A review of stencil printing for microelectronic packaging

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A review of stencil printing for microelectronic packaging

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Abstract

Purpose – The purpose of this paper is to present a detailed overview of the current stencil printing process for microelectronic packaging.

Design/methodology/approach – This paper gives a thorough review of stencil printing for electronic packaging including the current state of the art.

Findings – This article explains the different stencil technologies and printing materials. It then examines the various factors that determine the outcome of a successful printing process, including printing parameters, materials, apparatus and squeegees. Relevant technical innovations in the art of stencil printing for microelectronics packaging are examined as each part of the printing process is explained.

Originality/value – Stencil printing is currently the cheapest and highest throughput technique to create the mechanical and electrically conductive connections between substrates, bare die, packaged chips and discrete components. As a result, this process is used extensively in the electronic packaging industry and therefore such a review paper should be of interest to a large selection of the electronics interconnect and assembly community.

Keywords Stencil printing, Microelectronics packaging, Innovation, Packaging processes

Paper type General review

1. Introduction

Stencil printing is used in the electronic packaging industry primarily to generate the mechanical and electrically conductive interconnects between two devices. The devices themselves can be pre-packaged chips, individual die, wafers, discrete devices and substrates such as PCBs, flex substrates or ceramic multi-layer circuits.

Stencil printing uses an angled blade, called a squeegee, to press a viscous material through pre-defined open apertures in a solid foil onto a substrate. The configuration of the stencil apertures determines the basic layout of the deposits. In a modern stencil printing machine for electronic packaging the stencil is normally located in the front of the machine, with the squeegees positioned above the stencil, as shown in Figure 1. The substrate carrier is then passed through the side of the machine and subsequently aligned to the stencil. During the printing process the substrate is brought into contact or proximity with the stencil. The squeegees are placed onto the stencil with a set pressure and driven across the surface of the stencil at a pre-defined speed. This action causes the paste material to roll across the stencil and the apertures on the stencil are filled with a viscous material, usually solder paste or an isotropic conductive adhesive (ICA). When the stencil is released from the substrate the resulting contents of the filled apertures are ideally transferred to the bond pads, thereby forming deposits that will create the interconnects. With one print stroke, millions of deposits can be placed simultaneously onto the substrate surface. This process, that takes place within seconds, can be repeated thousands of times with the same stencil onto subsequent substrates, thereby creating a low cost, high throughput process. Photographs of a modern stencil printing machine are shown in Figure 2.

The stencil printing process was originally adapted from the screen printing process, whose main difference lies in the actual artwork through which the printing material is transferred. The screen is a woven mesh, which has been photopatterned to create a defined image, whereas a stencil is a solid foil with suitably placed holes.

Records indicate that the screen printing process was developed long before stencil printing, by the Chinese and Egyptians for the production of consistent artworks and decorative clothing, respectively (Biegeleisen, 1963). In that respect, such applications are still relevant today in the art and textiles industries (Supplier Relations US, LLC, 2007). The use of stencil printing for the deposition of conductive interconnects, called surface mount assembly (SMA), was developed in the late 1960s, as companies looked to increase the interconnection densities of their products and improve down production costs (Gurnett, 1999). By 1999, SMA was used for the assembly and packaging of around 93 per cent of all PCBs produced globally (Houson, 2001). By moving away from through hole component assembly to single sided SMA the functional density can be doubled for the same surface area and further increased by mounting components on both sides of the board (Houson, 2001). Stencil printing does not require massive capital investment or highly qualified technicians. This cost advantage, coupled with the ability to deposit solder alloys and ICAs, makes stencil printing the most attractive proposition for high volume assembly.

Consumer demand for lighter, cheaper, smaller and smarter electronic products is pushing the electronics industry to utilize the smallest packaging footprint possible. In this respect, flip-chip packaging is seen as the ideal platform to satisfy the drive for faster

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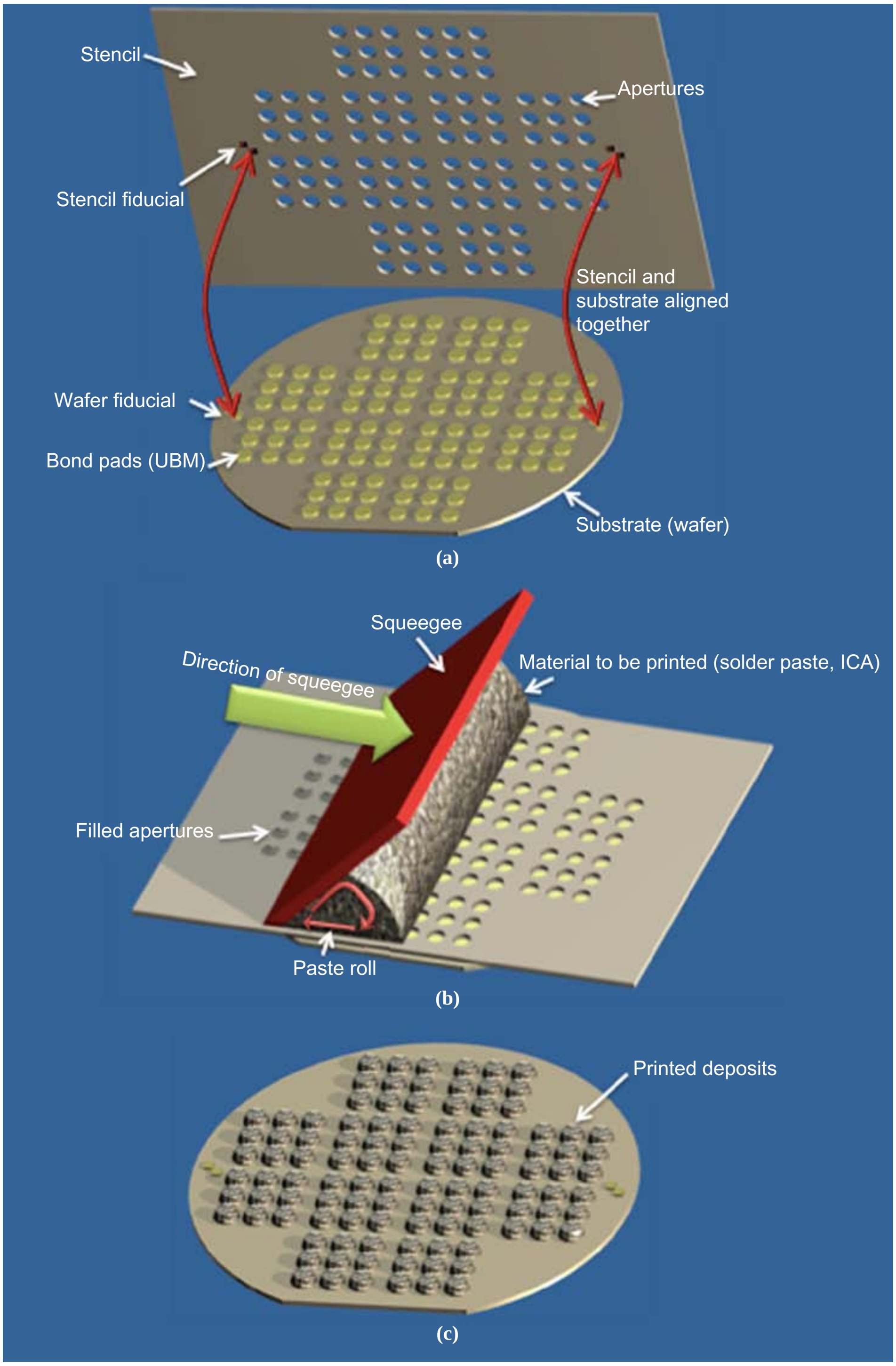
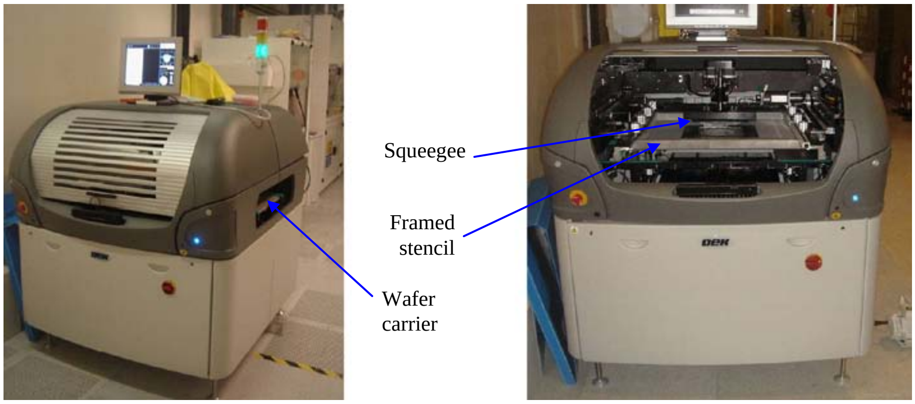
Figure 1 Overview of the stencil printing process for wafer level bumping



