Low Temperature Flip-chip Packaging based on Stencil Printing Technology

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Abstract

The MAT21 project, funded by the British funding agency, EPSRC, aims to integrate microsystems and flip-chip technology into commercial contract high volume electronics manufacturing assembly lines. The technology is based on flip-chip applications and is viewed as a step towards advanced assembly and packaging processes for future MEMS technology markets. The project seeks to deliver commercially viable processes for ultra-fine sub-100μm pitch connections using stencil printing at a length scale of one order magnitude less than presently available. The project consortium of two Universities: Heriot-Watt and Greenwich are engaged in a highly interdisciplinary research program involving microsystems manufacturing, materials science and computational modeling. The consortium is strengthened by the industrial support from leading-edge companies including Celestica, Cookson, Merlin Circuit Technology, DEK Printing Machines, Electronic Technology Services and Micro-Emissive Displays, which cover the whole supply and manufacturing chains in electronics packaging.

Significant results reported in this paper include the development of next generation electroformed stencils with repeatable apertures size down to 10μm on a 20μm pitch, and down to a 10μm web. Successful prints of silver filled Isotropic Conductive Adhesive (ICA) was printed down to 50μm pitch with consistent printing demonstrated at 90μm pitch. The performance of the micro-engineered stencil in terms of fluid flow dynamics during the deposition of the bonding material was developed using multi-physics simulation and modeling. Rheological tests of the rolling of the paste were also carried out. Current and developed computational models were used to predict the reliability of such microsystem assembly processes with the underfill characteristics aiding in identifying possible process weaknesses. An end user prototype chip was assembled to prove the feasibility of the developed packaging process.

Introduction

The rapid growth rate of Microsystems manufacturing (30% per annum) makes it the world's fastest growing manufacturing industry [1]. The trend towards ever increasing miniaturisation and the capacity to shrink electronic devices while multiplying their capabilities has profoundly changed both technology and society – for example high performance computing systems, mobile phones and visulation equipment. Research into microsystem technology for sensing and actuation has resulted in a number of Universities and small companies producing miniature components. In general, microsystem components have not found their way into mass produced commercial products because cost-effective packaging and assembly to standard microelectronics has presented a critical stumbling block (one notable exception is their use in accelerometers in car airbags). The challenge is now to interface such technology into commercial electronic contract manufacture assembly lines. To achieve this, a compatible, cost-effective, process route is required that uses flip-chip bonding technology to integrate Microdevices into systems. Flip-chip is the fastest growing bonding technique used in electronics to achieve high-density assembly onto printed circuit boards [2]. A proliferation of flip-chip interconnection technologies have been developed by the electronics manufacturing industry [3], such as, evaporation, electroplating, adhesive dispensing, solder jetting, stud bumping, and stencil printing. Each process has advantageous attributes in terms of technological potential, manufacturing costs and testing. However traditional contract electronic manufactures assembly based on surface mount technology (SMT) is built primarily around capabilities, equipment and consumables that utilize stencil printing. Stencil printing has been proven to be the most economical solution for flip-chip interconnection [4]. Stencil printing also allows the deposition of conductive adhesive, an enabler of low temperature bonding.

The MicroSystems Assembly Technology for the 21st Century (MAT21) project was established to identify a process route to integrate microsystems-based components using low cost flip-chip assembly. The project adopts microsystems technology, to manufacture stencils with ultra fine apertures (<50μm) for printing adhesives onto a substrate. Novel substrates with stencil printed adhesive bumps will then be used to bond bumped microsystem devices using flip-chip assembly technology – enabling microsystems chip (MEMS, MOEMS, etc) interconnection at sub 100-micro pitch.

The project objectives include:

- The manufacture of electroformed stencils capable of printing sub-50μm diameter bumps at sub-100 μm pitch.
- The development and validation of numerical modeling technology to predict the performance of the micro-engineered stencils in terms of fluid flow dynamics during deposition of bonding material.
- The implementation of a zero post-processing, environmentally friendly, low-temperature (T<100°C) assembly technology - based on flip-chip bonding with novel conductive adhesives - that can bond microsystem chips onto low temperature organic and propriety membrane substrates.
- The use and extension of current models to predict the reliability of this microsystem assembly with the underfill characteristics and identify process weaknesses.
- The recommendation to industry of generic processes that will allow the integration of microsystems technology and different types of microsystems components into commercial products.

Figure 1 displays the three phases of the project.

