Reusable, Unzippable, Sustainable Electronics (Reuse) Interconnet System for the Circular Economy

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Reusable, Unzippable, Sustainable Electronics (ReUSE) Interconnect System for the Circular Economy

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ABSTRACT

Recycling levels of electronics are increasing however a higher proportion are still going to landfill. EU Waste Electrical and Electronic Equipment (WEEE) legislation targets recycling levels within Europe, but true recycling with current technologies using reinforced epoxy glass substrates is a considerable challenge. An alternative approach (ReUSE) using thermoplastic substrates and novel adhesive systems for both bonding dielectric layers and for component attachment has been proposed. An important feature of the technology is the end of life disassembly, which following a simple soak in near boiling water, the components can be pushed off the assembly with minimal force. This report discusses this approach as well as materials testing and manufacturing process development. Results are presented on reliability testing, has proved the technology to be robust until disassembly is required. Finally the disassembly process at end of life is presented for a functioning demonstrator.

Key words: Recycling, WEEE, sustainability, PCB, disassembly, end-of-life
1 INTRODUCTION

Fabrication of recyclable electronics will present major new opportunities over the coming decade. Current EU legislation sets WEEE collection targets at 4kg per capita [1]. The recent recast of the WEEE legislation calls for a 5X increase in this level by 2019 [2]. Currently over 2 million tonnes of WEEE are discarded annually in the UK alone, one of the fastest growing waste streams [3]. This figure is estimated to be over 300 million units in the US [4], where 141 million mobile units alone were discarded in 2009, of which only 12 million were collected for recycling [5]. About 70% of the heavy metals (including mercury and cadmium) found in landfills come from electronic equipment discards. These heavy metals and other hazardous substances found in electronics can contaminate groundwater and pose other environmental and public health risks [6]. Electronics must develop more environmentally friendly materials and new end-of-life disposal strategies.

Whilst the enclosures around the printed circuit assemblies (PCAs) are often substantially recycled, the PCAs within (estimated at 50,000 tonnes per annum in the UK) are not [7]. Some estimates put the world-wide levels of PCA scrap to be over 10 million tonnes per annum [8]. These PCAs (components and substrates) are almost exclusively based on thermoset substrates. These substrates do not currently have viable recycling strategies. The current state of the art for PCA recycling involves separating the assemblies from their cases or enclosures, followed by removal of high pin count (socketed) components. These components are removed, generally not for reuse but to make precious metal reclamation from them more efficient. The remaining components are then shredded to allow furnace reclamation of their metal content. Thus considerable quantities of reusable components are destroyed during these recovery operations. Based on the levels of recycling required by WEEE legislation in the UK, we estimate the original cost of components on recycled assemblies is in excess of 3.5 Billion Euros per annum. This is equivalent to the gross domestic product of a small country (Mauritania, GDP US$4.2 Billion, population 3.4 million, area 1 million km\(^2\) [9]). Recycling of electronic components on this level would produce a series of challenges for the industry including separation and sorting infrastructure, refinishing of component terminations, repackaging, reliability of reused components, traceability and counterfeit components, and economic viability to name a few. However, with the worldwide consumption of electronics products averaging a compound annual growth rate (CAGR) 6-17% [10], it is difficult to envisage recycling at this scale in the future.

To improve the recyclability of PCAs, a step improvement in the recyclability of substrate materials is required. The majority of substrates are manufactured using reinforced thermoset resins (glass fibre reinforced epoxy/polyimide), which do not have viable recycling routes. Thermoplastics would provide a better alternative for recycling, but survivability of the soldering process means the options in thermoplastic materials are limited. Such PCBs have been produced in the past, especially from polyetherimide (PEI) [11], but these examples are not numerous. Few thermoplastic laminates are available commercially, and these are reinforced with woven glass or similar, to modify mechanical properties and constrain the thermal co-efficient of expansion (CTE) and therefore less attractive from a recycling point of view.

The aim of the ReUSE project was to develop an innovative technology to enable a significant improvement in the recycling levels of PCBs through the use of thermoplastic substrates and easy-to-disassembly interconnects.

