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Combining Fine Line Photoimageable with Multi-Step Thick Film for Improved Circuit Density

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Abstract—**There is a strong market need for further miniaturization of microelectronic ceramic-based products; electronic components require an increasingly finer pitch interconnect. Screen-printing resolution is a limiting factor in further miniaturization of classical thick film. Photo imageable thick film technology (PITF) was proposed decades ago as a successor technology to thick film, to achieve finer pitch patterns. However, where classical multilayer thick film provides good routing and interconnect capabilities, but insufficient fine line resolution, PITF does the reverse: no multilayer routing but advanced fine line performance. A combination of PITF for fine pitch mounting with advanced MLTF for efficient routing has been developed, targeting a linewidth of 50 μm line/spaces and below. Test and demo panels were made, using combinations of PITF pastes and conventional screen-print materials. Results, process performance, and limiting factors are discussed.**

Keywords—**Interconnect, fine line, photoimageable, resolution, thick film**

INTRODUCTION

A. Motivation

There is an increasing demand on highly integrated electronics that require advanced interconnect technologies, coupled with a growing market need for further miniaturization of microelectronic ceramic-based products. Although these products are becoming physically smaller, their electronic components (namely the integrated circuits such as BGA, FC, WLCSP) must also be interconnected on a finer pitch, and typical structures such as interposers are used to solve local fan-out routing limitations. For many years this has driven development to improve patterning resolution in conventional multilayer thick film (MLTF) technology. However, the screen-printing resolution has become the process capability bottleneck. This is due to both the dynamic rheological properties of the paste and the screen properties themselves.

Typical thick film industry capability today is 150 μm L/S (line width/spacing width), whereas advanced thick film using special screens and tailored pastes reaches 100 μm L/S and somewhat below, but at the cost of process reproducibility and robustness. This is insufficient for the emerging advanced packaging needs. Several technologies that include optical lithographic or laser patterning principles have been proposed to boost the capability of thick film interconnectivity (employed in both conventional thick film as well as cofired ceramic processes) to dimensions below 100 μm line width and spacing: photoimaging or photo etching [1, 2] diffusion patterning [3], laser patterning [4-6], or the additive direct plated copper (DPC) process [7, 8]. Application of these technologies has remained limited, when applied to more complex multilayer products, and literature source is scarce. Photoimageable thick film technology (PITF) stands out because of its compatibility with standard thick film screen-printing materials and infrastructure. Although PITF did find its applications in single-layer processes for plasma displays and microwave applications on low temperature cofired ceramics (LTCC), application in multilayer hybrids has remained limited. PITF competes with similar technologies as DPC and thin film that offer better fine line characteristics, but bear higher cost and less suitability in multilayer designs.

For advanced interconnect, potential lies in further development of a cost-effective technology that combines PITF for fine pitch mounting in combination with advanced MLTF for efficient routing. This method reduces the number of layers required by locally employing PITF high density patterning to solve the fan-out routing issues associated with fine pitch components. By combining the photoimageable patterning technique with conventional MLTF, the process window is expanded and accommodates 50 μm L/S features. PITF does bear higher material cost because of its subtractive nature; cost effectivity is reached by local application, where needed.

Results of our technology study are available, where 50 μm L/S PITF and standard MLTF were combined on standard alumina substrate. Circuits having special test structures were evaluated. Silver, silver palladium, gold, and dielectric paste materials were used. Paste performance was investigated in terms of resolution, profile, structure, and substrate effects. Compatibility of photoimageable and conventional paste materials was studied by cross-sectioning and electron microscopy. Energy dispersive x-ray (EDX) analysis was done to determine intermetallic and diffusion effects.

B. Photoimageable Technology

PITF materials technology, having its origin already in the 1980/1990s [9, 10], was developed by Dupont (Fodel series) and in parallel was pioneered by Hibridas in Lithuania and later by ITME in Warsaw. From materials and processing perspective,

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Table I
Photoimageable Pastes Used

	Product code	Supplier
Ag	Fodel 6778	Dupont
Ag	PF-1065	ITME
AgPd 4:1	PF-2008	ITME
Au	PF-3005	ITME

the technologies are basically similar. The pastes contain similar inorganic and organic compounds as regular thick film materials, but UV photo-initiators and reactive mono and polymeric compounds are added. Ultraviolet (UV) exposure initiates a polymerization reaction in the material which acts as a negative resist in the consecutive wet development process. There, nonexposed material is removed by the mechanical abrasive action of high pressure sprayed developer solution; solubility of the nonexposed parts is chemically enhanced by the developer solution.

