Materials and basic processes in microelectronics

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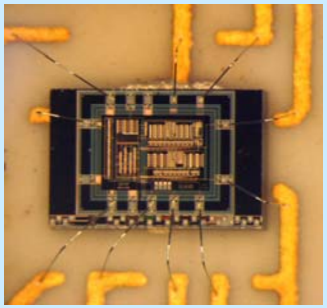
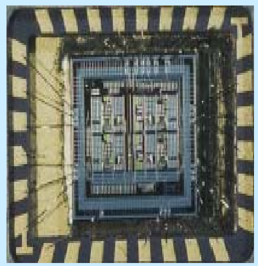
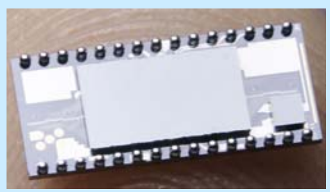
Introduction
Materials and basic processes

Die attach

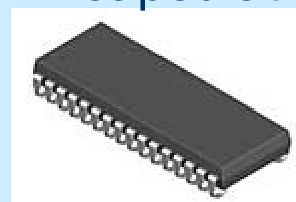


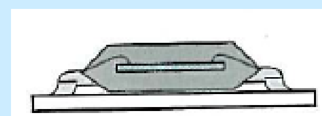
Interconnect



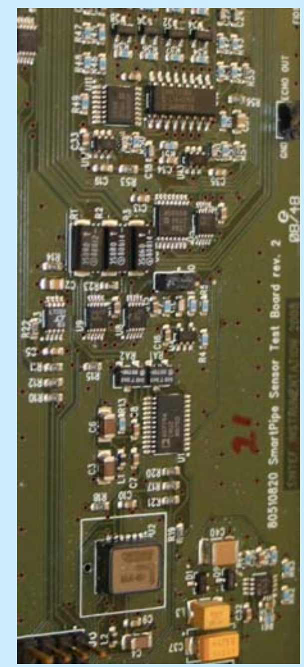


Encapsulation





Board assembly



Metals

Important functions:

- Electrical conductors
  - Printed circuit boards
  - Contacts
  - Cables
- Mechanical
  - Welding
  - Soldering
- Heat transport
  - Component cooling

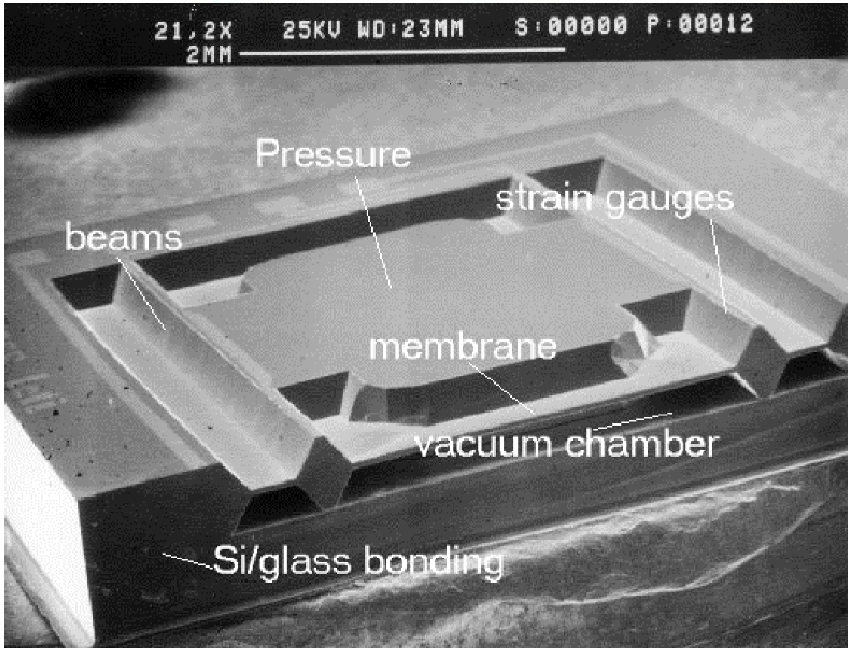
Table 3.1 a): Properties of some important materials in electronics: Conductors[3.1].

Metal/Conductor	Melting Point [°C]	Electrical Resistivity [10^{-8}Ohm•m]	Thermal Exp. Coeff. [10^{-7}/°C]	Thermal Conductivity [W/m·°K]
Copper	1083	1.7	170	393
Silver	960	1.6	197	418
Gold	1063	2.2	142	297
Tungsten	3415	5.5	45	200
Molybdenum	2625	5.2	50	146
Platinum	1774	10.6	90	71
Palladium	1552	10.8	110	70
Nickel	1455	6.8	133	92
Chromium	1900	20	63	66
Invar	1500	46	15	11
Kovar	1450	50	53	17
Silver-Palladium	1145	20	140	150
Gold-Platinum	1350	30	100	130
Aluminium	660	4.3	230	240
Au-20%Sn	280	16	159	57
Pb-5%Sn	310	19	290	63
Cu-W(20%Cu)	1083	2.5	70	248
Cu-Mo(20%Cu)	1083	2.4	72	197

Semiconductors (Silicon)

- Crystalline
- High thermal conductivity (150 W/m K)
- Low CTE (2.6 ppm/K)
- Electrical conductivity controlled by doping

- Silicon micro-sensors:
  - Silicon is machined by anisotropic wet-etching or reactive ion-etching
  - Silicon is elastic

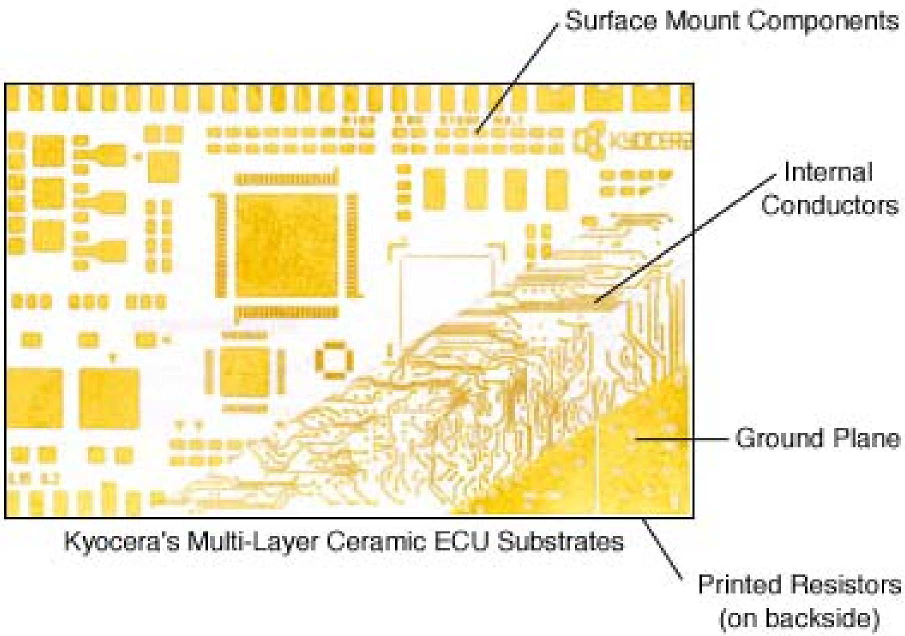


SOI trykksensor fra Leti

Inorganic materials

Ceramics

- Non-metallic materials processed in high temperature reactions (>600 °C)
- Electrical insulator
- Powder method:
  - Powder is mixed with binder and pressed in a mould,.
  - During subsequent heat treatment (sintering) the binder evaporates and the materials are partly melted together
  - Considerably shrinkage during sintering (15-20%)



Kyocera's Multi-Layer Ceramic ECU Substrates

Ceramics (cont.)

- Chemically and thermally very stable materials
- CTE range from negative to 20 ppm/K
- Thermal conductivity can vary a lot
- Most ceramics are brittle materials. Tolerates high compression, but little strain.

Non Organics	Relative Dielectric Constant	Thermal Exp. Coefficient $[10^{-7}/\,^{o}C]$	Thermal Conductivity $[W/\,m\cdot{}^{o}K]$	Approximate Processing Temp. $[^{o}C]$
92% Alumina	9.2	60	18	1500
96% Alumina	9.4	66	20	1600
Si3N4	7	23	30	1600
SiC	42	37	270	2000
AlN	8.8	33	230	1900
BeO	6.8	68	240	2000
BN	6.5	37	600	>2000
Diamond - High Pressure	5.7	23	2000	>2000
Diamond - Plasma CVD	3.5	23	400	1000
Glass-Ceramics	4-8	30-50	5	1000
Cu Clad Invar (10%Cu)/ (Glass Coated)	-	30	100	800
Glass coated Steel	6	100	50	1000

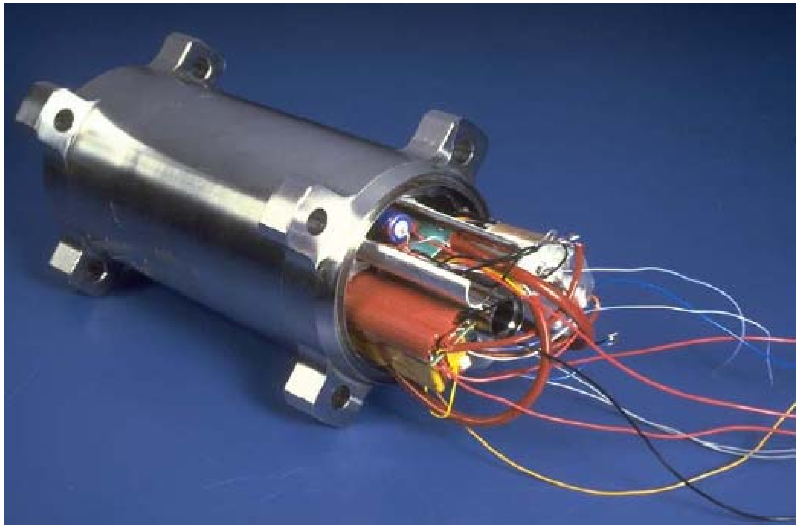
Inorganic materials
Glass

- Amorphous structure
- Used for
  - Binder and insulating layers on ceramic circuit boards
  - Insulation in electrical feed throughs

Glass feed-throughs from Schott

Organic materials - plastic

- Plastic can be found in nearly all electronics:
  - Mechanical building material (like IC moulding)
  - Thin dielectric layers on PCB (like polyimide)
  - Cable insulation (like PET, polyimide, Teflon)
  - Binder in organic circuit boards (like epoxy in FR4)
  - Conductive and non-conductive adhesives (like epoxy)
  - Photo resist in PCB production

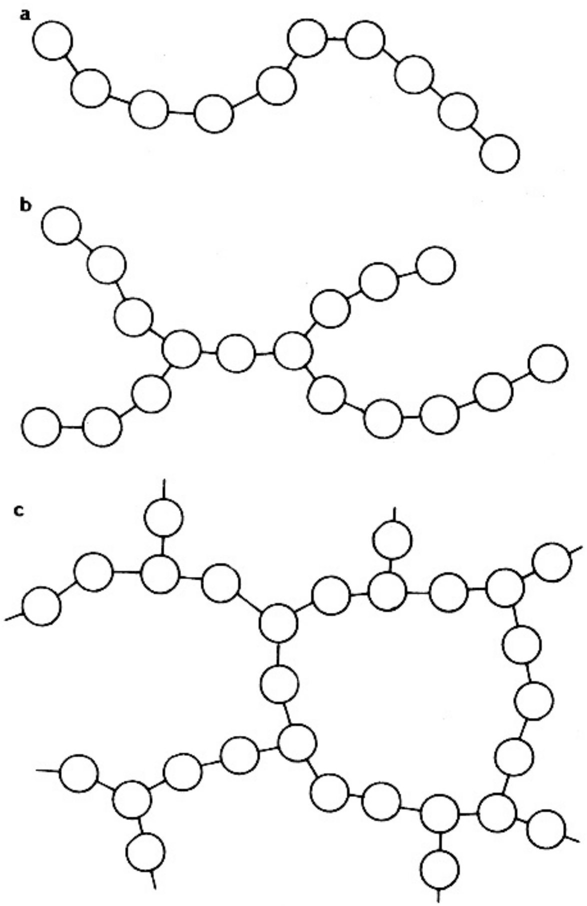


Motor control, SINTEF-project

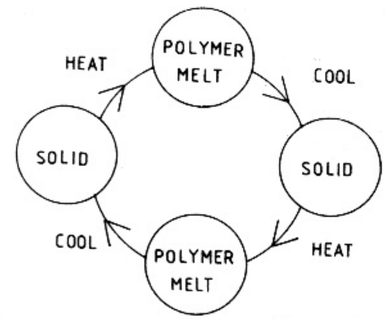
Important properties of plastics

- High electrical resistivity, high breakdown strength, low dielectric loss, low dielectric constant
- CTE is often higher than for metals or semiconductors
- Plastic with high mechanical strength or soft and flexible properties are available
- Adhesion - many plastics have good adhesion to other materials, but not all (like Teflon)
- Easy to process
- A certain water absorption takes place, little influence on material properties.
- **Cheap** raw material and production

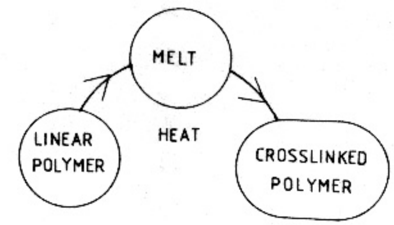
Plastic molecule structure



Linear (a), branched (b)
and cross-linked (c) polymer chains



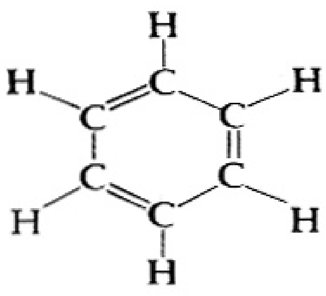
Thermoplastic



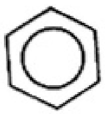
Thermosetting

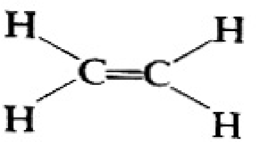
Plastic
Building blocks

- Consist of long chains of organic molecules
- The repeating block is termed a monomer
- The process of forming long chains is called a polymerization process.