2 TECHNOLOGY DEVELOPMENT

A consortium of three UK companies was formed to develop the ReUSE solution. These were Gwent Electronic Materials (GEM, a supplier of electronic materials for structural, functional or decorative applications), In2tec Ltd. (designer and manufacturer of electronic interface products) and the Electronics Interconnect Group of the National Physical Laboratory (NPL, specialists in reliability measurement and lifetime prediction of electronic systems).
GEM developed a series of special polymer layers and binders to allow straightforward, end-of-life unzipping or disassembly of new circuit structures manufactured from recyclable thermoplastics and rigidisers. These included a non-conductive adhesive (designated StoR (substrate to rigidiser) in Figure 1) for bonding substrate layers together and an isotropic electrically conductive adhesive (ICA) for component attachment (designated CAt (component attachment) in Figure 1), allowing low temperature assembly of assemblies using electronic components with tin finished terminations. The other element in Figure 1 is the ToS (tracking to substrate). Both of these were designed to provide robust electronics assemblies which could be separated easily in hot water at the end of their useful life. In2tec designed, developed and manufactured a series of demonstrators and test vehicles utilising these unique materials. They further developed cost effective manufacturing processes to ensure future exploitation. NPL undertook extensive fitness for purpose testing of these assemblies.

3 ASSEMBLY FABRICATION

The typical lay-up of the demonstrators is shown in Figure 1 with an exploded diagram of a typical design shown in Figure 2. This lay-up consists of a multilayer flexible circuit, with conductive tracking achieved using silver loaded polymer inks and multi-layered using dielectric inks. This flexible circuit was bonded to a rigidiser using the StoR adhesive to provide mechanical support. The rigidiser is not necessary for operation of the circuit but reproduces the mechanical characteristics of a fibre reinforced epoxy resin substrate. This bond allowed the circuit rigidiser to be easily separated from the flexible circuit at the end of life. The rigidiser represents approx. 70% by weight of the overall circuit. The flexible and rigid substrates used were polyethylene terephthalate (PET). This material is in regular use in flexible electronics circuits and also has an existing recycling infrastructure used for clear drinks bottles. Commercial surface mount (SM) components with Sn termination finishes, are attached using the upper bond line (CAt below), allowing easy harvesting of components for reuse or recycling.
Attachment of the SM components was achieved using conventional SM assembly techniques. The specially developed ICAs were stencil printed onto flexible substrate and RoHS compliant Sn finished components were placed using an automatic surface mount placement system. The adhesives were cured for 30 mins at 150 °C.

4 FITNESS FOR PURPOSE TESTING

Membrane switch panel: A range of demonstrators and test vehicles were developed for fitness for purpose testing. The first demonstrator produced and tested was a fully functionally membrane switch panel incorporating surface mount chip LEDs (see Figure 3). Each panel incorporated ten switch circuits whose operation illuminated SM LEDs. ReUSE materials were used throughout the fabrication. This demonstrator was built to determine any reliability issues associated with different StoR adhesive coverages. Panels were conditioned by thermal cycling for 500 hours from -30 to +85°C with 10 minute dwells at each extreme. The panels were removed from thermal cycling every 100 cycles for switch operation testing. One of the variants completed the testing successfully without any adverse effects on panel operation and these process parameters were chosen for future process development.

![Figure 3: Membrane switch panel demonstrator](image)

Resistance and joint shear strength test vehicle: The second technology demonstrator was designed to exercise the attachment of a range of different SM components. The test vehicle design (see Figure 4) incorporated a series of interconnected daisy-chained components to monitor component attachment integrity. Additional components were also attached to monitor joint shear strength during conditioning. Meanders and cross-overs in tracking on the flexible circuit were also incorporated to determine their integrity. To investigate the stability of the CAT adhesive, rectangles (links) of adhesive were printed over and between chip component pads. Internal resistance of the switching system, contact resistance and component resistances were also monitored. Analysis of these combined measurements allows determination of the probable cause of any changes in circuit resistance. ReUSE materials were used throughout the fabrication. Two variants of the specially formulated ICA were trialled (designated D2 and D3). Additional SM chip resistor components were incorporated to monitor any degradation in adhesion strength during environmental conditioning.

Each test vehicle incorporated the following:

- 10 circuits of 1 daisy-chained SOIC component for continuity
- 10 circuits of 4 R1206 components for continuity
- 80 × R1206 components for shear testing
- 10 circuits of 4 R0603 components for continuity
- 80 × R0603 components for shear testing
- 10 tracks without components for continuity
- 5 ICA links for continuity
Environmental conditioning of the test vehicles was undertaken using damp heat testing for 1000 hours at 40°C/90%RH and 85°C/85%RH. Thermal cycling was also undertaken for 1000 cycles from –20 to 70°C, 10 minutes dwells.

