ENVIRONMENTALLY SOUND ASSEMBLY PROCESSES

The worldwide semiconductor market reached $137 billion in total revenues in 1997 (1). The assembly of these semiconductor devices into value-added electronic components and products represents a major, if not the dominant, economic activity in many countries. The introduction of the concept of product stewardship (2) into electronic products has become increasingly urgent as consumers realize that most of the electronics products end up as solid wastes in landfills after the end of their service life (3). An integrated solution must be found to solve the problems associated with the creation of these products; that is, it is important to minimize the environmental impacts from production activities that are associated with devices design, assembly, and product end-of-life management.

This article covers current environmentally sound assembly processes with an emphasis on processes that produce faster and smaller electronic products such that the goal of energy and material conservation can be achieved during and after product assembly. Specifically, the following subjects will be discussed in detail: (1) processes and materials selection, (2) pollution prevention methodology, and (3) product end-of-life management.

ENVIRONMENTAL AWARENESS

The need to phase out chlorofluorocarbons (CFCs) and other related ozone-depleting chemicals in the early 1990s triggered an international competition that has since resulted in more than 80% reduction in production of all CFC materials in 1997 (4). Companies working cooperatively with governments have produced many CFC alternatives that also make good profits (5). Encouraged by the dramatic success of the CFC elimination programs of the electronics industry, both the devices and packaged electronic products sectors expect more stringent environmental regulations to be imposed by the government. These proposed regulations may include restrictions on perfluorinated compounds (PFCs) usage (PFCs are a common plasma etchants) because PFCs are extremely stable in the atmosphere and produce heat-absorption effects that are up to 25,000 times more potent than those of carbon dioxide (6). Toxic metals that are currently used in the consumer products are facing similar potential regulations. Specifically, the use of lead in today's electronics assembly may be jeopardized by the past success following the elimination of lead in the paint and gasoline industries. The drastic reduction of lead deposition in rural landscapes far away from polluting sources represents the critical criterion for which the success of the elimination program is judged (7). This result, in conjunction with other environmental movements (8), may justify strict future regulations on toxic metals such as lead, cadmium, and antimony used in various electronic appliances.

It has been demonstrated repeatedly that an environmentally sound manufacturing process can also be a profit-making one (5). Miniaturization of electronic packages and process simplification are the keys to profits, in addition to waste minimization and efficient recycling. Miniaturized packages such as chip-scale packages (CSPs) (9) occupy much less (only 20%) footprint (area on the circuit board) as compared to conventional plastic quad flat-packs (PQFPs) and consume less power at a faster clock speed. The goal of providing consumers with high-performance electronic products without polluting the environment in which these products are manufactured can be realistic and achievable.

The rules that govern the "green" assembly processes can be summarized as follows:

- Avoid applying steps that do not add value.
- Avoid using materials that cannot be recycled or reused.
- Use materials that do not cross-contaminate each other.
- Use material- and energy-efficient processes and tools.

Specific examples of these rules will be discussed in the respective sections.

Other important environmental aspects can be addressed beyond assembly level. Concepts such as design for disassembly (DFD) (10) provide guidelines for environment-friendly design that emphasizes waste minimization and product recyclability. It is critical to design products that are easy to disassemble because this improves the ability to reuse or recycle parts of used or defective products. One important conclusion from the DFE (design for environment) studies is the

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necessity of minimizing the number of mechanical fasteners, such as screws and rivets, on the circuit boards that may interfere with product recycling. Elimination of lead-containing solder, reduction of PFC and hazardous air pollutant (HAP) emission, and reduction of energy consumption in integrated circuit (IC) manufacturing have all been proposed in the 1997 issue of *National Technology Roadmap for Semiconductors Technology Needs* (11).

ENVIRONMENTALLY BENIGN MATERIALS SELECTION

An assembly process starts with proper selection of materials that will minimize impacts on the environment during assembly. Materials selected should allow (a) hazard-free handling during assembly and (b) ease of recycling and disposal at the end of product life.

Circuit Boards

The assembly process begins with a patterned substrate of either a ceramic substrate or mutilayer fiberglass-reinforced epoxy board. Ceramic substrates are generally not recyclable and therefore is not the preferred choice. The circuit boards contain different glass types and glass-to-resin ratio that produce different dielectric constants to fit different applications. In general, the common FR-4 board contains 55% (in volume) of epoxy resin reinforced with 45% of borosilicate (E glass) fiberglass, that gives a dielectric constant of 4.9 and a glass transition temperature of 145°C. The epoxy resin is also blended with brominated fire retardants to render the board self-extinguishing in case of fire. Because of the presence of brominated fire retardants in the board, it is difficult to incinerate and also produces toxic dioxin in this potential energy recovery process (12). Ideally, a nonhalogenated (e.g., hydrated alumina) and heavy-metal (e.g., antimony)-free (13) fire-retarded organic board is the preferred circuit board choice.

Surface Finish

The patterned copper structures such as bondpads and vias that exist on the circuit boards are prone to air oxidation if not protected. Various surface finishes are available to protect these exposed copper structures. These include solder [hot air solder leveled finish (HASL)], organics [organic solderability preservative (OSP)], nickel/gold, and palladium. HASL is still the largest volume surface finish in use today (14). However, this solder-based finish does not meet either the coplanarity requirements for current fine pitch input-output (IO) leads assembly or the potential lead restrictions in the future. All other metallic finishes are either too new to establish reliability statistics (for palladium) or not cost-effective (for nickel/gold), and also they generate more processing waste than the OSP finishes (15). OSP treatment involves only three simple steps: surface cleaning, immersion, and drying. OSP protects the exposed copper from oxidation by forming organic copper complexes (16) on the copper surface that effectively prevent further oxidation. The copper complexes decompose or volatilize at reflow temperatures, thus rendering an oxide-free copper surface for soldering. Substituted benzotriazoles and immidazoles are the two most commonly used OSPs (17). They provide a cost-effective way to protect the circuit boards with little energy consumption and little waste production in the treatment processes. Flat, planar surfaces that are ideal for surface mount technology (SMT) assembly give the OSP-treated boards advantages in the fine pitch applications. However, all OSP boards are prone to air oxidation at temperatures above 100°C. Selection of proper aggressive fluxes, along with reflow in nitrogen, is required in order to produce consistently robust solder joints by using the OSP boards.

