Lecture #38

ERDM

Professor J. W. Sutherland

material adapted from
WTEC Report & Profs. Bergstrom & Friedrich

April 14, 2004

Electronics and the Environment

- **Serious end-of-life issue**
  - **Growing consumption**
  - **Decreasing product life spans**
- **Volume of manufacturing wastes**
  - **Wafer fabrication processes**
  - **Printed wiring board fabrication**
  - **Displays**

WEEE Directive

- **Waste Electrical and Electronic Equipment**
- **Member States should encourage the design and production of electrical and electronic equipment which take into account and facilitate dismantling and recovery, in particular the re-use and recycling of WEEE, their components and materials. Producers should not prevent, through specific design features or manufacturing processes, WEEE from being reused, unless such specific design features or manufacturing processes present overriding advantages, for example with regard to the protection of the environment and/or safety requirements.**

ROHS Directive

- **Reduction of Hazardous Substances**

- **Member States shall ensure that, from 1 July 2006, new electrical and electronic equipment put on the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE).**

Electronics Industry

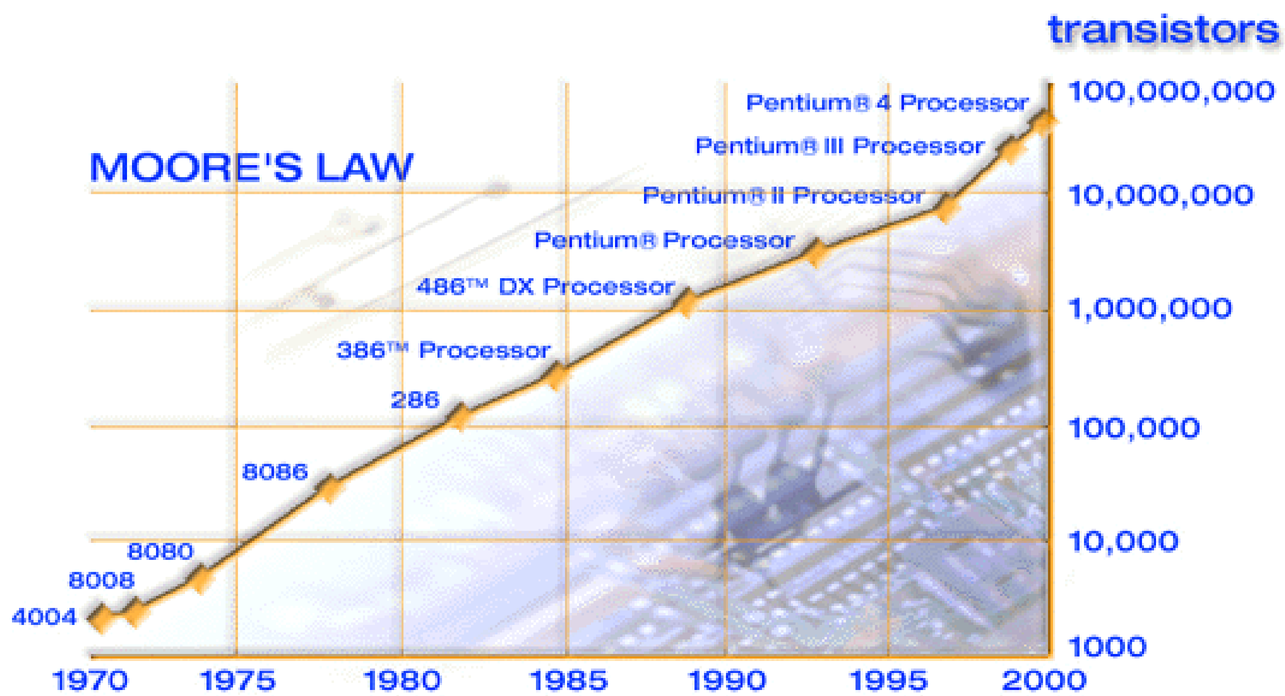
- Not highly toxic
  - only 1.6% of TRI emissions
- Extremely wasteful
  - Wastewater for fabrication of less than 1 pound of silicon chips:
    - 31 pounds of liquid chemicals
    - 9 pounds of sodium hydroxide
  - 4 pounds of printed wiring board (PWB) manufacture:
    - 46 pounds of material waste

Electronics Design

- Environmentally beneficial design and process changes can be implemented rapidly and at low marginal cost
  - Rapid technology change (18-48 months)
    - Moore's Law
  - Complete capital equipment turnovers as a result of design change (5-10 years)
  - Experts at managing and analyzing large amounts of data

Moore's Law

Moore's Law states that the transistor density on integrated circuits doubles every couple of years. This exponential growth and ever-shrinking transistor size result in increased performance and decreased cost.



