Investigating Mechanical Performance of PLA and CA Biodegradable Printed Circuit Boards

Attila Géczy, Dániel Nagy, István Hajdu
Department of Electronics Technology,
Budapest University of Technology and Economics (BME),
Egry J. u. 18., Budapest, H-1111
gattila@ett.bme.hu

Ákos Kmetty[2,3], Beáta Szolnoki[4]
2) MTA-BME Research Group for Composite Science and Technology, Műegyetem rkp. 3., Budapest H-1111,
3) Department of Polymer Engineering, Budapest University of Technology and Economics (BME), Műegyetem rkp. 3., Budapest H-1111
4) Department of Organic Chemistry and Technology, Budapest University of Technology and Economics (BME), Műegyetem rkp. 3., Budapest, H-1111

***Abstract*—The paper presents a set of experiments investigating the mechanical performance of PCBs manufactured from biodegradable, sustainable polymers, compared to conventional materials. Cellulose Acetate (CA), Polylactic Acid (PLA) and Flame-Retardant Class 4 (FR-4) substrates were compared during the experiments. The methods involved dynamic mechanical analysis (DMA), three-point bending tests and UL 94 flammability tests. Preliminary results show that the overall performance of the basic biodegradable, sustainable PCBs are considerably weaker compared to FR4 boards, however further improvements with additives and use in special applications can point to practical purposes of the substrates.**

Keywords—biodegradable, printed circuit board, sustainable, UL 94, dynamic mechanical analysis, 3 point bending test

I. Introduction

Electronic waste is gaining more attention as global electronics production increases year by year. With the amount of produced electronics, e-waste also increases from the aspect of quantity [1]. While different regulations were initiated for the removal of different hazardous substances (such as the RoHS directive for leaded solder alloys, which materials were ultimately substituted for unleaded alloys [2-3]), novel approaches are required to investigate and substitute the current electronic materials, which may not pose direct harm for the environment, but can increase the pollution during waste processing. Recycling and waste processing is also becoming more important, while most of the electronic materials are essentially non-degradable. Printed Circuit Boards (PCB) are amongst the most harmful parts of the generated e-waste, so it is important to find degradable substitutes of PCB base materials.

The literature presents limited experience about the applicability of such substances in electronics, and despite the advantageous properties of the materials, these solutions are rarely presented in commercial electronics, mainly due to the reduced mechanical performances and the reduced thermal stability of these materials. Thus it becomes a challenge to produce substrates which are compatible with the traditional electronics assembling technologies, such as trough hole components assembly, or reflow soldering with surface mount devices.

The latest articles are usually investigating the topic on the level of basic research. Staat et al. pointed their investigation on selected electric and mechanical properties of biopolymers (depending on different additives) [4-6]. Staat found that thermal stress is critical during the curing of screen printed conductive paste. Their team also found that different additives may improve such substrates from the aspect of electrical performance. Ohki et al. investigated the electrical conduction and breakdown properties of different biodegradable substrates. [7, 8] Mattana et al. showed that Polylactic Acid (PLA) can be considered as basis for all-solution-processed organic electronic devices [9]. Lately they continued their research (Quintero, Mattana et al.) with the investigation of printed conductors on PLA for sensing applications [10] with a proposal of proper encapsulation. PLA is investigated for base substrate of antennas for 2.45 GHz ISM [11]; CA was lately investigated as a possible substrate for 13.56 MHz RFID cards [12]. Schramm et al. investigated biopolymers from electronics manufacturing aspects [13]. Baecker et al. developed a sensor system for measuring degrading processes of biodegradable biopolymers [14]. Medgyes et al. investigated the electrochemical migration on biodegradable materials [15], and showed that due to better wetting on different biodegradable substrates, the failure criteria may occur earlier during migration tests, compared to conventional PCBs. Our previous work focused on Cellulose Acetate (CA) and PLA materials [16-18]; the investigations were combined with vapour phase soldering (VPS) joining method, where quality concerning results were similar to the typical findings of VPS investigations [19-23] with lead-free solder alloys. Our papers also showed limiting factors of solder joint production (the biodegradable substrates have lower melting point and lower glass transition temperature than standard FR4 PCBs), and limiting mechanical parameters of the produced PCBs. On the other hand however, the initial results were promising from the aspect of future research paths with low temperature SnBi solders and special applications (such as the aforementioned RFID cards). Figure 1 shows test vehicles (biodegradable CA PCBs) prepared for soldering.