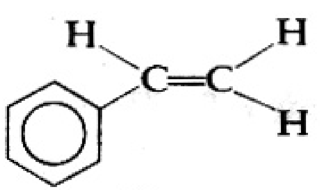


Benzene (C_6H_6)

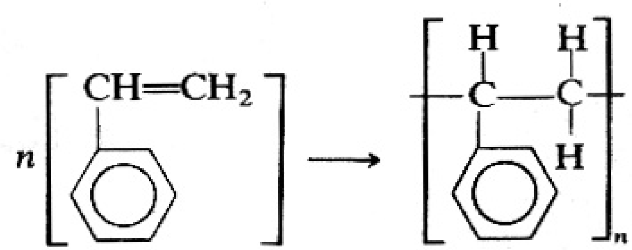




Ethylene (C_2H_4)



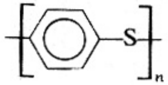
Styrene



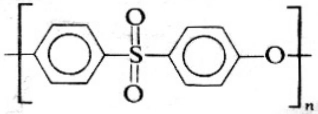
Styrene Polystyrene

Plastic
Building blocks

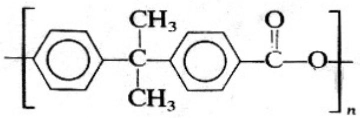
Structural unit



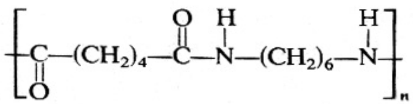
Polyphenylene sulphide



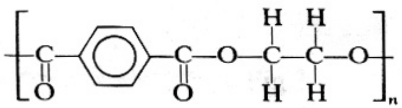
Polyether sulphone



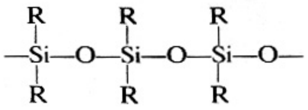
Polycarbonate



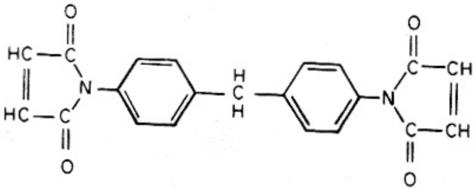
Nylon 66



Polyethylene terephthalate



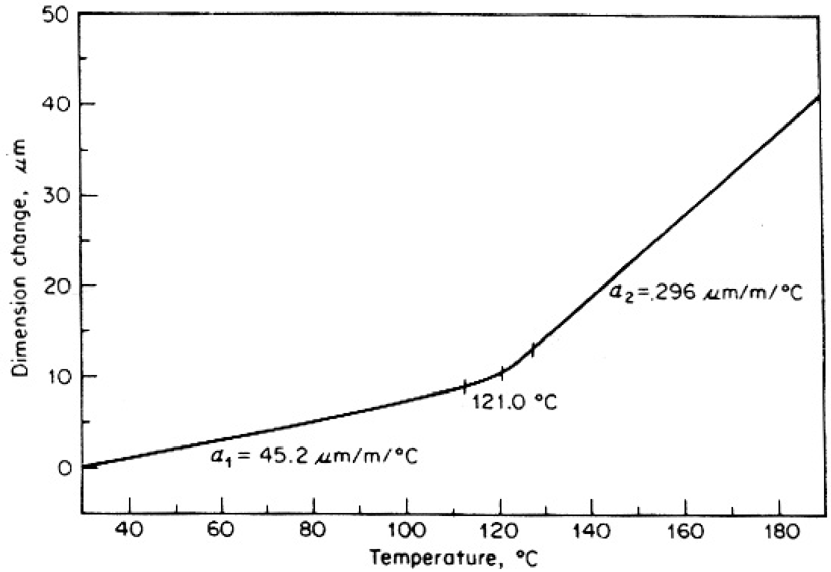
Silicone: R = CH_3: Methyl, C_6H_5: Phenyl, CH_2: Vinyl, OH: Hydroxyl



Polymide: Bismaldeimide

T_g: Glass transition temperature

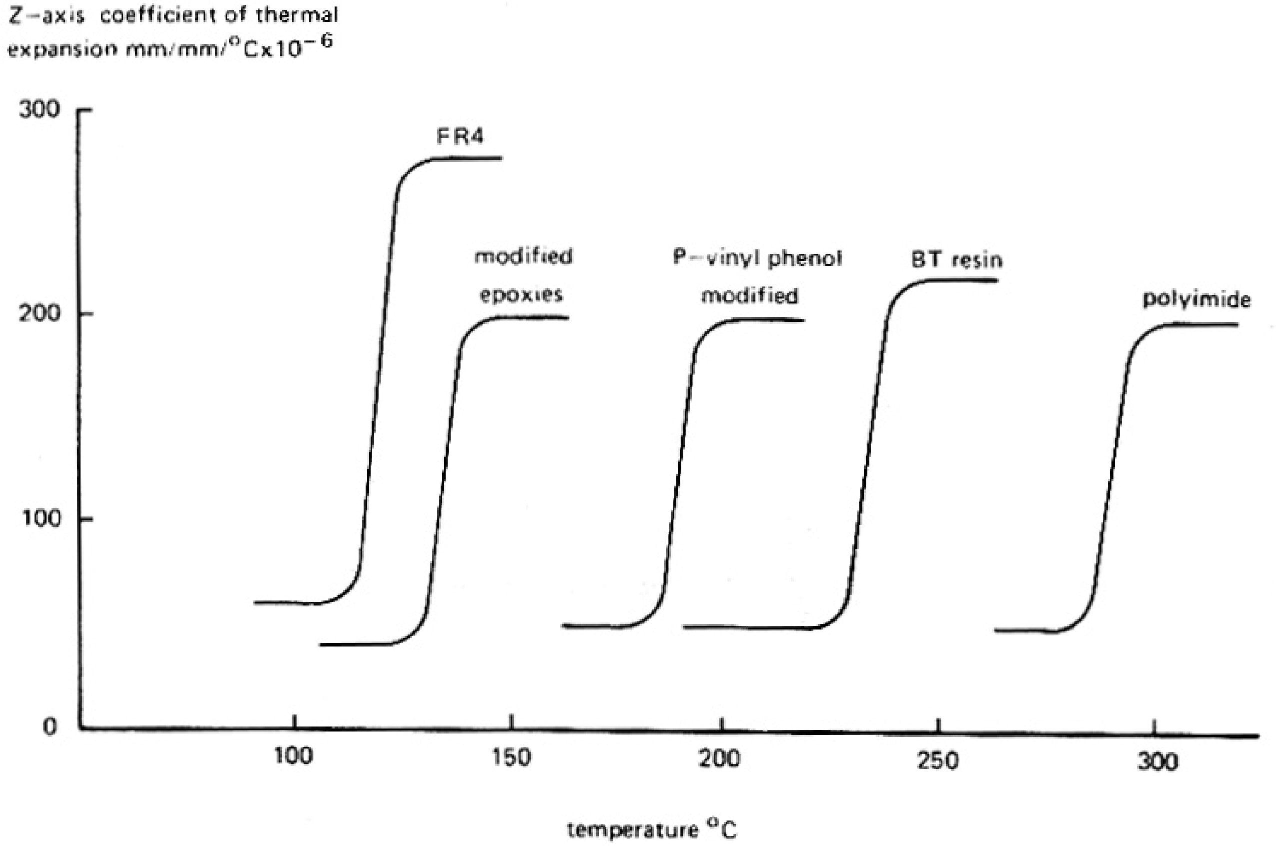
- Transition from a glass-like phase to a rubber like phase
- Below Tg the molecules are ‘frozen’. A certain thermal energy is needed for movement, Tg represents this limit.
- The material does not melt, but becomes more flexible.
- CTE is higher above T_g



CTE as a function of T, epoxy

Plastics, continued

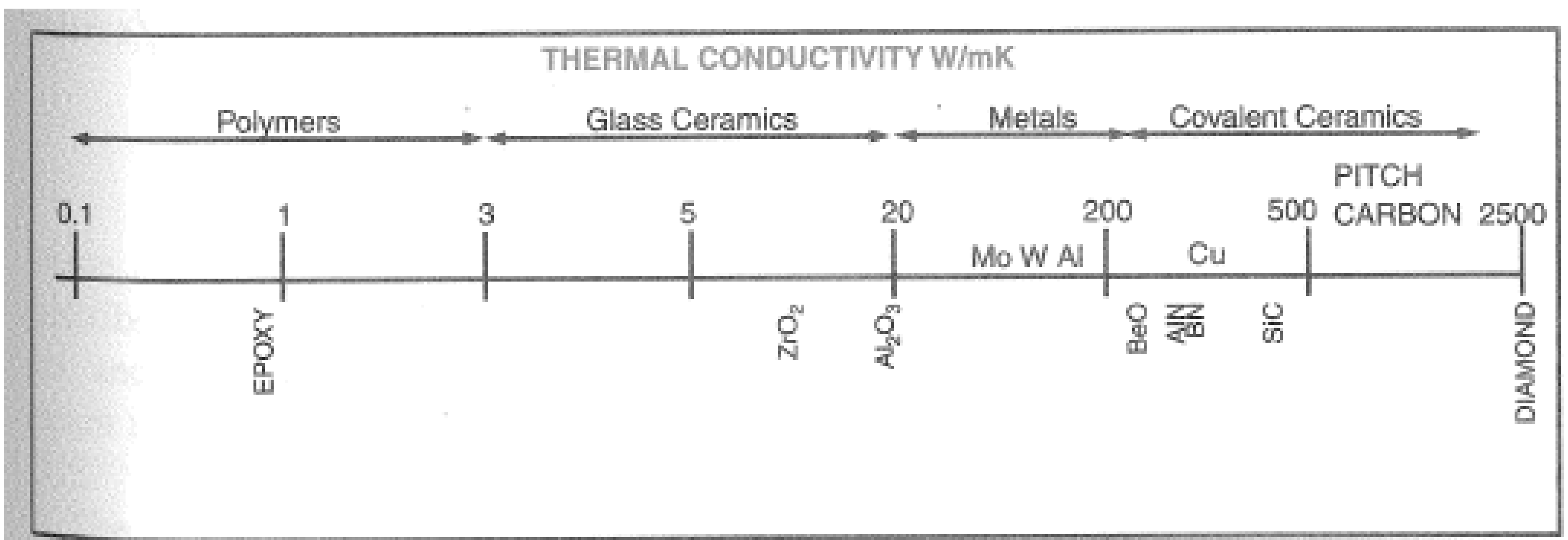
- "Glass transition": change from glass-like to rubber - like



Thermal conductivity

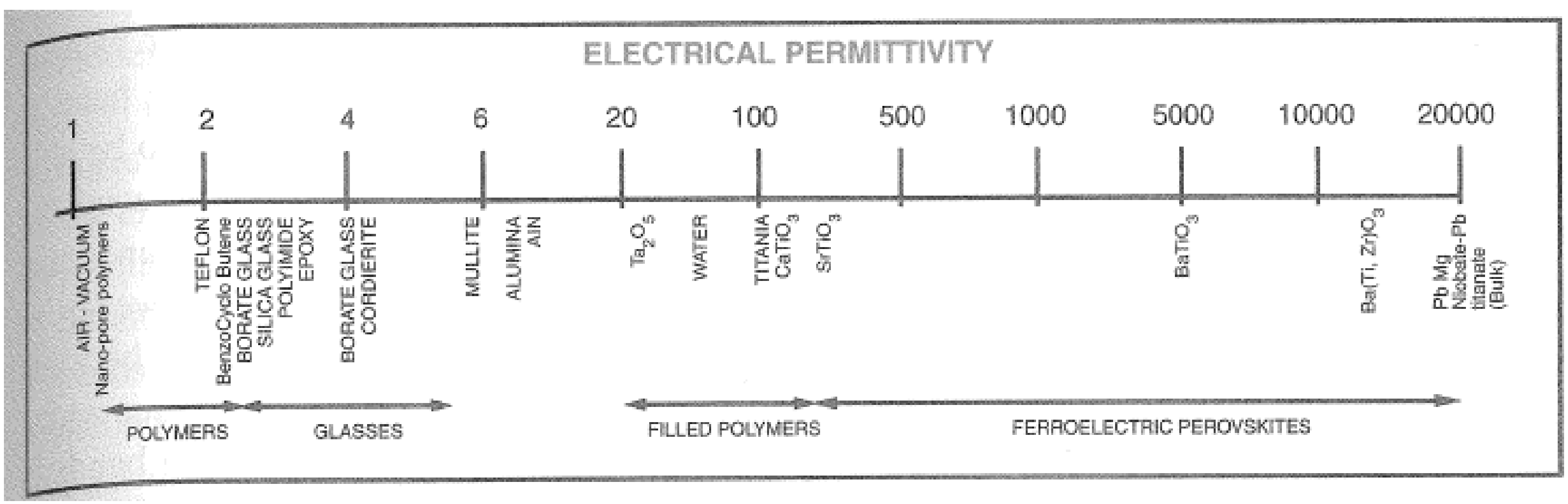
- Fouriers law: $\frac{dQ}{dt} = -\lambda A \nabla T$