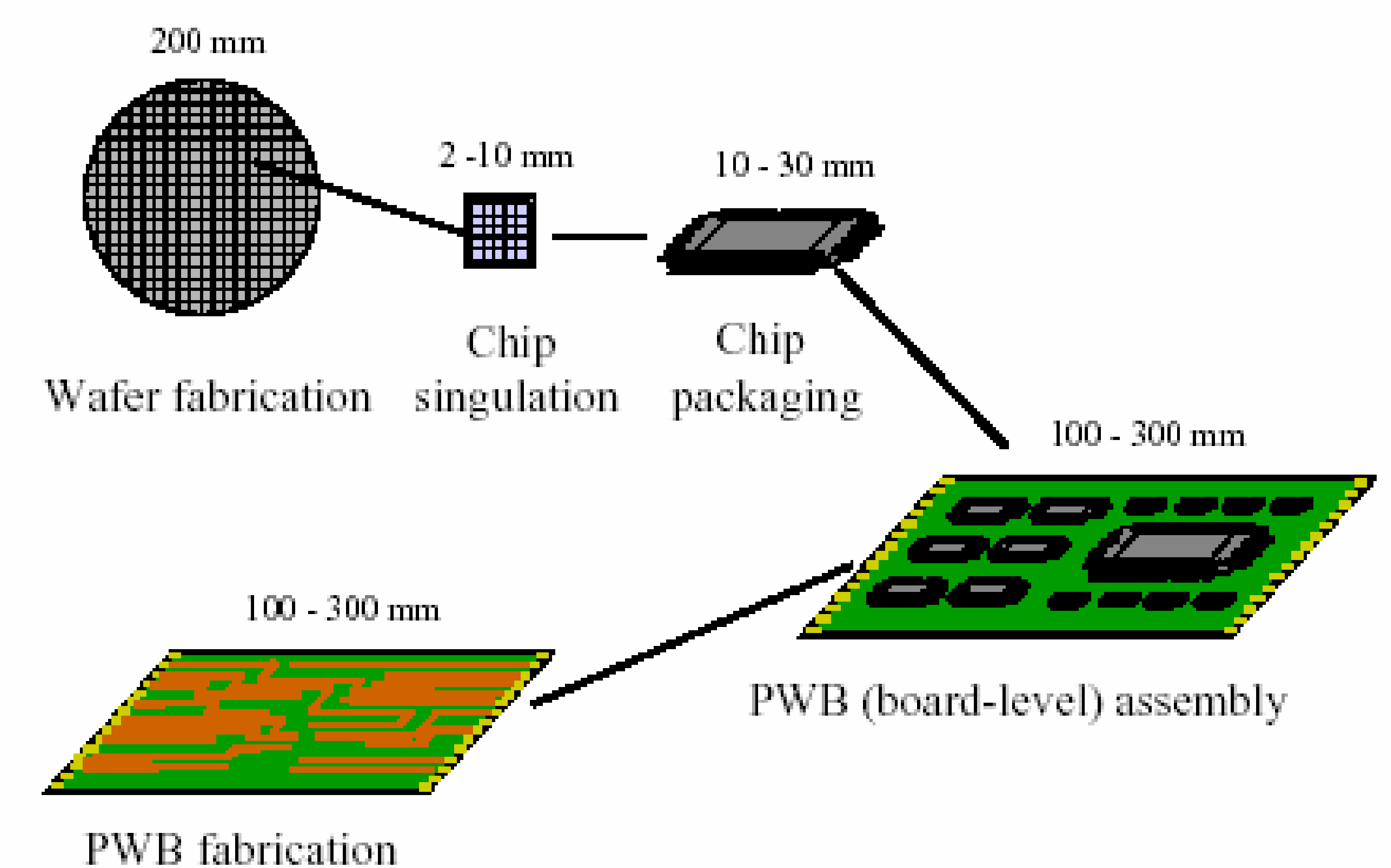
Focus Areas of Electronics Industry

- Materials – elimination/substitution
- Resource consumption – product volume reduction
- Design for disassembly/reuse
- Board-level assembly technology and materials
- Reduction in number of materials
- Emissions reductions
- End-of-life disposition