Figure 4: Second technology demonstrator design

Figure 5 shows a schematic of the different parts of the test vehicle which contribute to the overall resistance measurement. The electrical test and shear test procedures were designed to investigate any changes in each part of the system, so that an analysis of the likely cause of any changes in resistance could be determined. Seven regions of potential resistance change were investigated with periodic resistance measurements during environmental conditioning:

1. Probe contact resistance
2. Switching system resistance
3. Printed tracking resistance
4. ICA/tracking interface resistance and integrity
5. ICA/component interface resistance and integrity
6. ICA resistance and integrity
7. Component resistance

Figure 5: Schematic of test structure showing potential areas of resistance change
Shear testing during environmental conditioning: SM chip resistors are well suited to shear testing, having a flat edge for the chisel tool to address. Shear testing of resistors is illustrated in Figure 6. R1206 and R0603 components were tested on the vehicles in order to determine the ultimate shear strength for the joints (the maximum force at the point of failure). For the shear tests the stand-off height of the chisel tool above the test substrate surface was 80μm. During each test, the shear tool was moved forward at a defined speed of 200μm/s against the test component, and the force was monitored until the adhesive joint failed. The shear tester used was a Dage Series 4000, with a DS 100 Kg testing head.

Figure 6: Shear testing of chip resistor components

The average shear strengths of R1206 components measured periodically during the environmental conditioning are shown in Figure 7. No degradation was measured indeed the trend is shear strengths to increase during the conditioning, probably due to increased curing in the adhesive. These results indicate that any changes in the performance of the test vehicle are not due to any reduction in adhesion of the ICA to the component or printed tracking interfaces (regions 4 and 5) or to any failure of integrity in the ICA (region 6).

Figure 7: Average shear strength of R1206 during 1000 cycles of thermal cycling (–20 to 70°C) and 1000 hours damp heat (85°C/85%RH and 40°C/93%RH)

Electrical resistance measurement during environmental conditioning: The resistance of the test circuits was periodically tested by removing the circuits from the conditioning environment and using an automated test system incorporating a bed-of-nails probe fixture, PC-controlled digital ammeter,
switching system and voltage supply (see Figure 8). Continuous monitoring was not considered necessary because earlier work by the principal authors at the National Physical Laboratory has shown that degradation modes in conductive adhesives as a result of interfacial oxidation causing gradual resistance increases, rather than the intermittent failures experienced in solder joints due to fatigue cracking. This work also indicates the value in using damp heat testing and well as thermal cycle testing to accelerate interfacial oxidation [12-15].

Figure 8: Automated resistance test system

During these periodic measurements, probe contact (region 1) and switching system resistance (region 2) were monitored by shorting all probe pins using a copper plate. No changes in resistance of the switching system were noted. After conditioning was completed, the value of the resistors in failed circuits were checked (region 7) and showed no increased component resistance changes.

Figure 9 shows the typical changes in the printed track meanders during thermal cycle and damp heat conditioning. No significant changes in tracking resistance (region 3) were noted during 1000 hours or cycles in any of the conditioning environments. This data also confirms there were no changes in probe contact resistance (region 1).
Figure 9: Typical resistance values of printed tracks during 1000 cycles of thermal cycling (top, –20 to 70°C) and 1000 hours damp heat (bottom, 85°C/85%RH)

Figure 10 shows the resistance measurement results for the ICA links (regions 4 and 6) between pads for all the environmental conditioning. Again no significant changes in resistance were noted during 1000 hours or cycles in any of the conditioning environments.

Figure 10: Typical resistance values of printed links during 1000 cycles of thermal cycling (–20 to 70°C) and 1000 hours damp heat (85°C/85%RH and 40°C/93%RH)
Resistance testing of the daisy-chained components and CAt interconnects are shown for the R0603 and R1206 component attachments (regions 4, 5 and 6) in Figure 11 and Figure 12. The failure criteria for a circuit was an increase in resistance of the daisy-chain to above 100 ohms. In all scenarios, no significant changes in resistance occur during thermal cycling at –20 to 70°C or damp heat testing at 40°C/93%RH. Some failures did occur during the latter stages of damp heat testing at 85°C/85%RH (~50% for R0603 after 1000 hours and ~20% for R1206 after 1000 hours).