Flux

Traditional rosin-based fluxes have been the major flux materials on the market before the Montreal Protocol called for the elimination of Freon-113, the cleaning agent for rosin flux residue. Advantages of rosin-based flux include: good fluxing properties, tunability (producing different activity grades by simple formulation changes), and electrolytically stable and encapsulating characteristics (prevent reoxidation of solder and ionic migration). If a low solid flux (LSF, <2% nonvolatiles) (18) or water-soluble flux (19) is to replace the current rosin-based flux, some compromises have to be made. For LSF dispensing, an efficient ultrasound atomizer is required for a controlled flux deposition (20). This LSF dispenser produces uniformly fluxed boards that give reliable no-clean solder joints after reflow. The LSF dispenser also reduces VOC (volatile organic compound, i.e., solvents in flux) emission by using less flux in the operation. The reflow should be conducted in an inert atmosphere to avoid bad joints caused by solder reoxidation. LSF allows no post-reflow cleaning, thus eliminating the need to clean totally.

The water-soluble flux is formulated by using water-soluble organic acids as activator, water-soluble polymers (e.g., polyethylene oxides) as viscosity builder, and water-miscible/soluble solvents as the carrier. Water-soluble flux uses water as the cleaning agent and therefore minimizes the environmental impact. Since all the ingredients used are water-soluble, cleaning is an easy task, and usually pose no cleaning problems after reflow. However, the need to control the room environment (temperature and humidity) so that excessive humidity does not spoil the flux in the required work shift can be challenging. Water has a much higher heat of vaporization, and therefore the normal reflow profile may not work without significant modification. A successful VOC-free LSF using a simple mixture of 3% adipic acid in water has been demonstrated in the literature (21). A third category of the environmentally friendly flux is the thermally dissipated flux; that is, the flux volatilizes cleanly after reflow, thus leaving no residue on the circuit board. IBM (22) pioneered this approach by using a mixture of an organic activator (adipic acid), a flux base (camphor), and an organic diluent. The camphor provides tackiness to the board, and both acid and camphor thermally dissipate during the reflow operation.

The goal of soldering joints without flux can be realized by a plasma process called plasma-assisted dry soldering (PADS) (23). The process involves a principle similar to the effect of OSP to the copper; that is, it coats the solder with a compound that volatilizes at reflow temperatures. A PADS reactor uses plasma discharge in a chamber filled with fluorine-containing gases such as CF_4 or SF_6 to convert the tin oxides into tin oxyfluoride, which volatilizes to reveal a fresh, oxide-free solder surface for joining during reflow. This fluxless process has been applied successfully to flip-chip bonding of

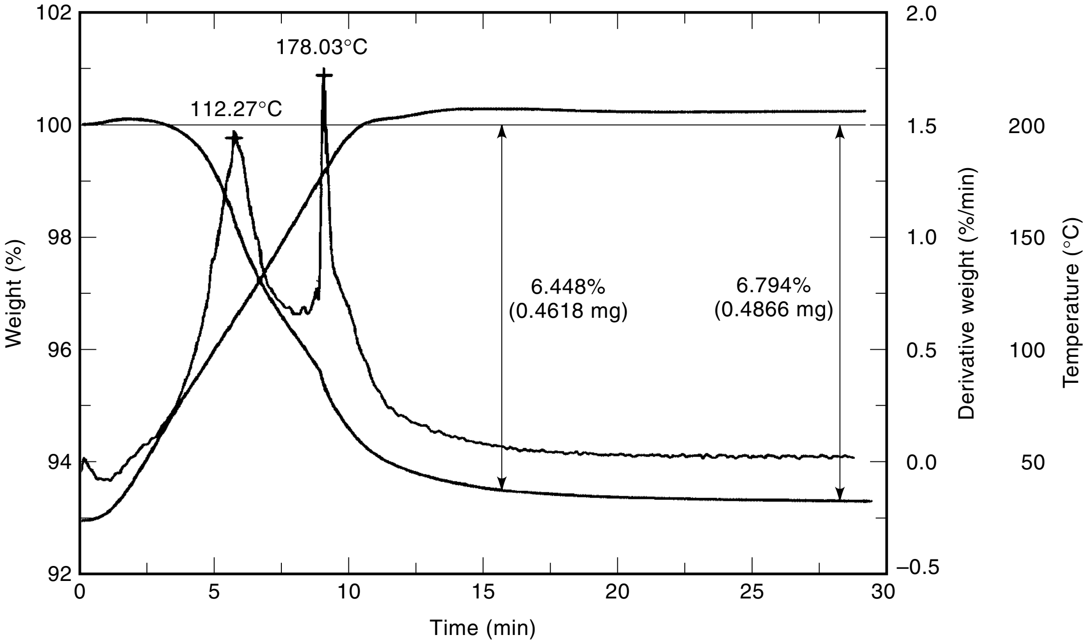

Figure 1. TGA thermogram of a typical no-clean solder paste, which shows a solder content of 93.2%. The two peaks shown on the left indicate the temperatures at which the weight loss occurs rapidly.

light-emitting diode (LED) devices that require extremely high optical transmission for display applications (24). The negative side of this process is that both CF_4 and SF_6 are greenhouse gases that cause global warming (6).

