IC Packaging

- **Purposes**
  1) Electrical connections
     - Signals
     - Power and ground
  2) Aids heat dissipation
     - Increase effective surface area for increased convection
     - Heat conduction into PC board
  3) Physical protection for IC
     - e.g., against breakage
  4) Environmental protection
     - Hermetic (airtight) seal
     - e.g., against corrosion or moisture
Rent’s Rule

- Empirical formula
- \( P = K G^\beta \)
- \( P \) = number of input/output connections (pins)
- \( K \) = average number of I/Os per “gate”
- \( G \) = number of “gates”
- \( \beta \) = empirically-found parameter that varies according to application; generally between 0.1 and 0.7

<table>
<thead>
<tr>
<th></th>
<th>( \beta )</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer (chip)</td>
<td>0.63</td>
<td>1.4</td>
</tr>
<tr>
<td>Computer (board)</td>
<td>0.25</td>
<td>82</td>
</tr>
<tr>
<td>Static memory</td>
<td>0.12</td>
<td>6</td>
</tr>
</tbody>
</table>

Package Metrics

- Electrical
  - Low capacitance
  - Low inductance
  - Low resistance
- Mechanical
  - Reliable across temperature variations (thermal expansion matching)
- Thermal
  - Low thermal resistance to get the heat out
- Economical (cost)
  - Purchase of package
  - Assembly (chip and board assembly)
  - System (heat removal equipment included)
Package Materials

- Plastic
  - Low cost
  - Typically requires a custom-designed package
- Ceramic
  - Better heat transfer characteristics
  - Generally more reliable
  - More likely an off-the-shelf part can be used
    - Good for research and prototyping

Interconnection Levels

- Multiple levels of packaging
  - Ease of handling
  - Reuse of intermediate-sized modules (e.g., DRAM memory stick)
    - Use in multiple products
    - Upgradeable in field
    - Repairable in field

  system
  printed circuit board(PCB)
  package
  chip
Solder

- Solder is the universal electrical “glue”
  - tin and lead alloy: 50/50%, 63/37% Sn/Pb eutectic mixture
  - low melting temperature: 183 °C or 361.4 °F for eutectic
  - good electrical conductivity
- Large efforts now under way to eliminate or reduce the use of lead
  - RoHS - Restriction of Hazardous Substances Directive
  - Many replacements available
    - Typical ones use Tin, Silver, Copper; maybe Bismuth, Indium, Zinc, Antimony
PC Board Stack With Host Computer
System

- J-Machine
- Built at MIT and Stanford in the early 1990’s
- 1024 processors

IBM Blue Gene/L

- The fastest supercomputer in the world is a 131,072-processor Blue Gene machine
IBM Blue Gene/L

- BlueGene/L: 1/100th the physical size (320 vs 32,500 square feet) consumes 1/28th the power (216KW vs 6,000KW) - compared to Earth Simulator

- Attained a sustained performance of 70.72 Teraflops - eclipsing 3 year old top mark of 35.86 Teraflops - Japanese Earth Simulator
- recent mark of 42.7 Teraflops at the NASA's Ames research center

Chip to Package Connections

1) Wire bonding
   - die attached
   - gold or aluminum wires
   - one at a time
   - not entirely repeatable
   - Electrical characteristics:
     - R: low
     - C: low
     - L: ~1 nH/mm
Wire Bonding

- Optical microscope view of bond wires for a two-pad package
Wire Bonds

- SEM view of bond wires for a two-pad package

Source: Assurance Technology

Wire Bonds

- SEM view of a single bond wire attachment

Source: Assurance Technology
Wire Bonds

- Gold wire bond on aluminum die pad

Source: SEM Labs, Inc.

Wire Bonding Machine

- Wire bonding machine

Source: TWI, Ltd.
2) Tape automated bonding (TAB)
   - Die attached to metal lead frame printed on polymer film using solder bumps
   - Tape then connected to package
   - Fast and parallel operation
   - Lower electrical parasitics (R, L, C)

Tape-Automated Bonding (TAB)

(a) Polymer Tape with imprinted wiring pattern.
(b) Die attachment using solder bumps.