Because of the strong optical absorption of the material, penetration of UV is limited to the first microns underneath the surface; consequently, polymerization is only initiated at that location. The paste composition should be balanced between the amount of photo initiator and the metal content, which do not only influence optical absorption characteristics and consequent wet development behavior but also the amount of shrinkage during firing. Proper process control minimizes undercut of patterns at their edges and prevents edge curl after firing.

The required process and equipment for the PITF fits well within conventional thick film production environments and offers interesting cost-performance benefits.

MATERIALS AND METHODS

A. Materials

Substrates used were 96% alumina Durastrate (Coorstek), size 4″ × 4″. Screen printing was done using 250 mesh screens. Photoimageable pastes were obtained from two suppliers, Table I.

Chrome-on-soda lime glass photomasks sized 7″ × 7″were acquired at JD Photodata. Development of the pastes was done using 1 wt% Na_2CO_3 in water for Fodel and 0, 1 wt% ethanolamine for ITME pastes. Additional screen printing of regular thick film materials was done using ESL9633-G-FL (Ag/Pd ratio 2:1) and ESL9635-HG (Ag/Pd ratio 6:1), ESL8844-G Au, all under standard processing conditions.

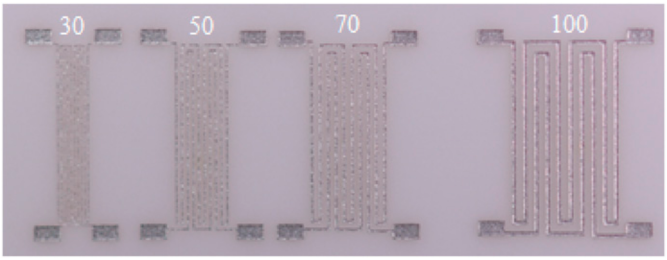

Fig. 1. Line test patterns down to 30 μm (Fodel 6778).

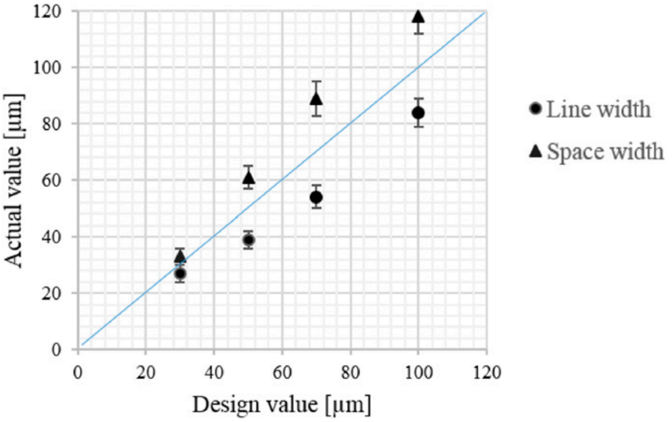

Fig. 2. Actual versus designed linewidth for symmetrical line/space patterns (Fodel 6778). Error bars display SDs measured over 5 panels, 10 lines per panel.

B. Equipment

Standard equipment for screen printing, drying, and firing was used. Paste exposure was done on a Hibridas MA-6K mask aligner/exposure unit equipped with collimated scanning UV light emitting diode (LED) array. Development was done on an SC-6K spin developer. Cyberscan CT-100 profilometer was used for dimensional and roughness analysis. SEM/EDX work was done at IMOMEC Hasselt on a FEI Quanta 200-FEG.

C. Processing Sequence

Processing sequence was as follows:

1. Partial screen printing of photoimageable paste on substrate (only in areas of patterning)
2. Leveling, t = 15 m
3. Drying, T = 90-120°C, t = 10-20 m (paste dependent)
4. Exposure, dose (time, intensity, and number of scan passes) dependent on paste type, range 30-80 mJ/cm^2
5. Development, time dependent on paste type/time-to-clear, range 10-20 s
6. Firing, T_max = 850°C, t = 1 h
7. Buildup of additional photoimageable layers (go to step 1) or additional standard screen-printed thick film layers.

EXPERIMENTAL RESULTS

A series of test panels and structures were made using combined PITF + MLTF to study patterning resolution and processing and material compatibility effects. In addition, a demonstration panel was developed.