- Component cooling depends on the thermal conductivity
- Rule of thumb: "10 °C higher component temperature will typically reduce the lifetime by 50%"



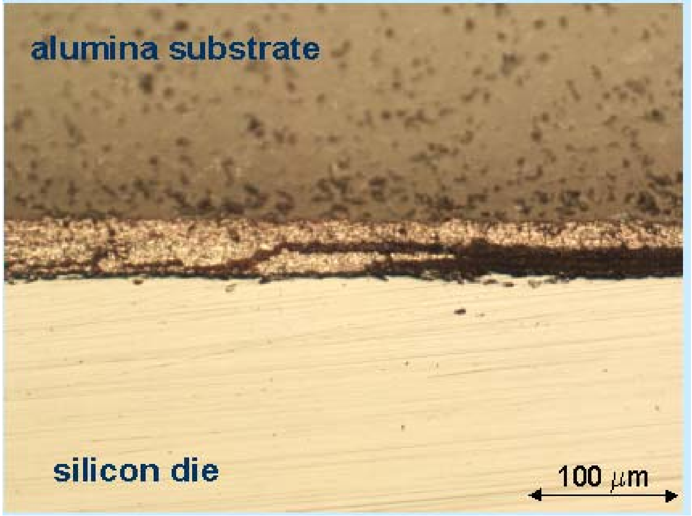
Electrical permittivity

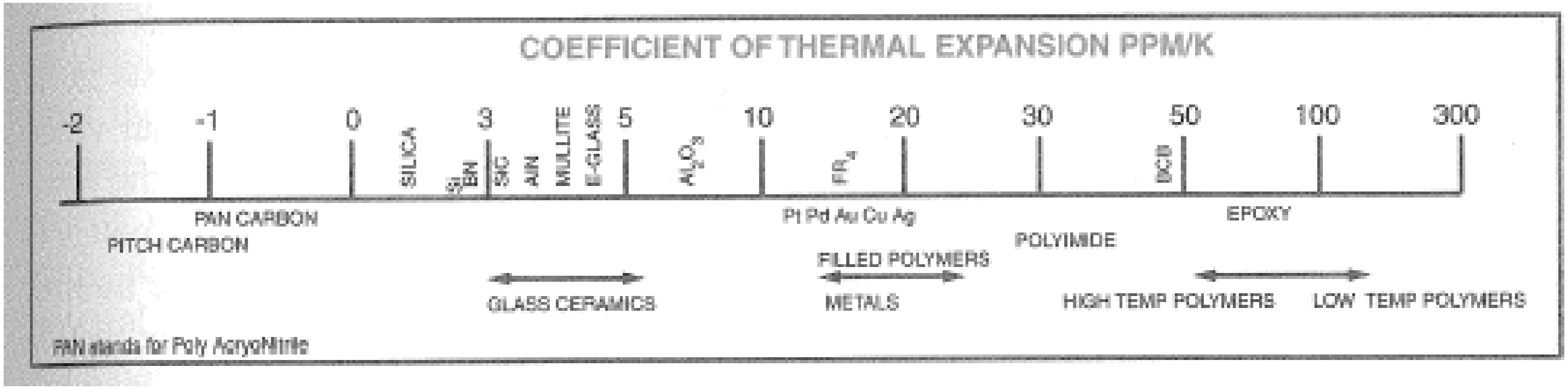
- Parallel plate capacity: $$C = \varepsilon_r \varepsilon_o \frac{A}{d}$$
- Non-perfect dielectrics will have a complex permittivity $\varepsilon = \varepsilon_o$ (k'+jk''). This gives rise to loss.
- tan δ = k''/k' = (1/R)/ωC = 1/Q



Coefficient of thermal expansion - CTE

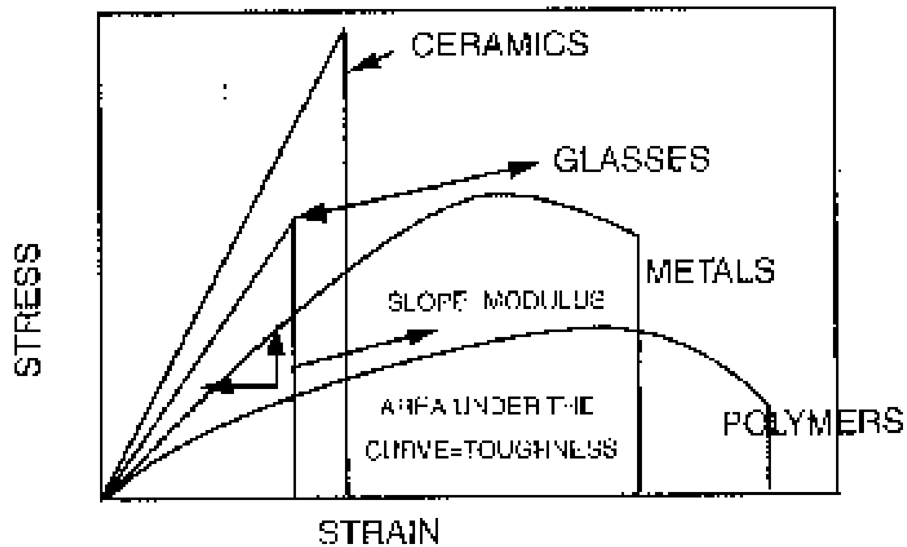
- Thermal expansion: CTE = Δl / ΔT
- Different thermal expansion in materials gives rise to mechanical stress. In worst case materials can de-laminate due to this effect.
- Thermal cycling of objects with CTE mismatch can cause fatigue.
- Silicon has a low CTE compared to most materials.

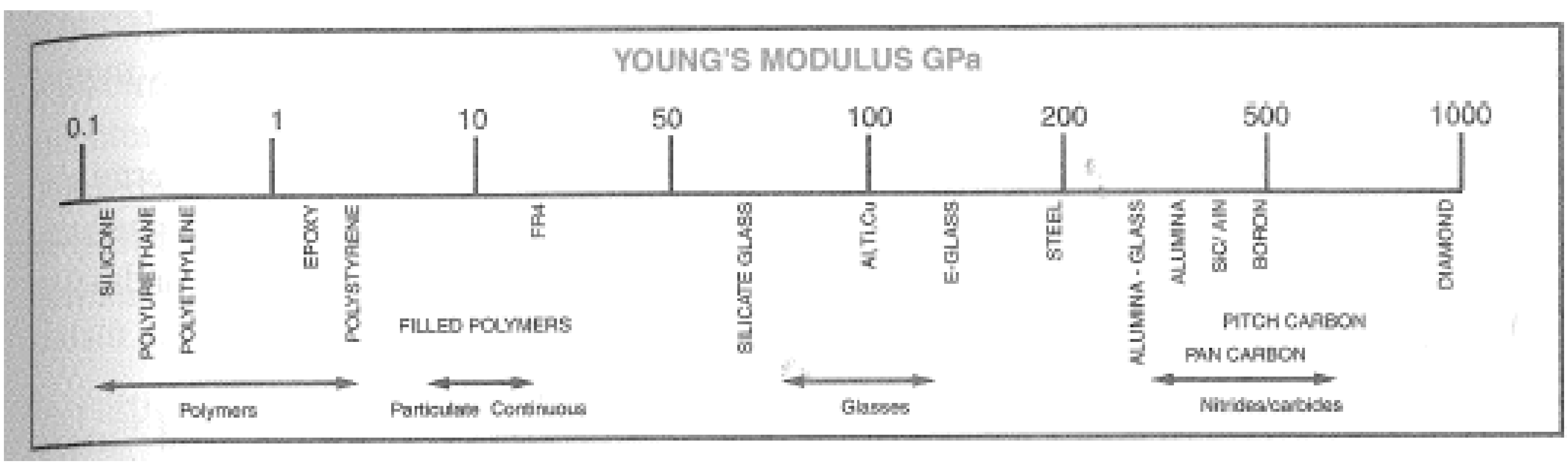




Mechanical properties
Young's modulus

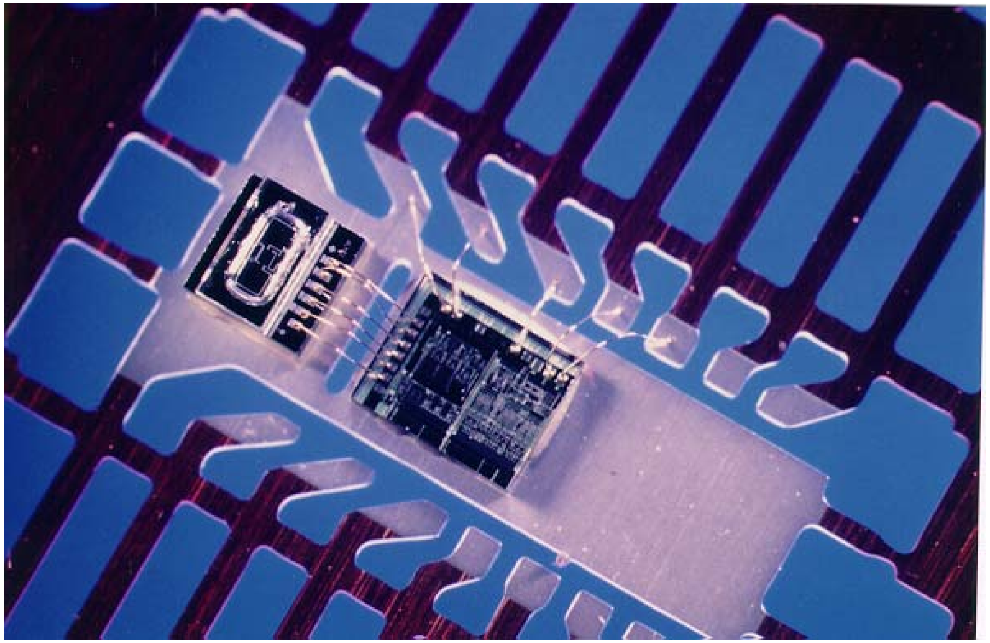
- Young's modulus (G) gives the relationship between stress and deformation (i.e. material stiffness)
- Stiff materials have little deformation
- Stress, σ : Force pr area (Pa)
- Strain, ε: Deformation
- Hooke's lov: Linear relationship between stress and strain ($\sigma = G\varepsilon$) Valid for elastic materials.





Important processes in microelectronics

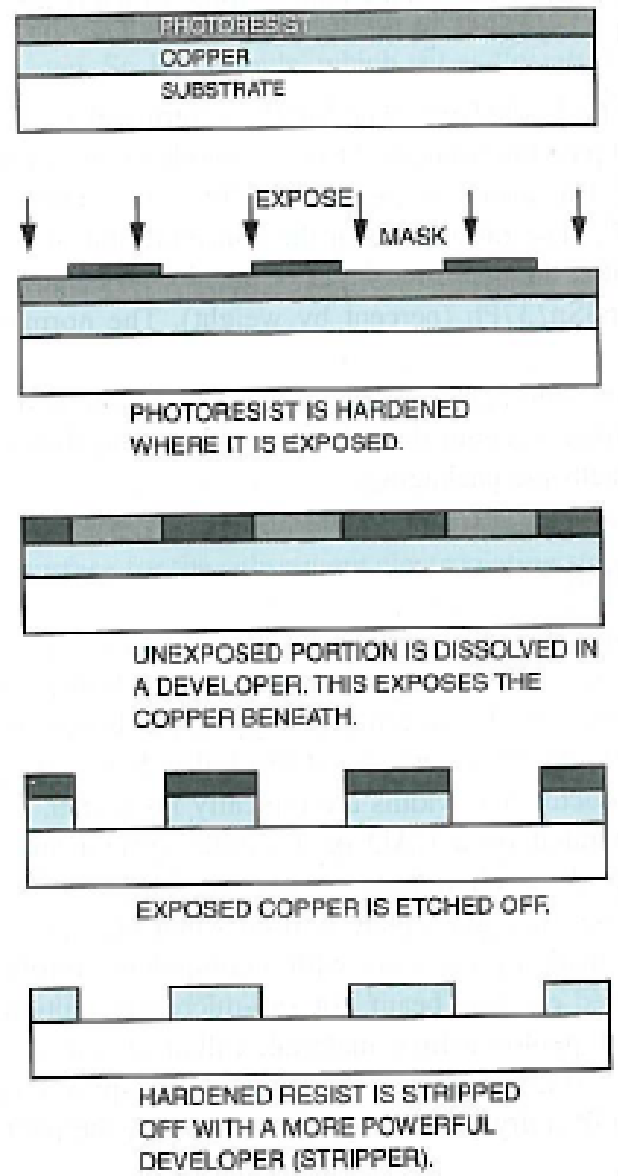
- Photo lithography
- Screen printing
- Etching
- Plating
- Sputtering
  - Vacuum sputtering
  - RF and DC sputtering
- Methods for electrical and mechanical interconnect:
  - Soldering
  - Gluing
  - Wire-bonding
  - Flip-chip bonding



