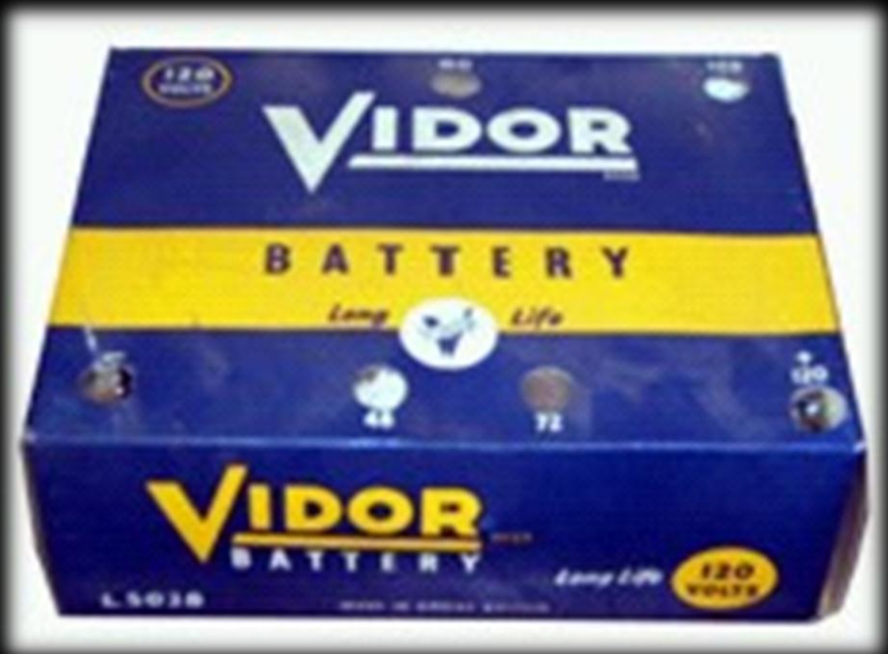
- A bank of six 2000 amp SCRs

# But selenium arrived first

- Early radios were battery operated
- They needed both a high tension battery and a low voltage rechargeable accumulator
- The high voltage battery was expensive and required frequent replacement
- Enter the battery eliminator with a selenium rectifier
    - ✓ Mains operated
    - ✓ The life was indefinite
    - ✓ There was (almost) nothing to wear out

# The 2 volt accumulator

# The HighTension battery




Designed for use with valve radios.
Used in conjunction with a rechargeable 2 volt accumulator

A massive battery about 7" along the long edge, giving 48V, 60V, 72V, 108V and 120V at various tapping points.

Potentially lethal! Connections made using "banana" plugs

# Examples of battery eliminators

Typical 1930s Bakelite cased unit

# Inside a battery eliminator


Selenium rectifier

Step down transformer

Smoothing choke

# The selenium rectifier


- No warm up time
- Simple manufacturing process
- Made from a multiple stack of plates
- High current possibility
- Each plate could handle 20 V in the reverse direction so by stacking multiple plates high voltages can be rectified
- Could slowly fail by going high resistance and giving off a foul bad eggs smell familiar to all TV repair shops of the 50s and 60s
- Silicon becomes the replacement

# End of intermission

Back to semiconductors again

# Successors to the Cat's Whisker


1940s – IN23 ceramic encapsulated microwave germanium point contact diode

1954 - OA51 glass encapsulated general purpose germanium point contact diode

# Semiconductors explained
# Back to basic physics - I

## What is a semiconductor?

Definition:

A semiconductor is a material with electrical conductivity intermediate in magnitude between that of a conductor and an insulator.

# Semiconductors explained
# Back to basic physics - II

Q. Why do metals conduct electricity?

A. Metals conduct electricity because they have de-localized electrons - electron clouds that do not "belong" to any one atom. Thus they are free to move through the crystal lattice

# Semiconductors explained
# Back to basic physics - III

## Why do non-metals insulate?

Non-metals have electrons in fixed orbitals. In order to move electrons from one side of the material to the other you need them to shove fixed electrons out of their places - a task that requires a lot amount of energy

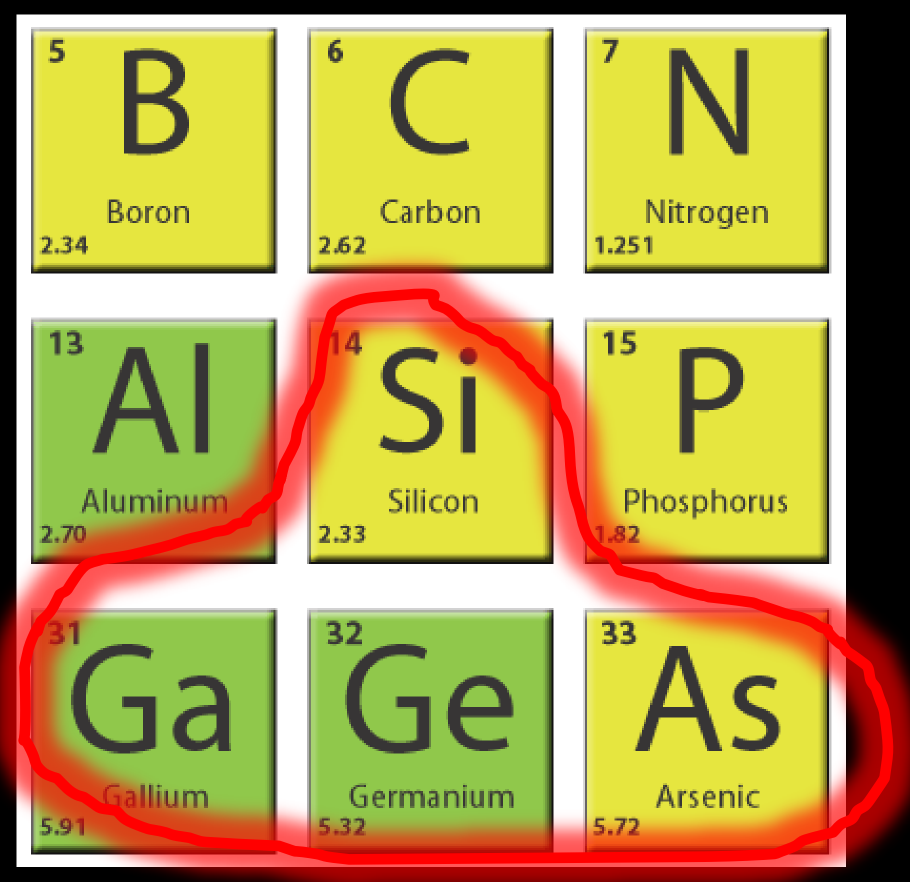
## So how do semiconductors differ?