Solder Paste

Five common ingredients constitute a standard solder paste: a solder alloy, a flux, an activator, a viscosity modifier, and a solvent. For no-clean pastes the activator should not leave corrosive residue that may degrade product reliability, nor excessive inert residue that may interfere with product electrical testing. Two quick routine paste testing methods (25) include (a) the thermal gravimetric analysis (TGA) (26) to screen amount of nonvolatiles after simulated reflow and (b) the copper mirror test to screen corrosiveness; these methods are effective in selecting the right pastes. Figure 1 shows a typical TGA thermogram of a no-clean solder paste that contains a solder content of 93.2%. For fine-pitch printing, type 5 (20 μm to 25 μm) solder powder at a metal loading of greater than 88% weight produces the best results. Most solder pastes use ethyleneglycol ethers as solvent. Being a VOC and reproductive hazard, other more benign solvents such as propyleneglycol ethers will start to appear in the paste formulations. Table 1 presents a list of critical performance characteristics of different types of solder pastes.

Lead-Free Solder Paste

The obvious technique to eliminate lead in the electronic parts is to start with a lead-free solder paste. There are many types of lead-free solder alloys to choose from, but availability of these alloys for paste formulation is only the first step. Almost all of these solders contain high concentrations of tin, some of which are almost pure tin (e.g., Sn/Ag 96.5/3.5, Sn/Sb 95/5), which may promote extensive intermetallic formation with nickel and other barrier metals (27). The selection of correct lead-free solder paste for a particular assembly process is a complex process that involves proper design of barrier metallurgy and boards that withstand the reflow temperature, in addition to the standard solder paste performance tests mentioned in the previous section.

Encapsulant

There are many different types of encapsulants available to the electronics industry, and molding compounds occupy the bulk of the current packaging market. Other encapsulants such as glob tops and underfills occupy only a small fraction of the application. Although quite different in their physical forms (molding compounds are in solid flakes, while glob tops and underfills are liquid in syringes), these encapsulants are quite similar in chemical composition. All consist of a mixture

Table 1. Critical Performance Characteristics of Different Types of Solder Pastes

Solder Paste Type	Printability	Slump	Solder Balling	Tackiness	Wetting	Profile Window	Reflow Atmosphere	Work Life
Standard	Good	Good	Good	High	Good	Wide	Air	Long
No-clean	Medium	Medium	Good	Medium	Medium	Medium	Air/nitrogen	Long
Low solid	Poor	Poor	Poor	Low	Poor	Narrow	Nitrogen	Medium
Water-soluble	Poor	Poor	Poor	Low	Poor	Narrow	Air/nitrogen	Short

of an epoxy resin, a curing agent, and an adhesion promoter, with the bulk being a silica filler. Molding compounds use a semisolid curing agent (phenol novolak) and a higher filler loading (80% to 90% of silica), resulting in a solvent-free mixture that cures without VOC emission. The length of the time for a molding compound to cure is directly proportional to the energy consumption of the molding operation, hence the environment impacts. A molding compound that cures faster is a preferred choice.

The presence of liquid curing agents or solids that are dissolved in reactive solvents in the underfills and glob tops are the keys in differentiating them from the molding compounds. Typical liquid curing agents include hexahydromethyl phthalic anhydride (HMPA), nadic anhydride (NDA) (28), and *N*-cyanoethyl-2-ethyl-4-methyl imidazole (EMIN). Reactive diluents are solvents that also participate in epoxy polymerization. Common reactive diluents used in underfills include phenyl glycidylether and γ-butyrolactone. HMPA-containing encapsulants require an intermediate soaking step in curing so that this volatile compound can be anchored on the polymer chain first before fully cure can occur. Contrary to HMPA, the EMIN-containing underfills can be "snap-cured" without emitting a significant amount of VOC, which makes this type of encapsulant more environmentally friendly.

Conductive Adhesive

Two major functions that a conductive adhesive serves in the circuit boards assembly are (a) components anchoring and (b) interconnection. Component anchoring using adhesives are common practices in heat spreader attachment and through-hole device attachment before wave soldering. Examples of adhesive interconnects are polymer flip chip (29) and anisotropic conductive film (ACF) interconnects (30). Advantages of adhesive interconnects include simple operation and environmental soundness due to the absence of lead alloys. ACF interconnects are self-encapsulated (i.e., no underfill operation is needed), and therefore they can be the most environmentally friendly type of assembly process to use.

Two types of resin polymers form the backbone of adhesives for assembly: epoxies and cyanate esters. The standard formulation involves mixing 50% to 70% of silver flakes into a resin-curing agent mixture to form the isotropic conductive adhesives. The ACF uses 1% to 5% of conductive spheres in a similar resin-curative mixture to cast a B-staged (50% cross-linked) film of 25 μm to 100 μm thick. Both silver flakes and conductive spheres serve to conduct electricity. The anisotropic nature and the low metal loading in the ACF prevent it from being an effective heat conductor, and this precludes ACF from being used in applications that require high thermal conductivity. Conductive spheres are made from electroless plated glass spheres or divinylbenzene–cross-linked polystyrene beads. Both silver and nickel/gold have been used as conductive coatings on the spheres. Common resins used in conductive adhesives include bisphenol A diepoxide, bisphenol F, and novolak epoxides. EMIN and other substituted imidazoles are common curatives in the adhesives. Bisphenol F-type resins develop superior adhesion to FR-4 boards and solder masks, making them a preferred choice. The cured cyanate esters form three-dimensional dendritic triazine cage structures (31) that also serve as a built-in desiccant in hermetic packages to maintain an extremely low moisture within the package. This unique property gives cyanate ester-based adhesives an advantage over other epoxy-based materials when low moisture within the package is critical.

The final forms of the adhesives can be found in premixed liquid syringes, B-staged tackiless film, or bulk two-part (resin and curing agent) jars. Syringes and films are more effective in terms of material utilization, but the two-part packages are convenient for long-term room temperature storage.