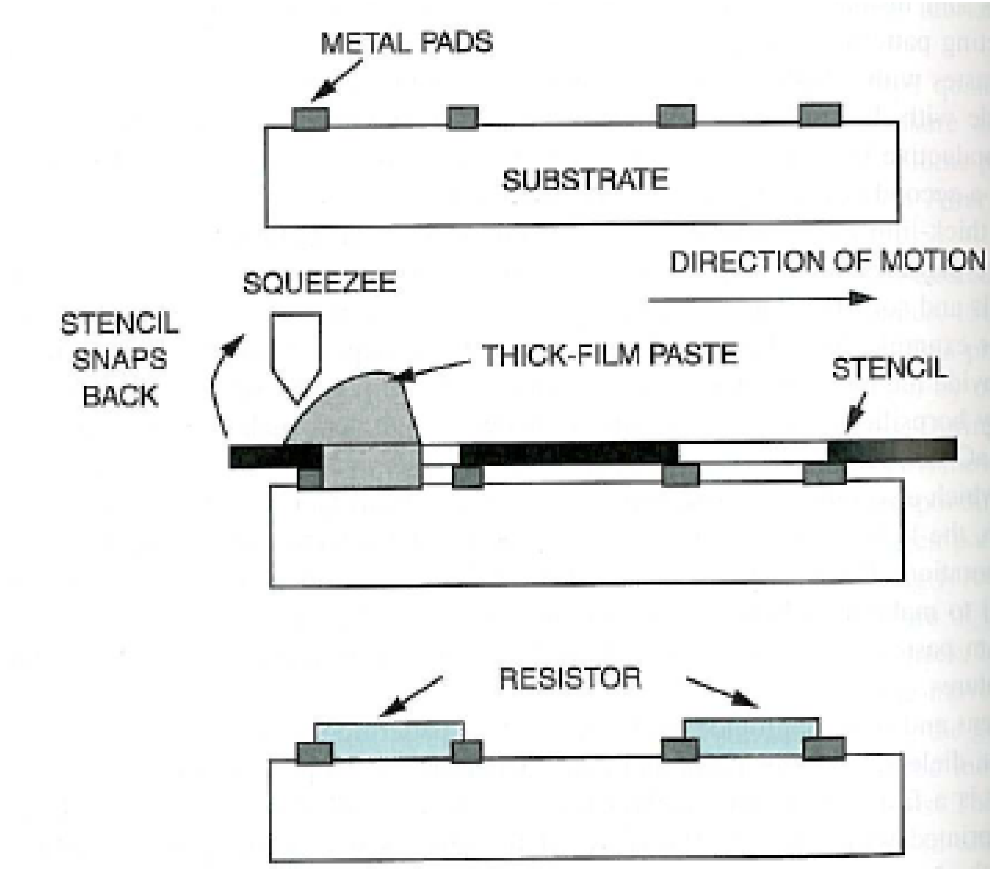
Chipsett - SP13 Tire pressure sensor (Sensonor)

Photo lithography

- The steps in photolithographic transfer of patterns and the subsequent etching of metal films with negative photo resist.
- If positive resist is used, it is the illuminated part of the photo resist, which is removed during the development.



Screen printing



Screen printing process for printing resistor between metal pads.

Etching

- Wet, chemical etching
- Dry plasma or reactive ion etching (RIE)

- Example – Define copper paths on a circuit board:

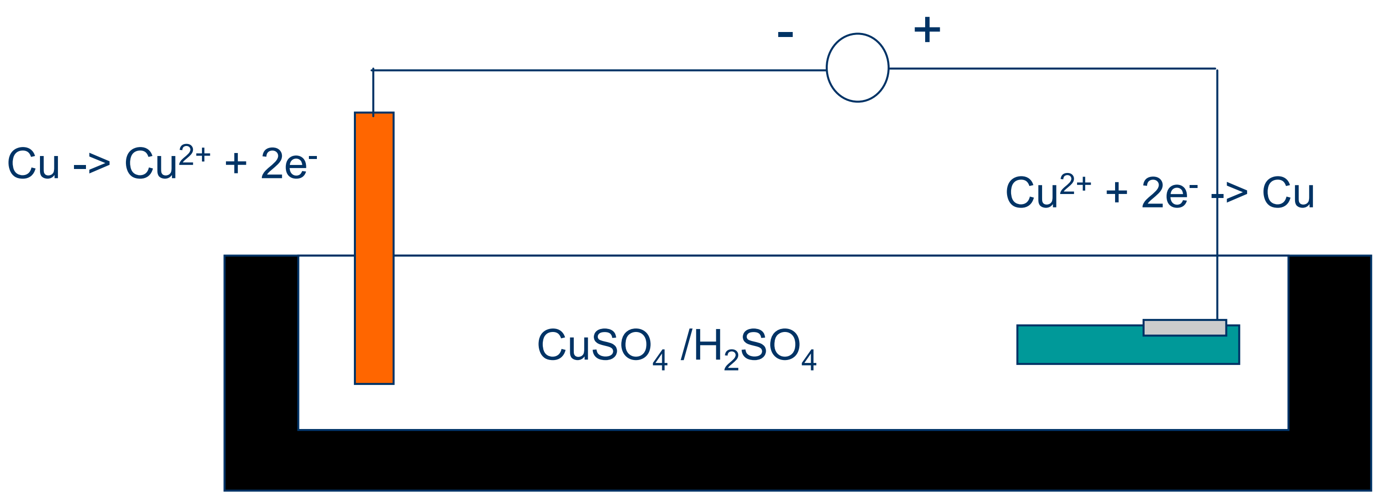
$FeCl_3 + Cu \text{ -> } FeCl_2 + CuCl$

In addition:
$FeCl_3 + CuCl \text{ -> } FeCl_2 + CuCl_2$

Organic films are not attached by ferric chloride, used as masking.

Plating

- Electroplating:
  - Electrical current through solution with ions. External voltage is needed. All areas to be plated must be in contact with external voltage.

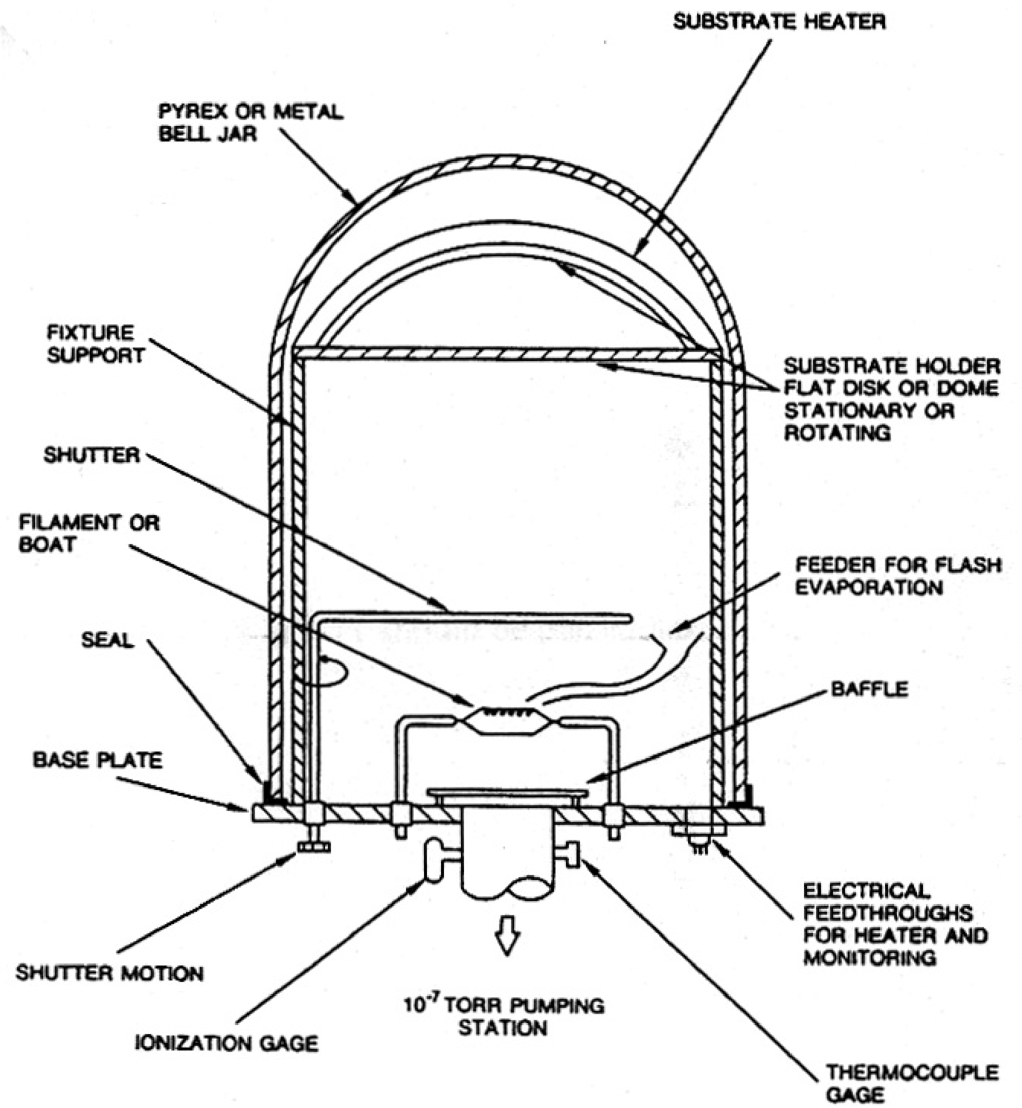


Plating

- Electroless or chemical plating
  - No external current/voltage
  - Must be utilized when plating non-conductive surfaces
  - Areas not to be plated is masked by photo resist.
  - Is often performed before electroplating to make all areas conductive.

Vacuum deposition/evaporation

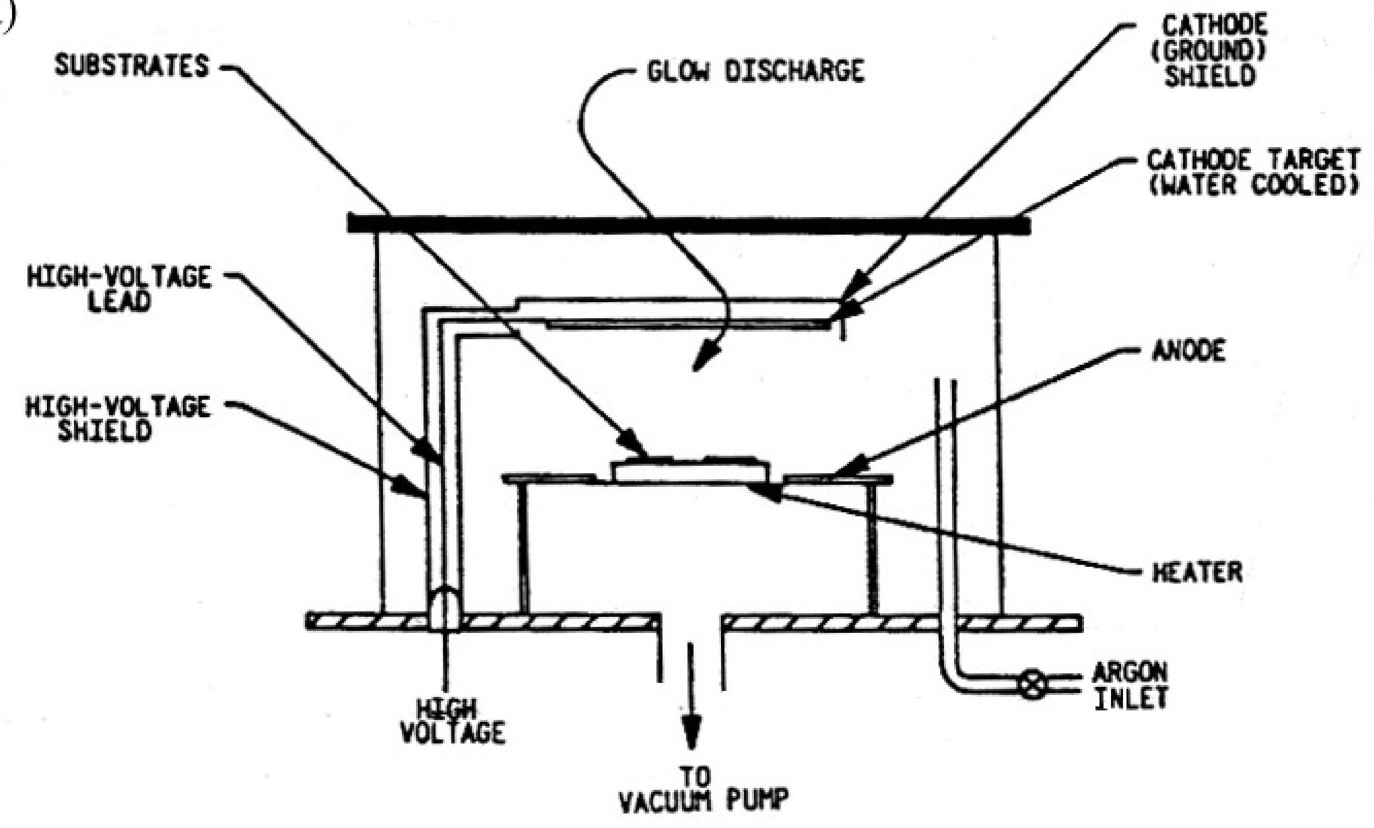
- Vacuum evaporation:
  - Chamber evacuated to less than 10^{-6} Torr
  - Resistance heating
  - Metal evaporation



