ADHESIVE OFFERING Z-AXIS CONDUCTIVITY, STRETCHABILITY AND MANUFACTURING SCALABILITY FOR LED LIGHT SHEETS

A. Stemmermann,[*] D. Balder,[*] M. Stemmermann[*], M. Poliks[**] and P. Lall[***]

[*]SunRay Scientific, 22 Meridian Rd Unit 1, Eatontown, NJ 07724, madhu@sunrayscientific.com
[**] Binghamton University, Materials Science Binghamton, New York mpoliks@binghamton.edu
[***]Auburn University, NSF Center for Advanced Vehicle and Extreme Environment Electronics, Department of Mechanical Engineering, Auburn, AL 36849, lall@auburn.edu

ABSTRACT

Many Anisotropic Conductive Epoxies (ACE) are on the market today in both paste and film forms. Compound annual growth rates (CAGR) for ACEs are the reason for the crowded market. The prime differentiator between them is (and will continue to be) manufacturing scalability. The particular epoxy discussed here - ZTACH® ACE uses a magnetic field for achieving the anisotropic z-axis conductivity. The material was developed by a small, woman-owned company and has moved into commercial production.

The second key differentiator is robustness of the electrical interconnects. Using an array of Light Emitting Diodes (LEDs) bonded to a flexible organic substrate as a test vehicle, ZTACH® ACE is shown to provide have excellent assembly performance. Initial reliability testing will be debuted at the conference. Previously unpublished characterization data from studies funded by government SBIRs and NextFlex consortium are also provided.

Keywords: interconnects, flexible, electronic packaging

1 INTRODUCTION TO ANISOTROPIC CONDUCTIVE EPOXIES

Epoxy resin-based electrically conductive adhesives (ECAs) have attained widespread use as solderless interconnection both on the chip-attach scale and at board-level as well as bonding to lead frames and to heat sinks. They are used on PV solar panels, touch panel screens, LED/OLEDs, and various other electronic devices. The market for ECAs is projected to continue at a CAGR of ~8% [1-2], up from 6.5% [3] with epoxy-based formulations leading the market. [2,4]

Isotropic conductive epoxies (ICEs) must be screen printed, or otherwise patterned [5] so that they do not cause electrical shorts between pads; analogous to solder ball grid arrays. The advantages of an adhesive interconnect over solder include low temperature or UV curing, good adhesion to various materials, low shrinkage, ease of controlling viscosity, availability of solvent free formulations, etc. [6] Epoxies also provide high chemical resistance, excellent mechanical properties, and are used for electromagnetic shielding. [2,7] If epoxy is applied as a film, pressure will be needed to ensure contact with the pads. A patterned adhesive, like a ball grid array, may require underfill to achieve the required robustness.

With increasing miniaturization, patterning an adhesive becomes untenable so designs call for adhesives that conduct only in the Z-direction. Component interconnection using ACEs does not require underfill. For these anisotropic adhesives, the low electrical conductivity of epoxy (~10^{-7} to 10^{-14} S/m) is an advantage in preventing conductivity in the XY plane.

Achieving alignment of particles into microscopic z-axis "wires" is done in various ways: electrical alignment [8], magnetic field alignment [9-13], the inherent tendencies for carbon nanotubes and cones to align [14-16], additive manufacturing [17] or a combination. One difference between materials available in film form vs paste form is that an anisotropic conducting film come pre-aligned but requires pressure to create the electrical bond. The bond line is generally thicker with a film. Figure 1 below shows particle alignment using a paste.

