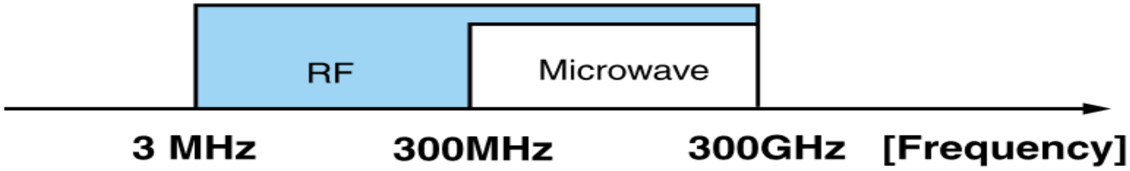
RADIO FREQUENCY

RF

- Radio Frequency (3 kHz – 300 GHz)

  Wavelengths of 1 mm – 30 cm



Base-mobile communication is standard

VHF: Very High Frequency [30 – 300 MHz]
UHF: Ultra High Frequency [300 – 3000 MHz]
SHF: Super High Frequency [3 – 30 GHz]
EHF: Extremely High Frequency [30 – 300 GHz]

Anatomy of RF Systems

- Transceiver
- Repeater
- Duplexer

Anatomy of RF Systems

- Transmission Quality
  - Dedicated frequency to minimize interference
  - Adequate power to ensure high S/N ratio
  - Sufficient bandwidth for high Voice quality
  - FM operation to minimize noise problems
- Service Quality
  - Accessibility and Usability
- Cell Phone Example
  - RF Transceiver → Low-pass Filter → Power Amplifier → A/D Converter → D/A Converter → Local oscillator → Antenna

Anatomy of RF Systems

- High quality filtering requirements
  - Low-pass (noise removal)
  - Processing performed at Intermediate Frequency
  - DSP is used in most modern cellular phones
    - Reprogrammable, fast, low power consumption

Fundamentals of RF

- **Radio Wave**

  Radiation and propagation of Waves (dropping stone info pool)

  Transverse Wave (Wave occurs in directions perpendicular to propagation)

- **Frequency**

  Number of cycles per second

Fundamentals of RF

- Audio Frequencies

  Range: 15 Hz – 20 kHz

  Devine by limits of human aural ability
- Radio Frequencies

  Range: 3 kHz – 300 GHz

  Largely used in radio transmission
- Wavelength

  Space occupied by one full cycle of a Wave at any time

  Wavelengths reduced at high Frequencies
    - Passive component size comes into play

Fundamentals of RF

- **Velocity**

  Speed of signal propagation through substrate

  Affected by

    - Barometric pressure
    - Humidity
    - Molecular content
    - Density

  Unaffected by Frequency

- **Filters**

Fundamentals of RF

- **Antenna**

  Interfaces RF systems with rest of world

  Radiated power is a function of distance

  - Power density decreases by $1/r^2$ in all directions

  Conductor and dielectric losses also are considerations

  Gain and directivity (uni/onmi-directional)

- Radiation pattern,gain, impedance matching, bandwidth, size and cost are some of the parameter

Fundamentals of RF

- **Bandwidth**
  - Affect performance of communications system
  - Ideal resonant circuit only resonates at one frequency
  - Circuit ‘quality’ affects resonance
  - Width of frequency band centered around the resonant frequency is the ‘bandwidth’
- **Noise**
  - Affect accurate reproduction of transmissions
  - Receivers must have bandpass response to limit noise

Fundamentals of RF

- External Noise
  - Generated outside of the receiver
  - Caused by atmospheric conditions, space, solar, cosmetic-noise, lighting
- Man-Made Noise
  - EMI traceable to non-natural sources
  - Ignition and impulse noise, which originates from car engines and electrical appliances

Fundamentals of RF

- **Internal Noise**

  Caused by passive/active devices inside a receiver

  Thermal Noise

    - Generated in resistances or impedances

  Shot Noise

    - Generated by the shot effect present in all active devices

- **Noise Evaluation**

  Signal/noise ratio

    - Radio of signal power to noise power
    - Higher is better for improved sound quality

RF Components and Devices

- Active, resistive, and reactive components
- Passive RF components have parasitics at raised frequencies
  - Used primarily for building filters and oscillators
- Microwave Discrete Circuits (MDCs)
  - Separate elements connected by conductive wires
  - Means ‘separately discrete’
- Microwave Monolithic Integrated Circuits (MMICs)
  - Single integrated circuit of all components
  - ‘monolithic’ comes from *monos* (meaning single) and ‘lithos’ (meaning stone)

RF Components and Devices

- Microwave Integrated Circuits (MICs)

  Combination of active/passive elements manufactured by successive diffusion processes on a semiconductor in monolithic or hybrid form

  Very high integration densities

  Very useful in low-power and low-density systems such as digital circuits and military applications

Noise Evaluation

- Signal to Noise Ratio

  Ratio of Signal Power to Noise Power

$$S/N = \frac{\text{signal power}}{\text{noise power}} = \frac{P_s}{P_n}$$

$$S/N = 10 \cdot \log\left(\frac{P_s}{P_n}\right)$$

RF Circuits

- Passive RF components exhibit parasitics at higher frequencies

  Inductors have stray capacitance

  Capacitors have stray inductance

Fundamentals of RF Transmission Lines

- Wave propagation in a transmission line:

  Voltage and Current assume spatial and temporal variations described by the propagating waves

  Parameters of interest:

  - Propagation velocity
  - Wavelength

Fundamentals of RF Transmission Lines

- Uniform Transmission Lines

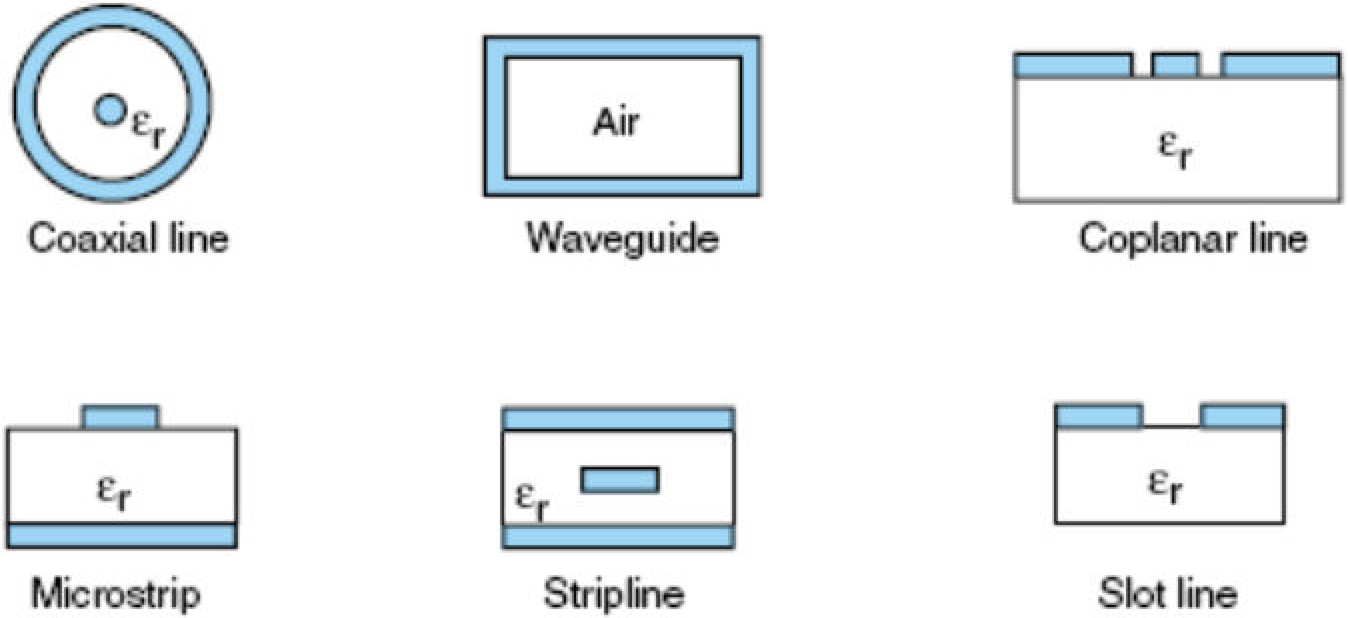
  Include two or more conductors that maintain the same cross-sectional dimensions