# The Periodic Table of elements - I

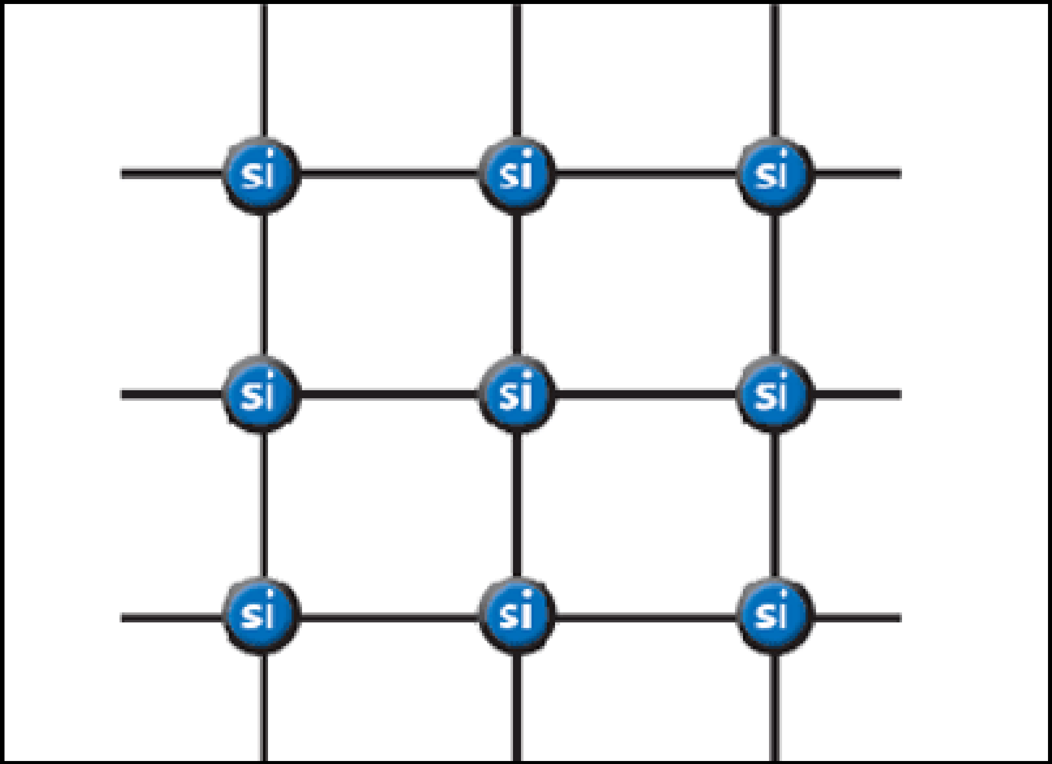
| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| Cs | Ba | | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| Fr | Ra | | Rf | Db | Sg | Bh | Hs | Mt | Uun | Uuu | Uub | | | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| La | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
| Ac | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lr |

# The Periodic Table - II

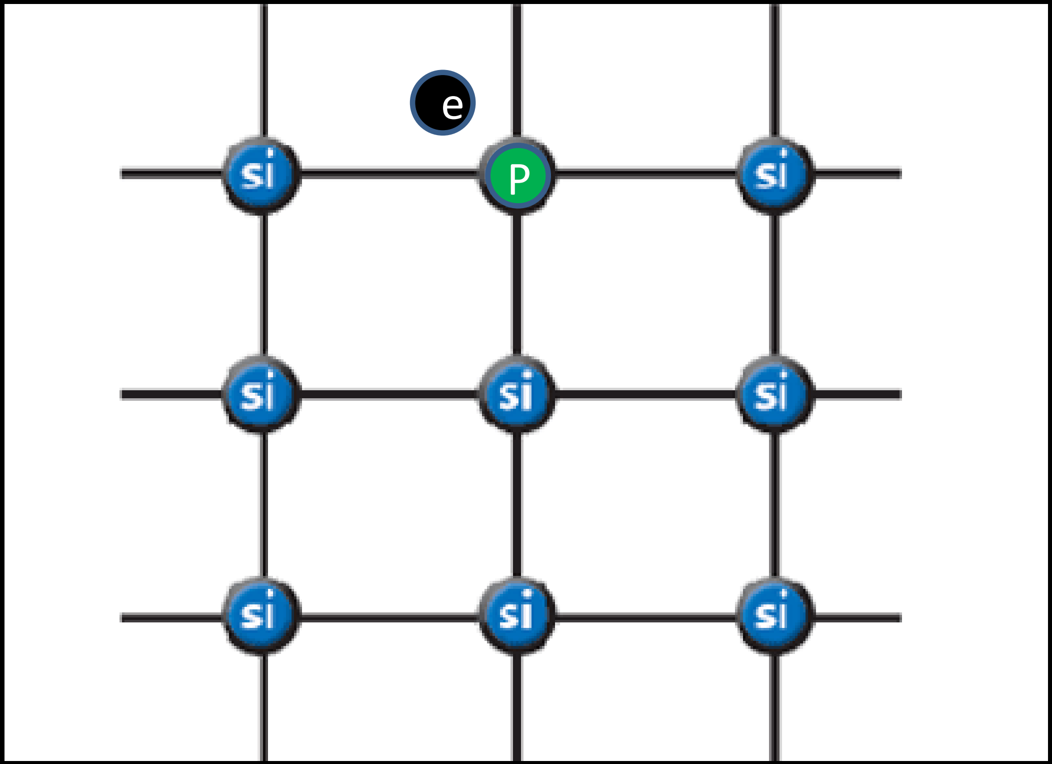


# The pure silicon crystal



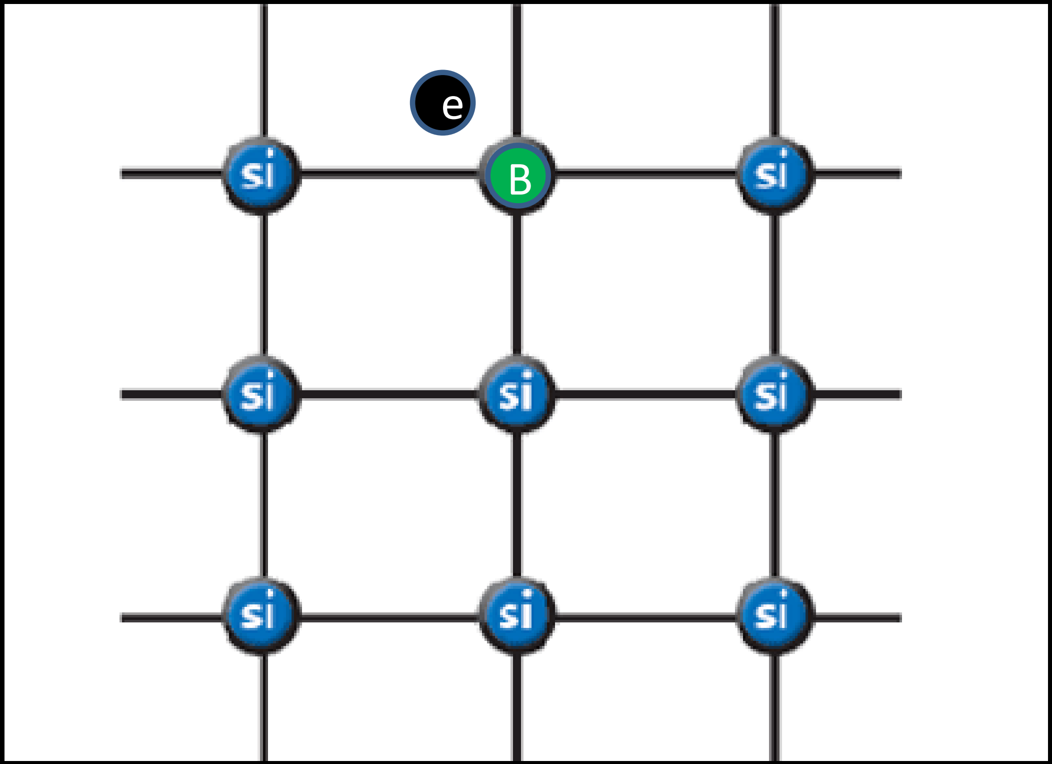

- Pure silicon is a non conductor - or an insulator because the VALENCE BAND is full of electrons with no spaces
- But if we "dope" it with tightly controlled impurities all this changes