Notes: (a) Stencil and substrate are aligned together; (b) substrate is brought in close proximity or contact with the stencil and the squeegee is driven across the stencil surface, as the printing material passes the apertures it fills them; (c) substrate is separated from the stencil and the contents of the apertures are transferred onto the substrate

and denser electrical input/outputs (Kay *et al.*, 2007), gaining, thereby, an increasing level of acceptance for many industrial sectors covering automotive, consumer and telecommunication applications (Ginsberg, 1989). Stencil printing for flip-chip packaging offers a cost reduction in packaging over competing technologies while, at the same time, preserving the increased package density and reliability improvement that flip-chip bonding provides.

Figure 2 Modern stencil printing machine



Source: DEK Horizon

In all instances of solder bumping, a surface finish is applied to the substrate prior to applying the solder interconnects. On a wafer this is called under bump metallization (UBM). UBM is a metal layer that is connected to aluminium pads on the IC. It allows solder to wet to bond pads during reflow. Several UBM compositions are available, and are normally selected depending on solder-alloy selection, reliability requirements and cost drivers. Chemical bumping processes, based on electroless nickel plating, have been presented by several authors as a low-cost approach for depositing the UBMs that are compatible with a stencil printing process (Kloeser *et al.*, 1998; Wong *et al.*, 1988; Yamakawa *et al.*, 1989; Simon *et al.*, 1990; Ostamann *et al.*, 1993; Aintila *et al.*, 1994; Audet *et al.*, 1995; Li and Thompson, 2000; Kloeser *et al.*, 1996). Kloeser *et al.* investigated a flip-chip technology based on an electroless Ni/Au bumping process (Kloeser *et al.*, 1996). They developed an interconnection method, which used fine pitch stencil printing of solder paste on silicon, ceramic and organic substrates. As an alternative to the lead-based eutectic Sn/Pb solder, different alloys, such as Bi/Sn, Sn/Bi/Cu, Sn/Ag, Sn/Cu, Au/Sn were investigated in a later paper by this group (Kloeser *et al.*, 1998). A very good uniformity of bumps was achieved and the results of reliability investigations were shown to be excellent. Costs for chemical Ni bumping are significantly lower, compared to other conventional techniques (Schuetz, 2003). In the case of using Ni/Au bumps for flip-chip assembly of wafers, chips or substrates must be prepared by deposition of solder in a separate process.

2. Stencil technology

There are three main existing conventional stencil manufacturing methods with hybrid variations within each process:

1 chemical etched stencil;
2 laser cut stencil; and
3 electroformed stencil.

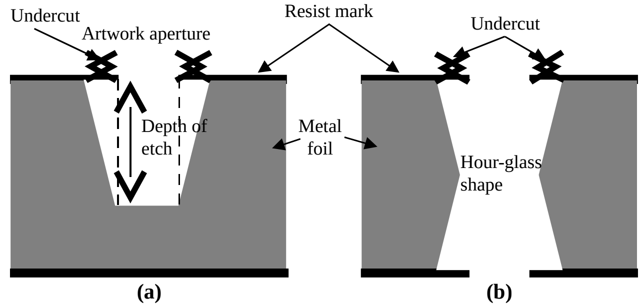
Laser cutting and chemical etching are both subtractive processes, where the surface texture of the stencil is determined by the material selection. Electroformed stencils are based on an additive process and, therefore, the final surface texture is determined by the electroplating process. The use of nano-coatings on stencils has the potential to impact printing performance and, in recent years, has gained more widespread use.

2.1 Chemically etched stencils

A metal foil, typically brass or stainless steel, is coated on both sides with a dry film photoresist usually applied using a laminator. The dry film photoresist is then photolithographically patterned through a pin-registered phototool onto one or both sides of the dry film resist. The photoplot masks are typically printed onto high contrast monochromatic photographic film. After exposure, the photoresist is developed to produce exposed areas where the apertures will be located. The foil is then chemically or electrolytically etched. This process dissolves the exposed metal areas in an isotropic manner on one or both sides of the stencil simultaneously (Coleman, 1993) as shown in Figure 3.