A. Pattern Resolution and Topography

Symmetrical line/space Ag patterns down to 30 μm lines were made in Fodel 6778, as displayed in Fig.1, as well as PF1065.

The actual pattern widths obtained are displayed in Fig. 2. Because of shrinkage during firing, the line width obtained is smaller, the corresponding space width larger than designed. Panel-to-panel variation in linewidth is in the order of 5-8%.

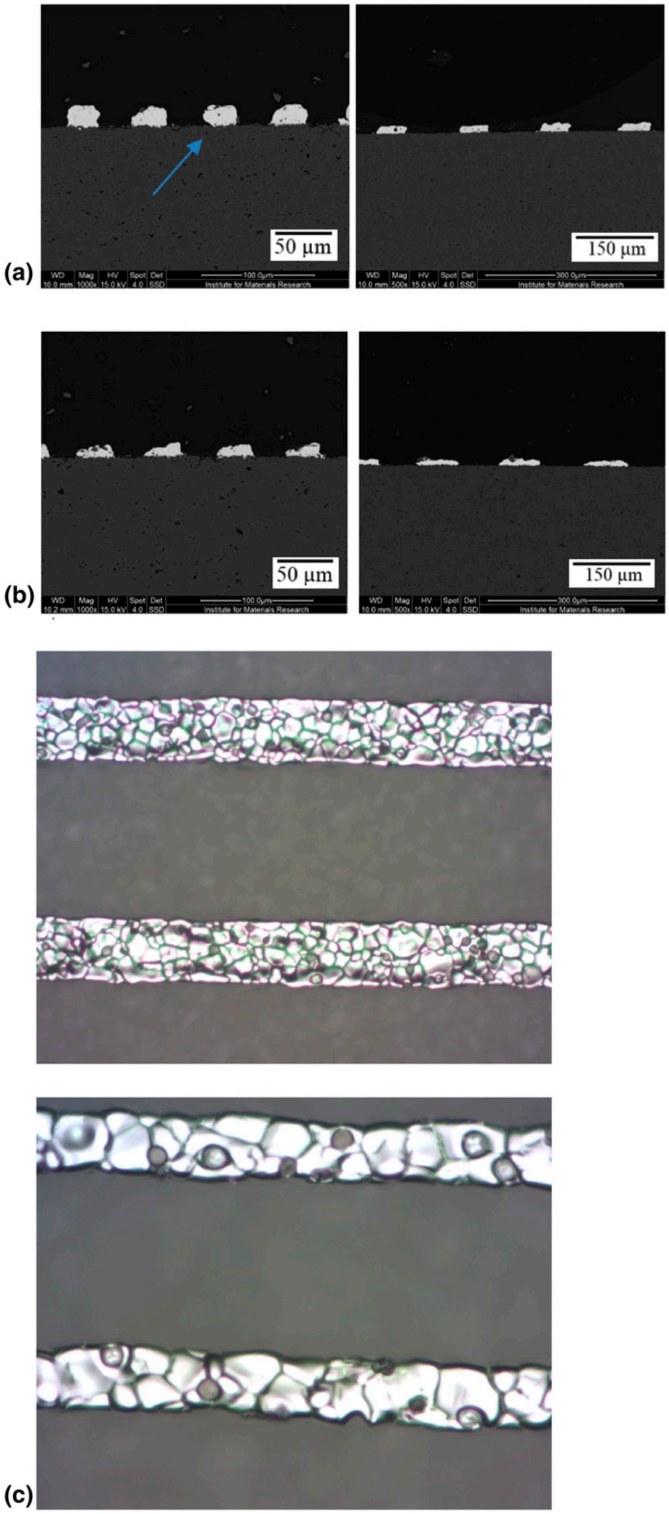

Fig. 3. (a) Fodel 6778, left picture 30 µm, right picture 70 µm lines (design value). Blue arrow indicates undercut in the developed structure. (b) PF-1065, left picture 30 µm, right picture 70 µm lines (design value). (c) Optical microscopy of 50 and 30 µm (design value) lines in Fodel 6778.

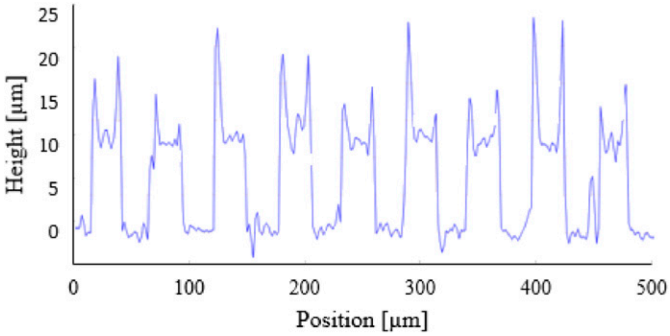

Fig. 4. 30 µm L/S (design value) profilometry.