# Doping the crystal – N type



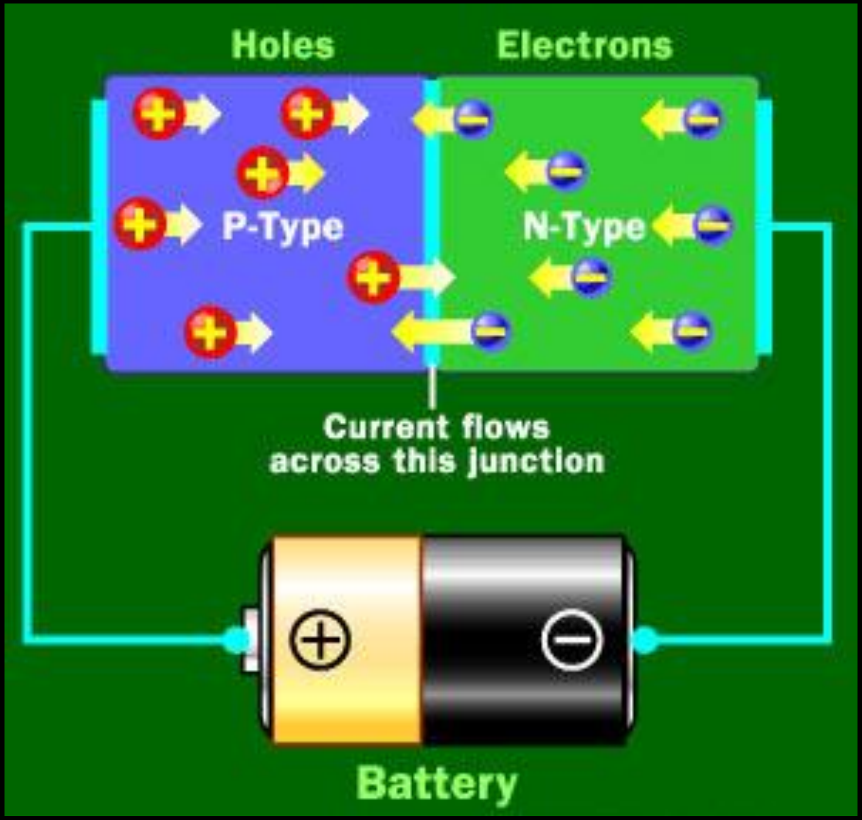

- The phosphorus atom fits into the silicon lattice but has 5 electrons so there is a spare which is free to roam through the crystal lattice
- Minute quantities are needed.
- This creates an "N" type semiconductor

# Doping the crystal – P type



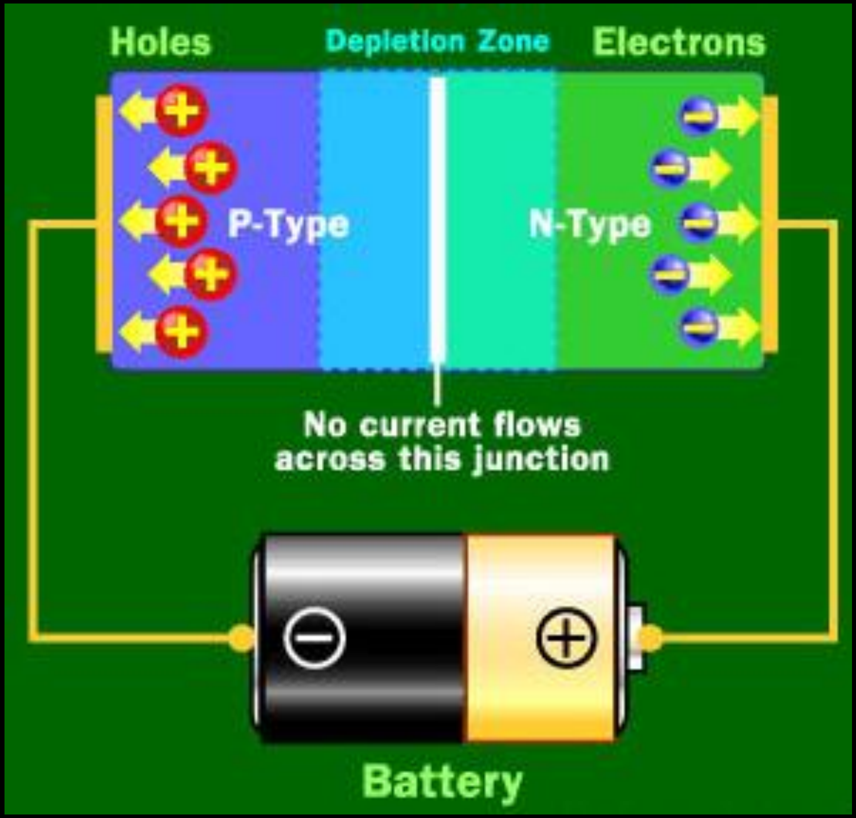

- If instead we dope the silicon with Boron, which has 3 electrons in the outer orbit we create an ABSENCE of electron or a HOLE which gets filled by stealing an electron from the adjacent atom
- Holes appear to be positive charges and travel in the opposite direction to electrons!

# The PN junction – a "forward biased" diode




- Connect a battery across a PN junction
- When the negative end of the circuit is connected to the N-type layer and the positive end is connected to the P-type layer, electrons and holes start moving across the junction