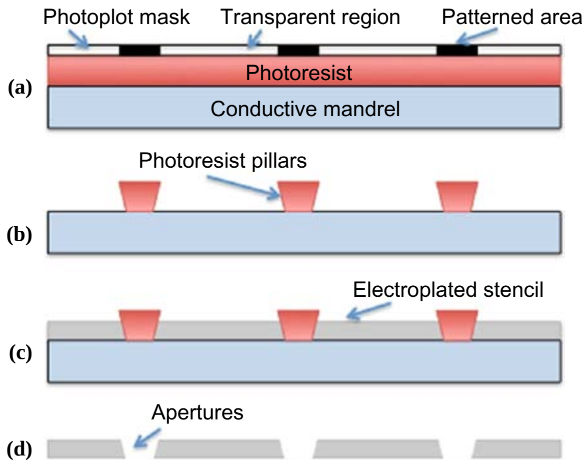
The minimum aperture size of the stencil is a function of the stencil thickness due to the isotropic nature of the etching process. A technique to improve the resolution of the stencils utilises double sided etching which, in effect, halves the undercutting artifact of the process and speeds up the manufacturing time, Figure 4(b). Since bulk metal foils are polycrystalline, the etching solution will etch along different crystalline boundaries at different rates, causing a slightly porous and rough inner aperture wall. This artifact influences the amount of paste released from the apertures. Owing to the tapered over-sized apertures, the minimum pitch that can be printed using a chemically etched stencil is about 300 μm,

Figure 3 Effect of undercut etching



Notes: (a) Etching one side of the metal foil; (b) etching on both sides of the metal foil

Figure 4 Illustration diagram of the conventional electroformed stencil process



however, for repeatable printing results this process is normally used for pitches greater than 500 μm.

2.2 Laser cut stencils

Laser cut stencils are manufactured on a thin substrate that is usually made of metal. This substrate is then mesh mounted into an aluminium frame to hold the foil flat and allow it to fit into the stencil printing machine after manufacture. The stencil is then placed into a high powered laser cutting machine that ablates each aperture sequentially in a pre-defined manner. Laser cut stencils are the most commonly used stencils in the microelectronics packaging industry, especially for SMA applications (Ashmore and Zahn, 2006). This is primarily because of the low capital equipment cost, flexibility of the machines and fast manufacturing times of the stencil. Since the laser cutter ablates each aperture individually, as the number of apertures increases, so does the time and cost of production. Therefore, for some applications like wafer bumping, where there may be a requirement for hundreds of thousands of apertures, laser cut stencils are not cost effective to produce. Moreover, the interaction between a metal foil and laser does not always result in the aperture being fully ablated. The laser indeed generates a heat-affected zone in the material causing localised damage to the foil. Contamination is also an issue, as the molten material cannot be fully expelled and "remelts" can land onto the surface of the stencil. As a consequence, the aperture sidewalls are commonly left with a rough edge which impacts on paste release.

Developments in the laser cutting process include smaller laser spot sizes and faster equipment operation speeds. In addition, changes in the types of materials that are used for the cutting process have improved the aperture tolerances and quality of aperture sidewalls, thereby allowing finer and more consistent printing. The bulk of laser cut stencils are manufactured on rolled sheets of stainless steel. The crystal structure and alloy composition of the material have an impact on paste release. Finer grained grades of stainless steel materials will give a better paste release. In addition, laser cutting equipment using a water guided laser jet has been introduced (Richerzhagen, 1995), which allows the creation of a fine cut edge with smoother internal aperture sidewalls. A conventional focused laser beam has a limited working distance of a few millimetres due to beam divergence. In laser guided cutting the laser beam, is completely reflected at the air-water interface, where the beam can be guided over a distance up to 10 cm. The water jet also cools the substrate while removing the molten material from the cut and avoiding contamination (Porter *et al.*, 2006).

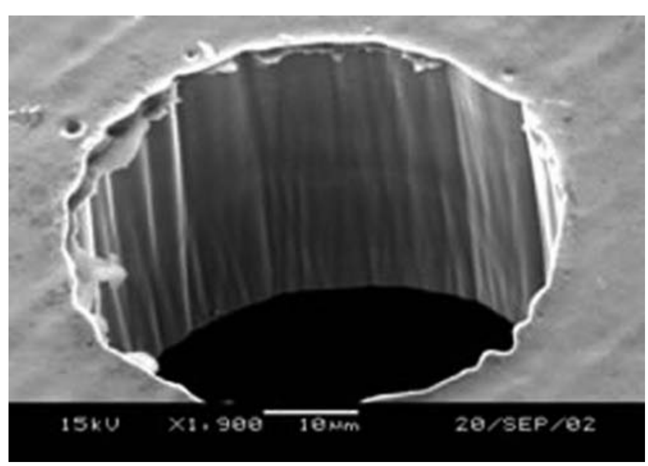
Another innovation in laser cutting processes is the use of nickel or polymer rather than stainless steel as the stencil material. Nickel laser cut stencils have been documented to show better paste release over standard stainless steel stencils. With polymer film stencils, it has been shown that the interaction between the laser and the polymer film gives a much cleaner cut, producing more accurate stencils (Heininger, 2002). One problem associated with polymer stencils is that the very active flux contained within most solder pastes reacts with the stencil material hence degrading the stencil, sometimes as soon as after a couple of prints (Wong *et al.*, 2000).

2.3 Electroformed stencils

The electroformed stencil process was originally developed in 1988 by Xerox (Blessington *et al.*, 1994). Electroformed stencils are manufactured on a conductive substrate called a mandrel as shown in Figure 4. This mandrel is coated with a dry film layer of photoresist normally using a laminator. The layer of photoresist is then photolithographically patterned using a photographic film produced on a photoplotter (Figure 4(a)). Next, the film is developed leaving behind tapered pillars that will form the apertures after the electroforming step (Figure 4(b)). The conductive substrate is then placed into an electrolytic plating solution normally of nickel or a nickel alloy. A DC current is applied to the mandrel, which begins the plating process (Figure 4(c)). Once the stencil has reached the desired thickness the plating process can be stopped and the photoresist can be chemically dissolved from the apertures. The stencil is mechanically peeled away from the substrate to release the finished stencil (Figure 4(d)).

Electroformed stencils are currently limited to about 140 μm pitch because of the sensitivity of the photoresist, the type of photomask used and the optical properties of the substrate. The resist normally contains striations traversing through the material after fabrication as shown in Figure 5. The patterned apertures on the resist have a naturally induced taper as a result of the lithography step, which limits the ability to bring the apertures together on the stencil due to the weaknesses of the web, defined as the metal aperture area between the apertures. For larger geometries this taper is seen as a benefit since it helps the release of the solder paste from the apertures.

Figure 5 SEM image from a conventional electroformed aperture



Standard DC electroplating causes a build up of the plated material around the resist pillars due to current crowding commonly referred to as a gasket (Coleman, 2005). This gasket is seen as a benefit for solder paste printing onto substrates containing a topography up to several microns, as the raised aperture edges help to ensure the stencil contacts the pad completely. However, this current crowding effect can cause a non-uniform deposition of nickel material across the stencil as shown in Figure 8. Differences in stencil thickness will result in different print volume deposition across the apertures. If this raised plated area is positioned on the substrate side of the stencil then this difference in thickness on a local scale can inhibit good contact of the full aperture to the printing area causing material bleed-out during the printing process. If the raised plated area is directed towards the squeegee side, faster stencil wear occurs with metal squeegees and the material smears in the recessed areas during printing.