Electronics Manufacturing

- **Sub-industries**
  - **Wafer fabrication and chip-level packaging**
  - **Printed wiring board (PWB) manufacture and board-level assembly**
  - **Display manufacturing**
  - **Final assembly**

Wafer and PWB Fabrication



Wafer Fabrication

- Si, SiO_2, Al, and sometimes Cu
- Deposition of very thin layers and etching patterns into sub-micron features
  - Energy intensive
  - Emissions – PFCs (perfluoro compounds)
  - Ultra-clean surfaces – water use
- NSF/ERC Env. Benign Semiconductor Mfg.
  - www.erc.arizona.edu

Wafer Substrate Material

- Primarily silicon refined from silica (SiO_2), commonly known as… sand, quartzite rock
  - 2nd most abundant material on earth
- Other substrates also used
  - GaAs, InP, InAs, and other III-V semiconductors
  - CdTe, HgSb, PbSe, and other II-VI semiconductors
  - Sapphire (Al_2O_3 single crystalline substrates)
  - Glass (Fused silica or borosilicate glasses)

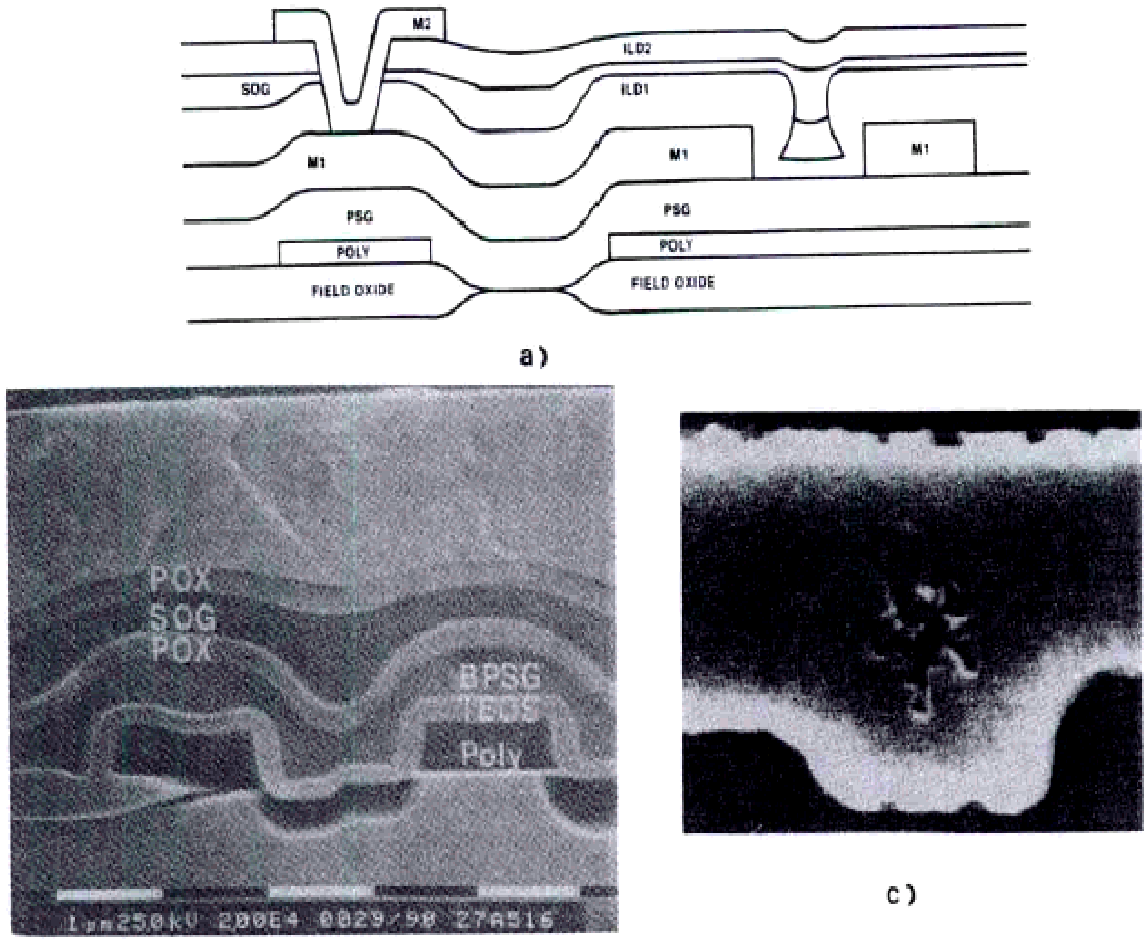
Substrate Material Refining

- First stage: metallurgical grade silicon (MGS)
  - Submerged electrode arc furnace using quartzite and coal, coke, and wood chips
- Second stage: HCl reaction with MGS
  - Forms chlorosilane liquid products in fluidized bed reaction
- Third stage: electronic grade silicon