Other methods for deposition of conductive or non-conductive films

- DC Sputtering

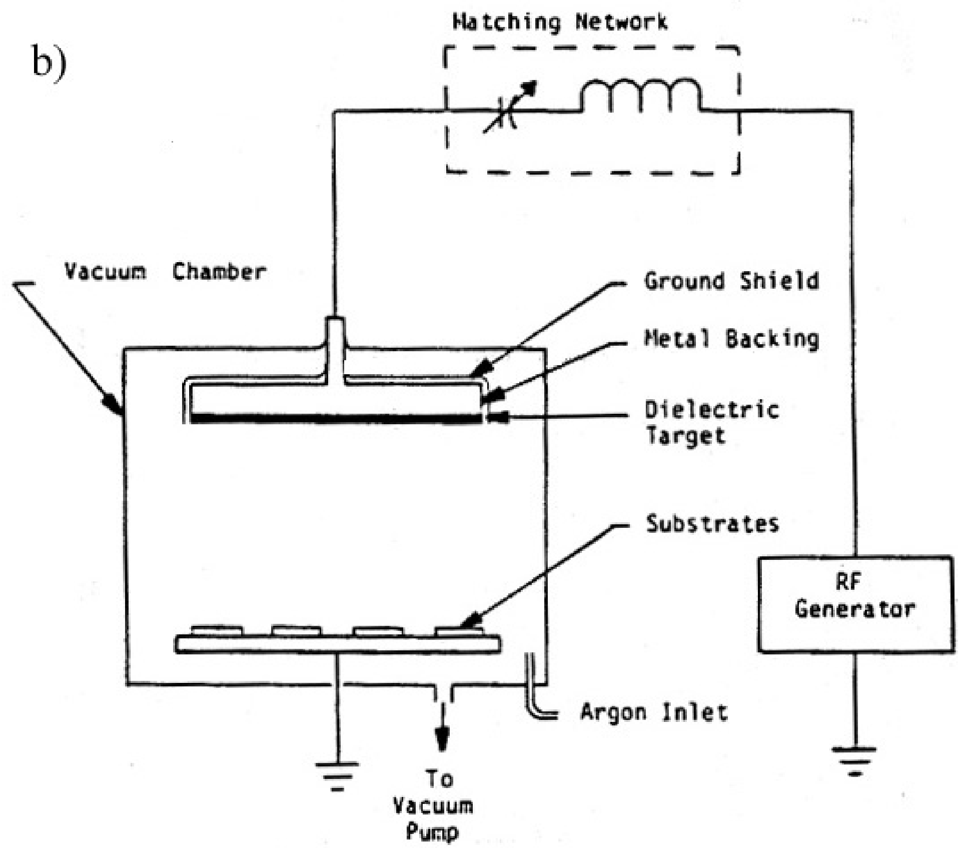
a)



Deposition (Cont)

Radio Frequency AC Sputtering

- RF necessary to avoid charging of non-conductive surfaces

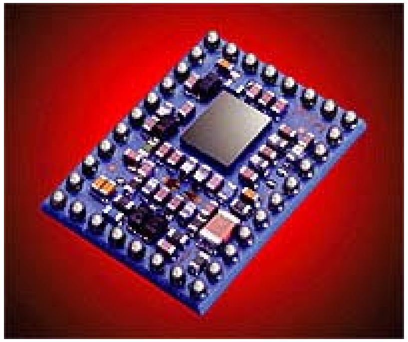


Methods for electrical and mechanical contact

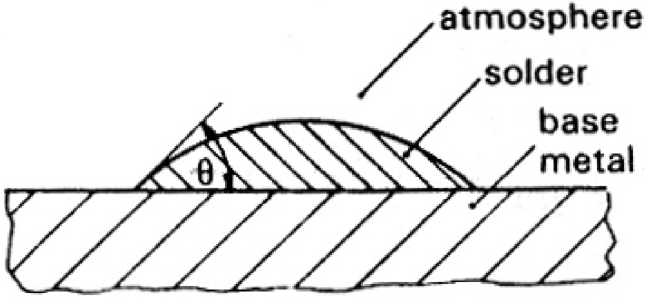
Soldering

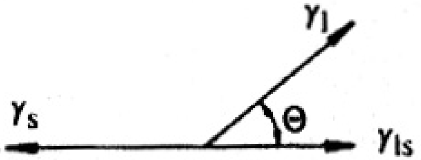
- Soldering: ”Create a metallic connection between two metal surfaces by applying a molten metal”.
- Wetting properties are important; the solder must wet the contact points, but not the area around.

Bluetooth tranciever Ericsson



Young´s equation: $\gamma_{ls} + \gamma_l \cos\Theta = \gamma_s$





$$\gamma_{ls} + \gamma_l \cos\Theta = \gamma_s$$

Soldering

Alloys

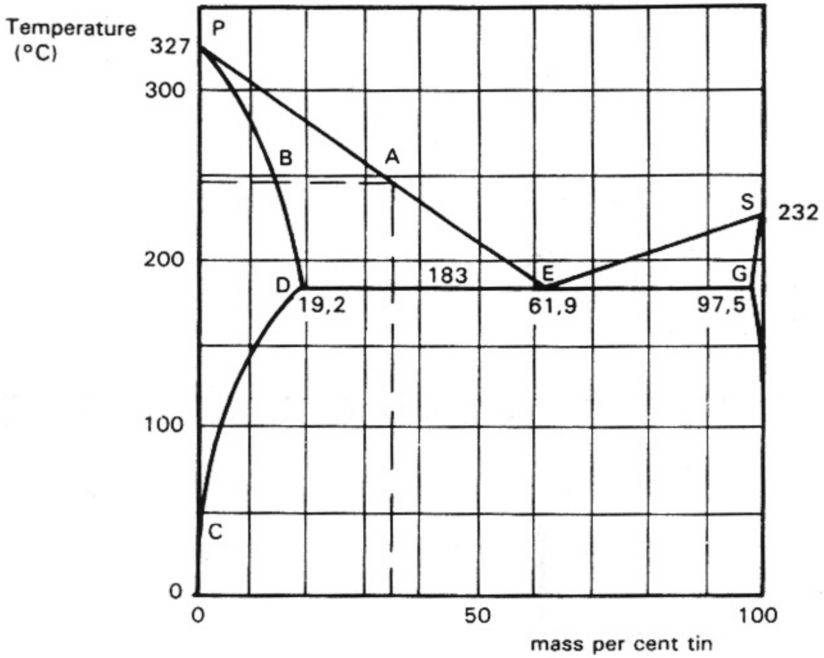
Table 3.7: Alloys for soft soldering [3.11]

Alloy System [mass%]						Code	Melting Temperature [°C]		Shear Strength at 1 mm min^{-1} [Nmm^{-2}]	
Sn	Pb	Ag	Sb	In	Bi		Solid	Liquid	20°C	100°C
100						Sn	232		22,1	19,0
63	37					Sn63	183	183	-	-
60	40					Sn60	183	188	33,6	21,6
50	50					Sn50	183	216	30,0	24,0
40	60					Sn40	183	234	34,3	13,7
10	90						275	302	28,9	14,7
5	95						310	314		
62	36	2				Sn62	179	179	43,0	18,6
10	88	2					268	299	-	-
5	93,5	1,5					296	301	23,8	15,7
96,5		3,5				Ag3,5	221	221	37,7	22,5
95			5			Sb5	236	243	37,2	21,1
	40			60		In60	174	185	-	-
	50			50		In50	180	209	-	-
37	37			25		In25	138	138	-	-
42					58	Bi58	139	139	50,0	19,5
15	33				52	Bi52	96	96	-	-
34	42				24	Bi24	100	146	34,3	17,5
43	43				14	Bi14	143	163	-	-

Soldering

Eutectic lead-tin

- Most commonly used solder up to 2006:
  63 % Sn / 37 % Pb (eutectic)
  Melting point: 183 ^{o}C



Phase diagram for 63Sn37Pb

Table 3.6: Properties of solder alloys 63 Sn:37 Pb or 60 Sn:40 Pb (weight %)

	Temp. [°C]	Value	Unit
Electrical resistivity, ρ	25 100	0.17 0.32	μOhm•m "
Thermal conductivity, °K	25 100	51 49	W/m°K "
Thermal coeff. of expansion, α		24.5	ppm/°C
Specific heat		46 000	J/kg°K
Modulus of elasticity, E	25	32 000	N/mm^2
Density, ρ		8.5	g/cm^3

Lead free solder

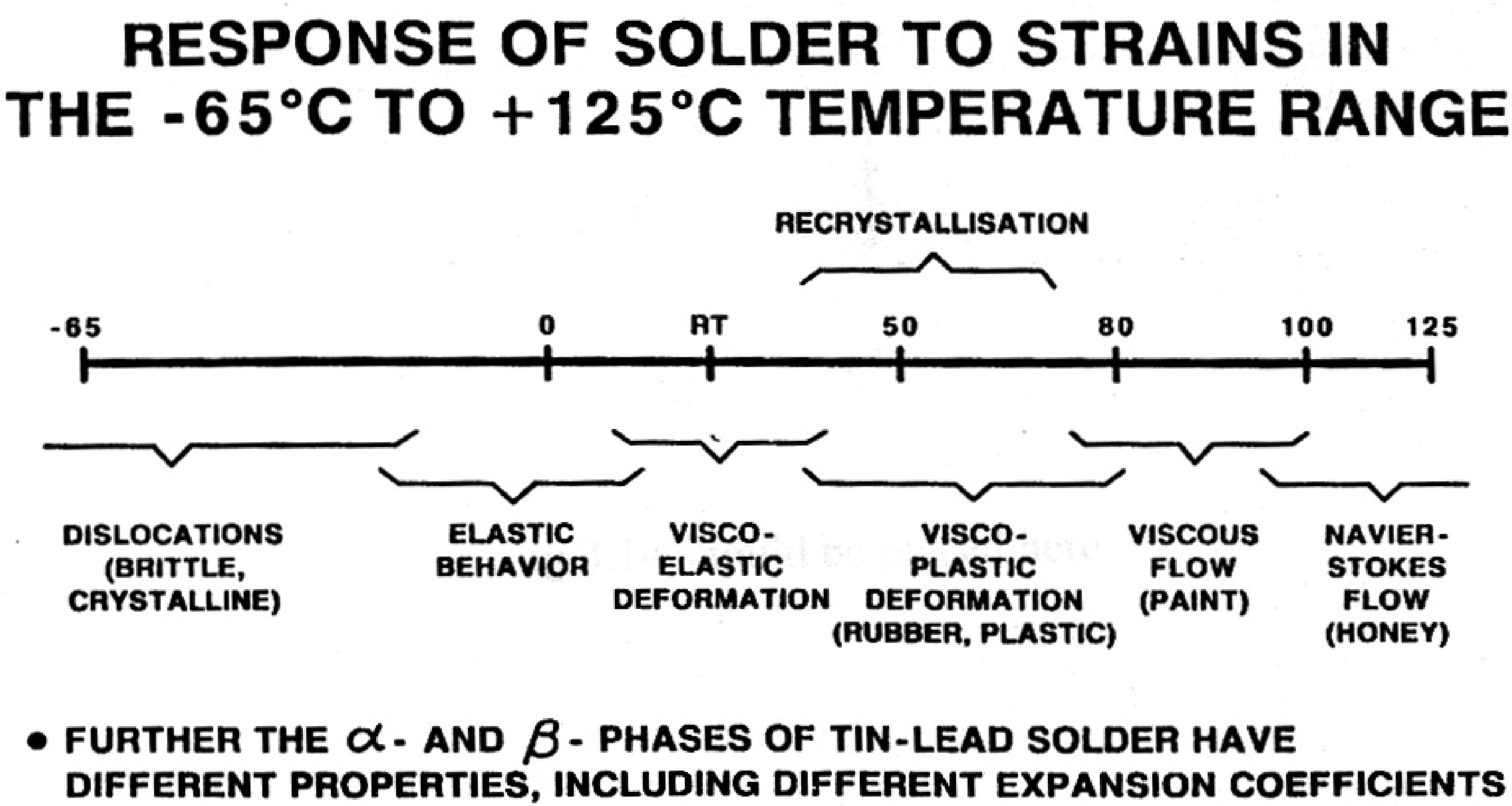
RoHS: Restriction of the use of certain Hazardous Substances in electrical and electronic equipment

- Transition to lead-free solder after the use of lead in electronics was heavily restricted by EU in 2006
- Tin-silver-copper (SAC) alloys are most commonly used for lead free soldering
  - Sn - 3.0Ag 0.5 - Cu = SAC 305
- Higher processing temperature compared to lead based solder
  - 240 - 260°C
  - Less experience and reliability data available

Tin whiskers: Occurs on components plated with pure Tin.
Have also been observed on SAC coated surfaces.

Soldering

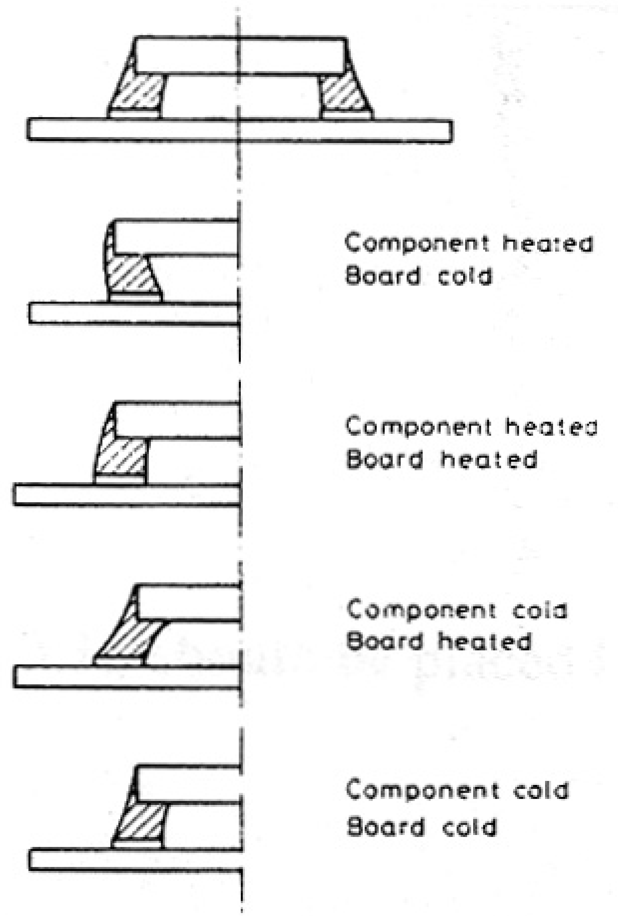
Temperature dependent properties



- Fig.3.15: Behaviour of solder metal at different temperatures, schematically. [W. Engelmaier].