ASSEMBLY PROCESS CONSIDERATIONS

An environmental-friendly assembly process should primarily focus on reducing the number of steps to achieve maximum product yields by consuming the least amount of energy. Secondary concerns such as waste minimization and product recyclability are also important. A typical circuit board assembly line consists of automatic pick-and-place robots that are fed by bumped die or device packages mounted on tape and reel or on waffle packs in either an SMT format or a through-hole interconnect (THI) insertion format. The bare circuit boards are carried by a conveyor belt to an in-line dispenser that is capable of depositing the following three different materials on selective areas of the board: a solder flux, a solder paste, or an adhesive. The selection of materials depend on the nature of the assembly processes. The dispenser can be a pneumatic pump or a screen printer, depending on the viscosity and amount of the material to be dispensed. Bumped die or other device packages are then picked, placed (for SMT), or inserted (for THI) in the selective board areas where the dispensed materials are located. A thermal treatment that reflows the solder bumps to form the device-board interconnects or that cures the adhesive to hold the devices on the board follows the components placement or insertion. For THI devices a new cycle of flux application and wave soldering (boards pass over flowing molten solder pool) completes the through-hole joining process.

After solder joining, an encapsulation process (underfill, glob top, or overmold) is then performed to protect the mounted bare die in the direct chip attach (DCA) process. Encapsulation processes that are time-consuming must be optimized or eliminated entirely by materials improvement or process changes. This can normally be achieved by using snap-cure epoxy as encapsulants or by applying a process that does not require encapsulation. For those prepackaged components such as ball grid arrays (BGAs), board level encapsulation is not normally required, and therefore significant process simplification is achieved. Figure 2 shows the simplified assembly process flows for three major assembly operations (DCA, SMT, and mixed technologies). All cleaning steps after reflow or wave soldering have been removed to conform to environmental friendliness. This can be done by using no-clean solder pastes in a high-purity nitrogen (<20 ppm oxygen) reflow oven to ensure reproducibility of reliable solder joints (32).

The continuing shift of the electronic assembly processes from THI to SMT in the past decade has produced more than 60% of the market share for SMT-assembled packages (14). Process simplicity is the key to the success: it involves only three steps: print, place, and reflow. Surface mount technology is a good example of the "green" assembly process that

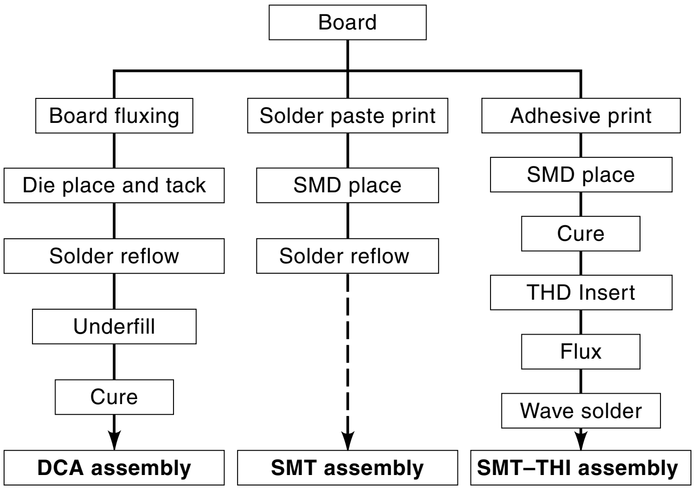

Figure 2. Simplified assembly process flows for three major assembly operations [DCA (direct chip attach); SMT (surface mount technology), and SMT-THI (surface mount technology–through hole interconnect)]. SMD (surface mount device); THD (through hole device).

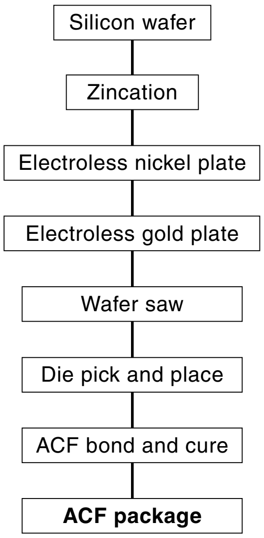

Figure 3. A process flow for the ACF-based bare die packaging assembly.

uses less material by increasing package interconnect densities through array-type IO leads. Ball grid arrays, especially plastic ball grid arrays (PBGAs), for example, have become the standard SMT components. To shrink the area of array interconnect components further, CSP inevitably becomes SMT's next logical target. Table 2 presents a comparison among the SMT, THI, and DCA assembly processes.

Certain polymer-based bare die assembly processes do not require post-bonding encapsulation, and thus they provide potential solutions to the slow encapsulation problem. The two underfill-free adhesive-based processes are anisotropic conductive film (ACF) (30) assembly process and area bonding conductive (ABC) (33) adhesive interconnect process. ABC is a special form of ACF that uses area-patterned conductive and non-conductive epoxy to form interconnects and encapsulation simultaneously during bonding operation. Figure 3 describes a process flow for the ACF-based packaging assembly.

Key to the success of all adhesive interconnects is a stable metallic bonding surface on the top of the aluminum bondpad, whether it is coated with metal finishes (e.g. Ni/Au, or Ti/W/Au) or, more preferably, by a simple maskless chemical process to preserve the Al surface from oxidation. One such approach is by using a cyanate ester-based adhesive in combination with palladium/chelate aluminum surface treatment (34) to form electrically reliable bumps on aluminum bondpads. The right side of Fig. 4 represents a process flow for this simple bondpad preservation process.

The solder bonding process is self-aligned; that is, the device-board interconnects are surface-tension-controlled so that even with some degree of bump-pad misalignment (up to 30%) the assembled parts still exhibit good joining after reflow. This self-repairing nature creates a larger processing window for solder assembly than those of adhesive-based processes. However, the need to maintain a solder-wettable surface in the metallurgical bonding does impose major constraints on the process—mainly the presence of flux to render solderability, and its removal after it has served this function.