Figure 11: Typical failure rates of R0603 daisy chains during 1000 cycles of thermal cycling (–20 to 70°C) and 1000 hours damp heat (85°C/85%RH and 40°C/93%RH)

Resistance testing of the daisy-chained components and CAt interconnects (regions 4, 5 and 6) are shown for the SOIC component attachments in Figure 13. The failure criteria was an increase in circuit resistance above 100Ω. No significant changes in resistance occurred during damp heat testing at 40°C/93%RH. However, some failures did occur during thermal cycling and significant failures (<80%) occurred after 1000 hours exposure at 85°C/85%RH although these were less than 20% after 500 hours. Current product applications under consideration, do not require exposure to 85°C/85%RH beyond a 500 hour limit.

Figure 12: Typical failure rates of R1206 daisy chains during 1000 cycles of thermal cycling (–20 to 70°C) and 1000 hours damp heat (85°C/85%RH and 40°C/93%RH)
Figure 13: Typical resistance values of SOIC daisy chains during 1000 cycles of thermal cycling (–20 to 70°C) and 1000 hours damp heat (85°C/85%RH and 40°C/93%RH)

Resistance and shear testing summary: Of the regions of possible resistance change identified above, environmental conditioning only caused increases in measured resistance at the interface between the ICA and the component. Shear testing indicated no loss in adhesion at this interface. The resultant resistance increases must therefore be attributed to degradation of the conductive path between the ICA and the Sn finish of the component terminations. Degradation of this interface is common in ICA systems and is due to the oxidation of the Sn due to exposure to damp environments or to galvanic corrosion due to the proximity of the Sn on the component and Ag in the ICA [16, 17].

5 END OF LIFE RECYCLING TRIALS

The final demonstrator of the project was an inverter circuit to drive an electroluminescent lamp from a 9v source. This is shown in Figure 14.

Unzipping of the demonstrator was undertaken by immersing the circuit in water at approximately 80°C for 30 seconds (Figure 15) [18]. This immersion was sufficient to soften the CA1 and StotR bonds to allow separation of the components from the flexible substrate and the substrate from the rigidiser with minimal mechanical force. Minimal force is necessary to prevent damage to the components and allow their reuse in another application. Figure 16 shows the components, substrate and rigidiser after separation.
Figure 14: ReUSE inverter circuit and electroluminescent lamp

Figure 15: Unzipping of the demonstrator by immersion in hot water
The unzippable materials developed allow easy separation of the constituent parts of the assembly. Component harvesting and reuse is significantly simplified. No damage to components is envisaged by the water immersion as the disassembly process is no different than aqueous cleaning. Typical component terminations and corresponding circuit pad after separation are shown in Figure 17. The majority of the ICA remains attached to the flexible circuit to allow recycling along with the flexible substrate. The separated rigidiser can be easily harvesting and reused or recycled. The silver can be reclaimed from the flexible substrate and it’s incorporated inks. Although this could be achieved chemically, it is more cost effective to do this in a furnace. The result is that over 90% of the structure can be recovered for reuse. In addition, the silver used on the flexible substrate and in the ICA can be reclaimed, resulting in a structure which is over 95% reusable, recyclable or reclaimable. The only parts of the circuit lost are the PET in the flexible circuit and the resin systems used in the tracking inks and the ICA.
6 CONCLUSIONS

An alternative approach (ReUSE) to improving PCB recycling levels by using thermoplastic substrates and novel adhesive systems has been developed. The technology allows electronics to be broken down in to readily separable layers along defined bond lines by using unique polymer formulations. Special dielectric bonding layers and ICAs for component attachment have been developed and extensively tested to prove fitness for purpose. An important feature of the technology is the end of life disassembly, which following a simple soak in hot water, the components can be removed with minimum force. These unzippable layers allow easy separation of components, substrates and interconnects. The final project demonstrator, an electroluminescent lamp inverter, exhibited recovery levels of over 90%. The technology lends itself to both rigid and flexible 3D structures, hence new design philosophies can be pursued, utilising less materials and improving sustainability. It is hoped the research will have a long term impact on electronics manufacturing and represent a significant step towards sustainable electronics systems.

7 ACKNOWLEDGMENTS

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8 REFERENCES


[18] http://www.youtube.com/watch?v=fzFR4mPI34E