This can be reduced by ensuring optimal mask-to-substrate contact in the exposure step.

Cross-sectional SEM images for 30 and 70 µm lines are shown in Fig. 3. Some tendency for edge curling is observed in the 30 µm narrow lines (arrow, 30 µm) of the Fodel, that has a lower solids content and higher shrinkage compared with the PF-1065, whereas the latter yields thinner layers. The PF-1065 image suggests a slope in the 30 µm which is probably caused by anisotropy in the wet development process.

Profilometric measurement as displayed in Fig. 4 on the majority of the panels made using Fodel 6778 shows strong edge curling of the 30 µm lines because of undercutting in the development process and consecutive deformation because of tensile stresses and shrinkage in firing. Fired thickness of the Ag lines is around 10 µm, curling is locally seen to lift edges up with up to 10 µm. Some of the 30 µm L/S patterns were seen to lose their adhesion. This effect limits the paste's maximal achievable resolution.

Fig. 5 shows 30 µm lines (design value), where edge curling has led to loss of adhesion of lines to substrate; whereas the track lines stay intact, corners have rounded. Excessive curling shows as black discoloration of the tracks.

Undercut/edge curling phenomena must be prevented to achieve functional interconnect patterns. This can be done by

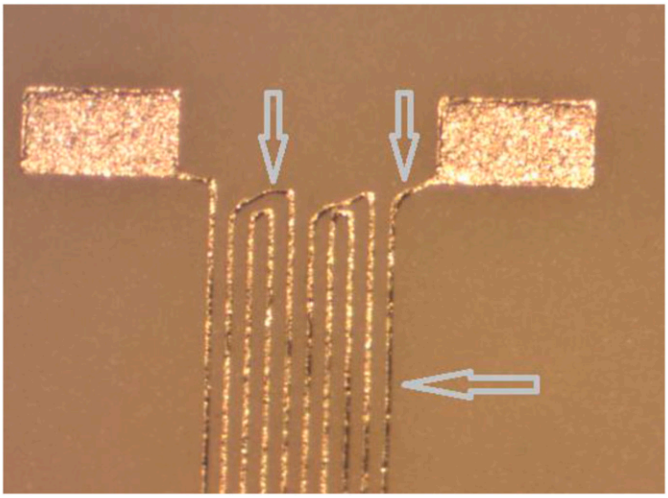

Fig. 5. Adhesion loss due to edge curling, 30 µm lines (design value) Fodel 6778 Ag.

Table II
Mean Surface Roughness Measurements Taken Over 20 Samples

	Ra, average [μm]	Rmax, average [μm]
Substrate Al_2O_3 96%	0.62	4.92
PITF Ag only [t = 15 μm]	0.72	12.4
ESL9635-HG only [t = 12 μm]	1.08	8.7
PITF Ag + ESL9635-HG	1.28	15.3

optimizing development time. Besides, the phenomenon is dependent on the optical characteristics of the paste; a deeper penetration of polymerization in optical exposure will lead to less tendency for undercut at a given layer thickness.

B. Compatibility Photoimageable Thick Film Technology + Multilayer Thick Film

To connect a local fine pitch pattern, made using PITF, to a regular MLTF pattern, an overlap area must be designed. Therefore, the metallurgical compatibility of photoimageable and regular pastes was investigated.

Photoimaged Ag pads (sized 200 × 100 μm Fodel 6778, thickness 10 μm) were overprinted with 15 μm of ESL9635-HG (AgPd 6:1). Roughness was determined in the central area of pads, Table II.

The photoimaged material has a low roughness but with local distinct peaks. The thick film conforms to the height variation in the PITF layer and does not planarize.

In cross-sectioning, strong void formation is observed:

In the area where PITF Ag (as first layer) was overprinted and fired with regular AgPd (second layer), large voids have formed as a result of Ag diffusion from the Ag to the AgPd alloy material, causing loss of adhesion. The Pd content in the double layer was homogenized completely at the right side of the line in Fig. 6. Clearly visible is the penetration of the paste's glass compounds into the semiporous structure of the alumina substrate.