# The PN junction – a "reverse biased" diode

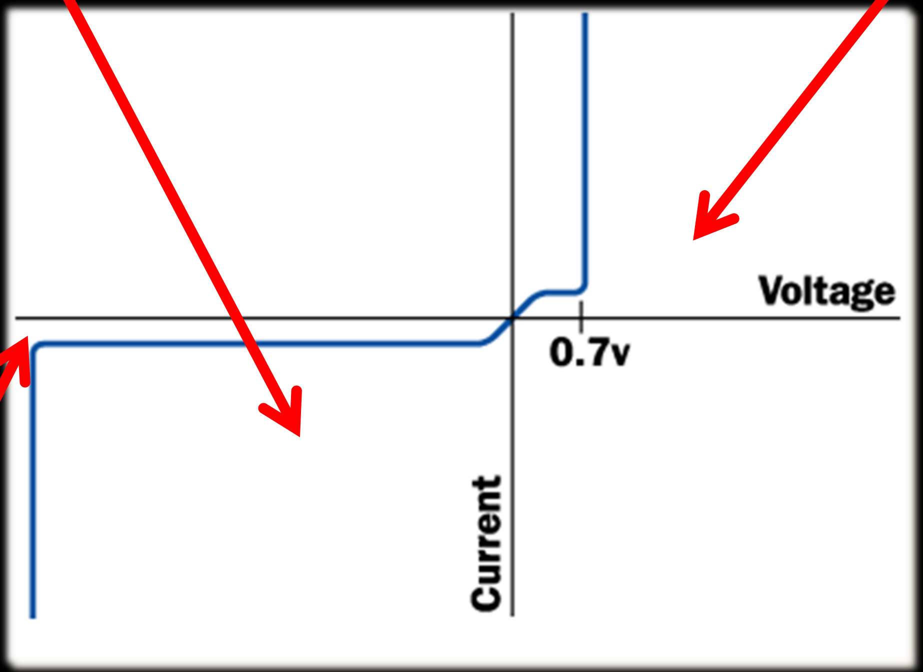



- Reverse the battery across a PN junction
- When the positive end of the circuit is connected to the N-type layer and the negative end is connected to the P-type layer, there is no movement of electrons and a depletion layer is formed

# Current flowing in a PN diode junction

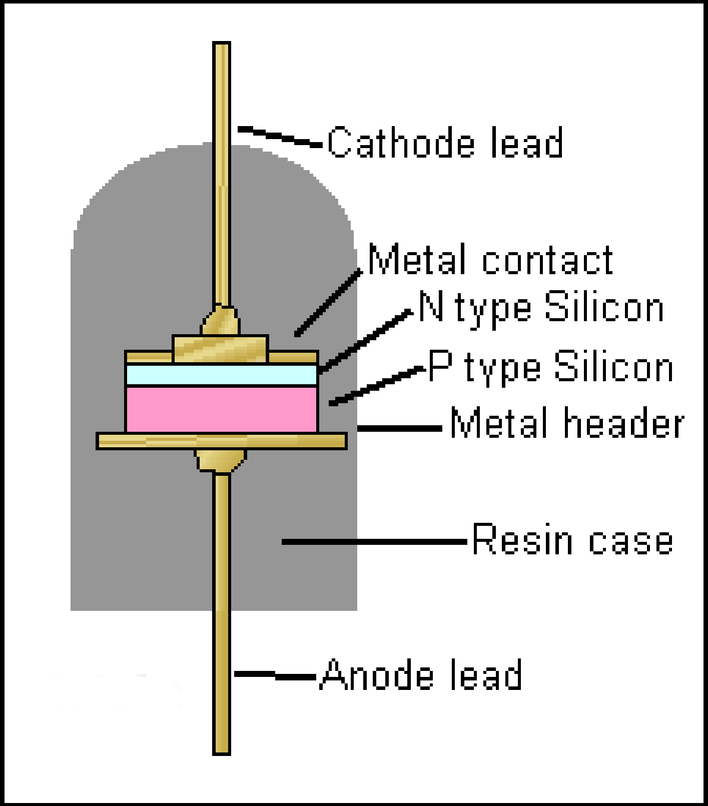
Reverse biased region.

Forward biased region




Apply enough reverse bias
and junction breaks down

# Schematic physical diagram of a PN silicon junction diode



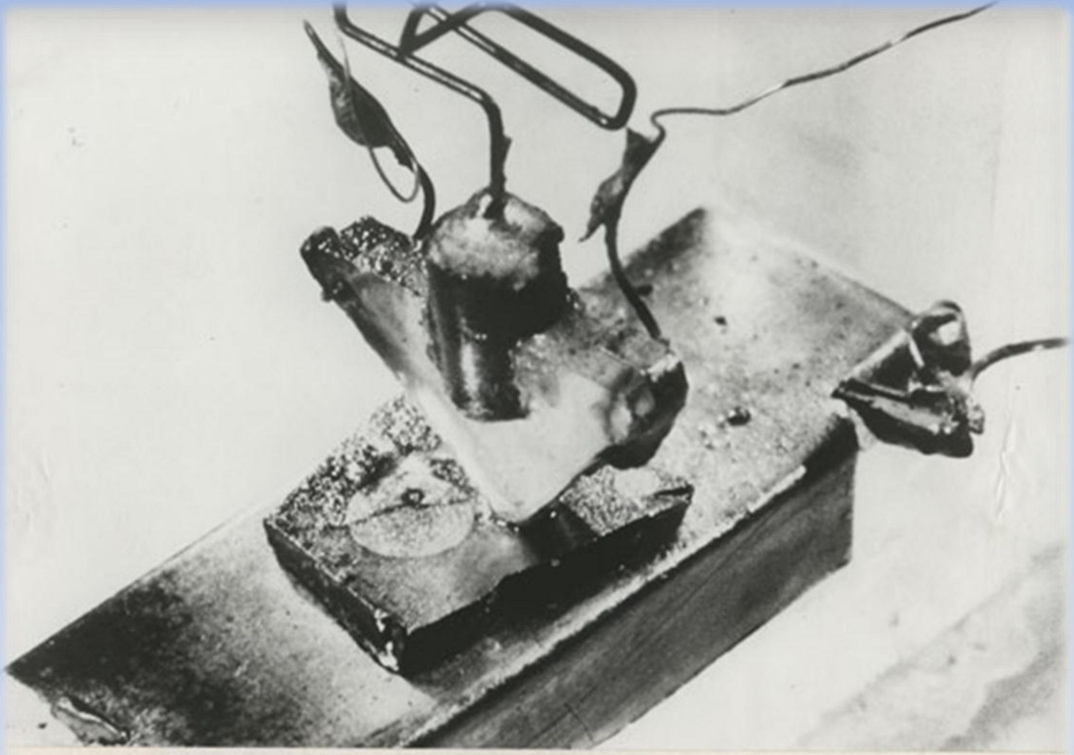
# Germanium versus Silicon

| Parameter | Germanium | Silicon | Comments |
|---|---|---|---|
| Depletion layer p.d. | 0.15V | 0.6V | Germanium can be useful for low voltage applications. |
| Forward current | A few milli-amperes | Tens of amperes | Silicon much better for high current applications. |
| Reverse leakage current | A few micro-amperes | A few nano-amperes | Germanium 1000 times more leaky than silicon. |
| Max. reverse voltage | Volts | Hundreds of volts | Silicon is the only real choice for high voltage applications. |
| Temperature stability | Poor | Good | Germanium more sensitive to temperature. Can be a problem or can be useful. |
| Junction capacitance | Very low (point contact) | Comparatively high | This is a useful feature for high frequency use. Note: low capacitance silicon diodes are also available but still higher capacitance than point contact types. |

# Genesis of the Transistor

- Every picture is worth 1000 words…
- No love lost between these guys. Bardeen Shockley and Brattain in a 1948 shot at Bell labs
- The transistor was invented in 1948 and patented by the three of them