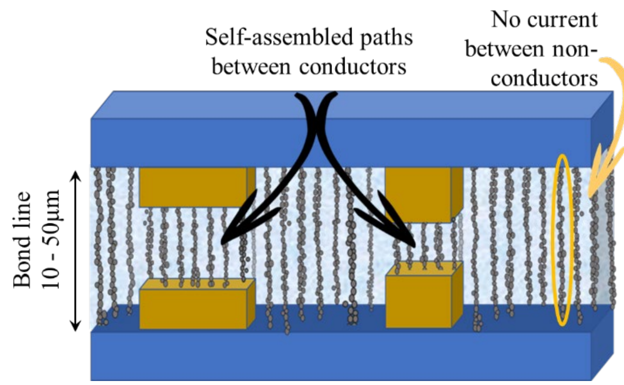

Figure 1 Aligning of particles into microscopic z-axis "wires" with excellent electrical isolation in between

Many aligned-conductor epoxies are available for purchase, leading to a crowded marketplace. The race for market dominance will rely chiefly on manufacturing scalability, but also on the relative mechanical/electrical performance and on characterization data that can be used for computational modeling.

This paper covers performance data for ZTACH® ACE, a patented paste using magnetic alignment, now in use on traditional electrical boards and on flexible and stretchable substrates. Bonding procedure uses commercially available surface mount technology (SMT) equipment.

2 LED LIGHT SHEETS

Traditional LED devices use either low temp solder or conventional conductive adhesives, both which require a secondary encapsulation process to provide structural protection when flexing. This adds to cost and may reduce optical properties of the LED. ZTACH® ACE maintains constant volume when stretched, allowing a substrate material to bend without the device popping off. [18] If an encapsulant is warranted, it can be chosen for properties other than maintaining the electrical connection.

LED light sheets represent a minimum viable product; see Figure 1. More importantly though, the design translates into focal plane arrays and other instrumentation important to aerospace and automotive industries. LED arrays are also an ideal vehicle for demonstrating scale-up. After robustness testing – be it thermal cycling, stretching and bending, or other – an LED will immediately show damage through a change in luminosity or a change in DC power input required to light it up.

Figure 2. Flexible LED light sheet illuminated

The traces in Figure 2 are printed with conductive ink on PET. ZTACH® ACE distinguishes itself by its compatibility with printed inks, including those that are solvent-free. [18] Curing at temperatures as low as 70°C or cure protocols using UV light provide equally good results.

2.1 Micro LEDs and Pad Pitch

The traditional LED has a pad size of ~150µm, which can be run in production with 100% yield using ZTACH® ACE. Mini-LEDs have a pad size above 50 but below 150 µm. Standard ZTACH® ACE formulations bonding bare die in 100 µm arrays have 100% yield. The process has been transfered to a major manufacturer of advanced connectivity systems.

Studies are ongoing to bring the pad pitch down to below 50 µm pitch; noble metalization will be required.

The bond line for ZTACH® ACE ranges from 10µm to 50µm, depending on the application. This is notably lower that solder. Moreover, ZTACH® ACE is able to simultaneously bond stacked architectures, accommodate rough or warped surfaces and to handle multimode attach in a single process. Figure 1 illustrates the interconnects formed during self-assembly.

3 SCALABILITY AND RELIABILITY

Scalability of a ZTACH® ACE - enabled SMT process has been demonstrated via multiple flex sheet through-put of a manufacturing line and replication at research partner sites. Auburn University's CAVE3 Research Center has sucessfully set up a UV cure line for interconnection of components using ZTACH ACE, being run by non-experts. Success was/is considered to be maintaining the initial 99% yield rate for throughput of one-dozen builds. In Figure 3 is a large LED array (bottom) and smaller, denser circuits in the center. Other coupons test coupons are for testing printed ink with resister arrays on the other side. Production continues to be successful.

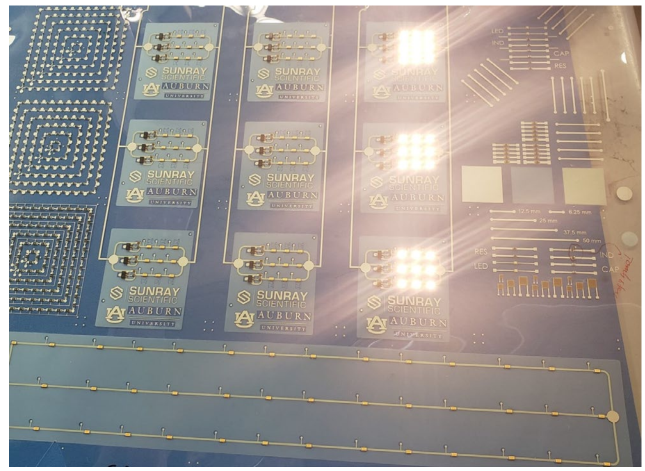

Figure 3 Test vehicle printed on melamine

Reliability testing on the vehicles will include thermal aging, temperature-humidity aging, and dynamic flexing (mandrel bend testing). LEDs are unencapsulated, relying solely on the ZTACH® ACE bond for mechanical stability.