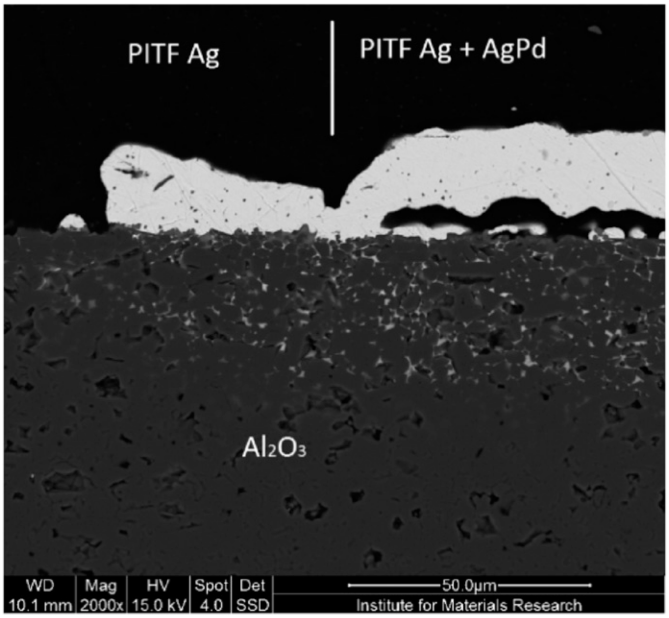

Fig. 6. Boundary zone between PITF Ag and PITF Ag + AgPd. Left side: one layer of Fodel6778 Ag was printed, right side: Fodel6778 Ag overprinted with ESL9635-HG AgPd. Fired twice at Tmax = 850°C.

Fig. 7. Cross-section after firing of PITF AgPd (PF-2008, original thickness 5 μm) overprinted with 2:1 AgPd (ESL 9633-G-FL, 11 μm).

However, use of alloyed AgPd PITF as first layer and overlapping with regular AgPd leads to void-free homogenized monolayer coatings while retaining the glass adhesion bond to the alumina substrate, Figs. 7 and 8.

The AgPd molar ratio in the PITF material PF-2008 was Ag: Pd = 4:1. Combination with either a higher Pd content thick film paste (ESL9633-G-FL Ag:Pd = 2:1, Fig. 7) or a lower Pd content paste (ESL9635-HG, Ag:Pd = 6:1, Fig. 8) leads to dense layers that are fully homogenized (note that the particles and fibers in the coating pictures are not voids but glass metal oxide constituents); Pd content throughout the coating was seen to be homogeneous throughout the layer at a level of 29% for Fig. 6 and 15% in Fig. 8.

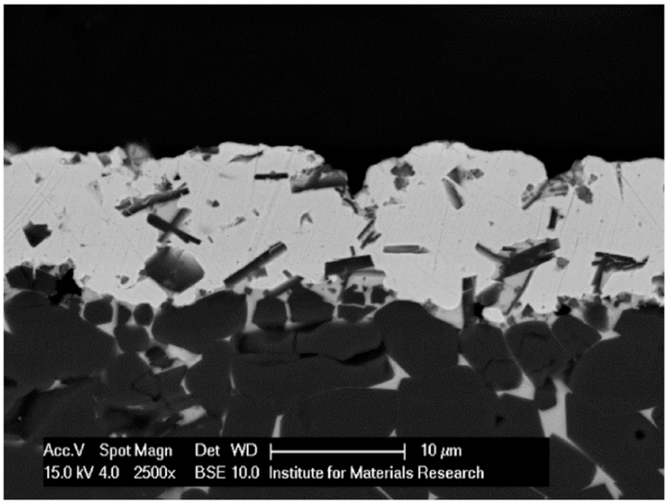

Fig. 8. Cross-section after firing of PITF AgPd (PF-2008, original thickness 5 μm) overprinted with 6:1 AgPd (ESL 9635-HG, 11 μm).