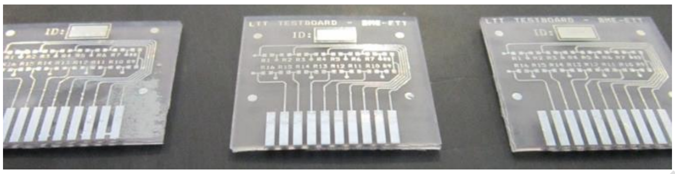

Fig. 1. Biodegradable test boards (CA) prepared for soldering

Different biodegradable substitutes for PLA and CA can also be investigated for PCB applications, such as reinforced bioepoxies. Niedermann et al investigated carbon-fiber reinforced, glucose-based composites with high glass transition temperatures [24]. The material shows promising performance according to the preliminary studies, where the results present similar mechanical parameters as the synthetic materials found in commercial PCBs.

According to the literature, focused mechanical analysis of such biodegradable substrates for PCB technology is still an underrepresented field, however investigating the mechanical capability (e.g. modelling approaches [25]) is a current research field in industrial engineering.

II. EXPERIMENTAL

To expand the knowledge on different mechanical parameters of CA and PLA materials as possible PCB substitutes, dynamic mechanical analysis (DMA), three-point bending tests and UL 94 flammability tests were applied on prepared CA, PLA and FR4 samples. It is expected, that biodegradable substrates will perform weaker than the FR4 glass fiber reinforced, flame retardant material (while the current bio-substrates are presented without any additives or reinforcement); however the basic performances must be investigated in order to continue development of these substrates.

All tests involved three different basic substrates: PLA, CA and FR4 (for reference). The FR4 PCB-s were bare glass-reinforced epoxy laminates stripped of covering copper layers. The PLA and CA boards were prepared with injection molding (with Arburg Allrounder 370S machine). The parameters of the produced boards (surface roughness, dimensions, etc.) are mainly depending on the machine setup. After the molding, it is possible to laminate copper foil onto the base [17], however for our investigations only bare biodegradable boards were used. The material parameters are presented in Table 1.

The test bodies were cut according to the dimensional requirements of the investigation methods. For DMA 60×10×2 mm, for the three point bending test 80×25×2 mm, for the UL 94 flammability tests 125×10×1.5 mm sized samples were prepared (Fig. 2.).

TABLE I. COMPARISON OF MATERIALS BY THEIR DATA SHEET PARAMETERS

Mat. type	**Investigated material parameters**			
	Density, g/cm³	***Tensile str., MPa***	***Melting temp., °C***	***Glass Tr. Temp., °C***
PLA	1,55	32	~150	~55-65
CA	1,29	62,5	~185	~105
FR4	1,85	~320	NA	150< [a]

a.) for lead free technology

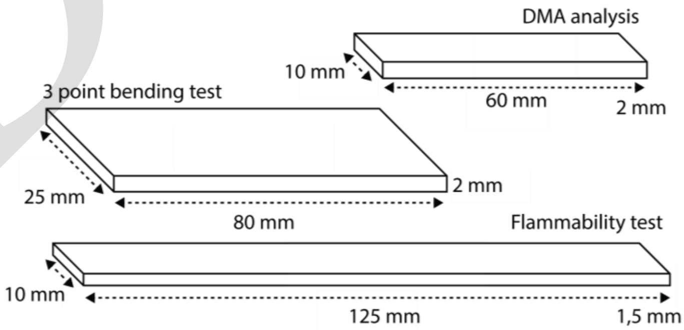

Fig. 2. Samples prepared for the different tests

A. Dynamic Mechanical Analysis

Dynamic mechanical analysis is used to investigate the glass transition temperature (T_g) of the given materials. The value gives information for the soldering process, where a low (T_g) can result in additional deformations on the boards. The (T_g) can be determined from the loss coefficient (1):

$$\tan\delta = \frac{E"}{E'} \quad (1),$$

where (*tan δ*) is the loss coefficient [-], (*E'*) is the dynamic flexural modulus, (*E''*) is the loss modulus – the flexural modulus is based on the ratio of (*E'*) and (*E''*). The (T_g) is determined at the maximum of the (*tan δ*) function plot.

For the investigations a DMA Q800 instrument was used (shown in Figure 3.) with the following parameters. The sample holder was dual cantilever type. The frequency was set to 1 Hz, the amplitude was set to 20 µm. The measurement range of the temperature was defined according to the working and assembling temperatures of usual PCBs plus the limitations of the bio-substrates: 0-160 °C with 2 °C/min ramp. The cooling medium was liquid nitrogen. The Poisson coefficient was 0.44.