Soldering

Thermal cycling gives rise to fatigue



- Fig. 3.16: Solder joint fatigue in surface mounted assemblies is often caused by power cycling.

Soldering

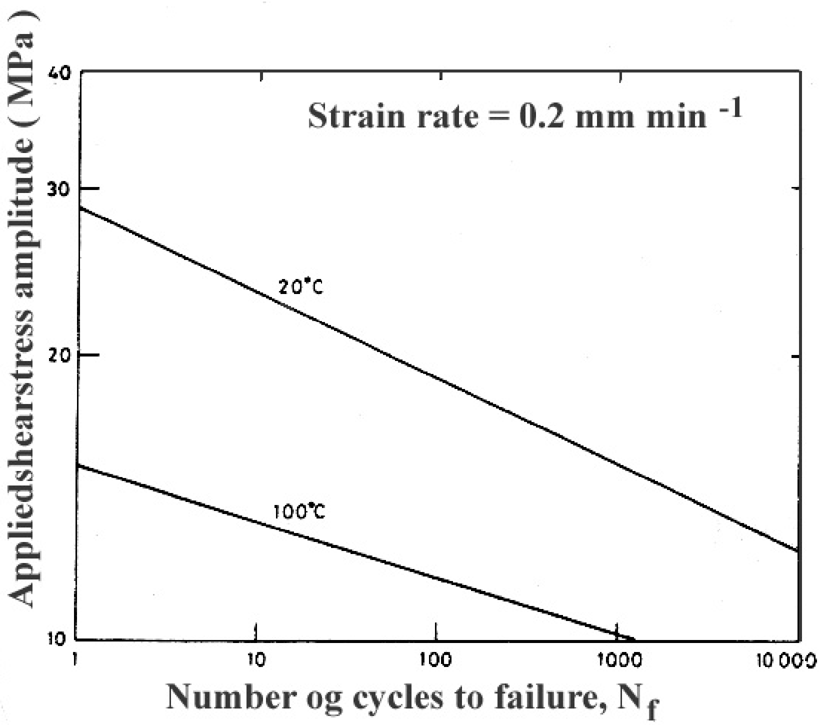
Coffin-Manson-equation

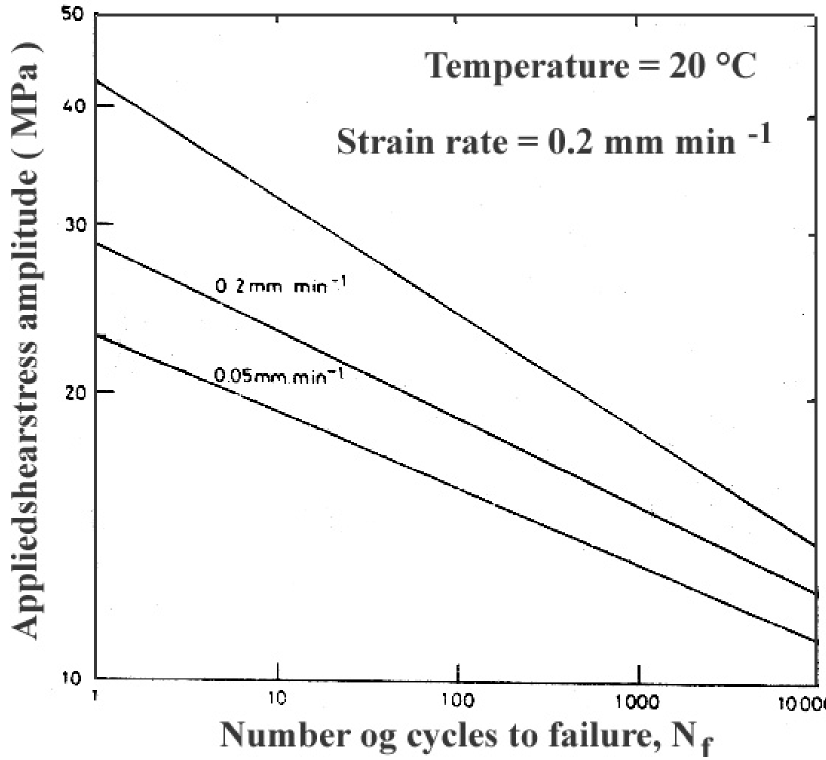
- Fatigue is important failure mode for soldered connections. Can give rise to intermittent failures.
- Coffin-Manson equation:

  $$N^{0.5} \times \gamma_p = \text{constant}$$

  where N is the number of stress cycles, γ_p is relative deformation amplitude.
- Note that both the number of cycles and the stress-level influence on the life time.

Effect of cyclic stress on life time

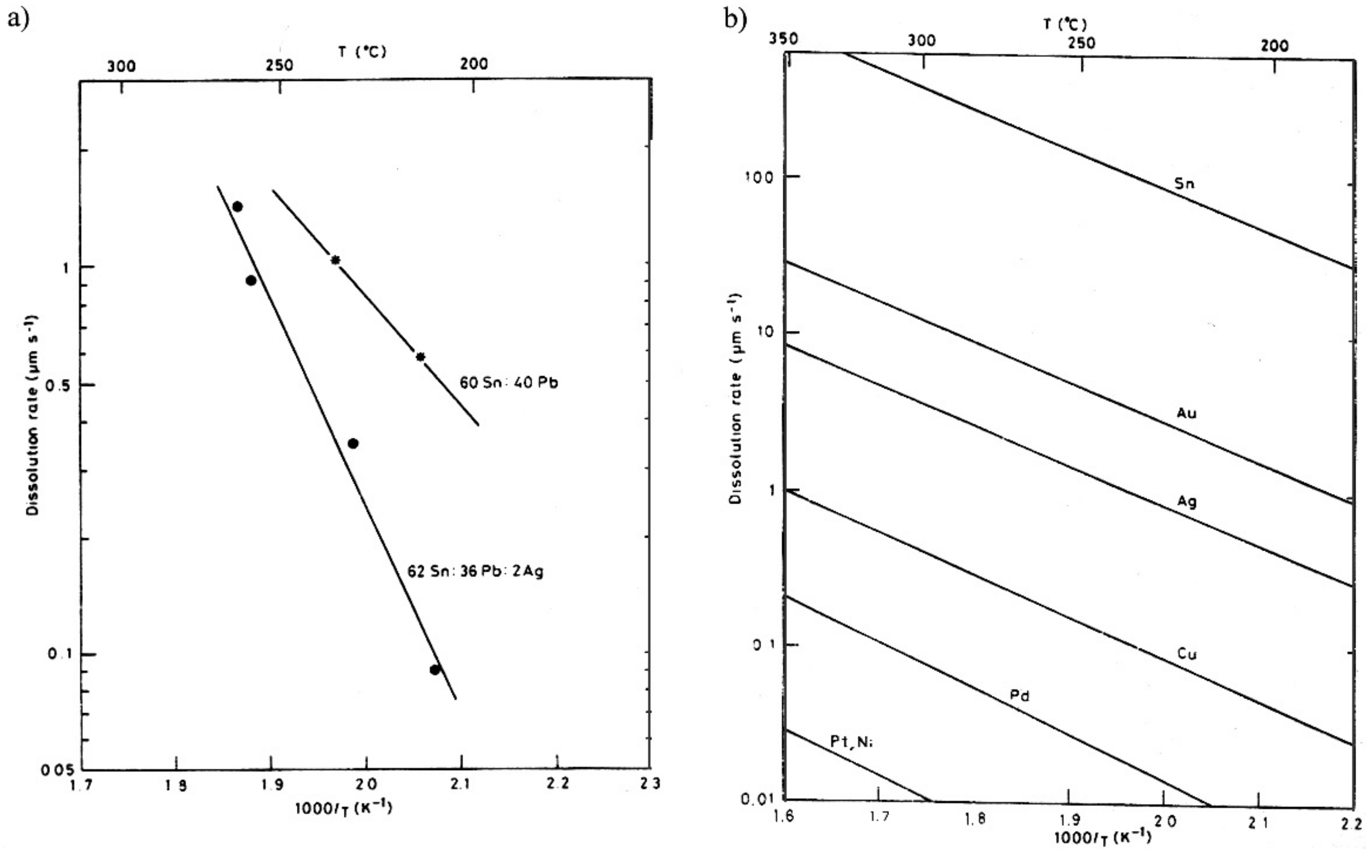




- Fig. 3.17: Experimental data for fatigue in Sn/Pb solder fillet by cyclical mechanical stress. High temperature and low cycling frequency gives the fastest failure, because the grain structure relaxes most and is damaged

Soldering

Contamination effects



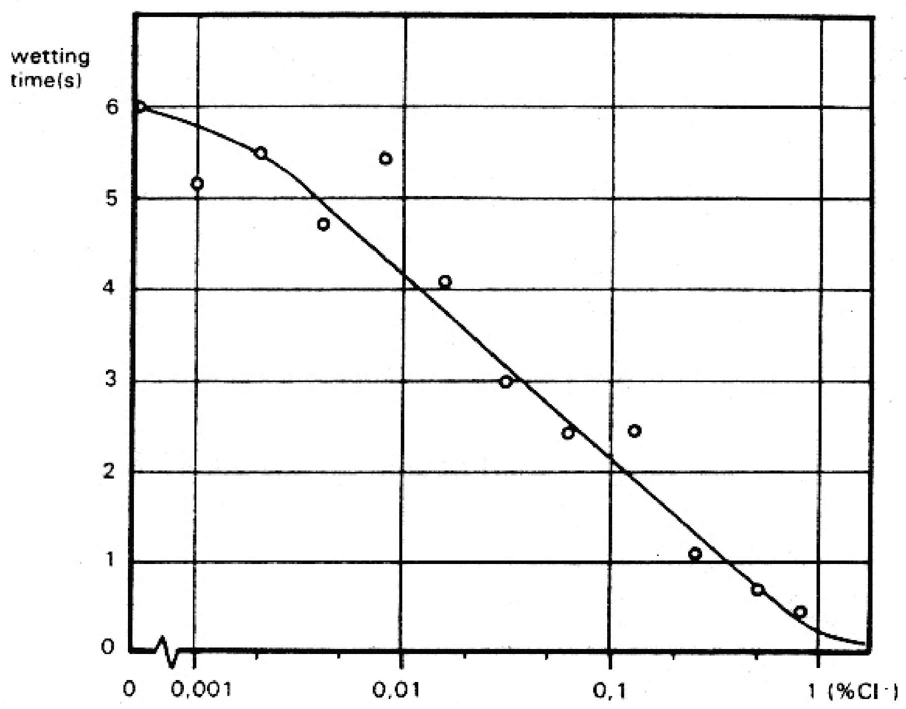
- Fig. 3.18. a) Left: Dissolution rate of Ag in solder metal, and in solder metal with 2 % Ag, as function of temperature
  b) Right: Dissolution rate of various metals in solder alloy

Flux and cleaning

- Flux
  - Dissolve and remove oxides on the surface.
  - Protect the surface
  - Improve wetting
  - Types:
    - Organic resin fluxes ("rosin")
      - R (Rosin, non-activated): No clorine added.
      - RMA (Rosin mildly activated): < 0.5 % Cl
      - RA (Rosin, activated): > 0.5 % Cl
    - Organic non resin based fluxes
    - Inorganic fluxes
- Cleaning
  - Freon (TCTFE) banned. Alcohol most commonly used. Trend towards no-cleaning

Soldering

Flux and wetting



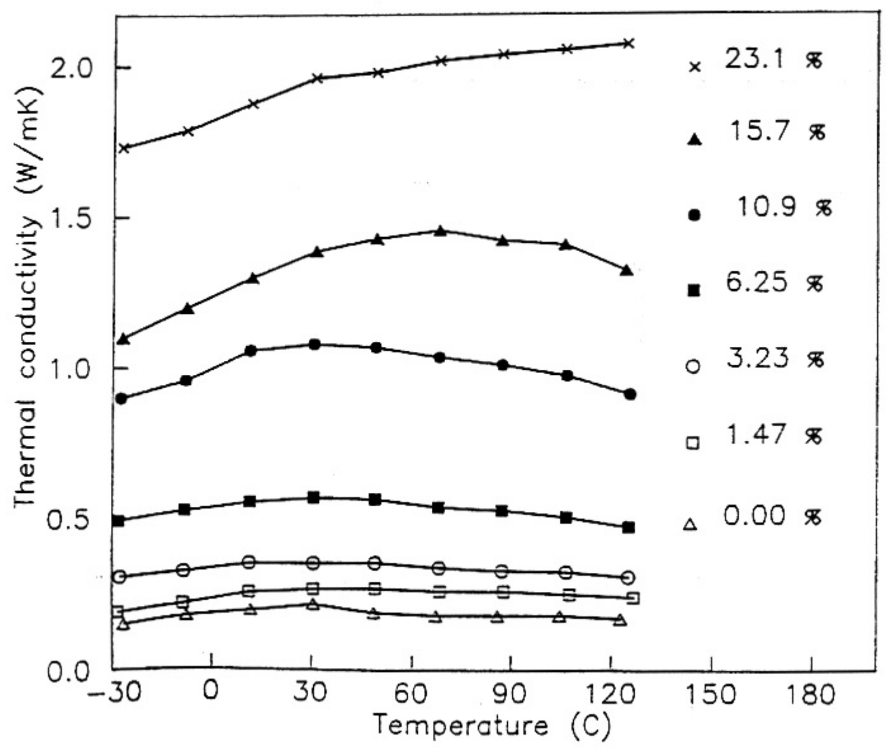
- Fig. 3.19: Time for solder alloy to wet a pure Cu surface, depending on the activation of the solder flux. The degree of activation is given by the concentration of Cl^- ions in the flux (temperature: 230 °C)