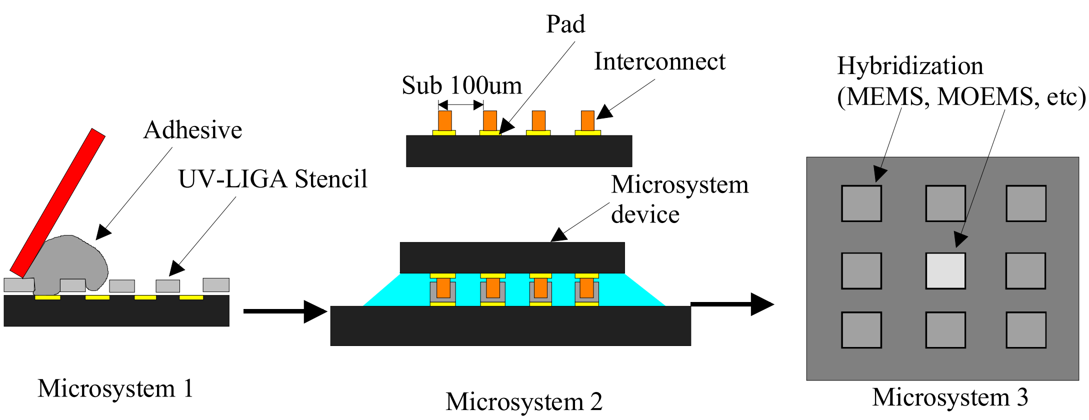


Figure 1, Three phases of MAT21 project

Sub-100 micron pitch Stencil Printing - Advanced Stencil Manufacture

The purpose of a stencil is to allow the transfer of solder paste, conductive adhesive or other similar material through its aperture openings onto a given substrate. Conventional stencil manufacturing techniques do not allow the generation of stencils capable of printing reliably below 130-150μm pitch. The undercutting artefact of the chemical etching step inhibits the generation of a fine web spacing needed to enable fine pitch. Laser cutting can ablate holes of the required diameter; however the interaction between the foil and laser does not allow the formation of perfectly defined and repeatable apertures. Also laser cutting is a sequential process, hence as the pitch decrease and the number of apertures increase the manufacturing time increases to an uneconomical point. Current manufacturing methods to generate electroformed stencils are still not suitable to fabricate sub-100μm pitch stencils. The uneven thickness distribution of the plated metal webs (metal space between apertures) causes weak spots with in the stencil, hence limiting the web to approximately 60μm. Also the lithography step does not create a suitably accurate mold for creating sub-50μm diameter apertures.

The stencil shown in figures 2a & b was fabricated using a novel microengineering process, which is repeatable and low-cost. The process is currently being patented at Heriot Watt University and commercialised through a spin-out company called MicroStencil Limited [5]. Perfectly vertical sidewalls are produced due to the unique process steps, type of photoresist used and the high collimation of the exposure source. Stencils are produced with apertures closely following the resist sidewalls during the electroforming process. The novel electroforming process generates the desired metallic properties with a uniform distribution across the whole stencil. Custom built equipment used to fabricate the stencil includes a highly collimated exposure gun and a doctor blade machine. The resist is coated by the spreading machine, which consists of a knife-edge and micropositioners. The micropositioners ensure that the correct and uniform thickness of photoresist is deposited across the wafer. The knife coat is better at applying a planar layer of thick photoresist than by spin coating. This is due to the high viscosity of a thick photoresist, solvent evaporation and the beading effect created at the edge of the wafer from the spin coat process.

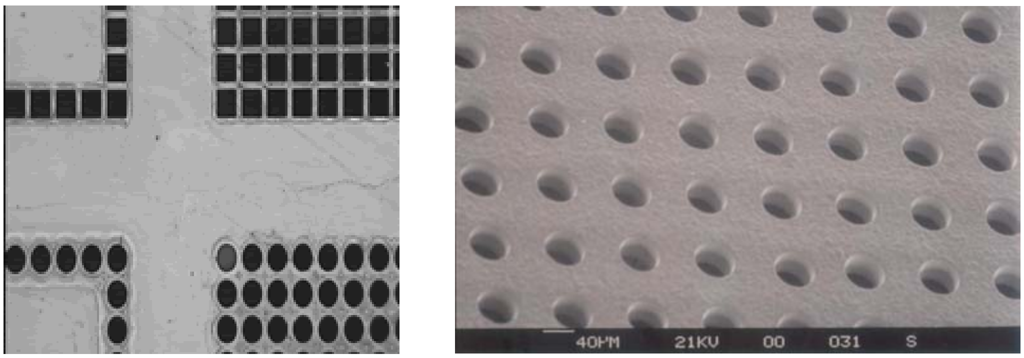


Figure 2, Microengineered stencil a) optical image of square and oval shape apertures at 90μm pitch b) SEM Images 50μm diameter aperture 100μm pitch

The novel electroforming process enables the partial control of the surface roughness of the stencil. In order to achieve consistent reliable prints the paste must be able to roll evenly across the surface of the stencil. The rolling motion is caused due to the driving force of the squeegee and the resistance of the stencil surface. The squeegee force and lateral motion also cleans the surface of the stencil during the printing process. As an example, figure 3 shows the comparison between the surface of a smooth stencil and rough stencil.