Flip-Chip Advantages

To fully utilize the advantages of SMT and its potential environmental benefits, all components to be assembled should be SMT-compatible. The smaller-footprint SMT-compatible packages such as CSPs are on the focal points. Two different device-carrier interconnect methods are in the mainstream CSP design: flip chip and wirebond. Examples of the CSPs are represented by Motorola's JACS-Pak (flip chip) (9) and by Tessera's μBGA (wirebond) (35). Although wirebond offers simplicity and maturity of the bonding technology to produce effective device-carrier interconnects, serious performance limitations do exist in this approach. High package parasitics (both inductance and capacitance) impair wirebond devices' performance (36) as well as larger footprint and longer interconnect distances in the final packages, which also demand higher power consumption. All these drawbacks bear conse-

Table 2. A Comparison Among the SMT, DCA, and Mixed Assembly Processes

Process	Number of Process Steps	Interconnect Density	Material Utilization	Disassembly	Solder Recyclability
SMT[a]	3	High	High	Easy	Good
DCA[b]	5	High	High	Difficult	Medium
Mixed	6	Low	Low	Difficult	Poor

[a] SMT, surface mount technology.
[b] DCA, direct chip attach.

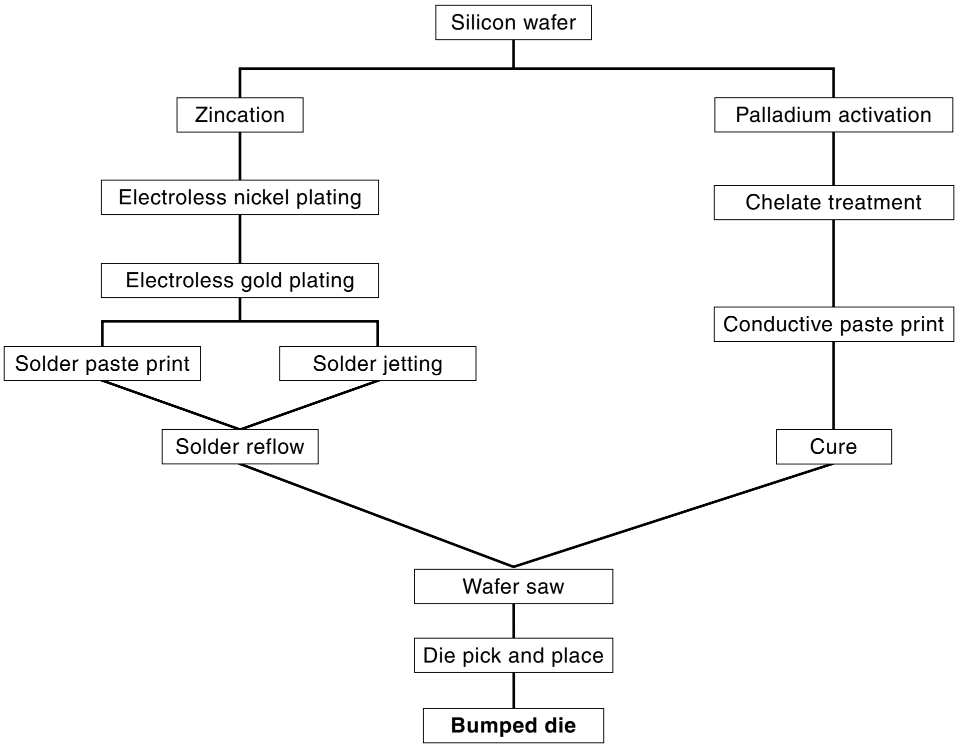

Figure 4. A process flow of an electroless nickel/gold (left) and polymer (right) wafer bumping.

quences that can have negative impacts on the environment. Fortunately, performance, power consumption, and material utilization can be improved significantly if flip-chip interconnects are incorporated in the package design.

Two major flip-chip material approaches currently exist: metallurgical and polymeric. The metallurgical flip-chip packages use solder bumps to connect devices to the substrates, while polymeric flip-chip packages use conductive adhesives to serve the same function.

Wafer Bumping

The prerequisite for an environmentally sound metallurgical flip-chip assembly process is an efficient wafer bumping process. IBM's flip-chip wafer bumping process (37), termed C4 process, which is an abbreviation for controlled collapse chip connect, was invented 30 years ago. The original process uses a molybdenum shadow mask to define a sequential vapor deposition of a high lead alloy (95% Pb and 5% Sn) onto device bondpads. Due to a long trajectory (for uniform deposition) and small apertures (for fine pitch bondpads) of the mask, solder utilization rarely exceeds 0.1%. The evaporative nature of the process also carries a poor energy efficiency tag. The need to clean evaporation chamber, mask, and wafer holder accessories and subsequent disposal of the lead-containing wastes make this bumping process one of the least environmentally sound bumping processes. Other bumping processes have also been developed, including E3 (evaporated extended eutectic) bumping (38), which is a variant of the C4 and hence has similar undesirable environmental impacts.

Nonevaporative Wafer Bumping. Electroplate solder bumping and electroless bumping/solder print (39) are the two more environmentally friendly bumping techniques. Both processes can reach a high degree of solder deposition efficiency (>90%). The electroless bumping involves maskless deposition of electroless nickel as a diffusion barrier, and a flash of Au is deposited subsequently by immersion of the wafer in a cyanide-free electroless gold sulfite bath (40). The bulk of the flip-chip bumps are formed by stencil-printing of solder on top of the Ni/Au under bump metallurgy (UBM). Due to the maskless nature, coating, developing, and stripping processes are all but eliminated in the bumping operation (41). The combination of the ability to choose various nonlead solder compositions and efficient metal deposition with cyanide-free gold baths makes the electroless bumping one of the most flexible and environmentally friendly flip-chip bumping processes available. The left side of Fig. 4 shows the process flow of an electroless nickel/gold wafer bumping flow.