Adhesives in electronics

- Why?
  - Mechanical interconnect
  - Electrical interconnect
  - Thermal interconnect

- Adhesive matrix:
  - Epoxy, acrylic, phenolic, polyimide, glass
- Additives
  - Metal particles for conductivity
    $\rho = 1 - 10 \times 10^{-6}$ ohm m
  - Metal or ceramic particles for thermal conductivity:
    $\lambda \approx 1 - 3$ W /m x ^{o}C
  - Ceramic particles for matched thermal expansion

Thermal conductivity



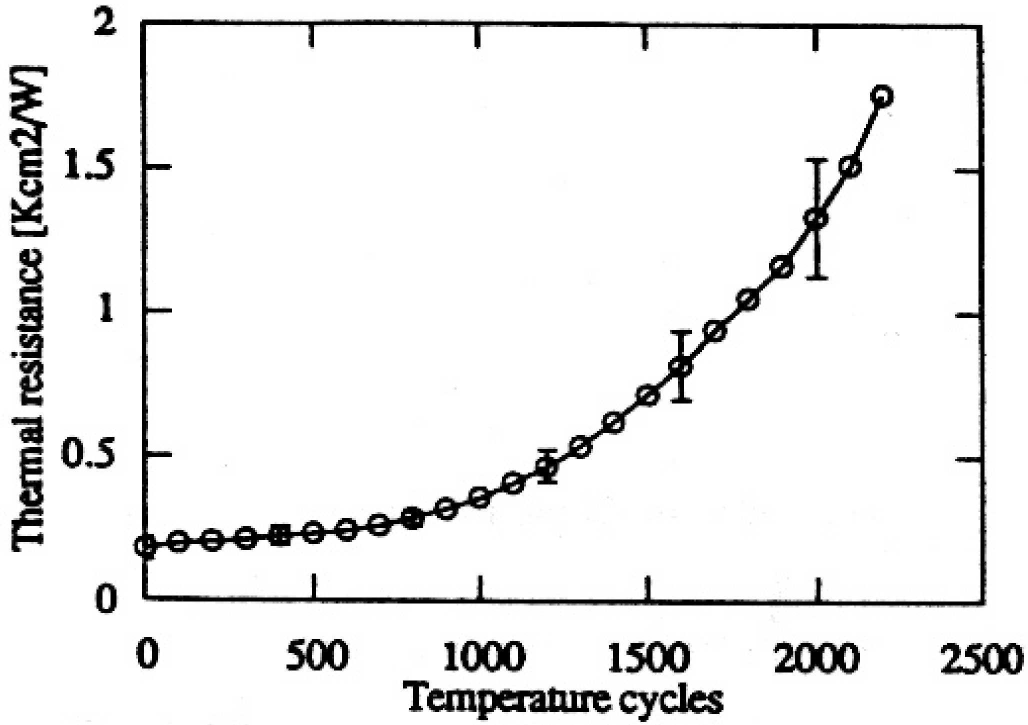
- Fig. 3.20: Thermal conductivity of epoxy adhesive with various amounts of Ag [3.16 a)]. The concentration is in volume % Ag. (23 vol. % corresponds to approximately 80 weight %).

Adhesives

Die-attach

Die attach methods:

- Eutectic die bonding:
  - Au/Si (363 ^{o}C), Au/Sn (280 ^{o}C)
- Soft soldering: Sn/Pb, Ag/Pb
- Gluing



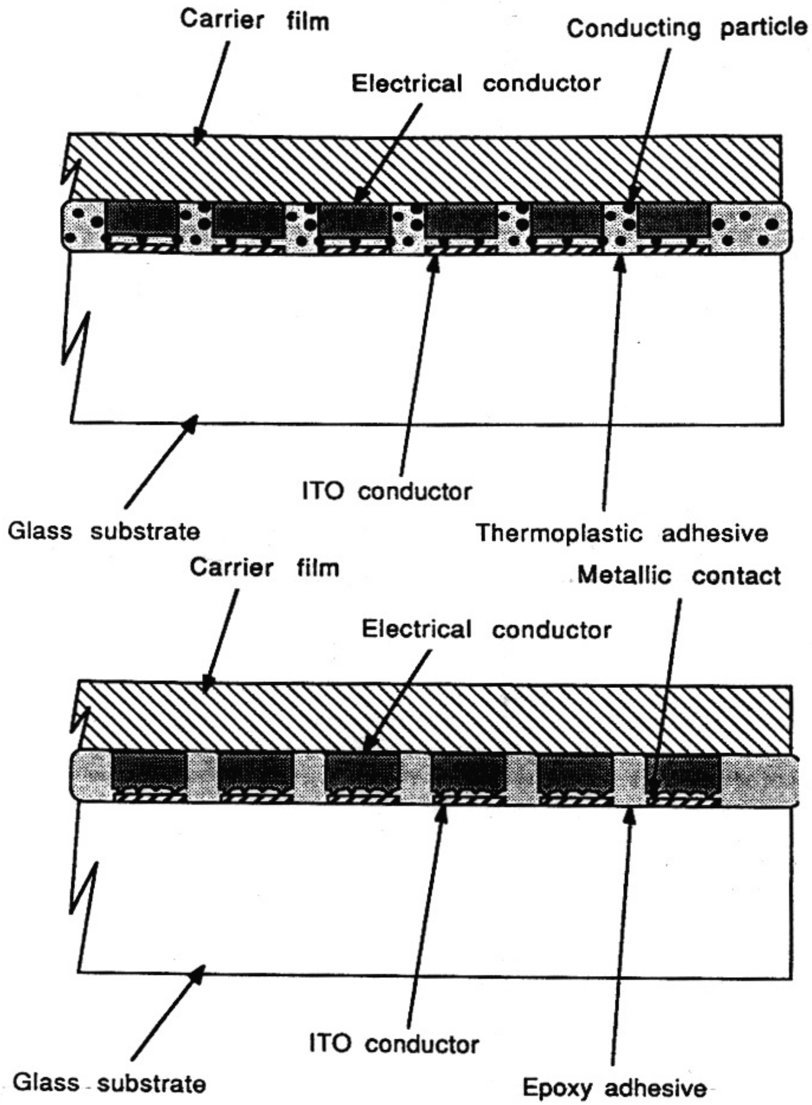
Adhesive cracking, fig. 3.23:
Thermal cycling induces defects giving increased thermal resistance.

Adhesives
Fine pitch interconnect

- Fig. 3.24: Use of adhesive for contacting IC-chips with small pitch, schematically:

  a): Anisotropic conductive adhesive, the conduction is through the metal particles in the adhesive;

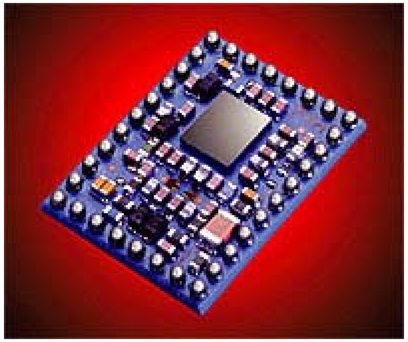
  b): Electrically insulating adhesive, the conduction is through point contacts where the adhesive has been squeezed out.



Electrical interconnect

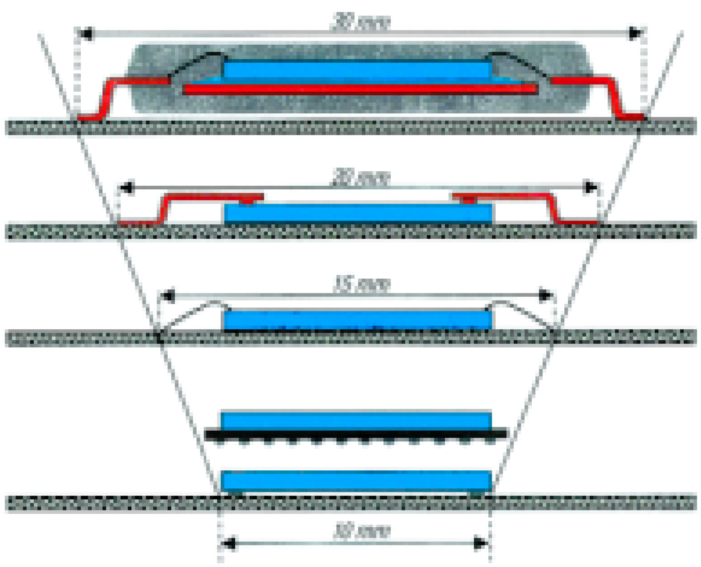
Miniaturization

Bluetooth transiver
Ericsson



- Increasing demand for miniaturization
  - Tape Automated Bonding
  - Chip on board (multichipmodul MCM)
  - Ball grid array (BGA)/ Chip scale package (CSP)
  - Flip chip

Comparison of Footprints



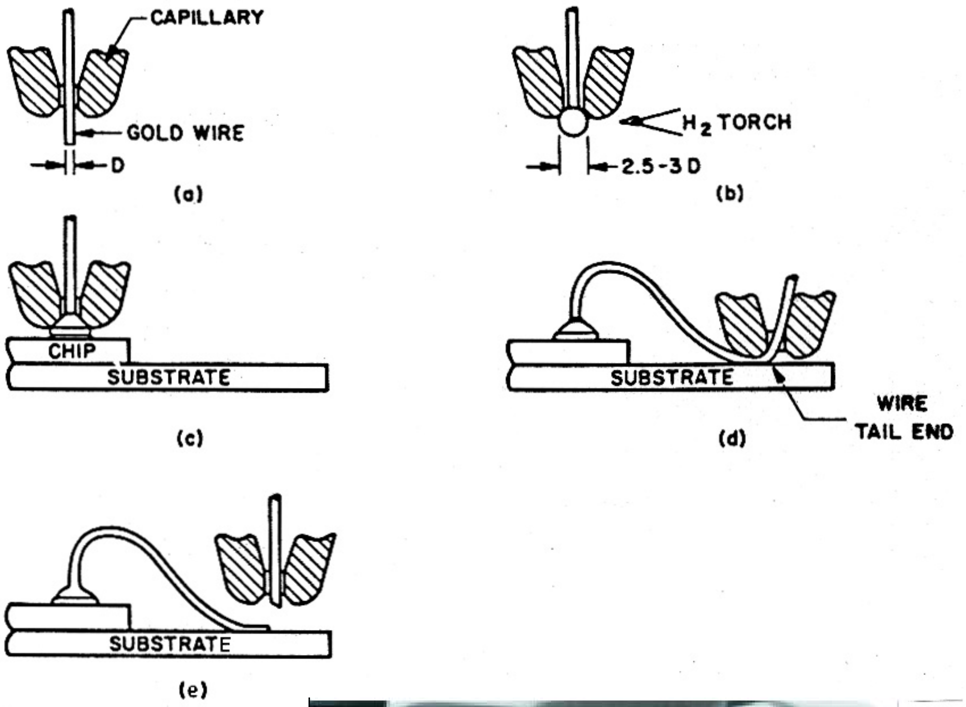
Package	PCB-Area
QFP	100 %
TAB	appr. 44 %
COB	appr. 25 %
FBGA/CSP	appr. 13 %
Flipchip	appr. 11 %

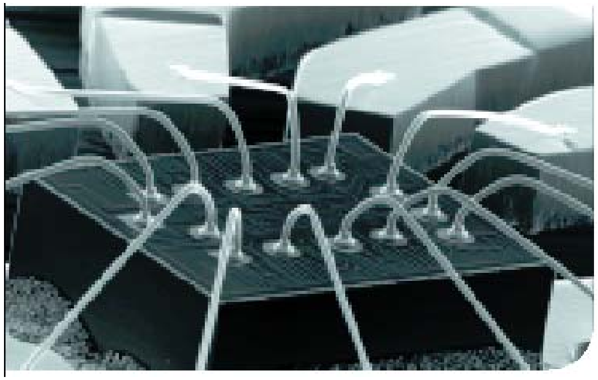
Electrical interconnect

Wire bonding

- Electrical contact from IC to substrate or package
  - Ultrasound
  - Thermo compression
  - Thermo sonic