  - Reacts chlorosilane liquid with hydrogen gas at high temperatures to produce purified polycrystalline silicon droplets
- Extraordinary purity in EGS product

Substrate Material Refining

- **Fourth stage: single crystal growth from electronic grade silicon**
  - **Liquid melt process to recrystallize silicon from starting seed crystal**
  - **High purity starting materials, combined with controlled dopants for electronic characteristics in final substrate**
  - **Crystal boule (ingot) is sliced and polished to form substrate wafers**

Cross Section of CMOS Device



a) b) c)

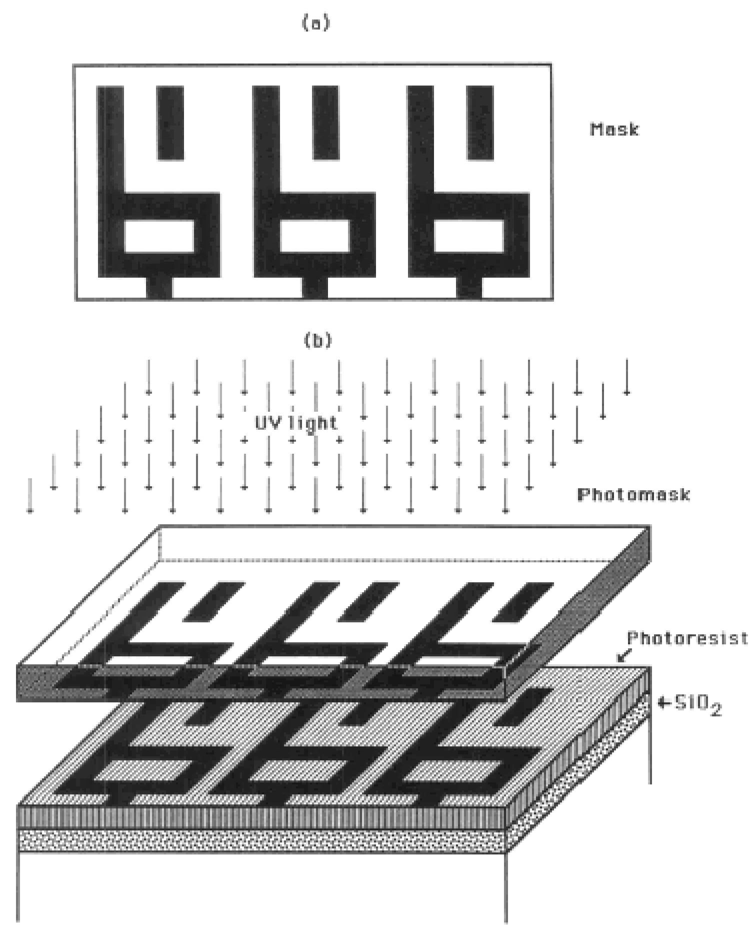
CMOS – Complementary metal oxide semiconductor

CMOS Fabrication Process Flow

- Repeated 2-D definition of depositing or diffusing, patterning, etching, and cleaning of multiple layers to define 3-D devices and interconnect.
  - Diffusion and thin film processes: dopant incorporation, oxidation, annealing, thin film deposition
  - Photolithography processes: pattern transfer from reference to photopolymer
  - Etch processes: liquid or gaseous plasma removal of patterned underlying layers

Photolithography

- **Lithography**
  - **Application of 2-D printing to form layer by layer 3-D structure**
  - **Photosensitive polymeric material**
  - **Exposure through a patterned plate**
  - **Developing photoresist for pattern transfer**