In 2003, a refined version of the DC electroformed stencil manufacturing process was described (Kay *et al.*, 2003). This stencil was manufactured using the UV-LIGA process alongside bipolar electroforming (Kay and Desmulliez, 2003; Jackson *et al.*, 2005). The process can produce stencils with apertures having micron tolerance and smooth sidewalls, hence giving excellent paste release. Such stencils are ideal for printing to a fine pitch (sub-200 μm) (Manessis *et al.*, 2006). The stencil improvements include the atomic control of the electroplating process and the ability to generate a high resolution photoresist mold using very sensitive liquid photoresists, optically perfect substrates and a glass photomask technology as shown in Figure 6 (Krebs and Kay, 2007).

2.4 Hybrid stencils

There are a number of stencil processes, which take elements of the three different stencil manufacturing processes described above. Step stencils are used when the substrate has a raised area such as a plug or socket on a PCB and therefore the stencil must conform to the surface. In addition, step stencils can be used when there is a high component mix of large and fine pitch devices whereby a stencil can be used to print different pitches or a complicated pattern more easily. Such stencils can be fabricated by a number of different means as shown in Figure 7. Step etching is where the pockets are formed on one side of the stencil and the apertures on the other. The apertures for the regions not containing the pockets can also be patterned and etched from both sides. Step stencils can also be produced by etching the pockets and subsequently laser cutting the apertures. Another technique to generate such step stencils can be through milling either just the pockets or, for course geometries, both the pockets and the apertures. It is, however, more common to mill the conductive substrate with the pockets and then electrochemically form a step stencil onto the substrate. Normally, the stencil apertures are subsequently laser cut. However, in theory, photolithography and electroforming could generate the apertures and even the step using a two-step electroformed stencil process (IPC, 2007; Coleman and Burgess, 2006).

Electropolished stencils are typically laser cut stencils that are given a post-processing electrolytic polishing step to smooth and deburr the rough inner sidewalls of the stencil apertures by removing small amounts of surface metal. The stencil, which acts as the anode, is immersed in a temperature controlled bath of electrolyte and then a current is passed from the anode, where metal on the surface is oxidized, dissolved in the electrolyte and transported to the cathode (Santos and Mohanty, 2008).

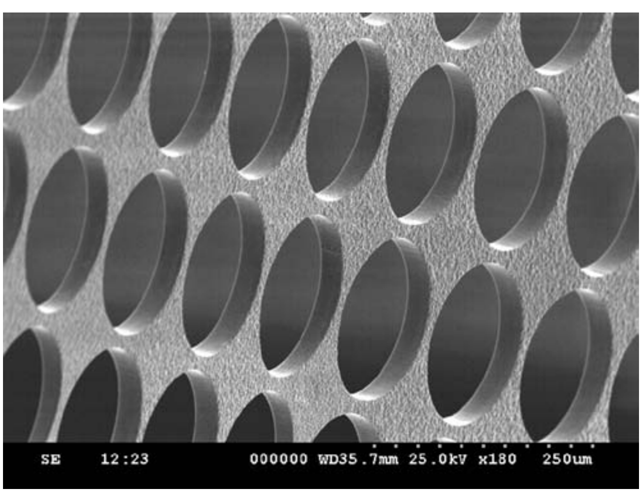
Laser cut electroformed nickel stencils are stencils that are produced using the same laser cutting process but the stencil foil is manufactured through electroplating a sheet of nickel to a desired thickness. This gives a wider range of potential stencil thicknesses just like an electroformed stencil.

Plastic stencils are also used to print adhesives for electronic packaging. Such stencils are typically manufactured from milling a thick plastic sheet (Whitmore *et al.*, 1997). Plastic stencils are typically much thicker than metal stencils (1.0-1.5 mm) and are used to print thick adhesive deposits.

2.5 Nanocoatings for stencils

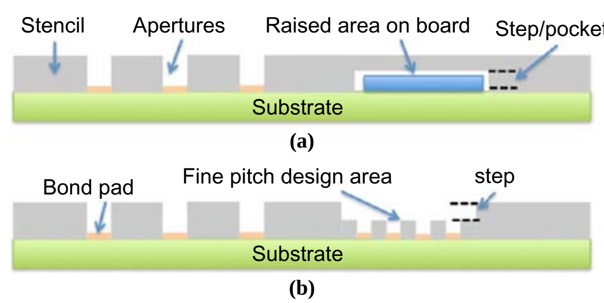
In recent years functional nano-coatings have been trialled on the apertures as well as the substrate side of stencils. The idea is to modify the surface characteristics of the stencil so that flux in solder paste is repelled from the aperture sidewalls to minimise the amount of material that is adhered to the apertures after printing. In addition, the coating is also used to stop paste spreading on the underside of the stencil, which reduces the underside stencil cleaning frequency, and also lowers defect rates. To date the limited investigations on nano-coated stencils have shown improved performance, especially on

Figure 6 Microengineered stencil, 200 μm pitch, 175 μm diameter apertures



Source: MicroStencil Ltd

Figure 7 Step stencil (a) for a substrate with a raised area; (b) for a substrate with a mixture of large alnd fine pith components



electroformed stencils and higher aspect ratio apertures (Mohanty *et al.*, 2011; Manessis *et al.*, 2008).

3. Printing materials

Many different interconnect materials are used for a variety of packaging requirements. On a most general level, two main types of material are used for printing through the apertures of a stencil: solder paste and conductive adhesive.

3.1 Solder paste

Solder paste is a suspension of solder particles in a printing medium containing a flux. The shape, size and oxidation levels of the particles and the flow properties of the flux vehicle must be controlled to optimise printing and reflow of the material. Solder particles can form an 88 per cent proportion of the overall paste formulation by weight, however, only account for half by volume (Nguty *et al.*, 1999). The solder alloy powder is the only permanent part of the metallurgical bond after reflow, which forms the mechanical and electrical interconnections. At the end of the soldering cycle, all the printing vehicle and flux components are present only as residues. The flux vehicle contains flux, solvents and binders. Flux removes oxidation from the surfaces to be soldered, seals out air, thus preventing further oxidation and improves the wetting characteristics of the liquid solder. The binders and solvents function to evenly disperse the solder powder throughout the paste, maintain paste consistency during printing, clean the surface to be soldered to and hold the flip-chipped device in place during reflow.