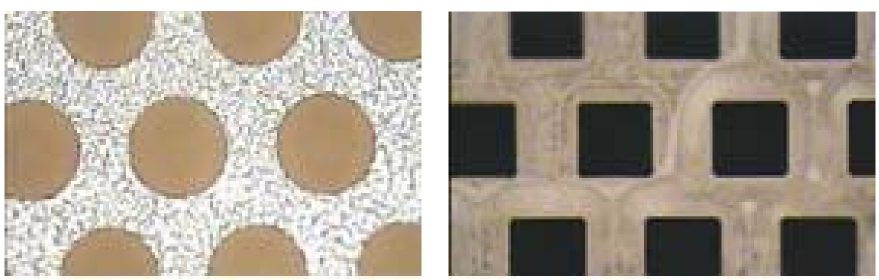


Figure 3, a) rough upper stencil surface, b) smooth upper stencil surface

Modeling Stencil Deformation

Parameterized finite element models of the stencils were designed to investigate the stencil stress levels and deformation caused from the framing and print force. A major concern in the project was the level of possible damage that could be induced on the stencil through elastic deformation which would eventually lead to misalignment of the prints to the pads. The stencil pitch, aperture shape, aperture diameter and magnitude of the force were modeled to characterize the trends of scaling down to very small pitch dimensions on a 50μm thick stencil.

The models indicated that only a 20μm deformation was induced in an 80mm square stencil with aperture pitches down to 200μm and the aperture diameter and framing tension were kept constant at 50μm and 38 N/cm, respectively. Decreasing the pitch below 200μm further resulted in a nonlinear increment of in-plane deformation, figure 4a. The highest stress levels simulated were concentrated in the middle of the web, between the apertures. The deformation starts to increase more dramatically when moving into the sub-100 micron pitch range Figure 4. It is however important to note the modelling study detected only elastic deformation in the stencil.

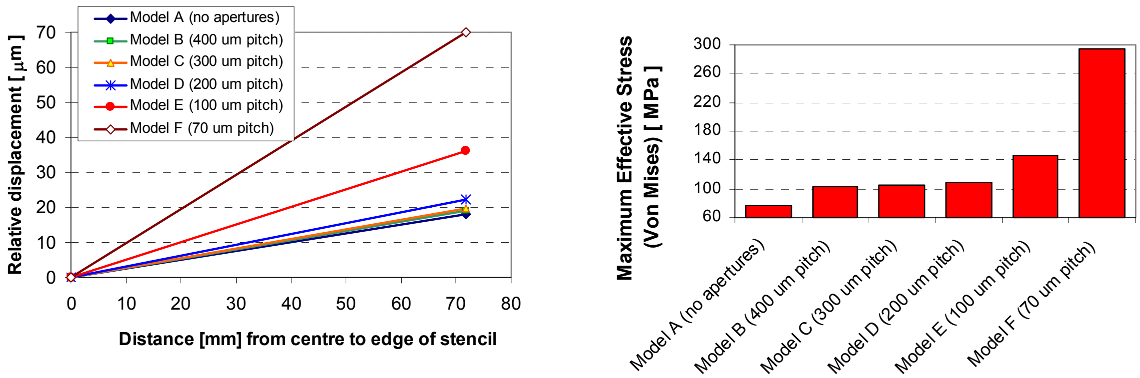


Figure 4, a) Stencil deformation vs. aperture pitch b) stress as a function of increasing pitch

Figure 5a displays the non-linear decrease in effective stress when the aperture diameter is reduced and the pitch is kept constant at 100μm. It was found also that a circular aperture shape reduces the stress induced in the stencil by 18% compared with the square aperture, figure 5b.