# Genesis of the Transistor



THE FIRST TRANSISTOR AS IT WAS PATENTED BY THREE NOBEL PRIZE-WINNING BELL LABORATORIES SCIENTISTS

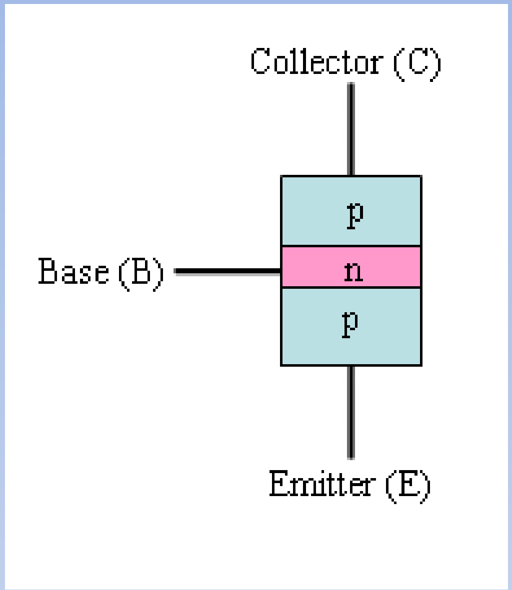
- This was the example on which the 1948 patent rested
- The semiconductor world really kicked off at this point
- The semiconductor material used is Germanium
- The three scientists were awarded a Nobel prize for their work
- In fact there were earlier patents as early as 1925 but no physical device was ever constructed

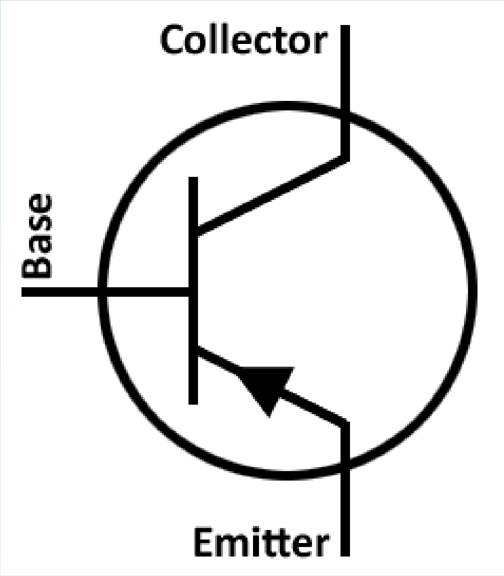
# What is a junction transistor - I?

- A transistor is created by using three layers rather than the two layers used in a diode. You can create either an NPN or a PNP sandwich. A transistor can act as a switch or as an amplifier.

- A transistor looks like two diodes back-to-back. You'd imagine that no current could flow through a transistor because back-to-back diodes would block current both ways. And this is true. However, when you apply a small current to the centre layer of the sandwich, a much larger current can flow through the sandwich as a whole. This gives a transistor its switching or amplifying behaviour. A small current can turn a larger current on and off.

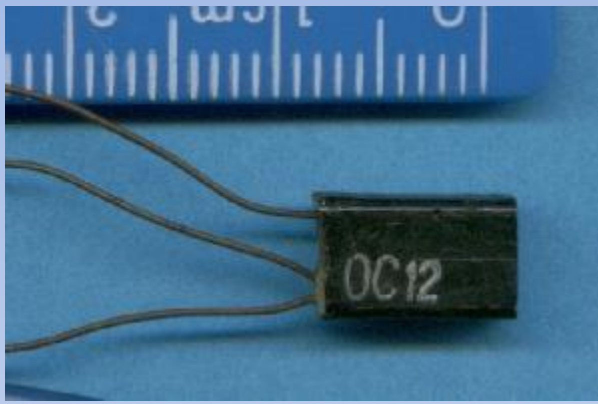
# What is a junction transistor - II?




- A Junction transistor is a three terminal device
- An signal current change in the base-emitter circuit produces a (much) larger change in the collector current
- This is the principle of amplification
- Maths-wise it is a bit more complicated because unlike the old valve triode (which the transistor replaces) there is some feedback between collector and base circuits

# Early Transistors

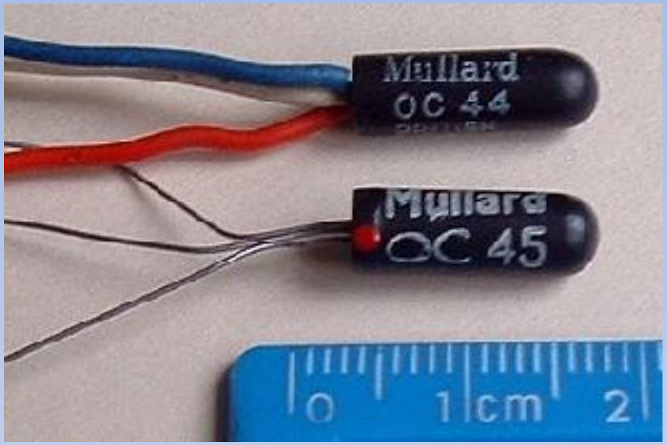



- Mullard grown junction transistor c. 1953
- Not a great success
- The semiconductor material used is Germanium


- Mullard alloyed junction transistor c. 1954→1960
- Glass encapsulated
- Low power Audio frequency applications
- Filled with bouncing putty**!!

**65% dimethyl siloxane 17% silica 9% Thixatrol ST 4% polydimethylsiloxane, 1% decamethyl cyclopentasiloxane, 1% glycerine, and 1% titanium dioxide

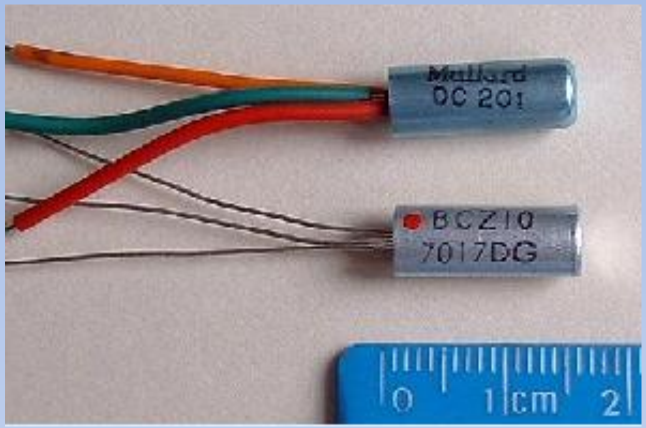
# More early Transistors




- "The first germanium RF transistor"
- Introduced 1956
- Used (extensively) by me while working for English Electric Guided Weapons division (now Bae)


- Mullard's first germanium power transistor
- Also introduced in 1956
- Typical of Philips "not invented here" approach, using a non standard stud mounting