Solder Jetting. This is a wirebonder equivalent of the flip-chip wafer bumping machine. Wallace (42) first demonstrated the feasibility of controlled generation of monodispersed molten solder droplets. Based on a similar operational principle of an ink-jet printer, molten solder droplets are forced out through capillary tubing by a piezoelectric actuator and deposited on the UBM. Oxide formation on the surface of the molten solder jet was shown to have a drastic effect on the droplet formation process, thus reflecting the importance of atmospheric control in the yield of bumps formation. The UBM can be of any type of solder-wettable surfaces—for example, gold, nickel/gold, or organic solderability preserved copper. Solder-jet wafer bumping eliminates all solder printing operations, which include stencil fabrication, solder paste application, stencil cleaning, and associated hazardous waste disposal. Solder utilization efficiency can be close to 100% under optimum jetting conditions. However, the durability of the jetting head must be improved significantly before this tool can be used in production.

Polymer Bumping. The advantages of polymer bumping include lead-free, flexible, and fatigue-resistant bumps, process simplicity, and no-clean. A surface treatment is applied to the device bondpads such that the conductivity between the adhesives and bondpads interface can be maintained throughout the product life cycle. This surface treatment uses palladium chloride to activate the aluminum bonpad surface first, followed by a chelate immersion. The chelate Tiron (4,5-dihydroxy-1,3-disulfonic acid) forms a stable aluminum complex on the surface, thus preventing it from further oxidation. Tiron complex also catalyzes the cyclotrimerization of cyanate esters; this further enhances the conductivity of the paste if cyanate ester adhesive is used (34). Bumping operation involves stencil-printing of wafers with silver-filled conductive epoxy or cyanate esters under proper squeegee pressure, snap-off, and printing speed. Cure is simple and fast, and it normally does not need the complicated profiling such as that required by solder pastes. High bumping yields ($>99\%$) have been achieved for small-pitch (150 μm) and low-bump-height (<40 μm) devices (43).

CFC-Free Cleaning Processes

The assumption that circuit-board cleaning after reflow is a non-value-added operation is now subject to debate (44). The primary incentive in promoting a no-clean process was a *reactive* response to the Montreal Protocol that mandated an aggressive CFC elimination agenda. As more and more cost-effective cleaning technologies become available to the industry, cleaning seems to be a logical process step to pursue in some high-frequency applications. These applications require zero residue level on the boards to reduce parasitic capacitance and crosstalk. The wafer bumping process, which tolerates no flux residue on the wafer after reflow, is also an important product line that demands the necessity of cleaning.

Aqueous Cleaning. This cleaning process has its roots in the common household cleaning method of using soap in water as the cleaning agent. Numerous modifications to this through using a mixture of nonionic surfactants and a strong base (45), organic (tetramethylammonium or choline hydroxide) or inorganic (KOH or carbonate), have since greatly improved cleaning efficiency. Aqueous cleaning is the cleaning method that emits virtually no VOC under normal operation conditions. In the past, problems associated with aqueous cleaning prevented proliferation of this potentially “green” process for the following reasons: (a) It required a high pH ($\sim$11) and moderately high surfactant (5% to 10%) concentration to work, (b) chelating agents in the suractant made heavy metals separation difficult, if not impossible, in the waste effluent, and (c) it is difficult to reduce the high BOD (biological oxygen demand, a method to quantify pollutants in water) in the effluent to meet regulatory requirements (46). With recent advancement in the surfactant technology, new “splittable” surfactants (47) that improve or eliminate most previous problems have become a reality. The new surfactant performs emulsification and cleaning functions at high pH and stops functioning and phase-separated in waste treatment tanks when pH is lowered by neutralization. This facilitates the reduction of BOD by surfactant removal, and thus it also allows effective separation of heavy metals from the waste stream by standard precipitation techniques.

The cleaning action begins with an array of rotating brushes that are partially immersed in the cleaning solution of an aqueous cleaner. The wave-soldered circuit boards are carried under the brushes where saponification (hydrolysis) occurs. The basic ingredients in the cleaning agent converts insoluble flux residue into a water-soluble form that dissolves in water. After cleaning, high-pressure deionized water spray removes traces of ionics; this is then followed by hot air dry to complete the cleaning cycle. Fine-pitch SMT assembly that contains reflowed parts of small geometry may not work with aqueous cleaning, due to the intrinsically high surface tension of water that prevents effective penetration. This is where the solvent-based semiaqueous cleaning is designed to work.

Other nonsurfactant-containing aqueous cleaners using ozonated water as the cleaning chemical has also been reported (48). Cleaning performance judged by residual metals and particles on the substrate surfaces was found to be better than the standard ozone-free mixture. This cleaning method has limited applications and is ideal for ceramics or wafer surface cleaning before bumping. This process may replace the standard plasma wafer cleaning that uses CF_4 or SF_6, both of which are subjects of regulations due to their global warming potential (6). On-site ozone abatement is a simple sulfite neutralization process, which is also compatible with current waste treatment facilities.

Solvent-Based Semiaqueous Cleaning. This cleaning process represents the mainstream of cleaning in the electronics industry due to its effectiveness in cleaning both SMT and THI parts. A solvent or solvents mixture that selectively attacks or dissolves flux residue constitutes the key element of the process. Unit operations include boards solvent immersion, deionized water spray, and hot air dry. All are completed in a conveyor-driven cleaning machine (46). Proper selection of solvents that remove the residue without attacking other elements on the circuit boards (solder, solder mask, adhesive, die markings, device passivation, and boards) is the primary consideration for selection. Secondary considerations include toxicity, flash point, biodegradability, recyclability, loading, stability, and cost. Only when most of these considerations are met can a solvent enter its rigorous final qualification phase.