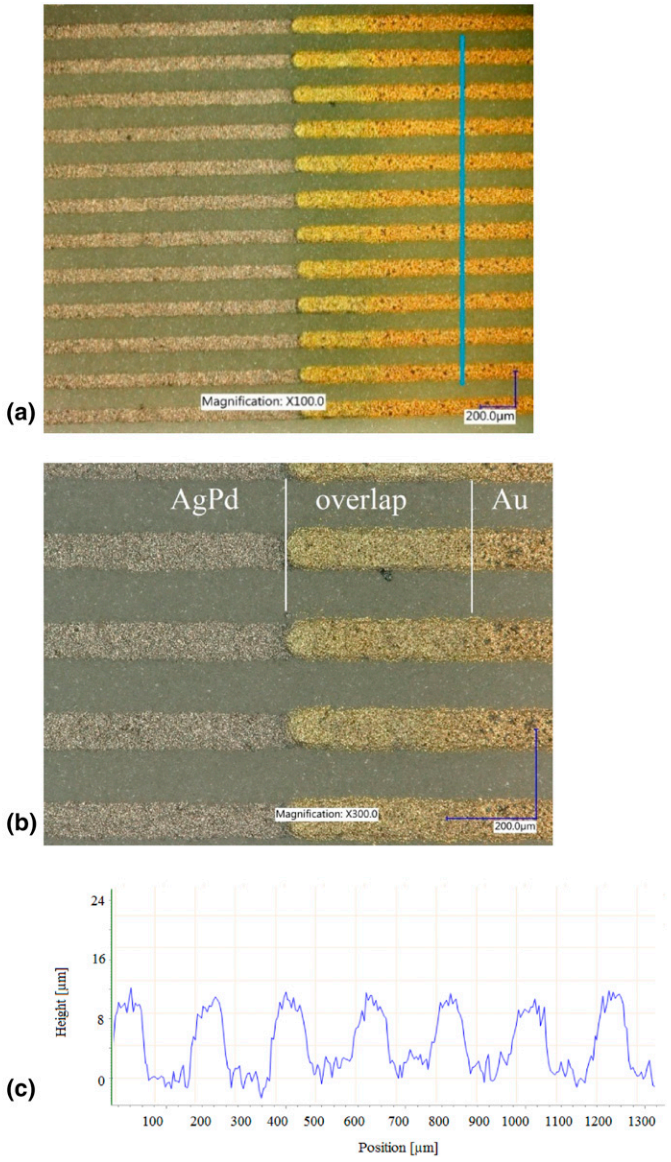

Fig. 9. 100 µm L/S patterns of AgPd (PF-2008) overprinted with PITF Au (PF3005): (a) overview (b) zoomed to overlap region (c) profile linescan of Au (scan trace = blue line in (b)).

C. Photoimaged Multilayer Structures

Application of a photoimaged layer on top of an existing structure was studied by photoimaging of an Au layer with fired thickness of 10 µm on top of 6 µm high photoimaged AgPd lines. Typical applications of such multilayer structures include wirebonding pads or gold-to-gold interconnects used in thermocompression flip-chip bonding. Lines of 50 and 100 µm wide, having an overlap of 350 µm long, were exposed, developed, and fired, Fig. 9. In the overlap, line widening by optical scattering in the 2nd exposure step (Au patterning on top of the AgPd) was absent. UV light is strongly absorbed by the Au paste in the exposure step, and minimal scattering by the AgPd structure underneath takes place.

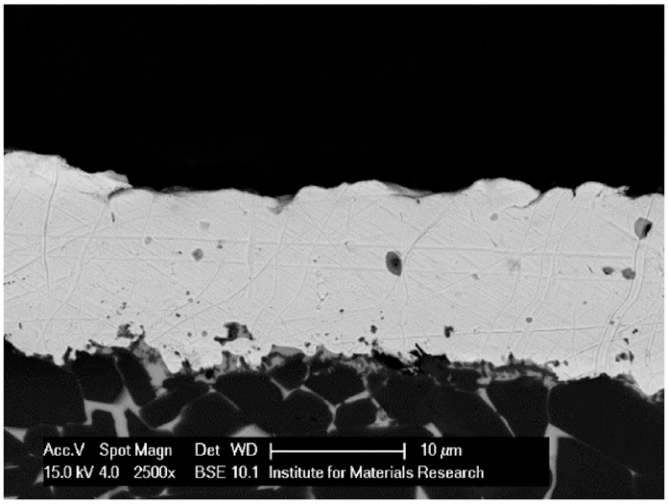

Fig. 10. Cross-section after firing of overlap region of AgPd (PF-2008) overprinted with PITF Au (PF3005).

Cross-sectional analysis of the overlap region shows a well adhering solid monolayer with homogeneous composition (71% Au, 20% Ag, and 8% Pd) throughout the depth of the film, Fig. 10.