  - Coaxial line
  - Two-wire (twin lead) line
- Planar Transmission Lines

  Conductors lie on flat dielectric sheets

  - Microstrip
  - Slot-line
  - Fin-line

Fundamentals of RF Transmission Lines



Reflection

- Any mismatch in impedance will generate a reflection
- From a packaging standpoint, reflections are unwanted
  - Reflections cause non-optimized transfer of power
  - ‘Good’ designs terminate the transmission line with an impedance equal to the line wave impedance

Crosstalk Noise

- Crosstalk Noise occurs as a result of coupling energy between two transmission lines
  - Result of capacitive and inductive coupling between lines
  - Generates unwanted signals in transmission lines resulting in false and corrupted information
- Coupling is proportional to the time rate of change of signals → more serious at higher frequencies
- Present-day high frequency designs require more compactness that compounds noise coupling problems
- Mixed-signal analog/digital circuits on the same substrate are susceptible to crosstalk noise from digital to analog sections
- System-on-chip (SOC) or system-on-package (SOP) designs must have crosstalk noise solution in place to be viable

Transmission Line Losses and Skin Effect

- 3 major types of losses that commonly occur in practical transmission lines:
  - Conductor loss
  - Dielectric loss
  - Radiation loss

Conductor Loss

- I^2R power dissipation due to heating that occurs in the pure resistance of the conductor
- Copper loss is usually greater in a line having a low characteristic impedance

  Lower-impedance → higher current = higher power dissipation (I^2R)
- Reduced current in a high-impedance line results in reduced copper loss without causing a reduction in transmitted power

Skin Effect

- A type of conductor lossAs frequency of applied current is increased, more of the electron flow is on the surface (skin) of the conductor

$$\delta_s = 10^3 \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu_0}}$$

$\rho = \text{resistivity of the metal in ohm cm} \cdot \times 10^6$

$f = \text{frequency in Hertz}$

$\mu_0 = \text{permeability}, 1.26 \times 10^{-8}\ \text{H/cm}$

Dielectric Loss

- I^2R power dissipation due to heating that occurs in the dielectric between conductors in a transmission line
- Proportional to the voltage across the dielectric

  Standing waves of voltage on a line increase dielectric loss
- Dielectric material stores energy in the form of electric charge
- Naturally polarized dipoles realign by rotating in direction of applied field
- Rotation causes part of electrical energy to be converted into heat (lost)

Dielectric Loss

- Lost energy in a dielectric may be characterized by its Dielectric Loss Tangent:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

$$\varepsilon'' = \text{lost energy (out-of-phase component)}$$

$$\varepsilon' = \text{stored energy (in-phase component)}$$

Radiation Loss

- Radiation from circuit increases rapidly with frequency
- Confining the fields to the interior of metallic enclosures (packaging/shielding) may prevent radiative power loss

Mode Generation

- Generated by discontinuities, unmatched terminations, and controlled by type of feeding
- Single-mode propagation is desired for higher bandwidth and optimum power transfer
- Three types of modes:

TEM: Transverse-electromagnetic modes

  - Often called transmission line modes
  - Transmission lines that have at least two separate conductors and a homogeneous dielectric can support one TEM mode

Quasi-TEM Modes

  - Inhomogeneous dielectric such as microstrip transmission line
  - Propagation characteristics exhibit a slight dependence with frequency when compared with TEM

Waveguide Modes

  - Can transport energy or information only when operated above distinct cutoff frequencies.
  - One of the most important aspects in the RF packaging design since any package operates as a waveguiding structure

Dispersion

- If phase velocity is different for different frequencies → individual frequency components will not maintain their original phase relationships

  Signal distortion will occur.This is Dispersion

Microwave Fundamentals

- Microwave frequencies range from approximately 1 GHz to 300 GHz
  - Travel essentially straight through atmosphere
  - Not effected by ionized layers of the atmosphere
  - Used for short-range, high-reliability radio and television links
  - Commonly used for satellite communication and control

Microwave Repeaters

- A Microwave Repeater is a receiver/amplifier/transmitter combination used for relaying signals at microwave frequencies
- Used in long distance, overland communication links

Waveguides

- Used to carry microwave energy at frequencies above 3 GHz
- Redline used at microwave frequencies
- Waveguide wall resistance is made as low as possible
- Are often purged with dry air or nitrogen to drive moisture from inside
- Attractive option because of wide-bandwidth and low-loss transmission characteristics

Digital vs. RF Packaging

- By contrast with digital designs, RF interconnects scale with frequency rather than technology (not directly subject to Moore’s Law)
- RF packaging is dominated by transmission lines and reactive elements
- Successful implementation of RF systems requires a departure from conventional circuit theory and design techniques

RF Packaging Design

- Problems that may arise include:
  - Rise-time degradation
  - Attenuation due to losses
  - Coupling between adjacent pins
  - Radiation of signals
- Major task: determine electrical parameters of the package at microwave frequency
  - Lumped model consisting of inductors, capacitors, and possibly resistors represents the package at RF frequencies

Flip Chip

- Flip chip has emerged as one of the most successful packaging technologies. Being used for RF systems where parasitic minimization is essential.Using ball arrays minimizes parasitic inductance

Passive and Microwave Components

- Many components such as band select, channel select, and tuning elements of the Voltage Controlled Oscillator VCO must still remain external to the chip
  - Inductors with high quality factors are not available in standard silicone processes
- Development of the following items will be a major step toward low-cost, fully-monolithic RF and microwave transceivers:
  - Better active device models
  - Active inductors
  - MEMS filter building blocks

RF Measurement Techniques

- RF components, devices and systems are measured using high frequency network analyzers
- Measurements involve extraction of scattering parameters (S parameters)
  - Describe interactions between incident and reflected waves from device under test
- Modern network analyzers cover frequency range up to 110 GHz

BOARD SYSTEM ASSEMBLY

Introduction

- Process of building functional electronic systems from individual components
- Mounting components to a PWB and soldering leads to the board

PWB Assembly

- Building systems from components
  - Provides for heat dissipation
  - Introduced around 1950’s with semiconductor tech.
- Through-hole to surface mount assembly (SMA)
  - SMA accounted for 80% of assembly in 1990’s
  - Size reduction, easier automated assembly

Surface Mount Technology

SMA: Surface Mount **T**echnology

SMD: Surface Mount **D**evice

SMT: Surface Mount **T**echnology

PWB: Printed Wiring **B**oard

PWA: Printed Wiring Board **A**ssembly

- Stencil-printing solder paste, placing, and heating
- Glue mounting and wave soldering