Source: Digital Integrated Circuits, 2nd ©
Tape-Automated Bonding (TAB)

Chip to Package Connections

3) Flip chip solder bump
   - chip placed face down in package
   - connected with solder bumps
   - very low parasitics
   - allows “area pads”
     • pads can cover chip area and are not limited to chip periphery
Flip-Chip Bonding

Package to Board Connections
1) Through Hole

- Classic approach
- Holes drilled and plated with copper
- Soldering
  - Chips placed inside holes
  - Bottom of board passed through a molten solder “wave”
Package to Board Connections
2) Surface Mount Technology (SMT)

- More wiring room inside PC board
- Reduced space between package leads
- Chips on both sides of board
- Stronger PC board
- Soldering
  - Solder paste applied
  - Heat supplied by intense infrared light, heated air,…

Package-to-Board Interconnect

(a) Through-Hole Mounting  (b) Surface Mount

Source: Digital Integrated Circuits, 2nd ©
SMT Leads

a) Gull-wing SMT package leads
   - Soldering issues

Ex: Thin Small Outline Package Type II (TSOP Type II)

http://www.twyman.org.uk/PCB-Techniques/

b) J-Lead SMT package leads
   - Many package types available
   - Less board space than gull wing

Ex: Small Outline J-lead (SOJ)

http://www.twyman.org.uk/PCB-Techniques/
http://www.ljmu.ac.uk/GERI/VERBONDS.htm
SMT “leads”

c) Solder Balls
- Similar to flip chip but at package-to-board level
- Very low parasitics
- Example BGA solder ball
  (with highlighted crack)

Package Examples

Source: Digital Integrated Circuits, 2nd ©
Package Types
DIP – Dual In-Line Package

- One of the oldest packaging technologies
- Low performance
- 48-64 pin packages are huge
- Cheap and abundant
- Plastic and ceramic

ZIP – Zig-Zag In-Line Package

- Not very common
Package Types
SOP – Small Outline Package

- SOP includes a large family of packages
  - SOIC – Small Outline Integrated Circuit
  - SSOP – Shrink Small Outline Package
  - QSOP – Quarter-size Small Outline Package
  - TSSOP – Thin Shrink Small Outline Package
  - MSOP – Mini Small Outline Package

http://www.carsem.com/services/package.php
http://www.mameworld.net/gurudumps/MyStuff/packages.html

Package Types
TSOP – Thin Small Outline Package

- One of the smallest packages available
- Type I – leads on short sides

- Type II – leads on long sides

http://www.mameworld.net/gurudumps/MyStuff/packages.html
**Package Types**

**QFP – Quad Flat Package**

- Common in modern electronics

- TQFP – Thin Quad Flat Package
  - Typical thickness 1.4 mm

**Package Types**

**SOJ – Small Outline J-lead**

- “J” leads on two sides
### Package Types

**PLCC – Plastic Leaded Chip Carrier**

- Also called QFJ – Quad Flat J-lead
- Common in many products

[Image of PLCC packages]

- [http://www.mameworld.net/gurudumps/MyStuff/packages.html](http://www.mameworld.net/gurudumps/MyStuff/packages.html)
- [http://www.globalchipmaterials.com/visitors/products_visitors_acp_plcc.htm](http://www.globalchipmaterials.com/visitors/products_visitors_acp_plcc.htm)

### Package Types

**PGA – Pin Grid Array Package**

- Material—the main body consists of co-firing multilayer alumina ceramics, and pin terminals made of an alloy of iron, nickel, and cobalt are attached with silver-brazing to the main body.
- 400+ pins possible
- Cavity up
- Cavity down

[Image of PGA packages]

• Physical dimension drawings
• Top-side chip cavity

PGA – Pin Grid Array Package
Example 132-pin PGA Datasheet

• Drawing of chip cavity and 132 bond finger pads to which the bond wires are attached
PGA – Pin Grid Array Package
Example 132-pin PGA Datasheet

- Drawing of map showing correspondence between bond fingers and package I/O pins

- Heat dissipation capacity depends strongly on the speed of the surrounding air
PGA – Pin Grid Array Package

Example 132-pin PGA Datasheet

• More general data presentation shows thermal resistance as a function of airspeed (presumably with no heat sink)

![Thermal Resistance Graph](image)