4 ZTACH® ACE CHARACTERIZATION

Glass transition temperature of the cured epoxy is 110°C, although temperature studies show that mechanical properties remain stable for another 50° or more. [18]

The thermal conductivity of ZTACH ACE in its standard formulation has a comparable to thermal grease (≈4.5W/mK) with room for optimization. [19]

Adhesive compatibility has been demonstrated with the generally problematic thermoplastic polyurethane (TPU) film, as well as polyethylene terephthalate (PET) including Coveme Kemafoil®, polyesters, Kapton® polyimide, polyethyleneimine, quartz, silicon, gallium arsenide, even aluminum foil, paper and woven materials, though not polytetrafluoroethylene aka Teflon®.

The ZTACH® ACE bond is used in rigid and flexible designs. Testing was performed at Binghamton U. [13,19]

4.1 Stretching; Flexible Hybrid Electronics

As of today, stretchable electronic devices are hybrid in nature, comprised of both soft and rigid electronic components. Of equal importance are a pressure-less assembly, fine pitch reliability and technology integrates well into traditional surface mount technology lines since stretchable devices are generally for a mass market.

During tensile testing, the electrical resistance increased with increasing strain and decreased during unloading to zero strain. After unloading (relaxed state), the resistance quickly returned to the initial value. Samples with a serpentine traces survived fatigue cycling for 100 cycles at 30% strain. The failure mode was partial cracking in the plated silver trace and not in the ACE joint. [20] Contact resistance remained low ~0.04-0.08 Ω. [19]

4.2 Electrical Testing

Dielectric breakdown was tested against ASTM D149. The breakdown voltage was measured at 11,000V at 4mm electrode separation distance. [19]

AC loss characteristics were measured using based on ASTM D150: the dielectric constant is 14.6. The material ampacity (Similar to AS4373 Method 507) was measured at current threshold: 66 amps; temperature threshold 206°C.

4.3 Environmental Stability

The first environmental study [19], used test vehicles with a single gold layer on quartz and silicon substrates with 150µm, 100µm and 50µm pitch ”daisy-chains”.

Dry resistance Test – samples were exposed to 125ºC for 24 hours. No change could be measured. [19]

Following humidity testing – 7 days @ 85ºC/85RH - established that after 144 hours, conductivity changed by less than 5%. This was followed by wet resistance: IPC TM-650, Method 2.6.14.1 - 85C / 85%RH, 500 hours; samples were 150 micron pitch on both quartz and silicon die with 36 and 40 contacts. Results showed that the bonds had a very stable performance: < 10% resistance change on all functional interconnects. Many test points showed < 1% resistance change. [19]

In high temperature functional testing, die were exposed to maximum temperatures of 200°C to determine resistance breakdown temperature; no change was found. [19]

Environmental testing of LED lightsheets forthcoming.

4.4 Reliability – Mechanical

Mechanical Stability Testing Mechanical Shear testing IPC 2.4.42.2 test method on a rigid glass surface had a strength that exceeds shear tool limit of 100Kg. The shear stress of a sample bonded to silicon was approximately 23.5 MPa demonstrating that the ZTACH® ACE has a higher shear stress limit. [19]

Another investigation looked at of the electro-mechanical performance of ZTACH® ACE as a bond media for e-textile based wearable applications. In all cases, the failure mechanism did not involve the epoxy bond. [20]

Other tests are ongoing.