D. Demo Panel Outline

To demonstrate the PITF process capability and compatibility with standard MLTF, a demo panel displayed in Fig. 11 was designed where three levels of interconnect circuitry scaling were created. Level I applies conventional MLTF screen printing, level II was made using a fine-line optimized printing process. Level III

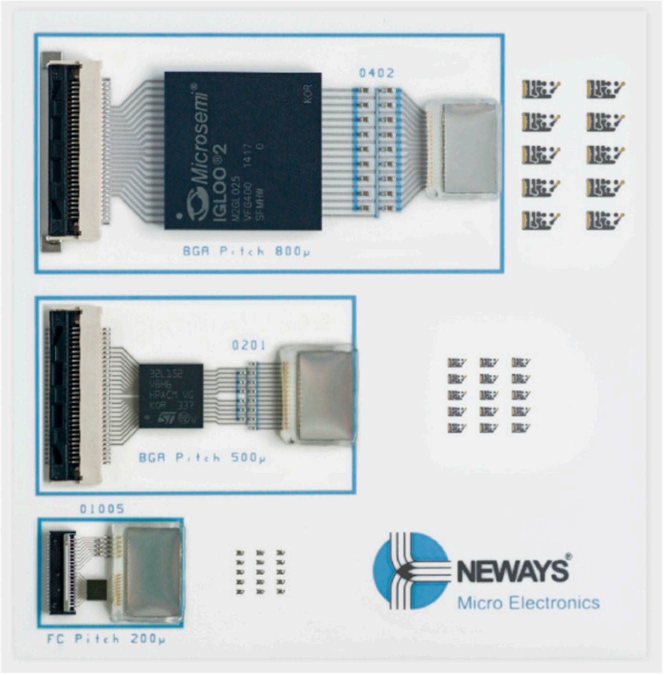

Fig. 11. Demonstration panel (sized 70 × 70 mm) with three different scale levels of interconnectivity.

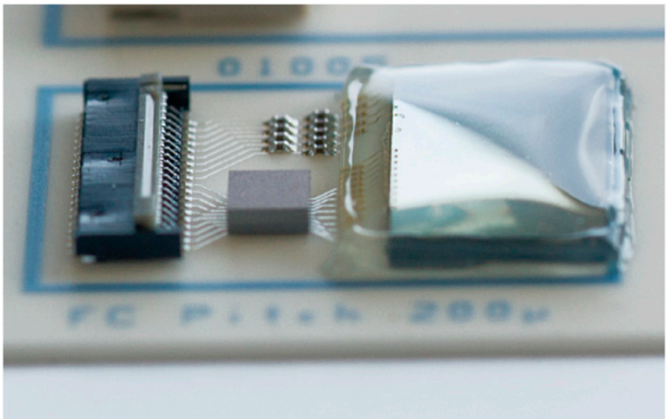

Fig. 12. Detail of level III of demonstration panel showing 50 μm fine line silver patterns.

was done by PITF with additional conventional MLTF and is shown in Fig.12. PITF patterning was done using Ag paste PF-1065, overprinted with ESL8844-G gold for wire bonding.

SMD 01005 components and BGA were mass-reflow soldered (SAC305) directly on PITF Ag. Electrical interface was ensured by Au wire bonding to the Si die that was successively covered by transparent glob-top. Wire bonding showed >8 g force at break using 25 μm thick Au wire. The electronic components and the L/S features of the demo panel are summarized in Table III.

REMARKS AND CONCLUSIONS

In this screening study, compatibility of photoimageable PITF and classical multistep MLTF was demonstrated. In this way, local fine line patterning down to 50 μm L/S is achieved, with the potential to go lower. The latter requires proper control of both exposure and development process and optimized paste material to prevent undercutting and consequent edge curling after. PITF pastes were seen to have postfired properties similar to standard MLTF materials given that all photosensitive and etchant materials are removed during the firing process. Intermetallic diffusion phenomena play a role as in standard MLTF.

Local integration of photoimageable patterning in conventional thick film multilayer designs is an attractive and cost-effective solution for complex hybrids in volume production. Further work is carried out to industrialize the process and increase process robustness. Besides, a study is started on multistep PITF as an enabler for further high density interconnect.

Table III
Test/Demo Panel Outline

Level	Patterning technique	L/S width [μm]	SMD component type	Flip chip pitch [μm]
I	MLTF	250	0402	800
II	MLTF	100	0201	500
III	PITF + MLTF	50	01005	200

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