### Electrical Characteristics

<table>
<thead>
<tr>
<th>Bond Fingers</th>
<th>$R_1$ (Ω)</th>
<th>$L_f$ (nH)</th>
<th>$C_f$ (pF)</th>
<th>$R_2$ (Ω)</th>
<th>$L_2$ (nH)</th>
<th>$C_2$ (pF)</th>
<th>$f_{op}$ (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,22,44,55,77,88,110,121</td>
<td>0.105</td>
<td>0.34</td>
<td>1.54</td>
<td>0.291</td>
<td>4.65</td>
<td>1.3</td>
<td>72.6</td>
</tr>
<tr>
<td>6,28,41,51,74,94,107,127</td>
<td>0.109</td>
<td>0.37</td>
<td>1.77</td>
<td>0.291</td>
<td>4.65</td>
<td>1.3</td>
<td>79.6</td>
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<tr>
<td>16,17,49,50,82,83,115,116</td>
<td>0.125</td>
<td>0.41</td>
<td>1.86</td>
<td>0.291</td>
<td>4.65</td>
<td>1.3</td>
<td>86.6</td>
</tr>
<tr>
<td>4,31,37,54,70,97,103,130</td>
<td>0.121</td>
<td>0.43</td>
<td>1.9</td>
<td>0.291</td>
<td>4.65</td>
<td>1.3</td>
<td>86.6</td>
</tr>
</tbody>
</table>

- **Electrical Characteristics**
  - Equivalent circuit and typical values
  - Notice very large variance in electrical performance for different package pins
  - Consider best pins for:
    - High-speed signals
    - Power and Gnd

![Equivalent Circuit Diagram](image)
Package Types
BGA – Ball Grid Array

- Very common for high-volume high-pin-count chips
  - 200-500 I/Os is common
  - Excellent electrical characteristics
  - Good heat conduction into PC board
  - Difficult to inspect once soldered to PC board
  - Difficult to replace

http://www.mameworld.net/gurudumps/MyStuff/packages.html
http://www.pcmag.com/encyclopedia_term/0,2542,t=BGA&i=38577,00.asp
http://www.electweb.com/bga_reballing.htm
http://www.tms.org/pubs/journals/JOM/9903/Frear-9903.html

BGA with Flip-Chip

Package Parameters

<table>
<thead>
<tr>
<th>Package Type</th>
<th>Capacitance (pF)</th>
<th>Inductance (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68 Pin Plastic DIP</td>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>68 Pin Ceramic DIP</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>256 Pin Grid Array</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Wire Bond</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Solder Bump</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Typical Capacitances and Inductances of Various Package and Bonding Styles (from [Sze83])

Compare with SMT values.
Mounting Die Directly to a Substrate

A. Multi-chip Module
   - silicon on silicon
   - many of other ceramic materials used
   - testing is big issue ("known good die")
B. “Chips on Board”
C. System in Package (SiP)

Multi-Chip Module

Source: Digital Integrated Circuits, 2nd ©
Package Types
SiP – System in Package

- Increasingly popular for high-volume small form factor products
- Can combine wire bonds with flip chip
- Nice solution for an application system with different types of chips and “passives” (R, L, C)

[Image of SiP arrangement]

Supporting Technology for 2.5D and 3D: “Stacked Die”

- Dense packaging methodology which places chips on top of each other
- Inter-chip interconnect can be made by a variety of means

[Images of stacked die]
Supporting Technology for 2.5D and 3D: “Through-Silicon Vias (TSVs)”

- Through-Silicon Vias are “vias” that connect pads on opposite sides of a chip by passing directly through the entire die.
- Example: Hynix High-Bandwidth Memory (HBM) with four DRAM dies (the lower three have been thinned), a base logic die, an interposer, and a laminate substrate.

Supporting Technology for 2.5D and 3D: “Through-Silicon Vias (TSVs)”

“Hynix disclosed a via middle process for their HBM in two papers (Electronics Components & Tech. Conf. 2013 and VLSI Tech. Digest 2014). The TSV openings are formed after the tungsten contacts to the gates and source/drain regions are made, using a Bosch TSV etch. An oxide liner is then deposited along the via sidewalls, lined with a Ta-based barrier and Cu seed layers, and filled with electroplated Cu. A thermal anneal process is used as a Cu stress relief. A CMP and etch process is used to thin the backsides of the DRAM wafer and expose the Cu TSVs. The backsides of the DRAM wafers are then passivated with oxide, followed by the formation of the backside microbumps.”


Reminder:
Cu = copper

Images are shown inverted compared to the two previous images.