Reserved for both through-hole and SMT

Solder-Paste Printing

- Screen-printing is old technology
  - Holes are too small for SMT
- Use stencils.
  - Solder pushed through brass sheets with holes
  - Smaller holes than screens
  - Improved precision
  - Squeegee pressure is important – too much wears the squeegee down quickly

Stencils

- Ni, Ni-plated brass, stainless steel, or plastic
  - Bare Cu or brass are less used (probably due to corrosion and oxidation)
  - Example of Ni-plated brass casings

Brass vs. Ni-plated Brass

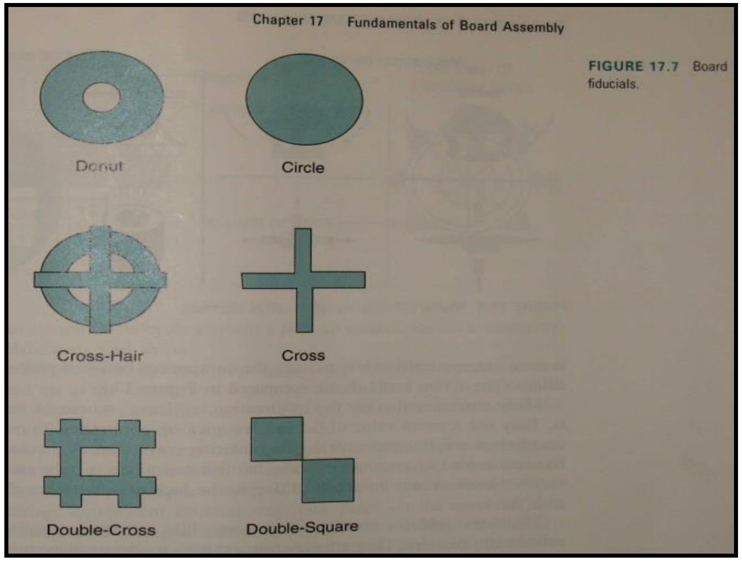
Property	**Brass**	**Ni-Plating**
Composition	62% Cu, 35% Zn, 3% Pb	~99% Ni
Hardness	B-70	B-100
Wear Resistance	Moderate	High
Oxidation Resistance	Low	High
Electrical Resistivity	6.40 μΩ-cm	6.84 μΩ-cm

Solder Paste

- Solder spheres, flux, and solvent
  - Solder is typically ~63/37 tin/lead
  - Sn and Pb have low melting points (Sn 232 °C, Pb 327 °C)
  - 50 – 90 wt% metals
  - Viscosity is temperature dependent

Pick and Place

- Component assembly is automated
  - ‘Pick-and-place’ machines
  - Camera detects marks for optical alignment
    - Fiducials
    - Improvement over mechanical alignment
    - Calculates optical offset and corrects



Chapter 17 Fundamentals of Board Assembly

FIGURE 17.7 Board fiducials.

Chip Shooters

- Assembles smaller components

Turret-Head chip shooter

  - Fixed placement position
  - Rotating drum head

Revolver-Head chip shooter

  - Vertical wheel on a robot
  - PWB is kept still during mounting

Multimodule chip shooter

  - Several densely packed pick-and-place modules
  - High speed
  - PWB moves forward slowly

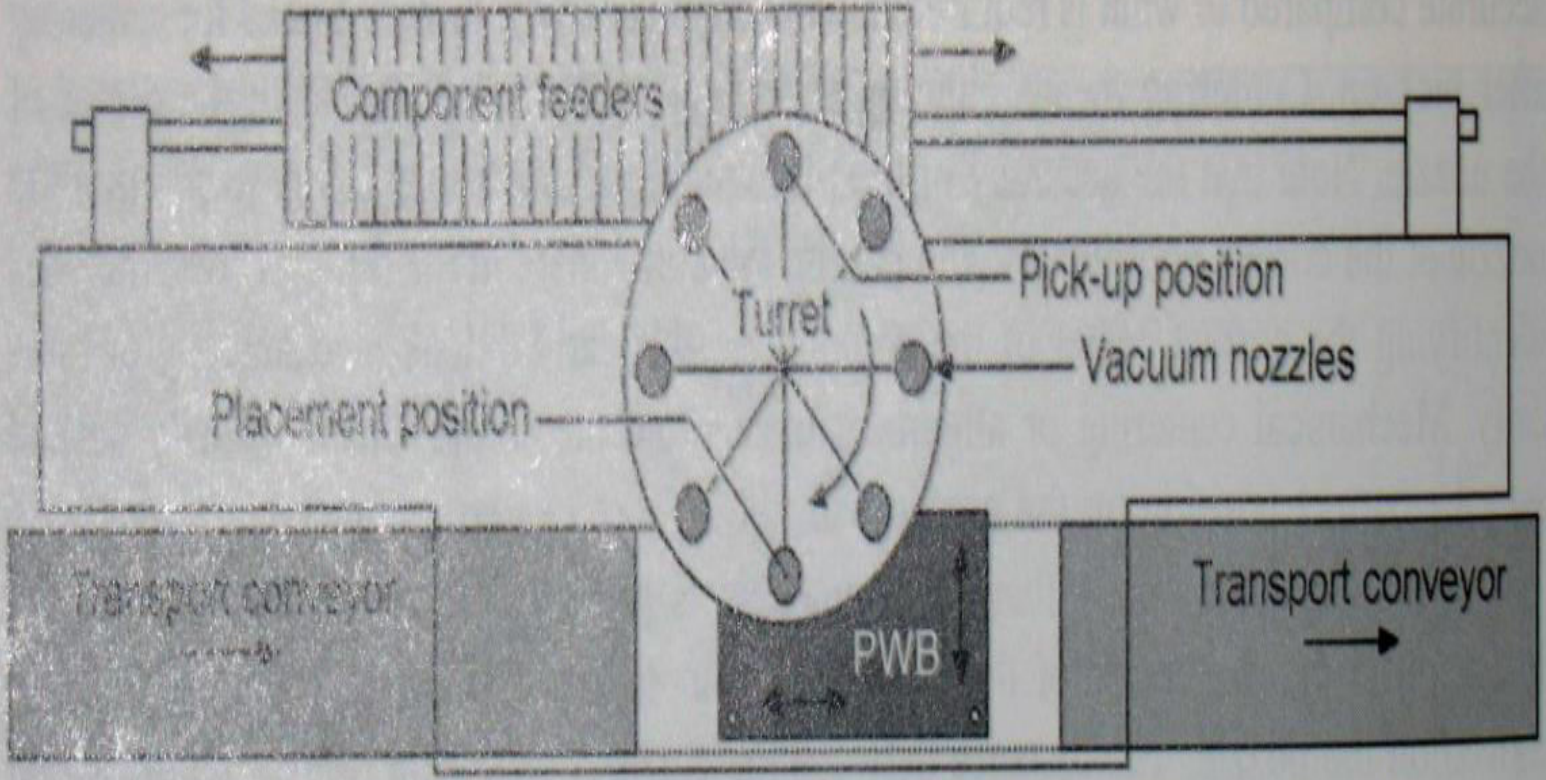


FIGURE 17.9 The turret head chip-shooter.