Photolithography Byproducts

- **Challenge for microelectronics industry**
  - **VOC emissions from solvents and photoresists**
    - **Major productions sites limited in total emission volume may have to shut down production for a period to keep below cap level defined by EPA**
  - **Liquid solvent waste byproducts stored for disposal**
    - **Fabs often "guarantee" BTU content with disposal contractor and incinerate or generate electric power**
    - **Significant groundwater contamination control concern**
      - **1950s-1960s industry history demonstrates several industry-practiced methods that resulted in TCE contamination**

Wafer Fabrication

- Heavy-industry
  - Coal/coke/wood chip usage in first stage
  - Electric power intensive in all stages
  - Chemical (liquid and gas) refining intensive in 1st through 3rd stages
- Solid waste silicon usually returned to earlier stages in refining process, minimizing solid waste

Wafer Fabrication

- Industry very aware of hazards and environmental impact and costs
  - Elimination or substitution of environmentally hazardous compounds
    - Trichloroethylene (TCE) a perfect example
  - Minimization of “required” liquid chemicals
    - Photoresist dispensing
    - Spray dispensing versus liquid bath processing
  - Minimization of effluent gases and neutralized liquids

Printed Wiring Boards (PWBs)

- Polymer composites, Cu (4 or more layers)
- Use of lead free solders
  - Require higher process temperatures
  - Epoxy-glass composite boards may have to low glass transition temperature (140-160°C)
  - Alternative substrates are needed
- Etched Cu lines
  - Water, energy, and chemical intensive

Printed Wiring Boards (PWBs)

- Plated through holes (PTHs) and surface metallization
  - Large amounts of water for plating baths
  - Complex chemistries (organic and inorganic)
- Lamination of layers
  - Large presses are energy intensive
- Drilling and trimming solid waste
  - As much as 50% of total material budget

Printed Wiring Boards (PWBs)

- **Completed PWB prepared with Sn-Pb solder**
- **PWB is heated to solder melting point**
- **Packaged integrated circuits (ICs) are placed on the boards (typically mechanical)**
- **Lead solder is the main manufacturing and end-of-life environmental concern**

PWBs – Mid-1990s DARPA Study

- IBM – laminate from renewable resources (lignin derived from pine trees)
- DuPont – commercial resist that eliminates need for copper passivation (oxidation)
- Dupont, Shipley, and Ormet – microvia technology with photoimageable dielectric

Microvia Technology

- Microvia - small hole in the range of 50-100 μm
- Devices need to be more portable
  - high interconnection density with finer lines and spaces, smaller holes, and decreasing thickness
  - Cell phones require from 250,000 to 650,000 blind (from outer layer to first inner layer) microvias per panel
- Most common techniques for blind vias:
  - laser drilling, plasma drilling, and photo-imaging
- www.techtra.pl/microvia_opis_eng.html (Technology Transfer Agency, Poland)