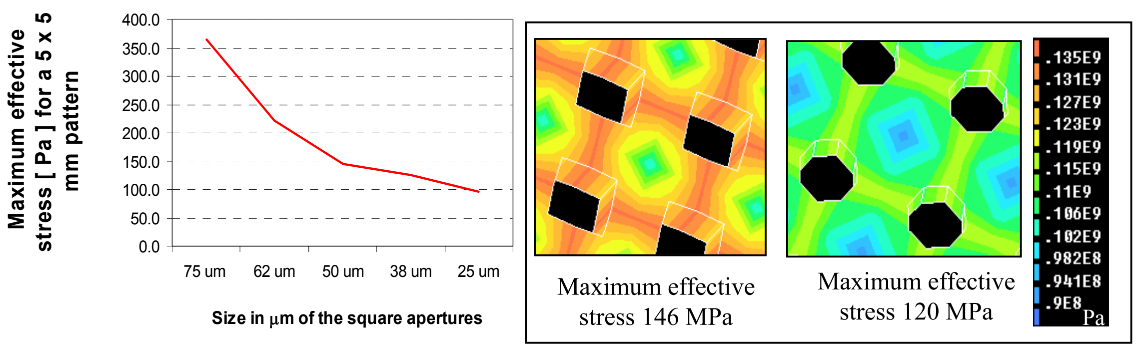


Figure 5, a) Stencil stress as function of aperture size b) stress as a function of aperture shape

Rheological characterisation of ICAs and solder paste

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. An isotropically conductive adhesive consisting of irregularly shaped silver particles (approximately 80% by weight) in an epoxy resin was investigated as a suitable material to print at fine pitch and subsequently cure at low temperatures. The silver flakes are responsible for providing the electrical connections, whilst the resin adhesive provides the permanent structural bond when cured. Prior to curing, the resin is in a fluid state and the bulk properties of the conductive adhesive exhibit non-Newtonian rheological characteristics such as shear thinning i.e. the reduction of viscosity with increased shear. The formulation of the adhesives is critical to providing the necessary constituents to form the electrical interconnections and structural bond as well as defining the flow properties and their printing performance. At a macroscopic scale, the adhesive may be considered to be a homogenous continuum, ignoring the solid particle content, size, shape distribution and inter-particle forces. The adhesive can instead be categorised by bulk macroscopic properties such as viscosity, and density.

A Reologica StressTech controlled stress and strain rheometer was used to investigate ICAs rheological properties and to compare them with conventional solder paste. A sample thickness of 0.5mm is sandwiched between two smooth flat plates having a 40mm diameter, figure 6. The deformation of the sample can be measured in either a controlled stress or controlled strain mode.

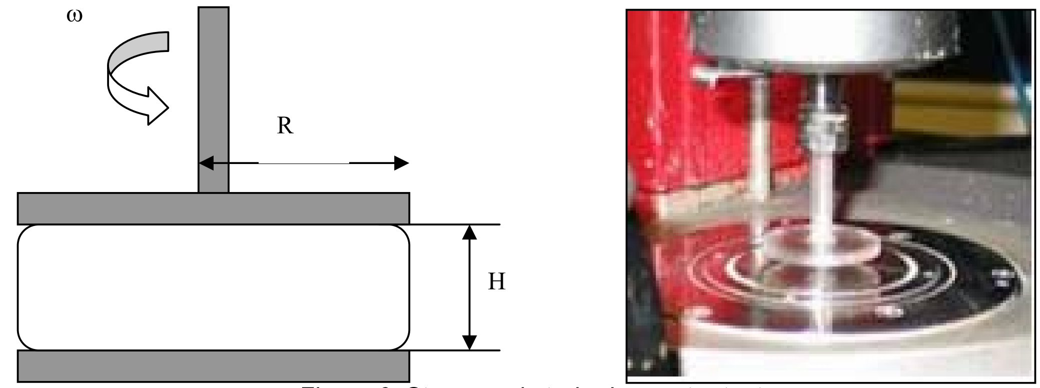


Figure 6, Stress and strain rheometer test

Steady shear rheometry involves the measurement of viscosity at different shear conditions. The sensitivity of a sample to changing shear rates is evaluated (shear thinning, thixotropy, hysteresis, etc). Shear thinning properties (the reduction of viscosity of a material when sheared) are essential to assist the entry of paste into the stencil apertures. The experiment was conducted at 25°C and the relative humidity was monitored. During the printing process, solder pastes and ICAs experience a range of shear rates from 0.01 to above 1000/s [6]. Although the shear rates investigated here are low, they can be used to predict the flow properties during aperture filling and paste release.

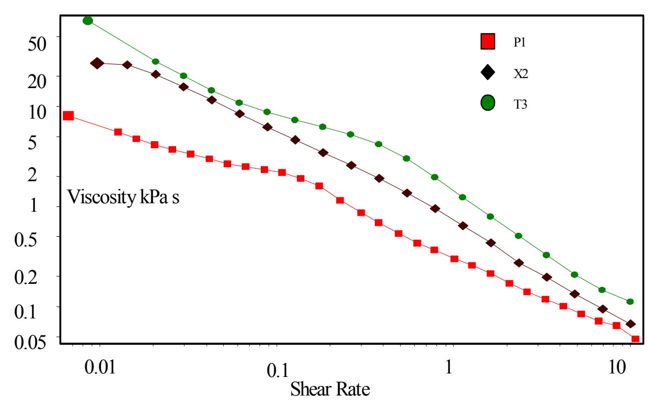


Figure 7 Viscosity vs. shear rates (1/s)