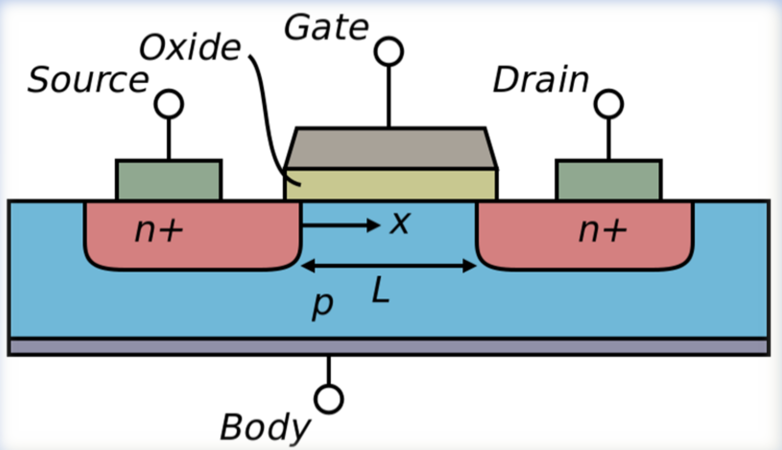
# Silicon replaces Germanium



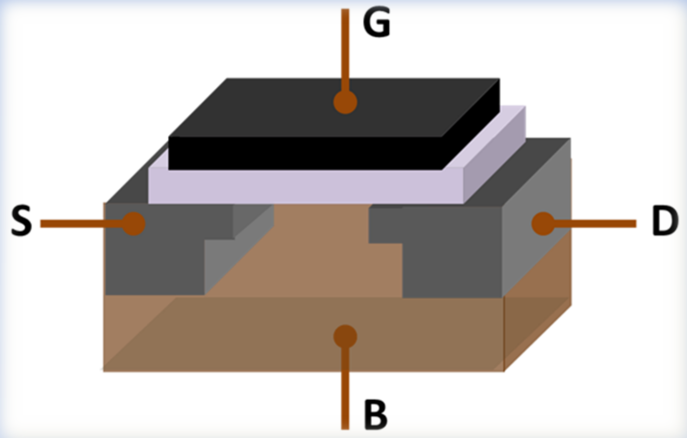

- Mullard introduced silicon transistors with all the advantages of silicon in 1959
- Glass in metal can construction
- Still packed with bouncing putty!
- Still alloy-diffused transistors and heavily manual manufacturing processes

# MOSFET
# Metal Oxide Silicon Field Effect Transistor

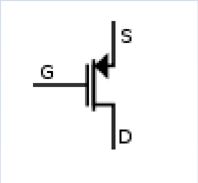
Theoretical cross sectional view

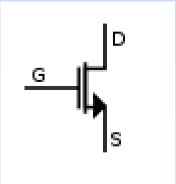



Isometric view




Circuit symbols



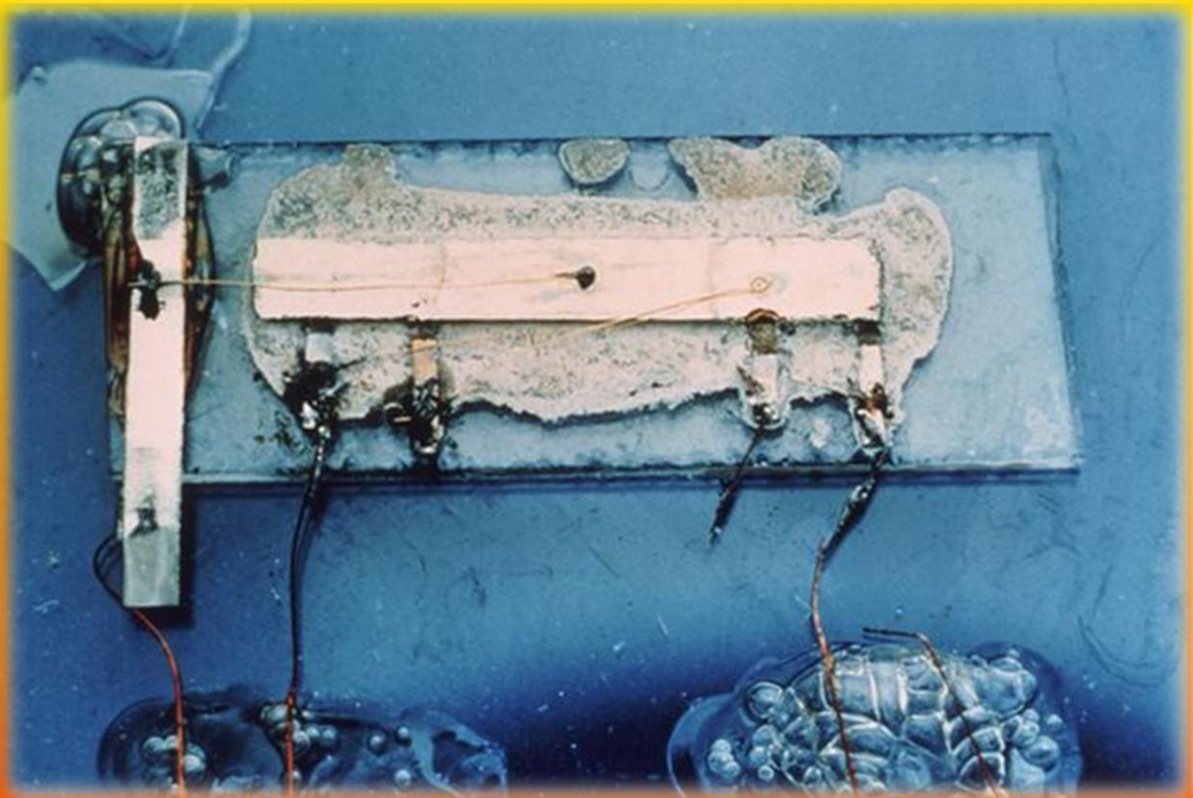
# Manufacturing techniques - I

- Given the perfectly grown crystal of silicon there was still much to do by way of technology
- In the early years there were many different manufacturing techniques for the bipolar transistor
- All strived to reduce costs; increase throughout; increase longevity of devices and consistency of performance
- Examples:
  - The grown junction
  - The mesa transistor
  - Alloy diffused transistor
  - The planar process
  - Use of epitaxial layer
  - UV based photolithographic processes
  - Ion deposition
  - Electron beam etching
  - X-ray lithography

# Manufacturing techniques - II

- The semiconductor industry recruited many senior chemists; physicists; metallurgists; photographers; statisticians and mechanical engineers
- Manufacturing a "wafer" of individual transistors was only the first step
- The back side of the wafer had to be coated in vacuo with am appprpriate metral to form an adherent ohmic connection
- All devices had to be tested with micro probes to weed out those devices failing the specification
- The wafer was then diced to produce each individual transistor die
- The die was mounted onto a header, using the right alloy: (an incorrect choice of alloy could lead to failure through the die either failing to be wetted to the header or being poisoned by one of the constituent elements
- Once successfully mounted, two remaining connections had to be made between the die and the terminal posts in the header. The correct choice of wire (gold or aluminium) and the bonding method (ultrasonic or thermocompression) were essential