Microvia Technology

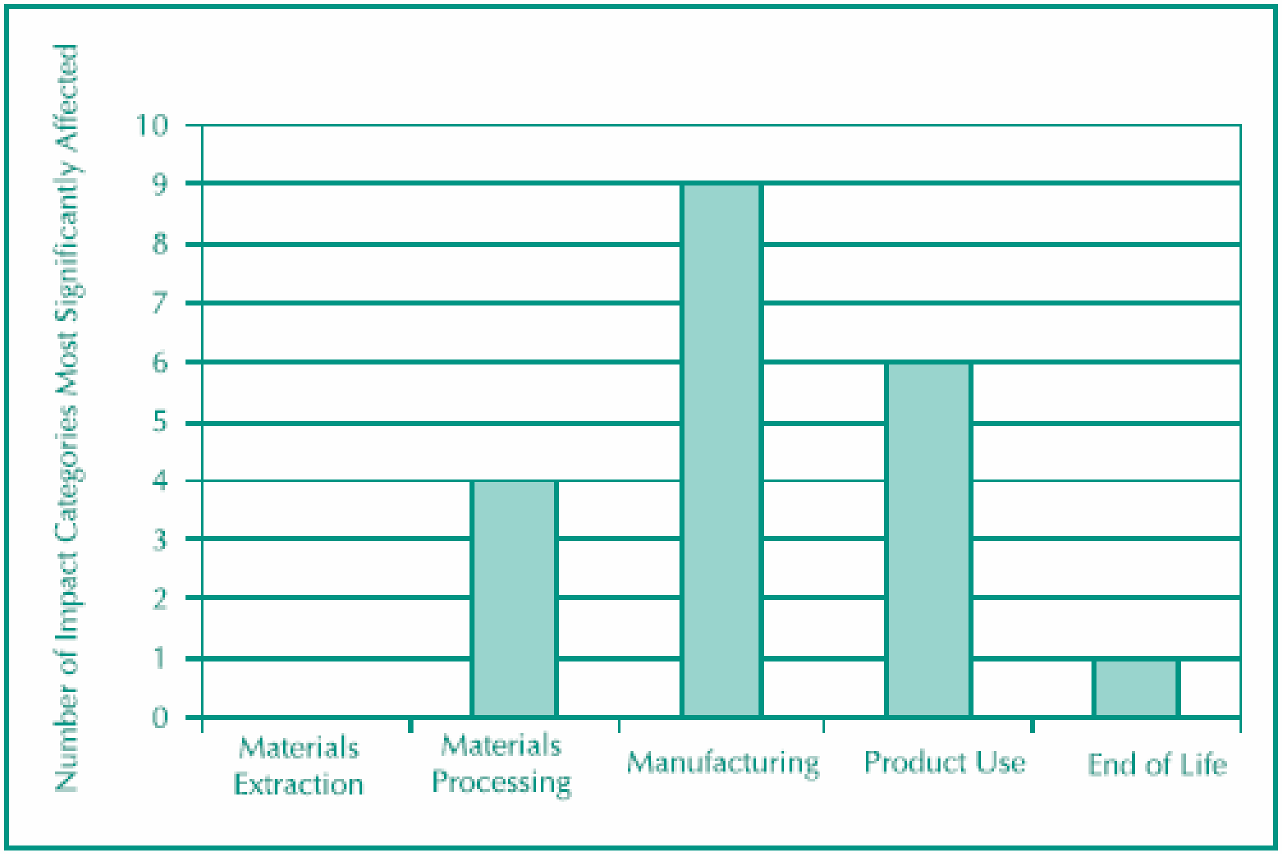
- Motivation is performance driven
- Less water and waste than conventional plated through hole (PTH) construction
- Fewer layers and smaller areas for equivalent wiring
- Reduction/elimination of drilling
- More precise equipment to maintain yield leads to less trim waste

Computer Displays

- Cathode ray tubes (CRTs)
  - Manufacturing
    - energy consumption to produce glass
  - Transportation - heavy
    - Large displays for the U.S. are made in the U.S.
    - Most small- to medium-sized displays are made in Japan
  - CRT end-of-life
    - Lead contained in the funnel and some panel glass

Computer Displays

- **Flat panel displays (FPD)**



Computer Displays

- **Flat panel displays (FPD)**
  - **Most are manufactured overseas with a proprietary process**
  - **Shredded and disposed of as a product rather than a set of materials, so hazardous substances are not controlled**

- **More good stuff: http://www.epa.gov/opptintr/dfe/pubs/index.htm#comp**

Other Components

- Nickel/cadmium batteries
  - Ban by WEEE Directive due to cadmium
  - Switching to lithium batteries
- Hard drives (IBM, San Jose)
  - Formerly Ni and Mg plated over Al
  - Switched to a glass substrate
    - Doesn’t require Ni adhesion layer
    - Simplified process also environmental benefit
    - Glass disks are recycled by a local recycler

Electronics Assembly

- ❖ Estimated that more than 3 billion pounds of plastics used in 1996 electric and electronics industry
  - ➢ 23% by weight of a PC is thermoplastic
  - ➢ Expected only to increase (cost, weight)
- ❖ Environmental concern is at end-of-life
  - ➢ Recycling issues: co-mingling and coatings
  - ➢ Incineration issue: brominated flame retardants (BFRs)

Flame Retardants

- **Halogenated flame retardants (Cl and Br)**
  - **Organic compounds**
  - **Detrimental to health and environment**
  - **Numerous commercial chemicals**
- **WEEE Directive concerns**
  - **Formation of dioxins and furans during incineration and recycling**
  - **Persistence and bioaccumulation**
- **Lots of good stuff in WTEC Report on BFRs**

Electronics End-of-Life

- Historically products have been easily recycled
  - Significant amounts of precious and base metals (steel housings)
- Now, recycling is less economically viable
  - Silicon chips no longer gold-backed
  - Smaller printed wiring boards (PWBs)
  - Thermoplastic housings
  - Less costly, shorter life components