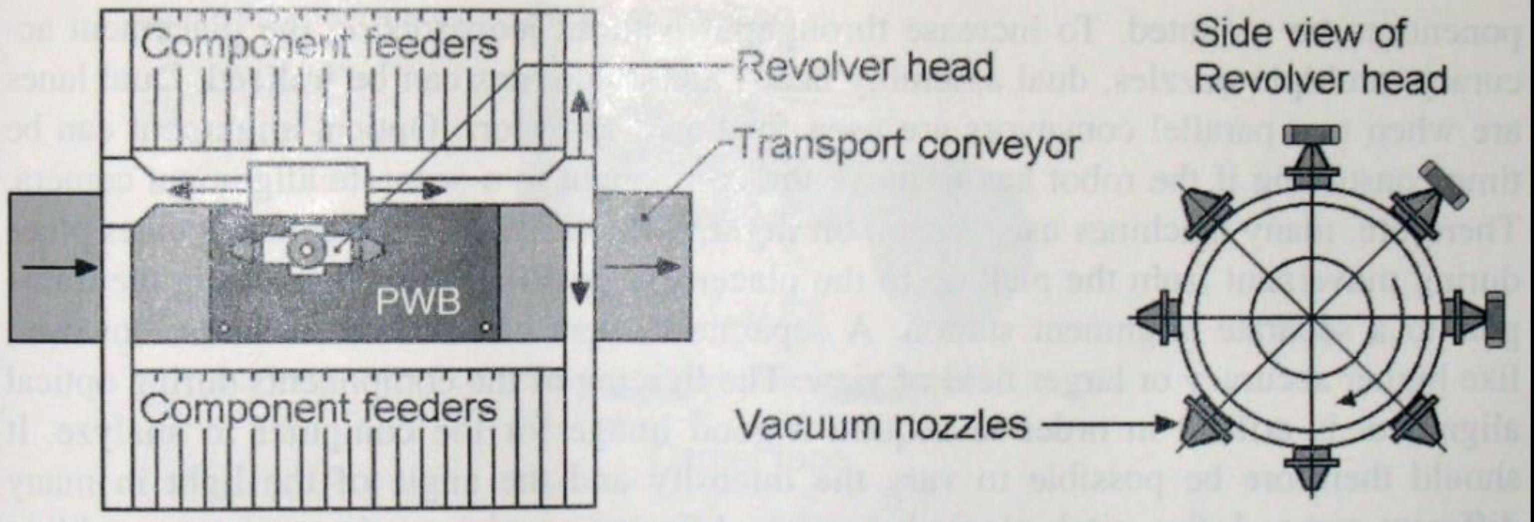


FIGURE 17.10 The revolver head chip-shooter.

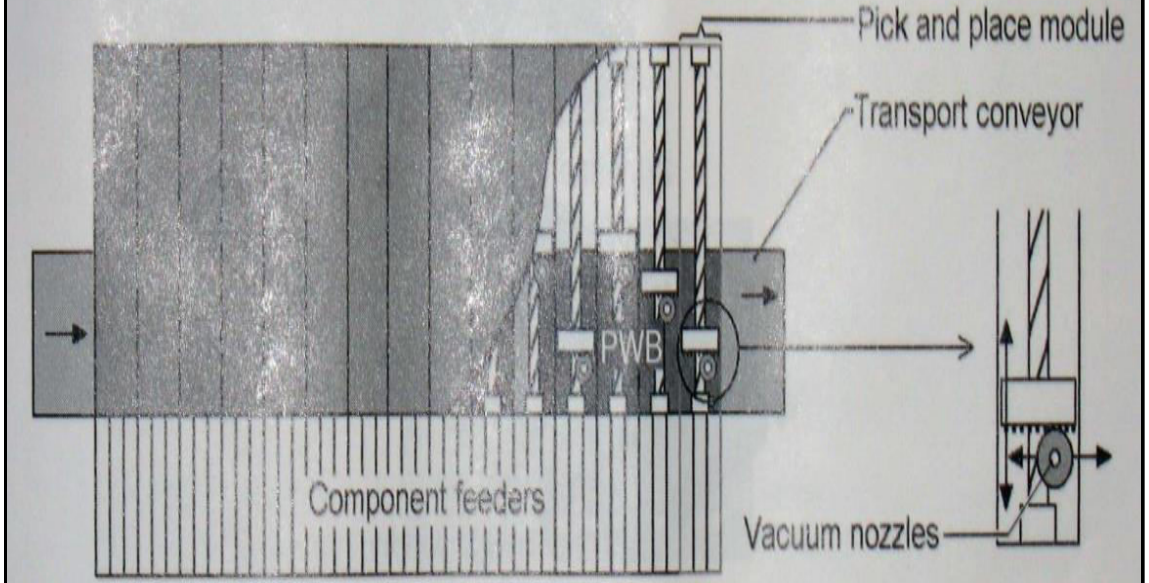


FIGURE 17.11 The multimodule chip-shooter.

Placement Terminology

- Coplanarity

  Variation in height of component leads
- Tape-on-reel feeders

  Common, feed components on paper or plastic tape
- Tray feeders

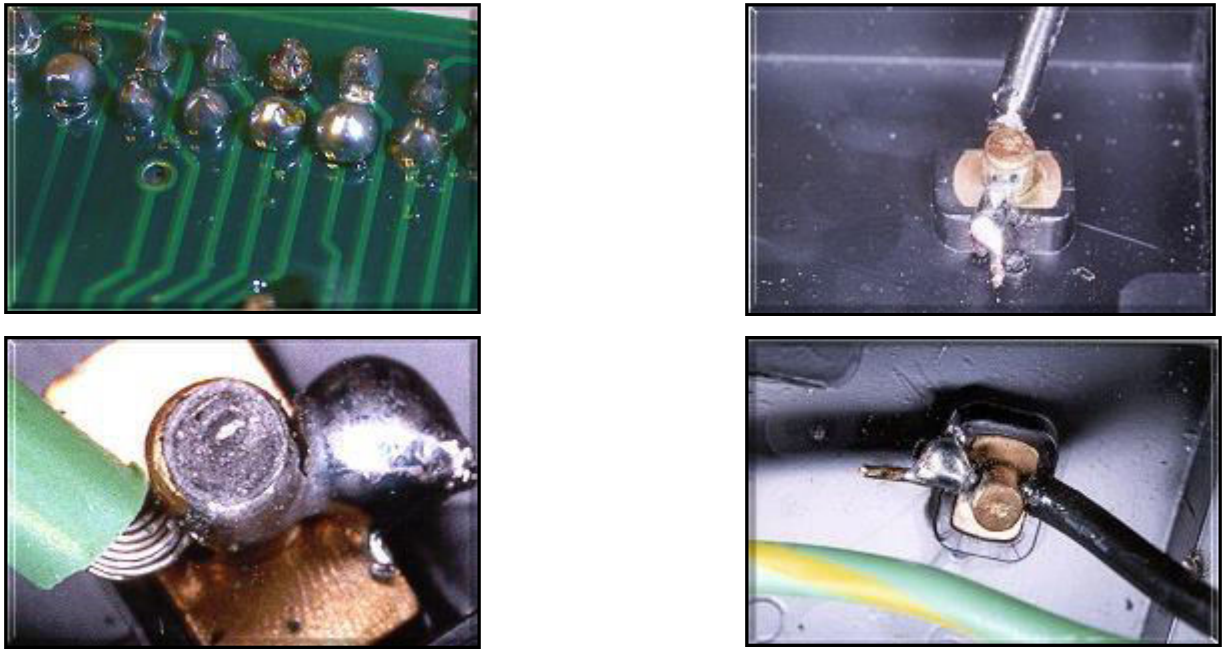
  Transfer one component at a time, fine-pitch elements
- Gel-pack