- Geometries
  - Ball - wedge: Se illustration
  - Wedge - wedge



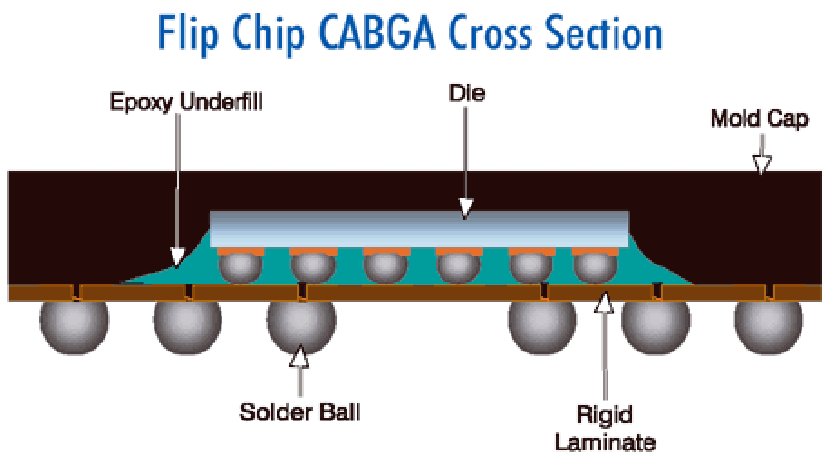


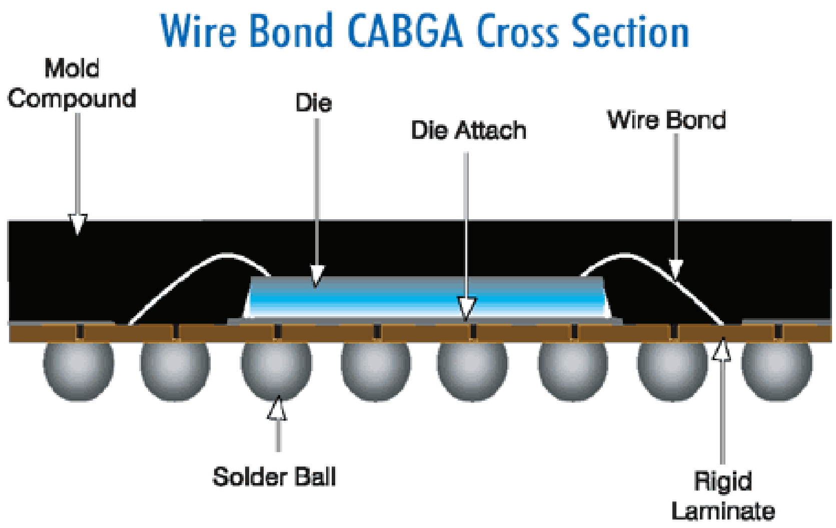
Ball-wedge wire bonding
SEM-image

Electrical interconnect

Ball Grid Array

- Comins flip-chip and package
- Easier to mount than on PCB than direct flip-chip
- Flexibility





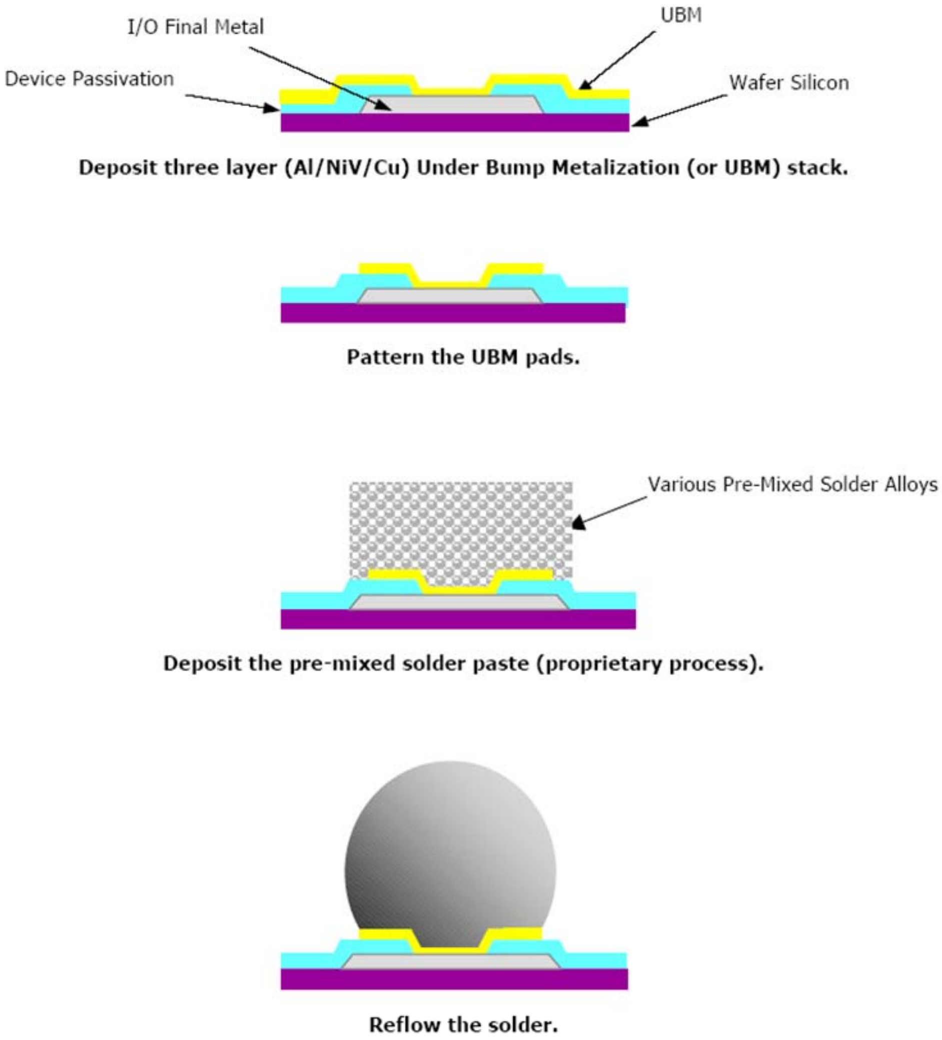
Electrical interconnect

Bumping for Flip Chip assembly

- Bumping directly on silicon wafer
- Small bumps (< 135 µm)
- Minimum pitch ~ 150 µm

- There are alternative processes were pre-shaped solder balls are placed on the wafer

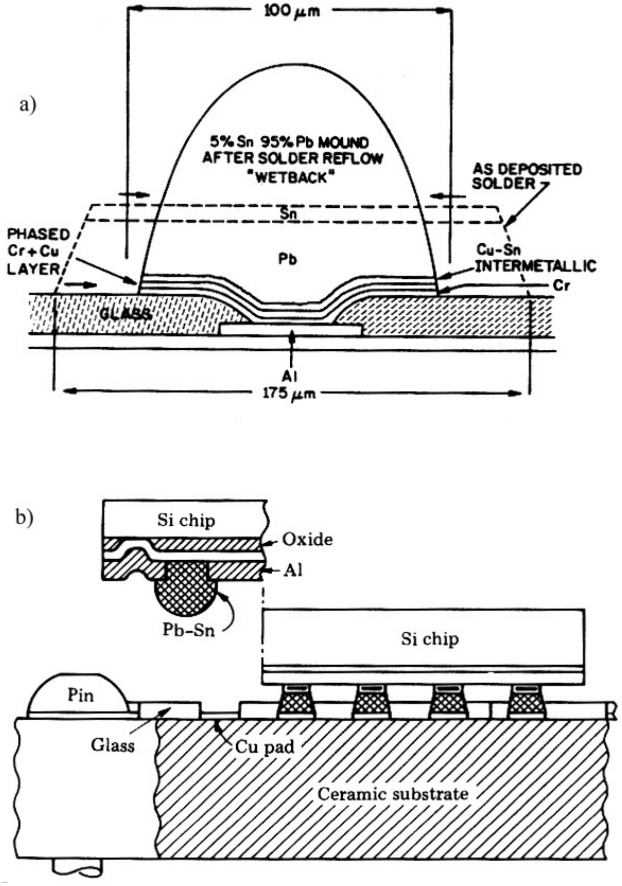
FlipChip International
Flex-on-Cap (Standard Flip Chip)



Electrical interconnect

Flip Chip

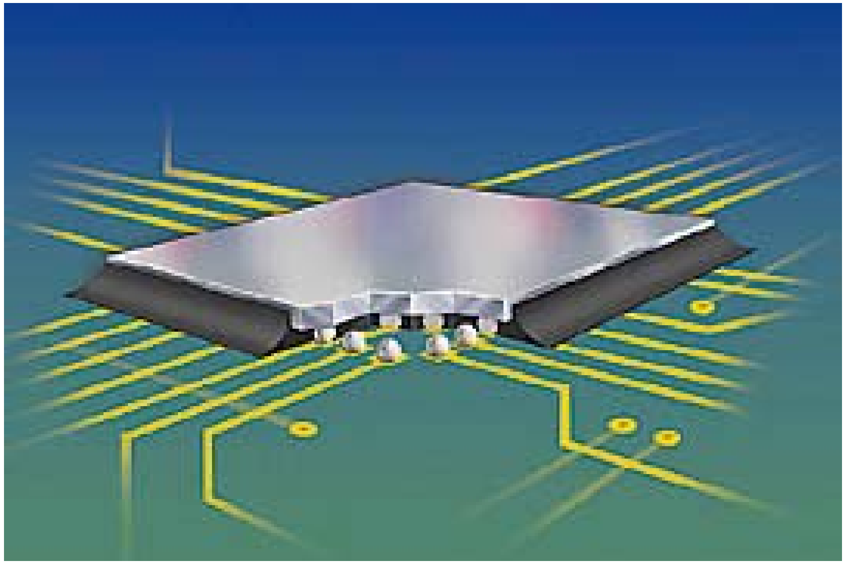
- Process:
  - Deposit barrier metal
  - Deposit solder alloy by photo lithography, printing or sputtering + plating
  - Reflow --> sphere shaped bump
  - Wafer dicing
  - Chipe is mounted on substrate
  - Heat substrate to melt the solder



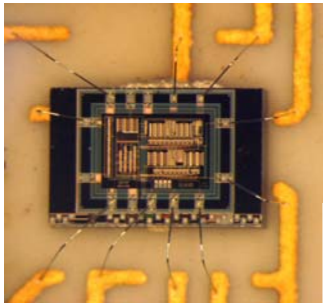
Electrical interconnect

Flip Chip

- Advantages:
  - Highest packaging density
  - Best high frequency properties
  - Up to 10 000 I/O
- Disadvantages:
  - Demanding assembly procedure
  - Little thermal flexibility
  - No repair possibilities

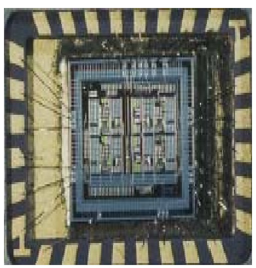
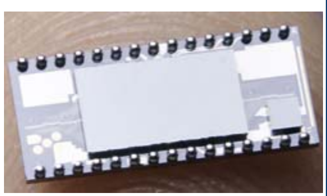


Summary - Chip attach

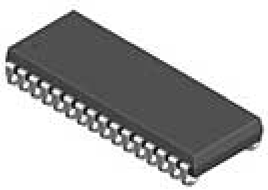
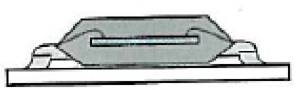
Packaging level	Function	Materials	Processes	Properties
Single chip Die attach 	■ **Mechanical attachment** ■ **Electrical Interconnection** ■ **Heat dissipation** ■ **Reliability**	■ **Conductive adhesives** ■ **non-conductive adhesives** ■ **Lead free solder** ■ **PbSn solder** ■ **AuSn solder**	■ **dispensing** ■ **curing** ■ **solder printing** ■ **reflow**	■ **Thermal conductivity** ■ **Electrical conductivity** ■ **CTE** ■ **Mechanical strength** ■ **moisture absorption**

CTE = Coefficient of Thermal Expansion

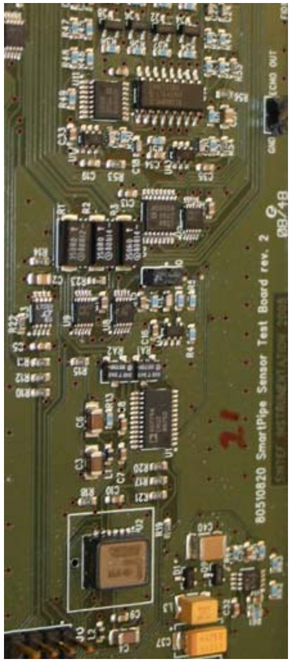
Summary - Chip interconnect

Packaging level	Function	Materials	Processes	Properties
Single chip Interconnect  	■**Electrical Interconnection** ■ **I/O density (pitch)**	■**Cu, Al or Au** ■ **Lead free solder (SnAgCu)** ■ **Conductive adhesive – epoxy with metal filler**	■ **wire-bonding** ■ **Flip – chip bonding** ■ **plating** ■ **printing** ■ **reflow** ■ **dispensing** ■ **curing**	■ **Electrical conductivity** ■ **Fatigue** ■ **Creep** ■ **Metal interdiffusion** ■ **Electromigration** ■ **CTE** ■ **moisture absorption**

Summary - Encapsulation

Packaging level	Function	Materials	Processes	Properties
Encapsulation   	■ **Protection**	■ **Polymer materials** ■ **Epoxy + filler** ■ **Ceramics** ■ **Metals** ■ **solder glass**	■ **Compression molding** ■ **Dry pressing** ■ **Glass sealing** ■ **welding**	■ **CTE** ■ **moisture absorption** ■ **Thermal conductivity** ■ **Temperature range**

Summary - Board assembly

Packaging level	Function	Materials	Processes	Properties
Board assembly 	■ **wiring** ■ **signal speed** ■ **Electrical connection**	■ **Glass-epoxy FR4** ■ **Polyimide** ■ **Electroplated copper** ■ **Lead-free solders** ■ **Conductive adhesives**	■ **Lamination** ■ **Electroplating** ■ **Photo lithography** ■ **Wave soldering** ■ **Reflow** ■ **Curing**	■ **Permittivity** ■ **Dielectric loss** ■ **Elastic modulus** ■ **CTE** ■ **Glass transition temperature** ■ **Temperature range** ■ **Moisture absorption**