Electronics End-of-Life

- **Pressure to recycle is growing**
  - **Low landfill space (Europe, Japan)**
    - **Netherlands – producer is responsible for cost of recycling**
  - **Increasing rates of obsolescence**
  - **Contamination (MA ban of CRT land-filling)**
- **Proper end-of-life handling needed**
  - **Sensitive information/technology (DoD, DOE)**

Electronics End-of-Life

- **Reuse**
  - **Limited reuse options due to obsolescence**
  - **After 5 years computers have virtually no value**
- **Recycling**
  - **Metals – well established**
  - **Glass – lead content inhibits recycling**
    - **CRT glass reused in CRTs**
    - **Leaded glass used in glass bricks (Florida)**
  - **Thermoplastics – dependent on higher petroleum prices**

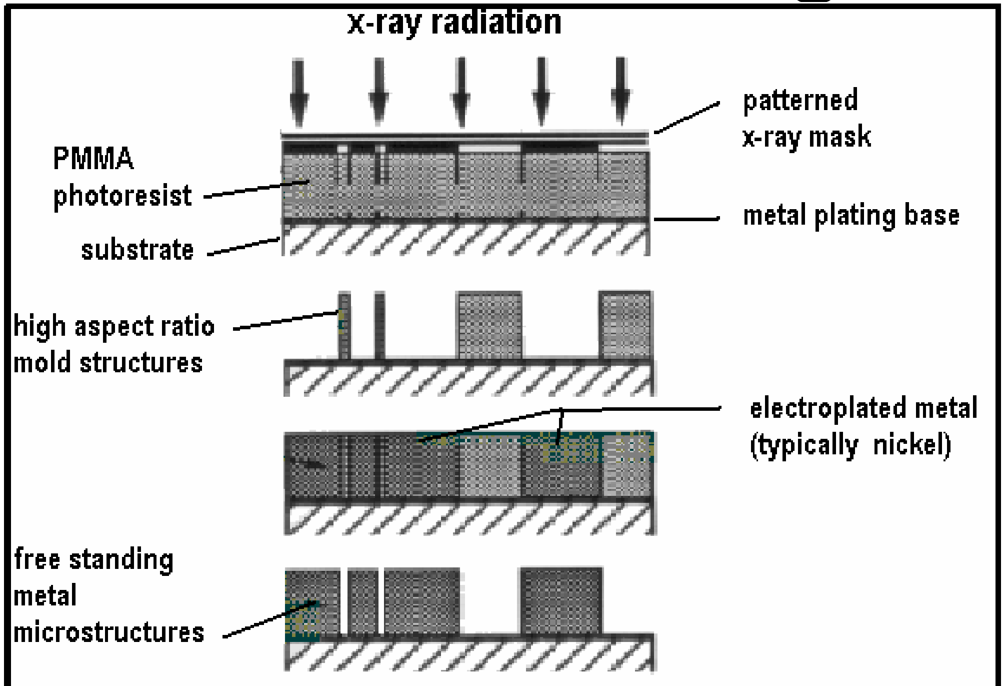
MEMS and Micromachining

- **Size Scales Used in MEMS**
  - 1 micrometer is one-millionth of a meter;
  - 8 micrometers is ~the diameter of a human red blood cell;
  - 25 micrometers is ~0.001 inches;
  - 100 micrometers is ~the diameter of a hair and the thickness of a sheet of paper.

Comparison of Microlithography and Micromachining

- **Lithography**
  - optical energy, chemical energy
  - forceless
  - easily adapted to mass production
  - expensive for small numbers of parts
- **Direct Machining**
  - mechanical failure of material
  - large forces per volume of material removed
  - easily adapted for small numbers of parts
  - expensive for large numbers of parts

Basic Steps in DXRL and Electroforming



Basic steps of the deep x-ray lithography process: The x-ray radiation comes from a synchrotron, is selectively passed or blocked by the patterned mask absorber, and penetrates the photoresist and deposits energy to expose the resist. The photoresist is then developed leaving cavities down to the metal plating base (provided sufficient energy was deposited to completely expose the resist). Metal is then electroplated onto the plating base and the cavities are filled. The remaining resist is removed leaving free-standing metal microstructures.

Thermopneumatic Micropumps
200 microliters per minute (no back pressure)