  Sticky tray for flipchip, held by a tacky gel
- Bulk-feeders

  Feeds directly from a box of components
- Stick-feeders

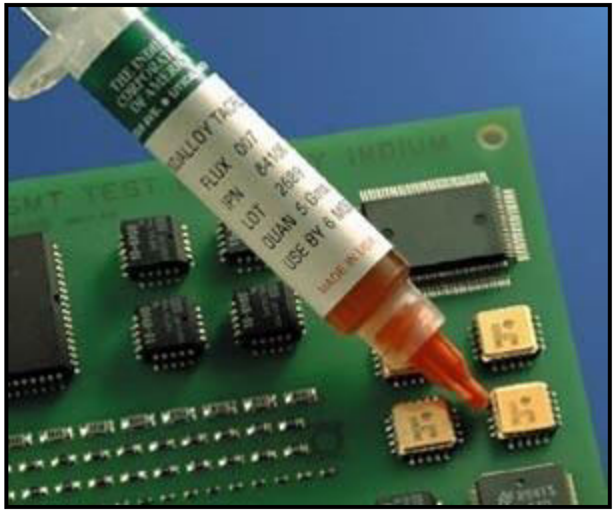
Soldering

- Electrical, mechanical, thermal connections
  - Quality determined by adherence to pads
- Reliability set by quality and amount of solder



Flux

- Reduces oxides on the solder-surface
  Improves adhesion to substrate
- **R** (rosin): non-activated fluxes (no activators)
- **RA** (rosin activated): active, most corrosive
- **RMA** (rosin mildly activated): requires good solderability on pads



Solder Alloys

- Sn, Pb, Ag, and In

  1st Most Common

  - Sn – 63% Pb – 37%

  2nd Most Common

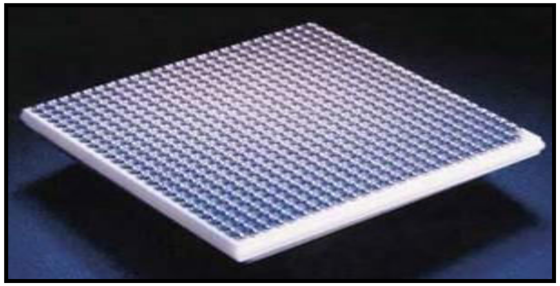
  - Sn – 62% Pb – 36% Ag – 2%

  Ag added for increased conductivity and corrosion resistance (Ag does not oxidize in air)

  - Sn does (SnO_2 used in superthermite explosives – ouch)

  Indium added to make solder extremely expensive

  - Possibly has other benefits as well (thermal fatigue)
  - Not very popular



Solder Spheres

Reflow Soldering

- Process where solder is already present on solder pads before soldering starts
  1. Solder paste is screen- or stencil-printed onto the solder pad
  2. Components are placed
  3. Reflow soldering performed

- Solder paste is a homogeneous mixture of the following:
  - Metal particles (solder powder)
  - Flux medium
  - Sometimes includes solvent (an activator) and viscosity regulating agent

Reflow Soldering

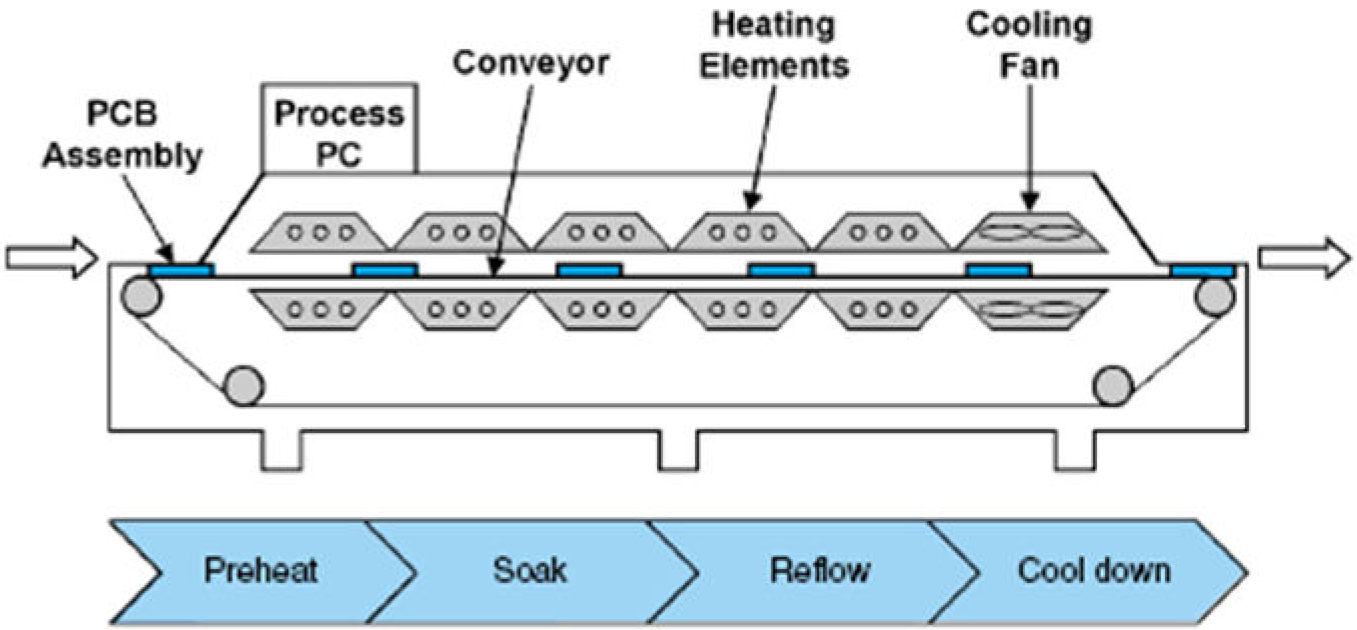
- Surface Mount Assembly (SMA) soldering process uses conveyorized reflow oven

- Three different types of ovens that are commonly used:
  - Infrared (IR)
  - Forced-convection
  - Vapor-phase soldering

- Forced-convection offers far better heat distribution in the board assembly (heat transfer is independent of component color)

Reflow Soldering

Reflow Oven



Reflow Soldering

- Reflow Profile can normally be characterized with four different phases:

  Preheat – increase board and components temps at a controlled rate to minimize any thermal damage

  Thermal soak – equalize temperatures of all surfaces being soldered

  Reflow – solder reaches its liquidus temperature

    - Rapid heating used to ensure entire assembly quickly reaches temperature above the melting point of solder

  Cool down – allows solder to solidify before exiting the reflow oven

    - Strictly controlled process: cooling too slowly causes larger grains to form in the solder

Reflow Soldering

- Reflow Soldering Considerations

  Reflow soldering processes can be performed in an inert environment

  - Advantage: no reoxidation occurs inside the oven
  - Disadvantage: added cost for nitrogen

  Components on the bottom of a board may fall off in the reflow oven

  - Adhesive may be needed for heavy components or components with leads on only one side of the board

  Boards may need multiple temperature sensors in IR or forced convection ovens

  - Ensure that all solder joints follow specified thermal profile

Reflow Soldering

Some of the most common defects in the reflow process are:

- Unsoldered joints, due to component coplanarity (lifted leads) or board warpage
- Cold joints, due to mass differences between components or bad thermal design of the board
- Solder balls, due to too rapid out-gassing of the solvent in the solder paste or bad design of the solder pads
- Short circuit between leads, due to bad solder printing, slumping of the solder paste or too rapid out-gassing of the solvent in the solder paste

Other Soldering Techniques

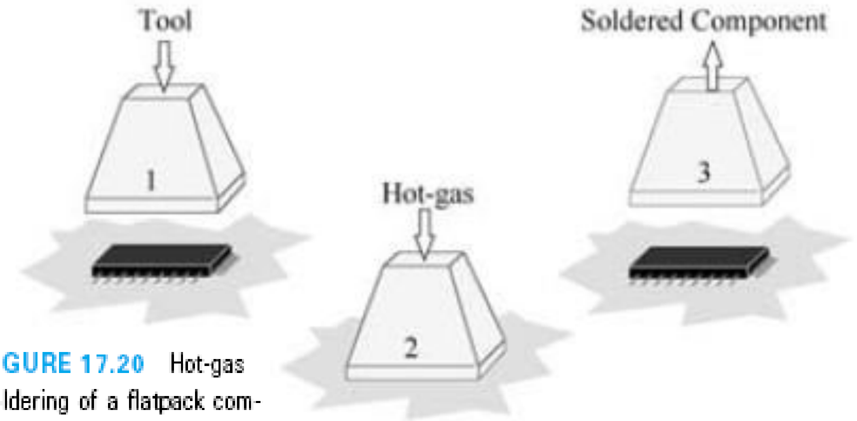


FIGURE 17.20 Hot-gas soldering of a flatpack component.

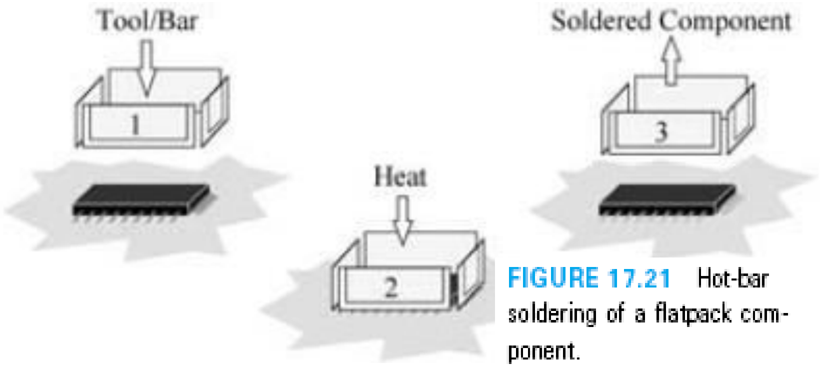


FIGURE 17.21 Hot-bar soldering of a flatpack component.

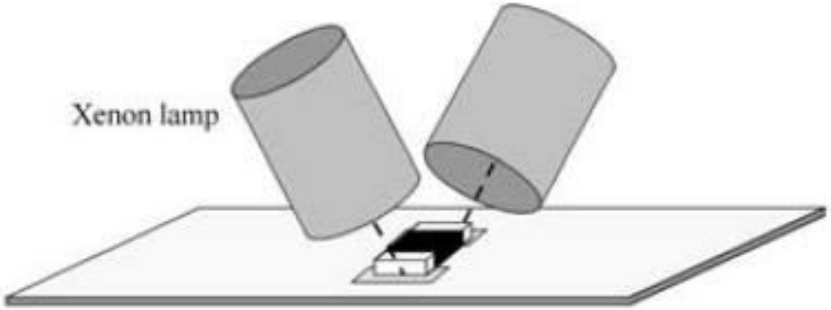


FIGURE 17.22 Soft-beam soldering of a chip component.

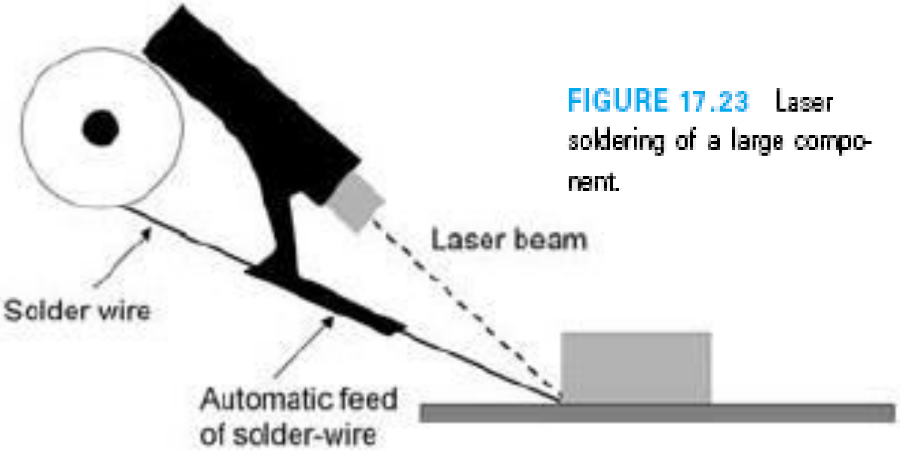


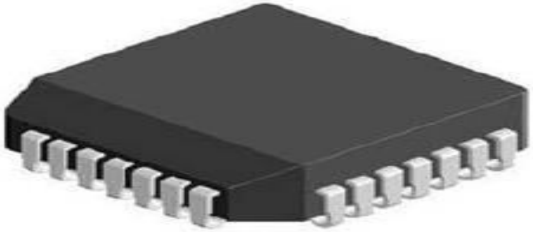
FIGURE 17.23 Laser soldering of a large component.

Surface Mount Components

- Pitch started out smaller than pitch of through-hole components (approximately 50 mil)
- Use less area on topside of board
- Do not use any area on inside or bottom-side of the board
- When pitch reached approximately 20 mils, challenges caused industry to search for new packaging solution

(a)

Small Outline Integrated Circuit (SOIC)

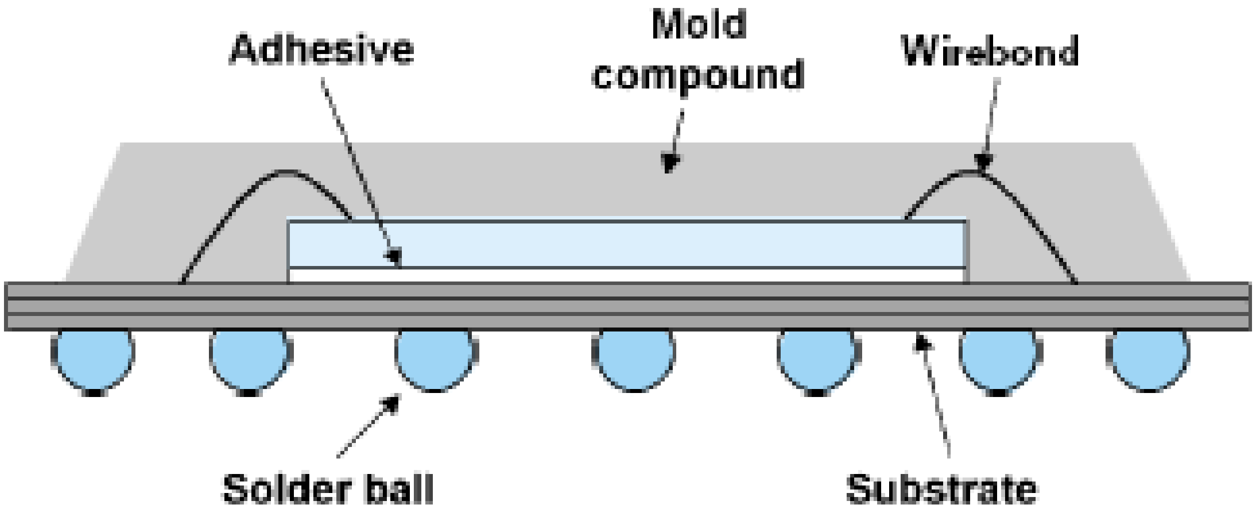


(b)