In Figure 7, the viscosity as a function of shear rates is shown for two types of solders pastes (X2 & T3) and conductive adhesive samples (P1). The sample T3 shows the highest viscosity followed by X2 and P1. A further analysis of the experimental data was carried out using the Cross Model [6] shown in equation 1, where η is the viscosity, η_∞ is the viscosity at infinite shear rate, η_0 is the viscosity at zero shear rate, K is associated with the breaking of structural linkages and m is a dimensionless constant. The degree of shear thinning is dictated by the value m: m tending towards unity represents shear thinning liquid while m tending towards zero represents Newtonian liquids.

(Equation 1) $$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty}=\frac{1}{1+K\dot{\gamma}^{m}}$$

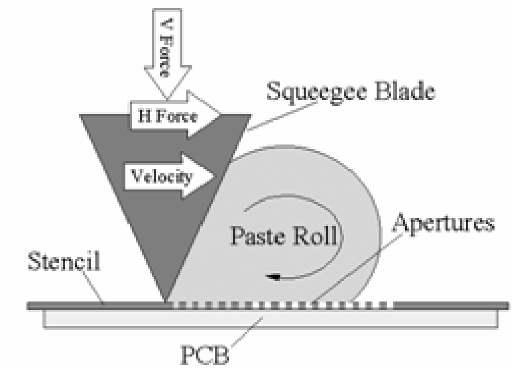
From equation 1, η_0 and η_∞ are estimated, including *K, m* and correlation coefficient, *r* as shown in table 1. From the table 1, the viscosity measured for the solder paste samples (X2 and T3) is higher than that of the isotropic conductive adhesives (P1). Based on the constant m, sample P1 and X2 showed a higher degree of shear thinning compared to sample T3. Between the samples X2 and T3, zero shear viscosity of T3 was much higher compared to X2. From the zero shear viscosity values, sample T3 showed a much higher resistance to flow compared to the two other samples. But the infinite shear viscosity of P1 and T3 are low compared to that of X2. The drop in viscosity is a good indication of structural re-arrangement of the particles in the direction of flow, which promotes the aperture filling during the stencil printing process. All samples showed a good fit to the Cross model.

Model Parameters	P1	X2	T3
η_0 (Pa s)	6025	27640	33060
η_∞ (Pa s)	45	62	79
K (s)	21	62	26
M	0.85	0.98	0.97
R	0.98	0.99	0.90

Table 1, Rheological constants defined by the Cross model for solder paste (X2, T3) and ICA (P1)

Computational Fluid Dynamics (CFD) applied to optimise the printing process

Computational Fluid Dynamics (CFD) was used to simulate the macroscopic bulk motion of adhesive paste ahead of a moving squeegee blade during the stencil printing process. Figure 8a) details the geometry to be simulated and figure 8b) details the results of velocity vectors across a stencil. The computational mechanics code – PHYSICA [7] – was used for these simulations.



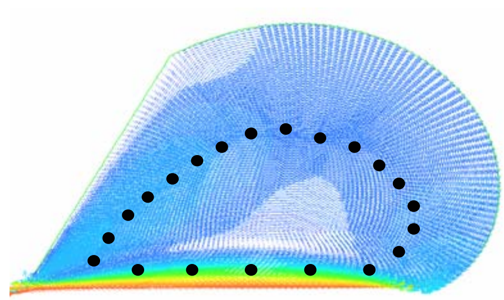


Figure 8, a) schematic of paste roll b) Results of velocity vectors using Non-Newtonian CFD

Non-Newtonian fluid dynamics is simulated by solving the Navier Stokes equations for flow with the Cross Model constitutive law, as detailed in the above section, to characterise paste rheology [8]. Pressure, velocity, shear rate and viscosity distributions can be determined throughout the paste material. Figure 9 shows the predicted pressure distribution in the paste along the stencil surface for a blade angle of 60 degrees and velocity 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 process depends on the paste behaviour and material properties encountered in this region adjacent to the stencil surface.