Solder paste can be made from any solder alloy. Until recently, the most frequently used alloy composition was eutectic tin-lead. However, the restriction of hazardous substances directive has proscribed the use of lead in many electronic packaging applications. Lead-free solder paste can be made up of many formulations, however, tin-silver-copper is the most common. This alloy has an increased melting temperature of around 217°C compared to the 63%Sn 37%Pb alloy which melts at 183°C (European Union, 2003).

The solder particle size, shape and size distribution determine how well a paste will print. Irregular particle sizes should not be used as they can clog the stencil apertures and therefore cause printing defects. The finer the pitch printing requirement, the smaller the average particle size required in the paste so that the material can effectively transfer through the aperture and so there is a consistent volume of material in each aperture. Particle size distribution (PSD) for solder paste is separated into eight main types as shown Table I. Currently, types 7z and 8 solder pastes are primarily development materials used in producing fine pitch flip-chip interconnects (Jackson *et al.*, 2005; Manessis *et al.*, 2006).

Sub-200 μm pitch printing requires a reduction of the PSD of the alloy from 20 to 45 μm (type 3) to less than 15 μm (types 6 and 7). An industry rule of thumb states that, in order for the stencil apertures to be filled during the printing process, the average particle size ratio must be less than five times the aperture diameter. The subsequent changes in PSD do affect the solder paste properties; for example, moving from a type 3 to a type 6 PSD increases the number of particles (per unit volume) by a factor of 15 and the fine particles in the solder pastes will inherently alter the paste rheology (Jackson *et al.*, 2003; Xiao *et al.*, 1992). In addition, for a given oxide thickness, more oxide will be present in the paste as the ratio of surface area to volume increases as shown in Figure 8 (Lea, 1988). As a result, the flux must be more active on finer PSD type solder pastes.

Table I Different solder paste classifications in terms of PSD

Paste type	Max. size μm (less than 1% larger than)	PSD μm (80% min. between)
Type 1	150	75-150
Type 2	75	45-75
Type 3	45	20-45
Type 4	38	20-38
Type 5	25	10-25
Type 6	15	15-5
Type 7	11	2-11
Type 8	10	2-8

Source: Electronic Industries Alliance and IPC (1995)

3.2 Isotropic conductive adhesives

ICAs generally consist of a certain percentage of metallic conductive particles (25-30 per cent or higher volume loadings) dispersed in a polymeric resin, as shown in Figure 9. The most common filler is silver (Ag) although there are other types of metal fillers such as nickel, gold, copper and metal coated particles. The advantage of using silver over other metal fillers is in its unique ability to conduct electricity even after oxidation. The most commonly used resin is epoxy, but other choices such as polyamides, silicones and acrylic adhesives are possible.

Figure 8 Volume of oxide versus diameter of solder particle

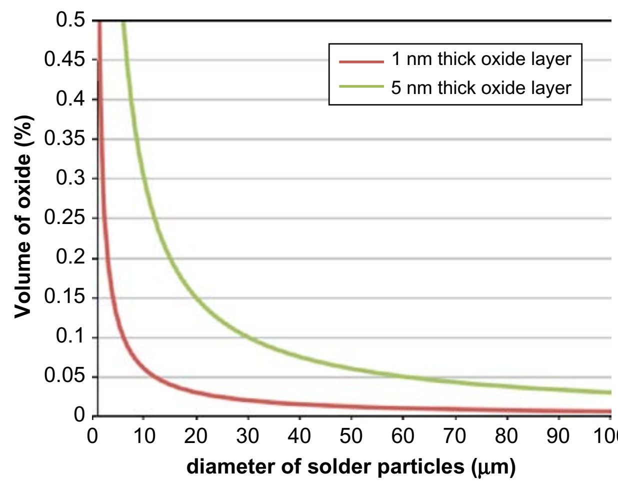
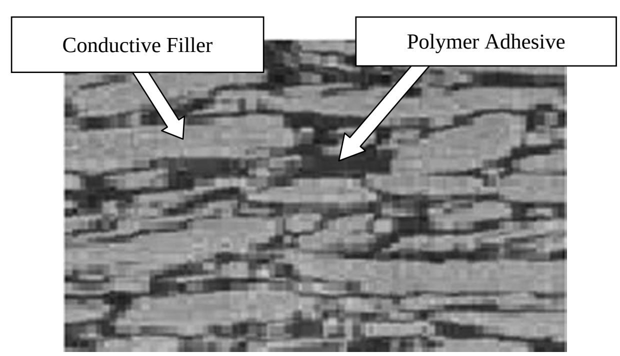


Figure 9 ICA composition



When this conductive adhesive paste is cured, the filler particles start to distribute uniformly. As the polymeric resin shrinks, the filler particles come into contact with each other and form an electrically conductive network within the polymer (Stoyanov *et al.*, 2007). Because of the nature of the metal particles network, the current can flow in any direction, hence the term isotropic conductive adhesive. ICAs have not found the same level of adoption as solder due to the reliability issues related to bonding strength to the bond pad and moisture absorption of the material. However, ICA interconnects have electrical conduction and performance similar to what eutectic solder can offer and have the advantages of lower temperature processing than solder. Also they do not require fluxes or other toxic cleaning products in the reflow process (Bailey *et al.*, 2002; Jagt *et al.*, 1995).

4. Stencil printing factors

Several factors determine the outcome of the print results (Nguty *et al.*, 1999, 1998; Haslehurst and Ekere, 1996; Ekere *et al.*, 1993; Rajkumar *et al.*, 2000) and these are:

- *Stencil.* Tensioning, aperture size, roughness and quality, dimensional tolerances, thickness, thickness uniformity, stencil surface texture and stencil material.
- *Printing material.* Material selection and rheology.
- *Environmental conditions*. Temperature, noise, humidity and air cleanliness.
- *Print parameters.* Print speed, print pressure, print gap, separation speed and print direction.
- *Squeegees.* Squeegee technology, squeegee material and squeegee angle.
- Alignment accuracy between the stencil and the substrate.
- Framing of the stencil.
- *Substrate*. Flatness, roughness, surface wetting characteristics, bond pad size and shape.
- Substrate support and substrate carrier.

4.1 Stencil

Stencil quality has a major impact on print performance. Several factors determine the ability of the stencil to allow successful material transfer during printing. These factors include foil tension, aperture size, roughness and quality, dimensional tolerances, thickness, stencil surface texture and stencil material. Many of these factors are determined by the stencil manufacturing process.

The stencil design has a critical impact on print performance. Stencil apertures are designed to deposit a certain volume of solder paste based on the stencil thickness and aperture area however, not all paste is deposited from the aperture. This transfer efficiency is dependant on the area ratio of the stencil apertures (AR = aperture area/aperture wall area) (Manessis *et al.*, 2002). Keeping this value as low as possible without impinging on other design limitations such as larger apertures nearly overlapping with adjacent ones can cause paste bridging. In addition, a thinner stencil has a shorter lifetime and is less dimensionally stable.