Terpenes are among the first solvents that enter the qualification process. Originally, terpenes were natural essence oils isolated from pine tree saps (pinene) or from citrus peelings (limonene). Currently, most cleaning-grade terpenes are from synthetic sources. Terpenes possess part of the rosin molecular structure, and in fact they are the precursors of rosin in the plants' biosynthesis path. This makes them effective solvents for rosin-based fluxes. For the same reason, terpenes may not work on non-rosin-based fluxes, and other solvents must be used. The unsaturation in the rosin hydrocarbon chain makes them susceptible to air oxidation, resulting in both loss of cleaning capability and gum formation in the cleaning tool. Wong et al. (49) reported a detailed account on the decay of terpene solvents during cleaning. Other effective solvents that have since emerged include esters, alcohols, and miscellaneous solvents from which a full spectrum of applications are covered. Table 3 lists some common characteristics of solvents that have been evaluated as flux residue cleaner.

Table 3. Characteristics of Solvents That Have Been Evaluated as Flux Residue Cleaners

Solvents	Residue Removability	Flash Point	Toxicity	Loading	Recyclability	Stability
Terpenes						
Limonene, pinene	Good	Low	Low	High	Low	Low
Esters						
DBE[a]	Medium	High	Low	Low	High	Low
Lactates	Medium	Medium	Low	Medium	Low	High
Alcohols						
IPA[b]	Low	Very low	Medium	Low	Low	High
DAA[c]	Low	Medium	Medium	Low	Medium	Medium
THFA[d]	High	High	Low	High	High	Medium
Other						
DPGE[e]	Medium	High	Low	Medium	High	High
NMP[f]	Low	High	Medium	Low	High	High
Isoparaffin[g]	Low	High	Low	Low	High	High

[a] DBE, dibasic esters of C4–C6 dicarboxylic acids.
[b] IPA, isopropyl alcohol.
[c] DAA, diacetone alcohol.
[d] THFA, tetrahydrofurfuryl alcohol.
[e] DPGE, dipropyleneglycol ethers.
[f] NMP, *N*-methyl pyrrolidone.
[g] Isoparaffin, C12–C18 isoalkane solvents.

Most of the solvent-based systems perform effective cleaning with minimum usage of water and energy. Solvents are also recycled and reuse on-site. Replenishment is normally kept to a minimum by a closed-loop design (5) that reduces solvent loss. All chlorine-free organic solvents are either combustible or flammable, and strict fire and explosion-proof measures have to be taken into consideration when designing the tool and process for cleaning.

POLLUTION PREVENTION

Pollution sources exist during assembly, tool maintenance, and in post consumer products treatment. HAP, VOC, and BOD are among the common terms associated with the assembly operation that we are interested in monitoring and controlling. A broader coverage is made here to discuss the monitoring of the sources of pollution in the assembly process and the appropriate prevention methodology. The largest sector of US industry continues to invest far more in equipment that treats polluted water and air, disposes of solid waste, and so on, than it invests in preventing the production of the pollutants. Pollution prevention can be achieved by increasing efficiencies in the use of raw materials, water, energy, and other natural resources. The importance of increasing efficiency is particularly of great interest. The low efficiency of the current manufacturing processes can be represented by the fact that it takes more than 4000 liters of water to convert a 200 mm diameter raw wafer (11) into product devices. Reducing water usage can effectively cut the pollution at source. Pollution prevention is not merely making business sense, it also carries a legal obligation. The ruling of the US Environmental Protection Agency (US EPA) as specified in SARA (Superfund Amendments and Reauthorization Act), Title III, Section 313, mandates companies to report publicly on certain chemical releases to the environment. Waste reduction is the first step toward minimizing releases. The final goal should be zero release to meet no reporting criteria. Figure 5 summarizes the structure of a general waste reduction scheme (50).

Source Reduction

The most effective way of cutting waste production is source reduction. In fact, the US EPA narrowly defines pollution prevention as mainly measures taken to achieve source reduction. In the electronics assembly lines, this can be done by using less volatile cleaning agents or by eliminating cleaning entirely. Process changes (such as shifting underfill operation to ACF interconnection) that do not require underfill fall into this category. Conversion of THI to SMT is an example of product changes that reduce waste production. THI uses more solder, uses materials that are not compatible (solder and adhesives), and produces solder sludges during operation. Lead elimination in solder alloys creates opportunities for new processes; polymer flip-chip technology (29) for example, is a direct result of this effort. Switching the PFC-based wafer cleaning processes into aqueous ozonated water cleaning (48) is another example of source reduction on PFC. Implementation of cyanide-free electrolytic (51) and electroless gold (40) baths in the plating processes have achieved the total elimination of this dangerous chemical and its disposal problems in the industry.

The mere conversion of CFC-based cleaning processes to aqueous cleaning does not itself constitute a source reduction. On the contrary, the standard aqueous cleaning process produces more waste in a much diluted form than the solvent-based processes. Until there is technological innovation, such as implementation of splittable surfactants in the aqueous process, the aqueous cleaning only serves to change the form of waste rather than to reduce it.

Recent incidents of HFC-123 (hydrofluorochlorocarbon-123) leaks prompt further attention on the toxicity of the CFC substitutes (52). The researchers concluded that HFC-123 is safe as long as exposure does not exceed the 50 ppm limit.