4.5 Radiation Hardness

Sterilization of medical devices, food preservation, and the space applications need component materials to withstand radiation. A Perkin Elmer study using alpha radiation indicated that the amount of filler (FeCr) mitigated the degredating effect of the radiation. [21]

For a test vehicle, ZTACH® ACE, a highly filled material, was used to bond a sensor and read-out chip. Samples were exposed to a Cobalt-60 source at Sandia National Laboratory and to neutron flux at McClellan Nuclear Reactor Center at U.C. Davis. Electrical behavior and material characteristics were unchanged by exposure to gamma ray irradiation of 1 MGray of total ionizing dose, and neutron fluence of $1x10^{15}$ 1 Mev neutrons/cm^2. Electrical resistance of bond remained < 1ohm. [22,23]

4.6 Cryocycling

Cryogenic testing was performed at the Dept of Energy’s (DOE) SLAC Laboratory at Stanford U. Temperature cycling used a flexible circuit comprised of 150 µm pitch daisy chain test die with 168 total contacts in 8 chains. These were cycled from room temperature to liquid nitrogen (77 K) ten times. Dwell time was 10 seconds each cycle. No change in resistance of chains between chains could be measured; no shorting was observed between adjacent microwires in the cured ZTACH® ACE. [22]

4.7 Electromagnetic Performance

Given that cured ZTACH® ACE structures have nanowires comprised of submicron ferromagnetic particles, it is natural to question whether this will pose a problem when used to build antenna and other structures that send and receive information via a signal encoded on a slice of electromagnetic spectrum.

RF frequency behavior has been tested. S-parameter measurements of ZTACH® ACE bonds show consistent performance up to 90 GHz. Insertion loss is 1.33 dB at 50 GHz and 4.07 dB at 90 GHz. [24]

Regarding microwave electrical performance the ZTACH method has been tested to 0.7 dB insertion loss at X Band (8–12 GHz) and 1.5 dB at Ka-Band (26.5–40 GHz). The measured reflection coefficient is less than -20 dB at X-Band and -10 dB at Ka Band. Insertion loss has been verified to approximately -3 dB at W Band (75 to 110 GHz), with a reflection coefficient of $^-$10 dB. [24]

5 CONCLUSIONS

Paste lends itself to use in SMT equipment in part because it requires no pressure during cure. To a first order, the ability of non-experts to use ZTACH® ACE with SMT processes demonstrates scalability. Unencapsulated LED arrays are being manufactured and tested at Auburn

University. Based on prior testing, we expect compelling results.

REFERENCES

[1] Global Electrically Conductive Adhesives Market April 2018 https://www.techsciresearch.com/report/global-electrically-conductive-adhesives-market/2730.html retrieved 27-March-2022.

[2] Global Electrically Conductive Adhesives Market February 2019 https://www.maximizemarketresearch.com/market-report/global-electrically-conductive-adhesives-market/26397/ retrieved 27-March-2022.

[3] Global Electronics Adhesive Market Professional Research Report 2014-2026, https://www.globalmarketmonitor.com/reports/612814-electronics-adhesive-market-report.html retrieve 27-Mar-2022.

[4] Epoxy Based Electrically Conductive Adhesives, 08-Jun-2021, https://www.precisionreports.co/epoxy-based-electrically-conductive-adhesives-market-18472753 retrieved 8-Feb-2022.

[5] J. Nasrullah, et al., Designing Software Configurable Chips and SIPs using Chiplets and zGlue, Internat'l Symposium on Microelectronics, 2019/10/01, https://doi.org/10.4071/2380-4505-2019.1.000027

[6] R. Aradhana, S. Mohanty, S.K. Nayak, A review on epoxy-based electrically conductive adhesives, Intn'l Journal of Adhesion and Adhesives, 99, 2020, https://doi.org/10.1016/j.ijadhadh.2020.102596.