The aperture sidewall roughness and choice of material can both impact transfer efficiency. A rough inner sidewall effectively increases the surface area of the aperture and thereby decreases transfer efficiency. A more hydrophobic stencil aperture wall material will inhibit paste from adhering to the aperture sidewalls. Nano-coatings can change the surface properties of the bulk stencil material with the aim of making the surface less hydrophilic.

4.2 Printing material performance

Rheology is the science of flow and deformation of matter when subjected to stress. The rheology/flow behaviour can be correlated to the performance of the materials during the stencil printing process as described in Riemer (1988a, b), Owczarek and Howland (1990a, b), Mannan *et al.* (1995) and Clements *et al.* (2007).

Prior to reflow or curing, the printing material is in a fluid state and the bulk properties of the material exhibit non-Newtonian rheological characteristics. The formulation of the printing materials is critical not only to ensure the necessary constituents to form the electrical interconnections and the structural bond, but also to ensure the desired print performance.

At a macroscopic scale, the solder paste or adhesive may be considered as a homogenous continuum and the solid particle content, size, shape distribution and inter-particle forces can be neglected. The printing material can then be characterised by bulk macroscopic properties such as viscosity and density (Glinski *et al.*, 2001).

Investigating the shear rates of a solder paste can help predict the flow properties during the aperture filling and paste release in the printing process.

Computational fluid dynamics (CFD) techniques have been used to simulate the macroscopic bulk motion of adhesive paste ahead of a moving squeegee blade during the stencil printing process in order to obtain a better understanding of the printing process. Glinski *et al.* (2001) looked at viscosity as a function of shear rates for two types of solder pastes and a conductive adhesive sample. All materials were specified for fine pitch printing. Adhesive samples showed a lower viscosity compared with the solder pate. This information was fed into a CFD model to simulate the macroscopic bulk motion of solder and ICA materials ahead of a moving squeegee blade during the stencil printing process as shown in Figures 10 and 11 (Kay *et al.*, 2003).

In this study, non-Newtonian fluid dynamics were simulated by solving the Navier Stokes equations for flow with the paste constitutive law to characterise the paste rheology (Durairaj *et al.*, 2002). Pressure, velocity, shear rate and viscosity distributions determined throughout the paste material, as shown in Figure 12, show the predicted pressure distribution in the paste along the stencil surface for a blade angle of 60° and velocities of 1, 2, 3 and 4 cm/s. These distributions obtained along the base of the paste roll are of particular interest as the aperture filling

Figure 10 Schematic of paste roll

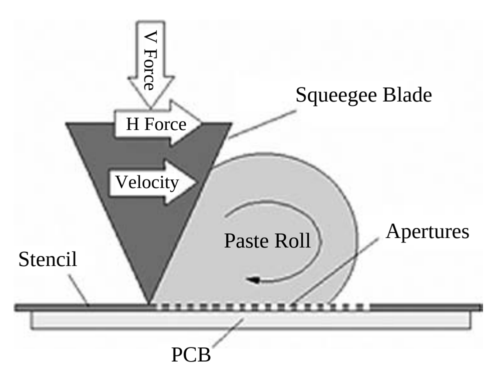
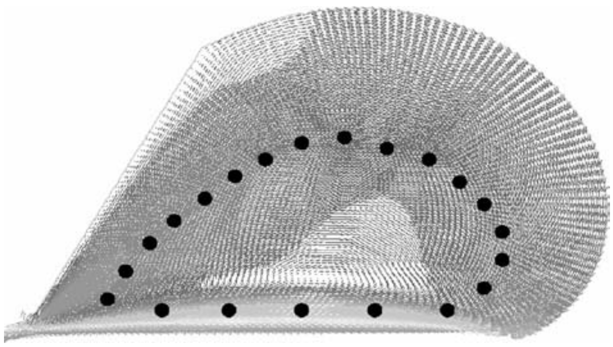
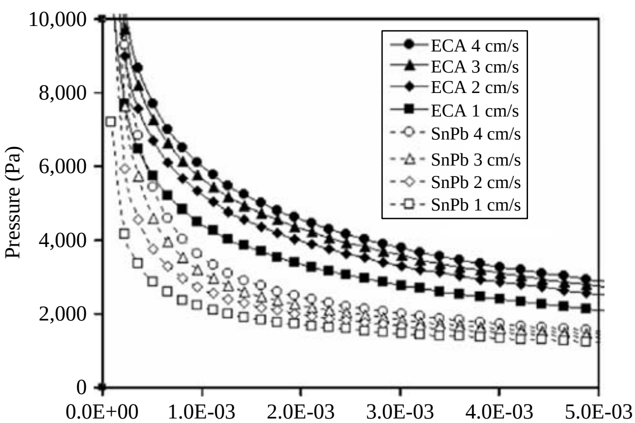


Figure 11 Results of velocity vectors using non-Newtonian CFD



Source: Kay *et al.* (2003)

Figure 12 Pressure in paste material at different distances from blade tip



Source: Durairaj *et al.* (2002)

process depends on the paste behaviour and material properties encountered in this region adjacent to the stencil surface.

Particularly large pressure gradients are observed in the region closest to the blade tip for both the tin-lead and ICA samples. There is a considerable difference in the pressure generated between the two paste samples. The pressure seen by the ICA is much higher than that observed by the tin-lead solder. Higher pressure with a lower viscosity in the blade tip region helps promote aperture fill. The CFD simulation results provide parameters for flow characteristics of the paste roll, which can be used for process control of paste print quality and tuning of the machine settings.

4.3 Printing environment conditions and print parameters

A controlled printing environment is necessary at finer dimensions for a stable and repeatable printing process. All environmental factors such as air cleanliness, background noise, humidity and temperature have an increasing influence on the results of the printing process. In that regard, most stencil printing machines used in flip-chip and wafer level packaging are located in some form of cleanroom environment of class 10,000 at least, with temperature, humidity and air cleanliness control and for some applications, vibration isolation. In contrast, most SMA lines are today typically found on the factory floor with just temperature control.

Printing parameters are specifically tailored to the printing pitch, stencil technology and paste material selection in order to obtain good print deposits (Ekere *et al.*, 1993). These factors are print speed, print pressure, print gap, separation speed and print direction.

The print speed is defined as the velocity at which the squeegee travels across the stencil. Too fast of a squeegee stroke can cause the printing material to slide rather than roll across the stencil, which results in inconsistent print deposits. Too slow a print speed can cause material to bleed out, resulting in bridged deposits as the paste material has enough time to seep underneath the stencil web between two apertures during the print stroke.