Plastic Leaded Chip Carrier (PLCC)

Ball Grid Array

- Ball Grid Array (BGA) is the most common area array
- Utilizes small solder balls for the connection between the component and the board
- Less inductance and less signal degradation
- Active chip in a BGA package can be interconnected to the package by wirebonding



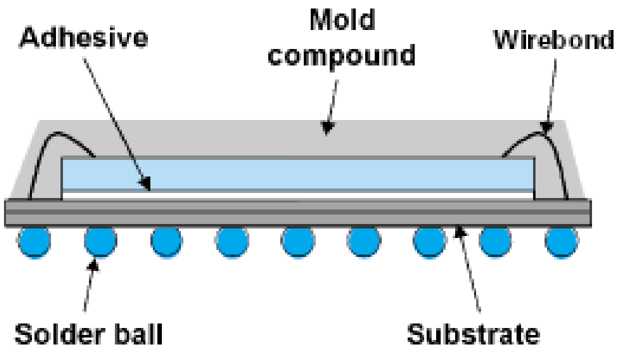
Ball Grid Array

- One drawback is the difficulty of inspecting the formed solder joints after assembly
  - Most manufacturers will use X-ray machines to inspect BGA components for errors in the assembly process
    - Very difficult to judge appearance of solder joint
  - Fiberoptic equipment is available to actually see the solder joint by getting underneath the component body

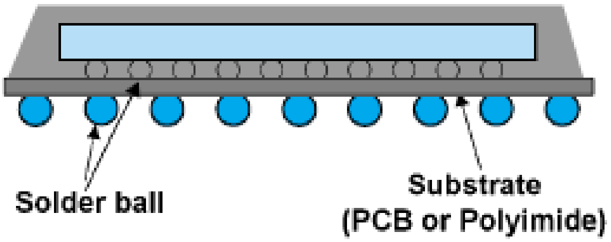
Chip Scale Package

- Having a side that is a maximum of 1.2 times the size of the chip

  OR
- Package is 1.5 times the area of the chip



Wirebonding



Flip-chip

CSP versus Flip Chip

- CSP can handle mismatch of Coefficient of Thermal Expansion (CTE) between the chip and the board

- Not necessary to “underfill” CSP

Advantages of Through-Hole Assembly

- The number of through-hole assemblies is constantly decreasing, but through-hole technology still has some advantages:
  - Stronger mechanical fastening to the board is used for large and heavy components
  - Beneficial for components like connectors that are exposed to large dynamic forces when plugged in and out
  - Used when large currents are conducted such as components on power supply boards

Component Insertion

- Through-Hole component leads are inserted into plated holes in the PWB and soldered
  - Wave soldering
  - Solder iron
  - Selective soldering system
- Component insertion can be done manually or automatically
- Axial components can be set up in a sequencing machine to be mounted on a board
- Axial insertion machine forms the leads, inserts them into the holes, and cuts and clinches them on the backside

Component Insertion

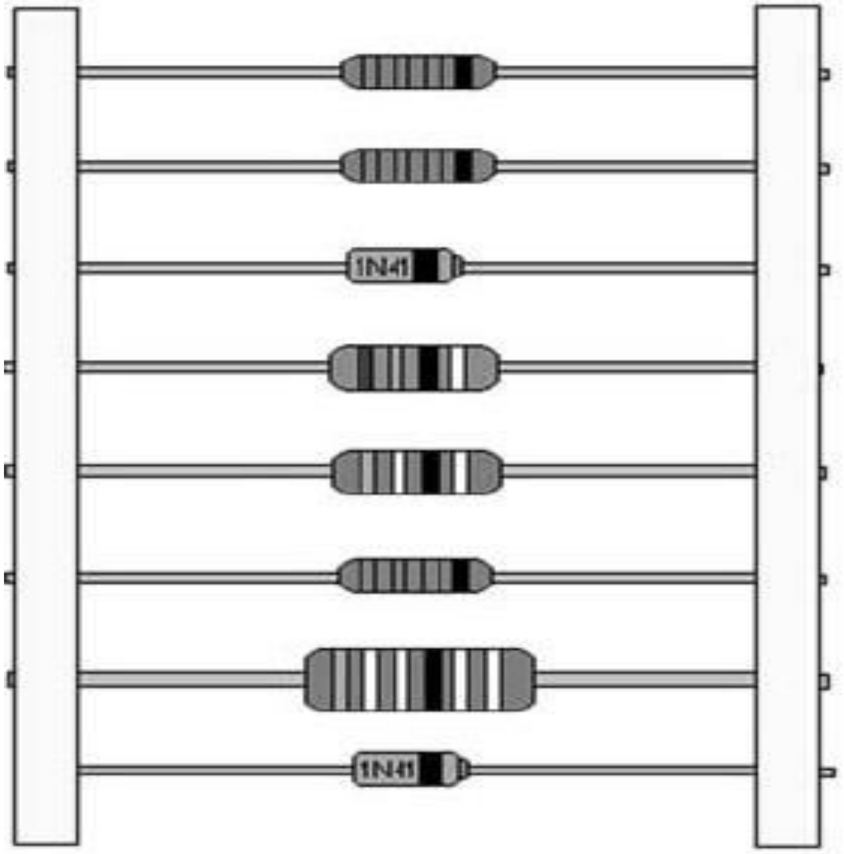


FIGURE 17.30 Component sequence.

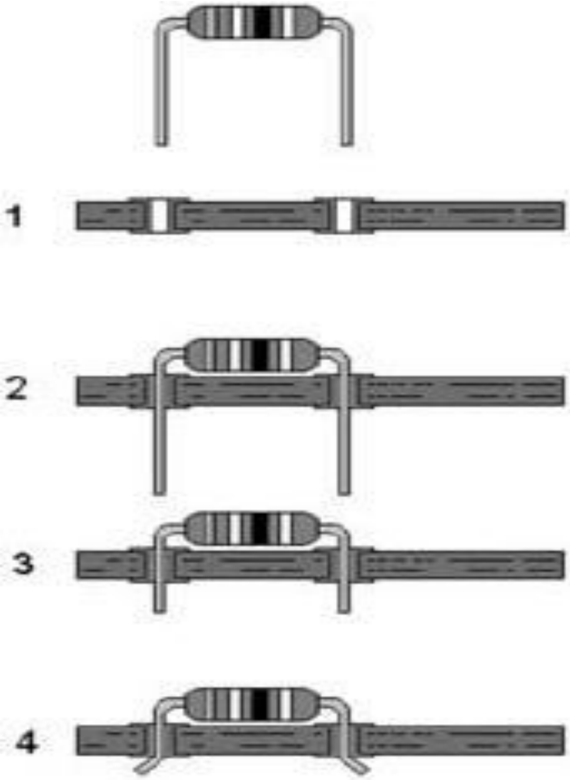


FIGURE 17.31 Axial insertion.