[7] T, Merizgui, et al., Electromagnetic shielding behavior of epoxy multi-hybrid composites comprises of E-glass fiber, Ag nanoparticle, and Ni nanosheet, Polymer Composites. 2021; 42: 2484–2491. https://doi.org/10.1002/pc.25993

[8] G.K. Johnsen, M. Knaapila, G. Martinsen, G.Helgesen, Conductivity enhancement of silver filled polymer composites through electric field alignment, Composite Sci Tech 72, 1841–7 2012, https://doi.org/10.1016/j.compscitech.2012.07.011

[9] J. Guo, et al. Reinforced magnetic epoxy nanocomposites with conductive polypyrrole nanocoating on nanomagnetite as a coupling agent. RSC Advances 4, 36560–72, 2014, https://doi.org/10.1039/ C4RA07359B.

[10] C. Ma, et al., Fracture resistance, thermal and electrical properties of epoxy composites containing aligned carbon nanotubes by low magnetic field. Composite Sci Tech 114, 126–35, 2015 https://doi.org/10.1016/ j.compscitech.2015.04.007.

[11] S. Wu, et al. Epoxy nanocomposites containing magnetite-carbon nano fibers aligned using a weak magnetic field. Polymer 68, 25–34 2015, https://doi.org/10.1016/j.polymer.2015.04.080.

[12] J.H Byeon, D.J Yoon , and K.W. Paik, A Study on the Magnetic Dispersion of the Conductive Particles of Anchoring-Polymer-Layer ACF and Its Fine-Pitch Interconnection Properties IEEE Trans on Components Packaging and Manuf Tech, 9, 7, 2019

[13] S. Ramkumar, A. Stemmermann, et al. (2020). Development of Next Generation Stretchable Materials for Flexible Hybrid Electronics. https://doi.org10.1109/ECTC32862.2020.00135.

[14] S.U. Khan, J.R. Pothnis, J. Kim, Effects of carbon nanotube alignment on electrical and mechanical properties of epoxy nanocomposites. Composites Part A, 49, 26–34, 2013 https://doi.org/10.1016/j.compositesa.2013.01.015.

[15] M. Felisberto, et al. Influence of filler alignment in the mechanical and electrical properties of carbon nanotubes/epoxy nano-composites. Physica B, 407, 3181–3. 2012 https://doi.org/10.1016/j.physb.2011.12.059.

[16] R.B. Ladani, et al. Improving the toughness and electrical conductivity of epoxy nano-composites by using aligned carbon nanofibres, Composite Sci Tech 117, 146–58. 2015 https://doi.org/10.1016/j.compscitech.2015.06.006.

[17] P.Lall, J.Narangaparambil, V. Soni, and S. Miller, Process-Recipe Development for Printing of Multilayer Circuitry With Z-Axis Interconnects Using Aerosol-Jet Printed Dielectric Vias. ASME. J. Electron. Packag.; 144(2) 021117, 2022 https://doi.org/10.1115/1.4053766.

[18] Unpublished data produced by Auburn University and SunRay Scientific under the auspices of NextFlex 6.0 set of funded projects.

[19] Unpublished SunRay Scientific data from DOE SBIR-l & ll Enchanced Electronic Interconnects using ZTACH® ACE. DE-SC0017879.

[20] A. Stemmermann, et al. Robustness and Reliability of Novel Anisotropic Conductive Epoxy for Stretchable Wearable Electronics. IEEE ECTC Session 18 May 31- June 3, 2022 San Diego, California; paper submitted.

[21] Perkin Elmer White paper: Effect of Radiation on Epoxy and FeCr Filled Epoxy Composites, https://resources.perkinelmer.com/corporate/cmsresources/images/44-153422app_effectradiationepoxyfecrfilledepoxycomposites.pdf

[22] Unpublished SunRay Scientific data from DOE SBIR-l Elimination of Wire Bonding for Cryogenic Applications; DE-SC0020705.

[23] J.D. Segala, et al., Radiation hardness results on a new anisotropic conductive adhesive to replace bump-bonding in HEP detectors, IEEE Nuclear Science Symposium, 28 Oct 2019.

[24] Unpublished white paper, Multilayer Silicon RF System-in-Package Technique Using Magnetically Aligned ZTACH® ACE.