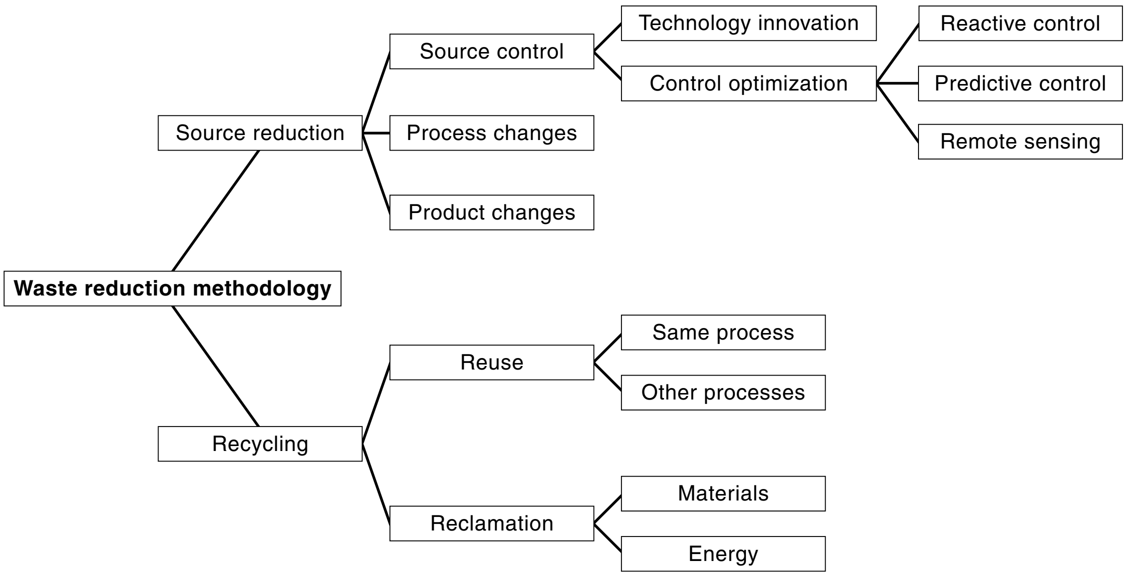

Figure 5. A tiered structure of a general waste reduction scheme.

This example illustrates the importance of monitoring and control as a means of achieving source reduction. Both reactive and predictive control (53) can be followed after the monitoring systems detect an emission. Predictive control forecasts an anticipated emission and takes appropriate measures to correct the situation before the pollution actually occurs, and therefore this is a preferable technique. Examples of applications of predictive control in the assembly lines include programmed solvent cleaner–scrubber control and loading-sensitive plating bath–sewer discharge management. Key toxic pollutants that are commonly used in the electronics industry include methyl ethyl ketone, tetrachloroethylene, trichloroethylene, dichloromethane, xylene, glycol ethers, cyanide, chromium, lead, and mercury. Source reduction of all these pollutants can be achieved by applying proper monitoring-control methodology. Table 4 shows some common techniques for monitoring the specific pollutants that are related to the electronics industry.

Recycling

Recycling involves using the material more than once in its original form (reuse) or in the degenerated form (reclamation). It represents the major unexplored area of the electronics industry's effort in cutting waste production. Due to the short product life cycles of this industry, the long-term prospects of components reuse is more challenging than in other traditional industries. The automotive industry, for example, can reuse the spare spark plugs it produced a few decades back without encountering problems, while today's personal computers can barely reuse any inventoried disk drives that are more than a few years old. The complexity of assembled printed wiring board (PWB) products is a deterrent that defies cost-effective reclamation attempts. On the other hand, current multilayer PWBs contain an average of ~600 ppm of gold (54), which is equivalent to 10 times the gold concentration in a high-grade gold ore; this can make gold reclamation from these products a profitable business. To strike a balance between pollution associated with the reclamation and effective resource recovery is an issue that needs to be carefully assessed.

Table 4. Common Techniques Used for Monitoring Specific Pollutants That Are Related to the Electronics Industry

Pollutants:	Monitoring method
VOCs[a]:	Infrared, flame ionization detector
BOD[b]:	Oxygen ion-selective electrode
Chromium:	AA/ICP[c,d]
Cyanide:	Direct ISE[e]
Lead:	Direct ISE
Mercury:	Electrochemical
Nickel:	AA/ICP/IC[f]

[a] VOCs, volatile organic compounds.

[b] BOD, biological oxygen demand.

[c] AA, atomic absorption spectroscopy.

[d] ICP, inductive-coupled plasma spectroscopy.

[e] ISE, ion-selective electrode.

[f] IC, ion chromatography.

Iji and Yokoyama (54) of NEC, Japan, developed a complete recycling scheme that involved breaking down the mounted PWBs into separate components, all by physical methods, and reused all recovered materials. This approach represents the most environmentally sound PWB recycling process to date. Since there was no generation of toxic fumes or waste water, the recycling carries little impact on the environment. However, the presence of a trace amount of lead, approximately 200 ppm, in the recovered resin–glass fiber mixture may limit its reuse as a filler in general applications. This result indicates that the use of lead-free solder or polymer interconnects should be at the top of the product life cycle if total product recyclability is desirable.

PRODUCT END-OF-LIFE MANAGEMENT

The concept of "product take back" (55) clearly identifies that manufacturers bear the final responsibility of the products they produced. An integrated model that addresses issues from product design to end-of-life (EOL) (3) product manage-

Table 5. A Summary of Products End-of-Life Activities and the Impacts

Activity	Operation	Design Implications	Cost	Environmental Impact
Resale	Recover and sale	Durability, spares	Low	Low
Remanufacture	Recover and restore	Cleanable, spares	Medium	Low
Upgrade	Improve functionality	Modular design	Uncertain	Low
Recycling	Disassemble material	Compatibility, disassembility	High	Medium
Scrap	Landfill or incinerate	Minimum value and volume	Low	High

ment has been discussed. Low and Williams (3) used the following five activities to quantify their model: resale, remanufacture, upgrade, recycling, and scraping. Table 5 summarizes the results of the study.

Resale, remanufacture, and upgrade reuse the bulk of the products and therefore are more environmentally sound than recycling and scraping. Major electronics companies realize the importance of developing products that can be reusable and recyclable. Motorola, for example, started tagging its plastic components so that when they are disassembled at EOL, proper material classification can be identified and recycled accordingly. Tagging is a simple and yet effective solution to the contamination problem. Cross-contamination of plastics has been a major problem that has discouraged recycling. Most of the plastics are not compatible and thus require classification before recycling. The impact of contamination is reflected by the low recycling volume of the plastics. Only 2% to 3% of all plastics that have been produced are recycled today. This number can increase significantly if measures such as tagging and products take-back become mandatory in the future.

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TRELIANT FANG
Motorola

ENVIRONMENTAL MONITORING/SENSING. See OCEANOGRAPHIC EQUIPMENT.