Wave Soldering

- Most common soldering method for through-hole assemblies
- Boards usually placed in a fixture and carries the boards through the following processes:
  - Fluxing station
  - Preheat zone
  - Solder wave
  - Cleaning (depending on flux type)
- Solder wave is formed by molten solder that is continuously pumped up and falls over an edge back into the solder reservoir

Wave Soldering

FIGURE 17.32 Wave-soldering machine. *(Picture courtesy of Sincotron, Vitronics Soltec DeltaMax)*

Press-Fit Assembly

- Mainly used for mounting connectors on boards
- Pin of larger diameter is pressed into plated through-hole of smaller diameter
- Usually “compliant” pin is used so it does not damage the wall of the hole

Mixed Component Assembly

- The use of SMD and through-hole components on the same PWB
- Wave soldering process has been adapted to incorporate surface mount assembly
  - SMT components must first be attached to the secondary side of the board using glue between the component body and the board
  - SMT components must be in special orientation to achieve good solder joints and avoid solder bridging

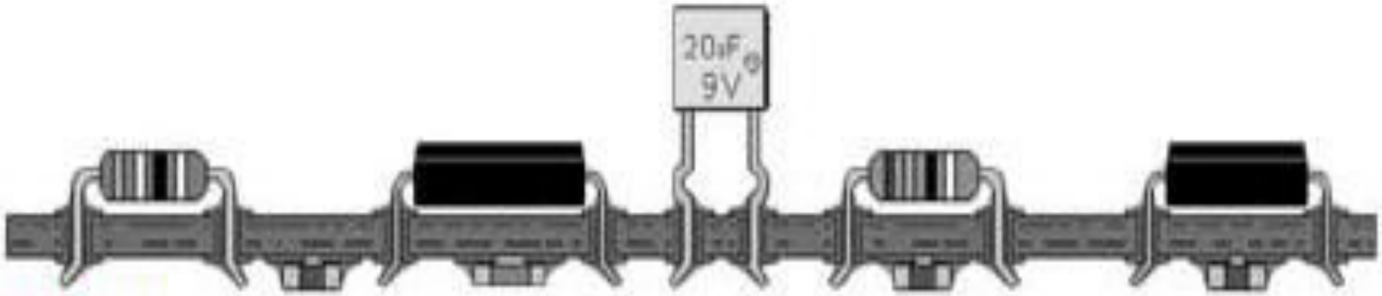
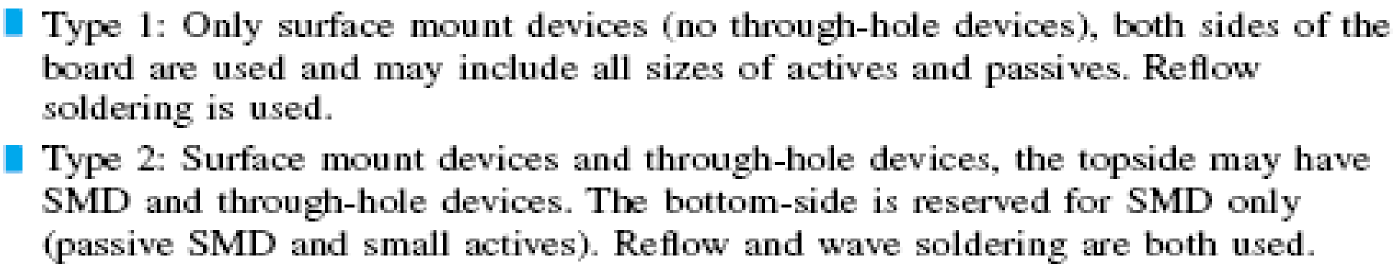


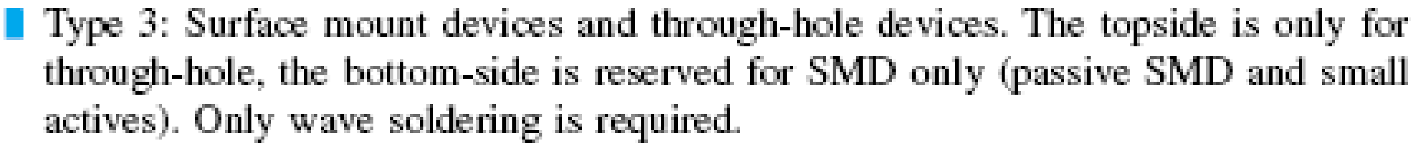
FIGURE 17.33 Mixed assembly.

Mixed Component Assembly

Board assemblies are sometimes divided into three different types:



- Type 1: Only surface mount devices (no through-hole devices), both sides of the board are used and may include all sizes of actives and passives. Reflow soldering is used.
- Type 2: Surface mount devices and through-hole devices, the topside may have SMD and through-hole devices. The bottom-side is reserved for SMD only (passive SMD and small actives). Reflow and wave soldering are both used.



- Type 3: Surface mount devices and through-hole devices. The topside is only for through-hole, the bottom-side is reserved for SMD only (passive SMD and small actives). Only wave soldering is required.

Generic Assembly Issues

- Additive materials include:
  - Flux
  - Conductive adhesive
  - Non-conductive adhesive
  - Thermally conductive grease
  - Conductive film
- Conductive adhesives are usually thermally curable epoxies filled with conductive particles
- Used to replace solder in special applications

  Advantages : lead-free and processing temp is not as high

  Disadvantages: Difficult to match the thermal, mechanical and electrical performance of solder

Cleaning

- Cleaning is used to improve reliability and prolong life of a product

  Note: products at Ball are cleaned before flying in space
  - Cleaning can unclude baking
  - Prevent “out-gassing” of certain materials
  - Prevent debris from coating optics
  - Prevent conductive debris from shorting components
- Aqueous Cleaning: cleaning of water-soluble flux by adding a saponifer to water and rinsing over flux

  Note: Samponifer turns the flux into a “soap”
- Semi-aqueous Cleaning: Assembly is first cleaned with organic solvent before water rinse takes place

Rework and Repair

- Failures in processing occur; particularly as line speeds increase and component sizes decrease
- Value of each assembly is increasing
- Most components can be replaced with a standard soldering iron
- Old solder should be completely removed before placing new component to achieve reliable solder joint

  Risk of lifting pads

  Risk of removing solder mask
- Good rework requires trained and highly skilled operator

Electrostatic Discharge

- When wearing certain types of fabrics, we can easily get charged up to 20,000 volts just by walking around
- Charge can be achieved when two materials are rubbed against each other, or separated
- ESD failure can be latent and difficult to pinpoint

Worst case: cannot be detected in production, but will show up much later out in the field

Process Control

- Assuming a board of 333 components:
  - Assume average of three terminations per component
  - Total of about 1000 soldered interconnections per board
  - Average of 99% soldered interconnections are correct = average of 10 defects per board: **Production Yield = 0**
- If 99% production yield is desired:
  - No more than one defect on every 100 boards = 100,000 soldered interconnections
  - 99.999% of solder joints would have to be correctly formed
- Industry commonly discusses defect rates in parts per million (ppm)

Design Challenges

- Decisions made at early stages of design that have substantial impact on the assembly result
  - Component package types
  - Spacing between components
  - Design of soldering surfaces
- Design for manufacturing (DFM) is critical

  Software tools readily available

  It is important to have guidelines based on capabilities and limitations of the manufacturing processes

  “A mistake in the manufacturing will affect one product or a batch of products, but a mistake in design will affect every product”