# The first integrated circuit



**Developed by Jack Kilby of Texas in 1958**

**A single transistor and supporting components on a slice of germanium**

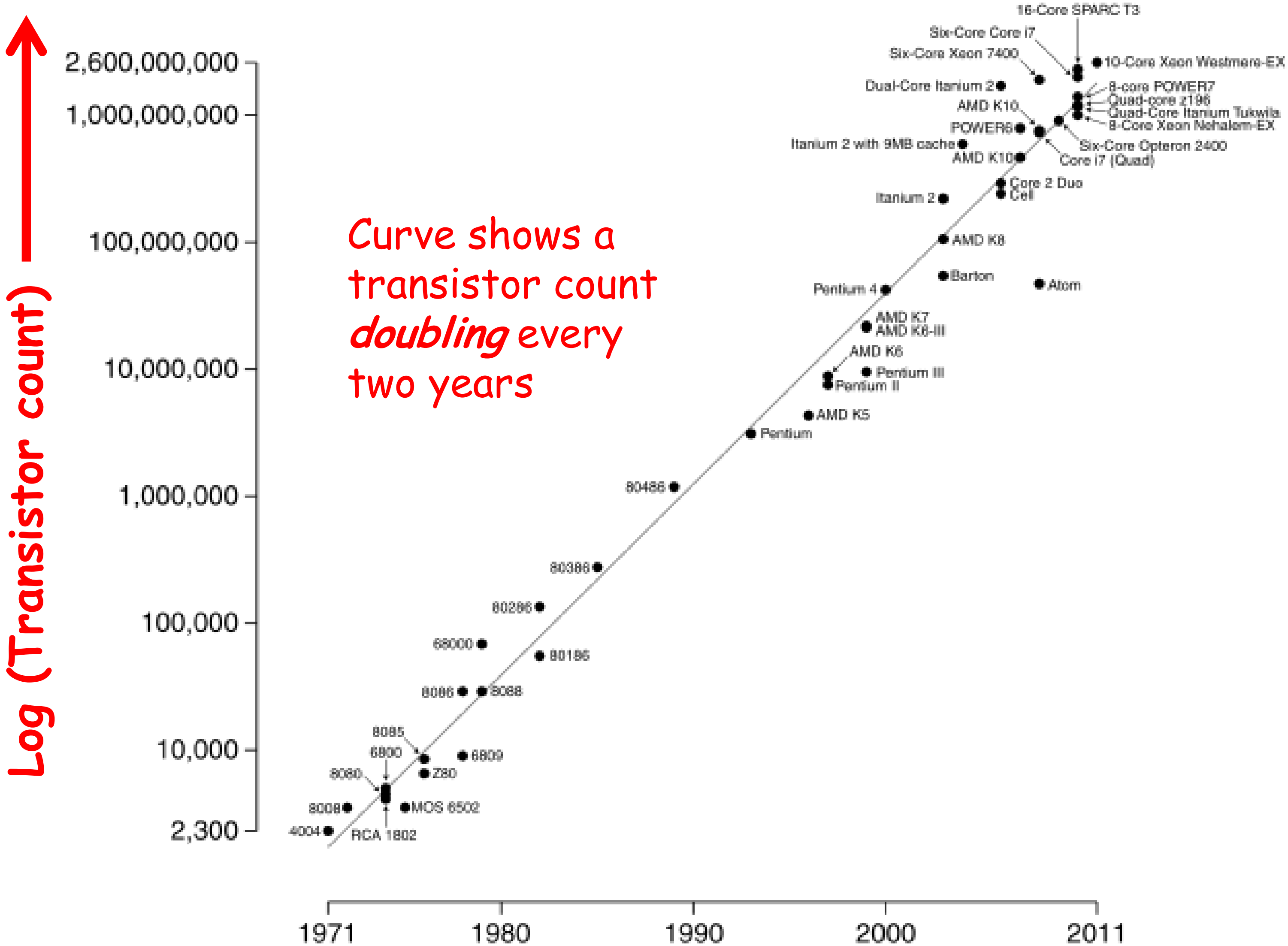
# Bigger and yet smaller

- **Moore's Law.** In 1965, Gordon Moore wrote that the number of transistors in an IC had doubled every year between 1958 and 1965 and that the trend would continue for 10 years…
- He was more than right. Moore's law has continued to apply for more than 47 years!
- Processing speeds double every two years
- Geometry gets smaller and smaller Currently we are working towards a 23nM geometry

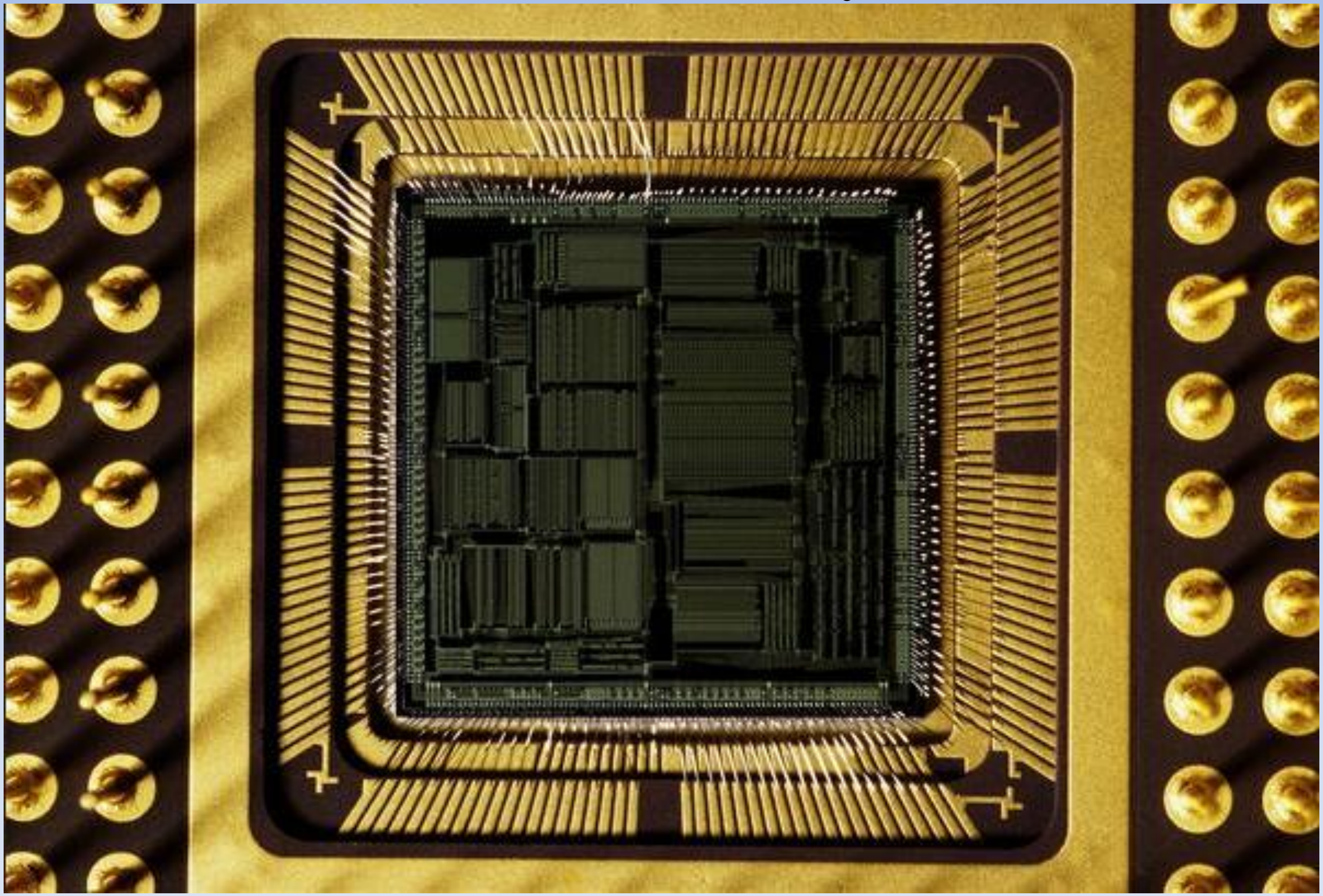
# Bigger and yet smaller

- SSI. Early 60s. Small Scale Integration. Less than 100 transistors on a chip
- MSI. Late 60s. Medium Scale Integration. Hundreds of transistors on a chip
- LSI. Early 80s. Large Scale Integration. Thousands of transistors on a chip
- VLSI. Very Large Scale Integration. Initially 10,000+ transistors on a chip. Now with the Central Processor chip we have 100,000 – 1,000,000+ transistors on a chip (10,000,000??)