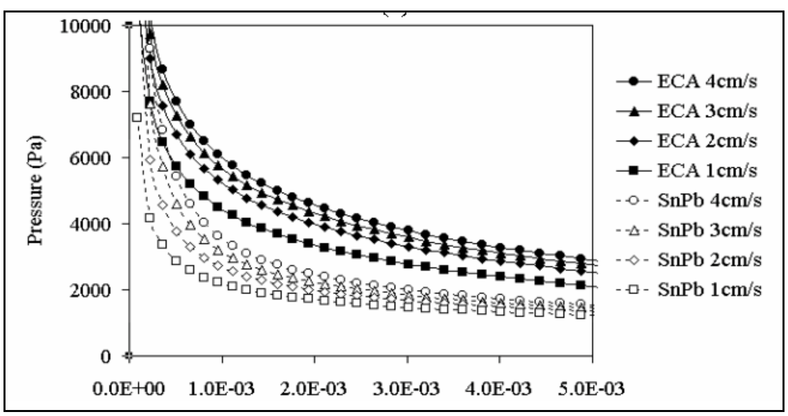


Figure 9 Pressure in paste material at different distances from blade tip

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.

Adhesive Printing Results

Initial print trials have been carried out using a small scale prototype stencil fabricated on a 3” wafer. Large arrays of conductive adhesive were printed down to 50μm pitch and consistently at 90μm pitch as shown in figure 10. Good shape definitions were repeatedly achieved for circular & square apertures without successive cleaning of the stencil.

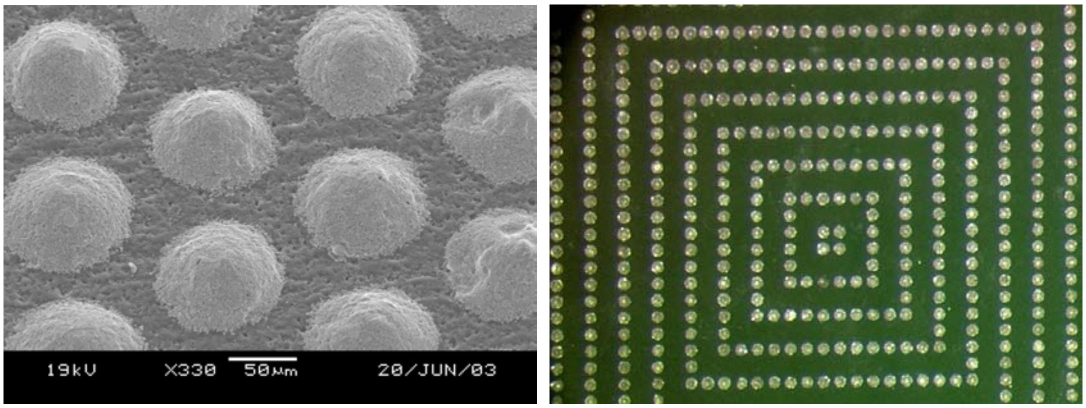


Figure 10, a) SEM Image of 90μm pitch adhesive print deposits b) Optical image of 100μm pitch adhesive print deposits

The physical characteristics of the deposits (height and volume) were measured using a Scanning Electron Microscope (SEM) and a Zygo NewView 5200 scanning white light interferometry system. A linear variation of the deposits height of as a function of the aperture diameter was measured.

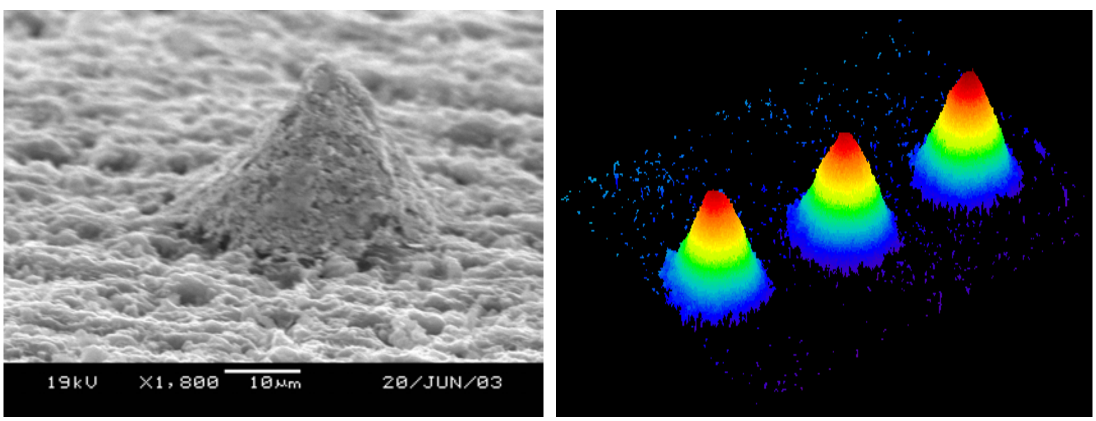


Figure 11, Side profile of adhesive deposit

The deposits have the form of a cone (figure 11) unlike solder pastes deposits, which are typically flat topped. Adhesives tend not release completely from the aperture like solder pastes. In most cases more adhesive is left in the aperture than deposited onto the substrate. This artefact of the printing process is caused by the stencil acting like an array of micro dispenser tips. If the surface area of the aperture wall is greater than the surface area of the substrate exposed through the aperture, a small portion of the adhesive will remain on the substrate whilst the rest will remain in the stencil aperture [9]. For a 50μm thick stencil, this behaviour takes place for aperture diameters less than 200μm. If the surface area of the substrate is much greater than that of the aperture, the deposit released has a relatively flat top and equal roughly the thickness of the stencil. This simplified explanation does not take into account the wetting properties of the substrate and aperture sidewall, which also play an effect in the fill and release characteristics of the aperture. Figure 12 display the variation in print height versus aperture diameter.