The print pressure is the pressure applied by the squeegee to the stencil surface. Too low a print pressure will cause the paste to smear on the stencil, resulting in its drying or partial curing. When the squeegee strokes this higher viscosity material on its return, it will not fully mix with the paste roll, potentially causing printed deposit or reflow issues. A low print pressure may also stop the material from rolling across the stencil effectively, again causing small or inconsistent deposits. Excessive print pressure can promote material bleed out during printing and speed up the wear of the stencil and the squeegee. A long stencil lifetime is important to make stencil printing a cost effective process.

The print gap is the gap between the stencil and the substrate prior to the application of the squeegee onto the foil surface. In very high density printing a small print gap minimises the issues of stencil release during the separation phase of the substrate from the stencil. Typically, more uniform print deposits are achieved when the stencil is in contact with the substrate.

Separation speed is the velocity at which the substrate is withdrawn from the stencil. A slow separation speed can allow the stencil to more uniformly release from the substrate, however, it slows down the process time.

The separation distance is a parameter tied into the separation speed. This is the distance that the machine separates at the separation speed before quickly withdrawing the substrate. This parameter influences the throughput of the printing process.

Finally, the print direction can have an impact on the print results. In most modern printers the paste can be printed in a forward and reverse direction by using a pair of squeegees placed diametrically opposite from each other. In very fine pitch printing applications, drifts between the deposit location from front and rear print strokes can sometimes be observed. Most modern stencil printing machines have a function which allows a slight offset versus the alignment centre point which can help compensate for any drift between the apertures and the bond pads on the substrate. In some designs certain print directions may also yield better printing results.

Rajkumar *et al.* (2000) presented results of a study on the optimisation of process parameters for flip-chip stencil printing using the Taguchi method. The key process parameters studied were: squeegee speed, squeegee pressure, stencil substrate separation speed and the print direction. Five different flip-chip solder paste formulations were evaluated in this study. The analysis of the paste deposit heights showed that, for the range of printer parameters tested and the solder paste particle used in the paste, skipping led to very small paste heights. The analysis also showed that the squeegee speed had the most effect on the printing process. A high squeegee pressure and also a low stencil substrate separation speed were found essential for printing at flip-chip geometries.

4.4 Squeegees

Conventional squeegees are flat blades typically made out of polyurethane or metal. The angle of the squeegee blade influences the print pressure in the paste roll. For some printing applications, more rigid squeegees have been shown to give better print consistency. Soft squeegees may scoop paste from apertures or squeeze into the aperture during the printing process, thereby forcing a lower volume or material in the aperture (Mannan *et al.*, 1993). Metal squeegees having materials with a lower coefficient of friction and higher hardness have displayed better print uniformity and slower wear of the stencil and the squeegee (Coleman and Richter, 1999).

Notable developments in fine pitch printing include vibrating squeegees (He *et al.*, 1998) and new printing heads such as the ProFlow and the rheometric pumping head (Nauss, 1998; He and Ekere, 2000; Howarth *et al.*, 1999). These new printing devices enclose the solder paste in a sealed pressurised chamber as opposed to the traditional open squeegee blade. Enclosed print heads increase the paste lifetime by sealing it from the external environment and impact the flow profile of the solder paste, potentially improving the volume of solder paste deposited onto the bond pads.

The behaviour of the solder paste under the action of a vibrating squeegee was investigated by He *et al.* (1998) to optimise the process parameters. Two vibration experiments on solder paste were conducted. In the first experiment, a prototype vibrating squeegee system was used to simulate the printing process: in a second experiment, paste samples were packed in a cylindrical container, which was horizontally vibrated. The first experiment simulated the stencil printing of solder paste using a vibrating squeegee. Experimental results demonstrated that the application of a vibrating squeegee generated a liquid rich layer at the squeegee blade and paste roll interface. This liquid rich layer acted as a lubricating agent between the blade and the paste roll that could reduce the squeegee blade resistance on the paste roll. Empirical evidence has shown that a good paste roll is essential for aperture filling and emptying, and thus for more consistent deposits on the pads of the substrate. The application of the vibrating squeegee can also help to reduce the potential for the paste roll to stick on the squeegee blade at the end of a printing stroke. For the paste sample used in the experiment, the suitable range of the vibration frequency was from 80 to 200 Hz and the suitable range of the amplitude was from 0.1 to 0.37 mm. In the second experiment, solder paste sample was vibrated inside a cylindrical container that, to some extent, reflected the response of paste packed inside the apertures to the vibration of the squeegee. Experimental results showed that, under vibration, a liquid rich layer was generated around the container wall, which implies that vibration may help the transfer of paste from apertures to substrate, thus reducing clogging defects. Microscope observation showed that, under vibration, the arrangement of solder particles was more uniform than without vibration. Uniform arrangement of solder particles may reduce the bulk viscosity because of the reduction of lubrication forces among neighbouring particles.

He *et al.* also showed that, with enclosed print heads the paste flow inside the chamber depended solely on the frictional force between the paste and the stencil at the slot and therefore the paste does not fill the apertures vertically. This horizontal component of the paste velocity at the flow was shown to lead to insufficient aperture filling at the trailing edge. Therefore, to counteract the influence of this undesirable velocity component they proposed a new horizontal shaft mechanism to drive the paste and cause it to flow against the printing direction in the chamber and hence promote vertical aperture filling. All modern enclosed print heads now follow this method.

4.5 Framing and alignment

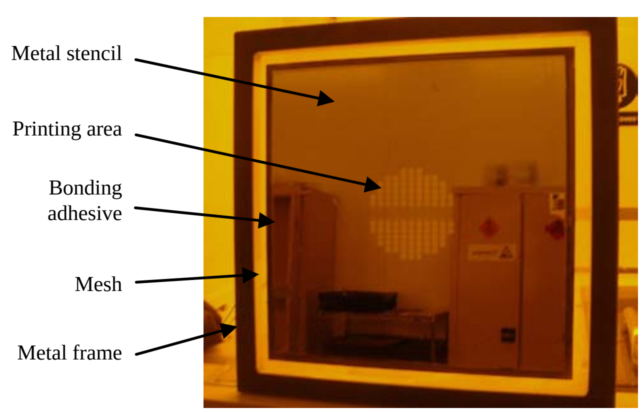
A stencil is typically mounted onto a tensioned fine mesh to hold it structurally intact during the printing process. Whereas the framing process for laser cut stencils occurs prior to cutting the apertures, this is not the case for the other types of manufacture. The mesh is normally made out of polyester or stainless steel and is pre-stretched onto a metal frame prior to being placed onto the stencil. An adhesive is subsequently used to bond the perimeter of the stencil to the mesh. The bonding adhesive is then cured so the mesh inside the bonded area can be cut away to transfer the tension into the stencil, as shown in Figure 13. This action keeps the stencil flat and rigid in the frame. Fine pitch printing stencils are typically thinner than 100 μm and can be deformed as a result of framing, causing the design to stretch (Kay *et al.*, 2007). Depending on the area to be printed and the amount of stretch from framing, it may be necessary to compensate for this deformation at the manufacturing stage.