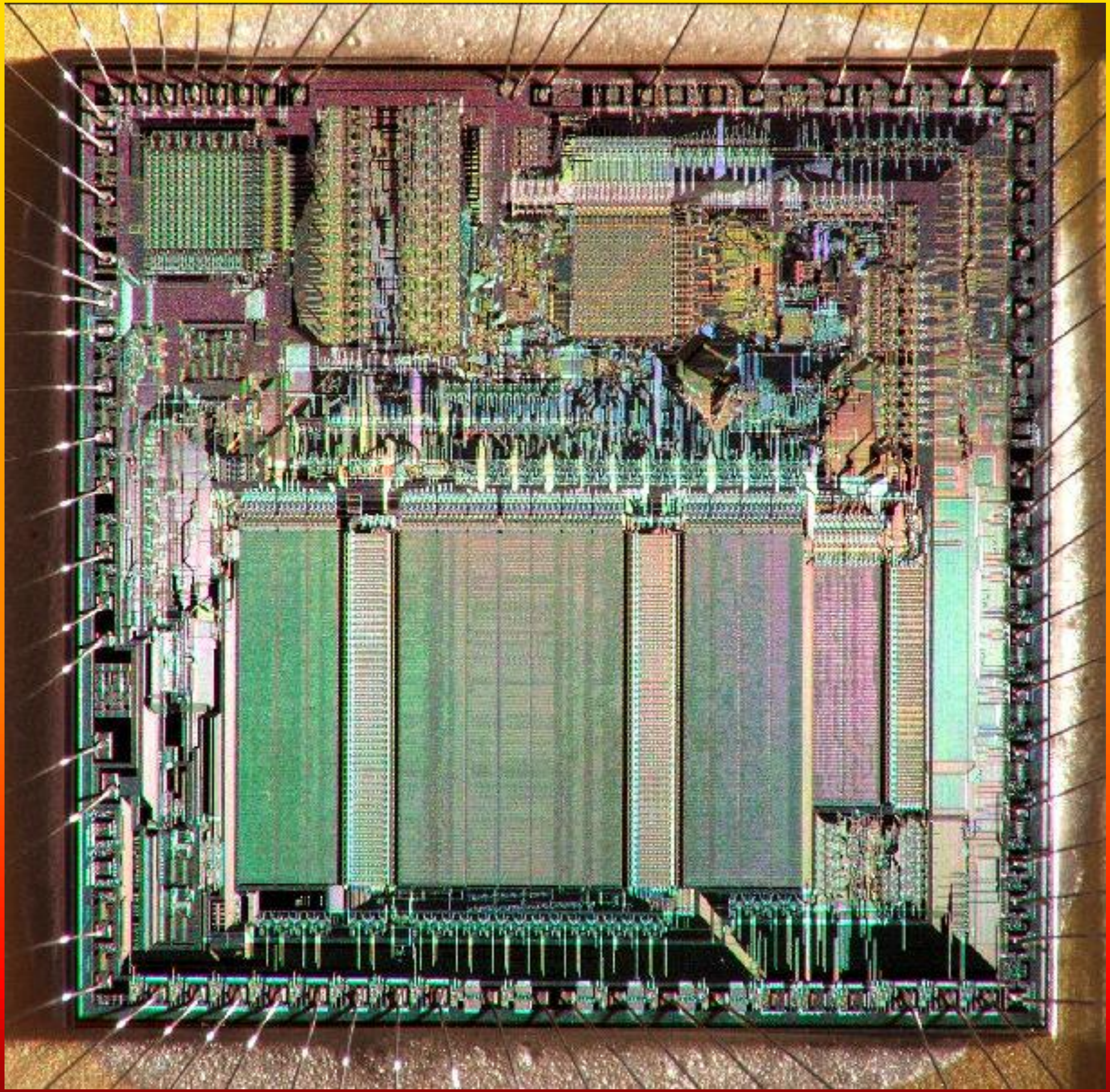
# Moore's Law - Microprocessor Transistor Counts 1971-2011



# Inside a computer CPU
# The brain of your PC



# The bigger picture



And now or something completely different

# Gallium Arsenide

# Gallium Arsenide – a band III band V semiconductor

- Gallium arsenide is a crystal – just like Silicon or Germanium but is comprised of alternate atoms of Gallium and Arsenic
- Advantages over Silicon:
  - ✓ Higher saturated electron velocity and higher mobility so can function at frequencies above 250GHz
  - ✓ Lower noise
  - ✓ Higher specific resistivity
  - ✓ Orders of magnitude harder than silicon when exposed to radiation
  - ✓ Several times faster than silicon
  - ✓ Direct band gap material so can be tailored to emit light
  - ✓ Can be used to fabricate GUNN diodes for Doppler radar devices

# Gallium Arsenide – a band III band V semiconductor

- No such thing as a free lunch though…
- Disadvantages compared with Silicon:
  - Neither abundant nor cheap
  - Highly toxic – disposal problems
  - Extremely brittle
  - Poor thermal conductor
  - No ability to create a passivating oxide like $SiO_2$
  - Low hole mobility so cannot be used for CMOS
  - Much higher power consumption than silicon

# Light emitting diodes (LED) - I

## GaAs; GaAsP; GaP; GaN

- An LED is simply a P-N junction that is forward biased
- LEDs are fabricated from complex semiconductors (like Gallium Phosphide; Gallium Arsenide Phosphide; Gallium Arsenide; Gallium Nitride)
- When electrons cross the junction from the n- to the p-type material, the electron-hole recombination process produces some photons in the Infra Red or Visible spectrum in a process called electroluminescence.

# Light emitting diodes (LED) - II

## LEDs – the timeline

- 1962 The first practical LED
- 1960s Use of low intensity red LEDs for indicators and 7 segment displays
- 1970s 7 segment LEDs displaced by increasing availability of LCD displays
- 1980s Green and yellow LEDs appear. Crystal defects mean that light outputs are still low
- 1990s Gallium Nitride LED gives brilliant and efficient blue light. Partial conversion with phosphor coating allows conversion to white light. White LEDs in production in 1993
- 2000s Higher and whiter (Warm white; white and Cool white available)

# Then there are Solar Panels

# U3A Science & Technology

Semiconductors - The End