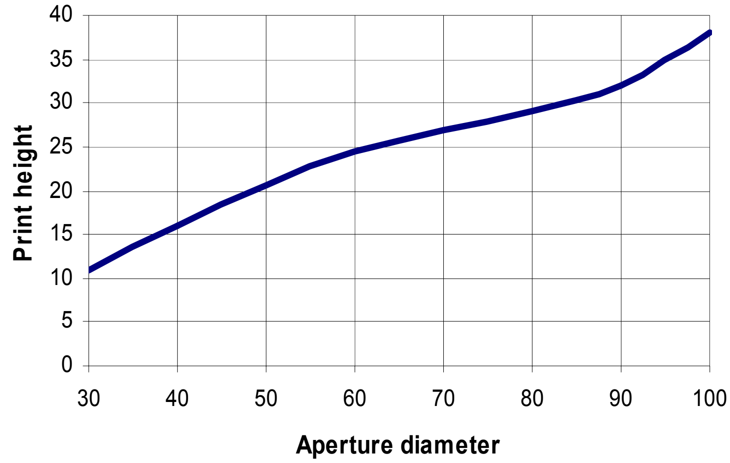


Figure 12 Aperture diameter vs. print height

Reliability modelling

Thermo-mechanical calculations have been undertaken to investigate key process parameters that ensure higher reliability [10]. Figure 13 shows the flip-chip assembly under investigation. Under thermal cycling the thermal mismatch in the materials will results in stress evolution and fatigue damage to the ICA joint. Examples of parameters investigated are; underfill properties, volume of ICA paste deposited and wetting height of the ICA along the device bump. The damage parameter used in the calculations was the accumulated plastic strain in the solder paste. Higher values of this would increase the likelihood of crack initiation and propagation.

Simulations show that decreasing the CTE (20 – 65 ppm) of the underfill and increasing its Young's Modulus (1 – 5 GPa) decreases the plastic strain in the joint. Minimizing the amount of adhesive that wets the sidewalls of the bumped pillars also helps reduce the plastic strain. The most important variable was the volume of adhesive deposited. Larger volumes of adhesive produce a decrease in the plastic strain. Thinner substrates also helped reduce plastic strain in the adhesive and hence increase lifetime of the joint.

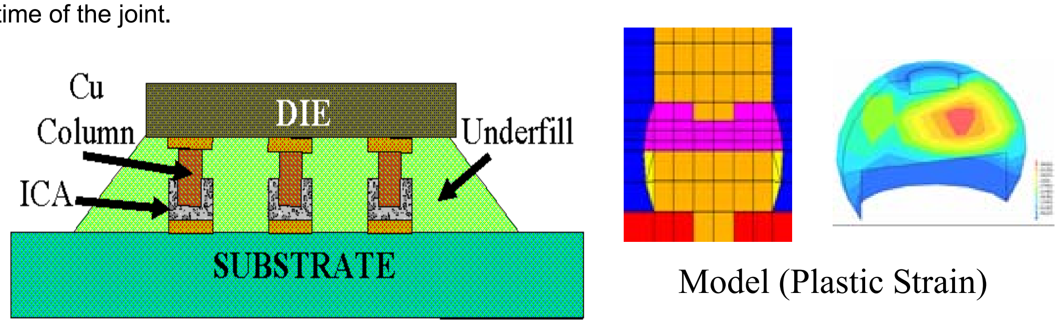


Figure 13, a) Flip-chip assembly under investigation b) Modeled results of Plastic Strain

Packaged test chip from Microemissive Display (Microsystem 3)

Phase three of the MAT21 project, as shown in figure 1, aimed at proving the feasibility of the developed assembly process by packaging end-users devices. One of the project partners, Microemissive Displays (MED), has developed a technology, which enables the manufacture of a full colour organic light emitting diode (OLED) array directly onto a microchip. The OLED array works as a 320 x 240 pixel microdisplay. Currently MED package their display dies in moulded plastic modules, however in the future the company would like the possibility of flip-chip bonding this device. Directly attaching the chip to the flexible substrate will save real estate and cut production materials. The MED chip covered most of the criteria specified in the MAT21 project including the requirement for low temperature assembly at high volumes.