In recent years meshless stencils, also commonly called quick tension or frameless stencils, have become available. These systems use a reusable frame that does not need the stencil to be permanently glued into the fame (Erdmann, 2002; Shaw *et al.*, 2004). This allows a reduction of costs, as the frame is being re-used and alleviates the need for storage space. For fine pitch printing, the simultaneous tensioning from all four sides and the more repeatable tension applied to the stencil enables a more consistent control over stencil deformation.

As the stencil releases from the substrate during the printing process, a stiction effect can occur due to the solder paste adhering to the stencil apertures and the substrate. This force holds the stencil in contact as the substrate releases and, if pronounced, can cause the thin foil to reverberate during printing and cause poor print results. Typically, the stencil will release from the perimeter of the stencil towards the centre as the separation distance increases. A slight print gap, or the appropriate stencil tension, can help to control this issue during printing.

Alignment of the stencil to the substrate in the *x*-, *y*- and *z*-axes is required for the fine registration of the paste deposits

Figure 13 Framed microengineered stencil



onto the pads of the substrate. Solder printing has the advantage that, as the material reflows, it wets to the metalised surface, withdraws from the non-wettable areas and coalesces on the pad to form a bump.

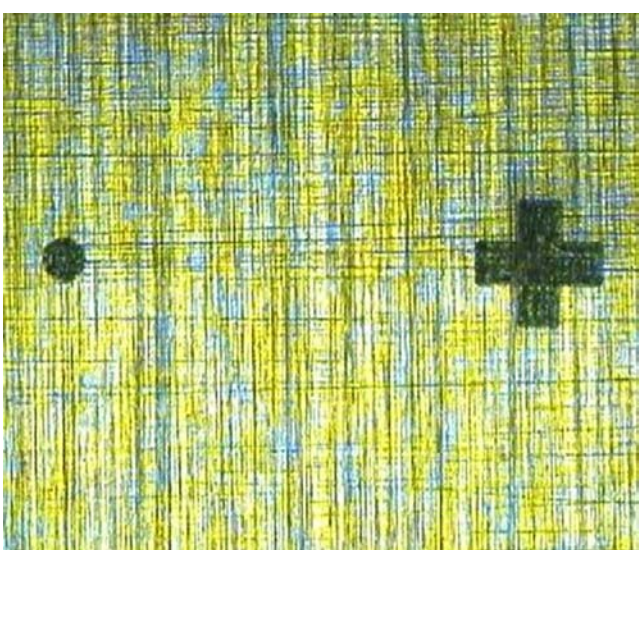
The substrate and the stencil should contain alignment markings called fiducials. For volume printing, a typical machine vision system would locate the centre of both corresponding fiducials and move the substrate or stencil into the correct position to begin the print stroke (Beale, 2003). Fiducials on the stencil are partially etched apertures manufactured through photolithography and etching or laser etching without ablating all the way through the foil. This partial etching reveals itself to the vision system as a pattern with a different contrast to the stencil surface as shown in Figure 14. Fiducials can be designed in a variety of shapes with the most common being a circle.

4.6 Substrate and bond pad

Types of substrates that are commonly stencil printed onto for electronic packaging include PCBs, wafers or die, flex and ceramic substrates. Differences in the substrate design density, substrate type, flatness, roughness, surface wetting characteristics, bond pad type, size and shape all play important roles for uniform and consistent printing across the full design area. Substrate size and manufacturing technologies influence geometric tolerances and substrate topography. The substrate topography creates zones where the stencil may not be in total contact as the squeegee passes creating paste bleed-out, bridging and non-uniform deposits. Surface wetting characteristics and roughness can limit the tendency of the printing materials to adhere to the substrate during the stencil release. Variation in the dimensional tolerances of the substrate can cause misalignment of the bond pad to the stencil.

Substrate carriers are commonly used in stencil printing for thin substrates such as in wafer level bumping, flip-chip packaging and flex substrates, due to the thin profile and the requirements to hold the substrates completely flat during printing. The substrates are normally supported and held flat by a carrier which uses a vacuum or clamping system to hold the substrate supported and flat (Bennett *et al.*, 2002).

Figure 14 Half-etched fiducials on a stainless steel stencil



5. Competing technologies

Stencil printing is currently the lowest cost bumping option for high volume production since it is an extremely high throughput process that requires low capital equipment costs and the stencil template can be reused many thousands of times, thereby keeping consumable costs low. In addition, stencil printing can deposit a wide composition of solder and adhesive materials including lead-free and low temperature reflow/cured materials. However, for solder deposition, stencil printing has the disadvantage that is struggles at very fine pitches (sub-100 μm). The stencil design rules must be adhered to, limiting the diameter of the apertures for a given stencil thickness and therefore, at fine pitches, the stencil becomes extremely thin. In addition, about 50 per cent of the paste is flux by volume and half of the printed material is removed during the reflow process. These two factors limit the maximum height of a reflowed solder sphere for a given pitch and also constrict what small geometries can be achieved. In addition, the main solder compatible competing technologies to bumping, such as electroplating, evaporation and ball placement, typically give better bump height coplanarity. All three of these processes are unable to deposit ICA material. Some competing technologies are better adapted to wafer level bumping over substrate bumping, as the processes were developed for the IC industry and wafer flatness and positional accuracy is typically better than with a PCB.

It is beyond the scope of this review paper to describe in detail all the competing bumping technologies to stencil printing. However, below, is a list of primary competing technologies including a brief description and references for information:

1. solder dam:
   - electroplating (Totta, 1980; Magill *et al.*, 1998);
   - chemical vapour deposition (Miller, 1969; Andricacos *et al.*, 1997); and
   - printing into a wafer mold (Yeh and Carter, 1998; Burgess, 2006).
2. ball placement (Foulke and Ohlenbusch, 2001);
3. solder jetting (Farnworth, 1999; Son *et al.*, 2005; Baggerman and Schwarzbach, 1998);
4. solder bump bonding (Cihangir and Kwan, 2002);
5. molten paste transfer using a non-wettable mold (Gruber *et al.*, 2004);
6. dispensing (Tangpuz and Cabahug, 2005);
7. anisotropic conductive film (Yoshida, 1993; Chang *et al.*, 1993; Yim and Paik, 1998); and
8. stud bump (Jordan, 2002).

6. Conclusions

Stencil printing is a preferred bumping technology for microelectronic packaging due to its flexibility, low cost and high volume potential. A number of factors determine a successful printing process including the stencil, printing medium, squeegee, printing parameters and environment, stencil framing and alignment and the substrate to be printed onto. This overview review paper has given an in depth insight into the complete stencil printing process for microelectronic packaging including details on each one of these key factors that impact the process.

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