Coined gold stud bumps were bonded onto the test dies as shown in figure 14a. ICA was subsequently deposited onto the substrate. The die is then flip-chip bonded directly onto the board. One of the issues solved by the team at Celestica was to ensure the underfill did not flow directly onto the display area of the device. A FR-4 board was manufactured with a cavity to simulate the display area. A suitable underfill was identified that could be applied to the edge of the package and then flow between the chip and substrate using surface tension effects. In the case of the MED device there is an open region where the display illuminates from. The underfill should flow around the interconnects between the chip and the board but stop flowing when it reaches the open cavity for the display, figure 14b. The complex and delicate 3-D structures on the surface of many MEMS and MOEMS devices are easily damaged by the underfilling process. This direct chip attach process demonstrates a suitable method to ensure underfill does not damage these delicate devices.

Figure 14, a) coined stud bumps (picture courtesy of Microemissive Displays) b) investigation of underfill flow between a substrate and die containg an open cavity

Mechanical and electrical characterisation is still needed to be undertaken in order to ensure the stability of the packaged microsystem system.

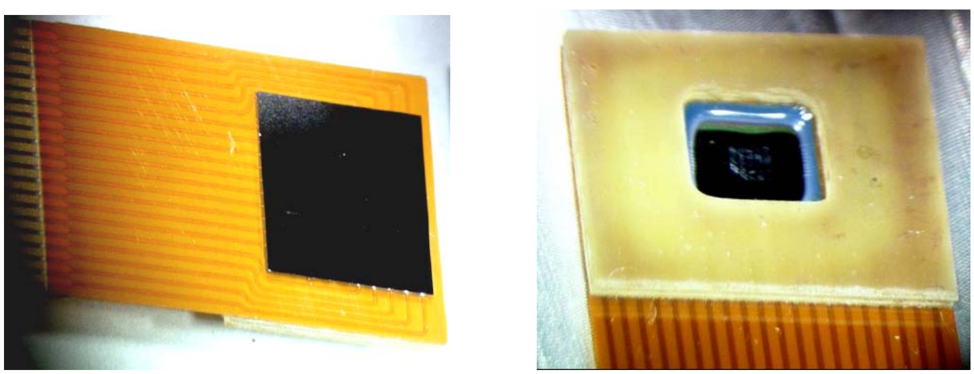


Figure 15, a) backside of MED test device b) front side of MED test device

Conclusions

50μm thick novel stencils have been developed with extremely well defined aperture shapes and smooth sidewalls. Stencil apertures have been fabricated from 10μm to 1000μm in diameter with a minimum web of 10μm fabricated. Modeling the stresses within the stencil after framing and during the printing process determined that only elastic deformation is seen in the stencil. The use of circular apertures reduces the stress built up by 20%.

Rheological characterisation has shown that the viscosity of the solder pastes was much higher compared to that of the ICAs. All samples showed a high degree of shear thinning when fitted to the Cross model. But as the shear rate increased the viscosity of all three samples dropped to a low value, which explains the good aperture filling observed during the printing process. However at lower shear rates the viscosity of each of the samples varied considerably which could have a large affect on the release process of the materials. This difference in release is exhibited in the print results, with more adhesive left in the apertures compared to that of solder paste.

Pressure, velocity, shear rate and viscosity distributions have been calculated throughout the paste material using computational modeling techniques. During the printing process the pressure gradients seen by the ICA is much larger than that observed by the tin-lead solder.

ICA was printed down to 50μm pitch with repeatable and consistent prints demonstrated and 90μm pitch.

The reliability of the Microsystem package simulations show that decreasing the CTE (20 – 65 ppm) of the underfill and increasing its Young's Modulus (1 – 5 GPa) decrease the plastic strain in the joint. In addition minimizing the amount of adhesive that wets the sidewall of the bumped pillar can also help reduce the plastic strain. The most important variable is the volume of adhesive deposited. Larger volumes produce a decrease in the plastic strain. Thinner substrates also aid in reducing the plastic strain in the adhesive and therefore increasing the lifetime of the joint.

An end user device was assembled using the developed low temperature bonding, high-volume packaging process. Celestica have demonstrated that an open cavity can create a barrier to stop underfill flowing due to the change in surface tension effects. This is especially important because many MEMS and MOEMS devices contain complex 3-D structures and open cavities. If these structures become coated with underfill the devices normally become useless. Overall a low temperature, fine pitch (sub 100μm), high volume flip-chip assembly process has been developed which slots in well to SMT manufacture lines enabling low cost Microsystems packaging.

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