Fig. 3. DMA Q800 instrument

B. Three-point bending test

The given test method was used in order to find the mechanical performance of the given materials exposed to flexural stresses. The three-point bending tests were performed according to EN ISO 178:2003 standards for polymers [26]. The basic setup of the three point bending test is shown in Figure 4, where (*l*) is the total length of the sample, (*L*) is the length of span between supports, (*F*) is the bending force applied to the bender head.

Fig. 4. Schematic of three point bending test setup

To calculate the flexural modulus values (E_f) of the given samples, the flexural stress and flexural strain (according to the deflection) has to be calculated from the measurements also. The methodology of the calculations can be found in detailed form in the documentation of the standard [26].

For the measurements a Zwick Z020 instrument was used, where the parameters were set according to the following. The Test speed was set to 5 mm/min, the stopping threshold was set to 12000 N, the fixture distance was set to 32 mm, the maximal bending distance was set to 3,2 mm (10% of the fixture distance).

C. UL 94 flammability tests

The flammability of the given biodegradable substrates is also an important question; in circuit board technology the standard FR4 material abbreviation refers to "flame retardant class 4". The epoxy resin binders in FR4 structures contain additional bromine to ensure the flame-resistant, self-extinguishing characteristic. The safety of FR4 flammability is determined according to UL 94 [27] horizontal and vertical tests. (A conventional FR4 board fits into the class: V-0).

Fig. 5. Horizontal test fixture for UL 94 HB classification [26]

For the given substrates horizontal burning tests (HB) were applied for initial inspections. In order to classify a material as "HB", the material should not have a burning rate exceeding 75 mm per minute over a 75 mm length. This rate is valid for specimens having a thickness less than 3.0 mm or which sample ceases to burn before the 100 mm reference mark [26]. Figure 5 shows the horizontal fixture for the HB test setup.

III. RESULTS

The results are presented in the following chapter according to the measurement method.

A. Results of DMA measurements

Initial results of DMA investigations (Fig. 2) show that from the aspect of soldering temperatures, the prepared PLA sample boards have inappropriate glass transition temperatures for assembly temperatures, and performed according to catalogue data. CA shows slightly higher *Tg* values than the catalogue values, FR4 shows similar performance as it was denoted in the catalogue

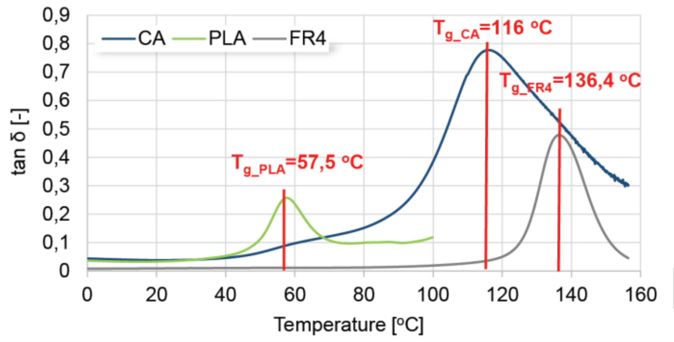

Fig. 6. DMA results show the Tg values of the different samples

The DMA results point out that from the aspect of soldering, the performance of CA is not far from the standard FR4 material, however there is some space for improvement. According to the combination of the glass transition and melting point temperatures CA may be suitable for low temperature lead-free soldering.

B. Results of the three point bending tests

The flexural modulus averaged values are shown on Figure 8 with standard deviation, where an order of magnitude difference is observable between the sustainable polymers and the FR4 material.

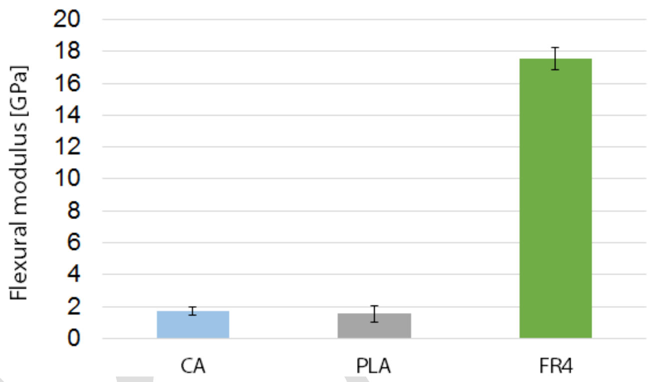

Fig. 7. Flexural modulus averages according to three point bending tests (with standard deviation).

The CA samples have slightly higher flexural modulus and lower deviance, than PLA samples which showed the least reliable mechanical performance as a circuit substrate during the bending tests.

C. Results of UL 94 measurements

Figure 8 shows the actual HB test, where the PLA sample melts and burns with an extensive flame.

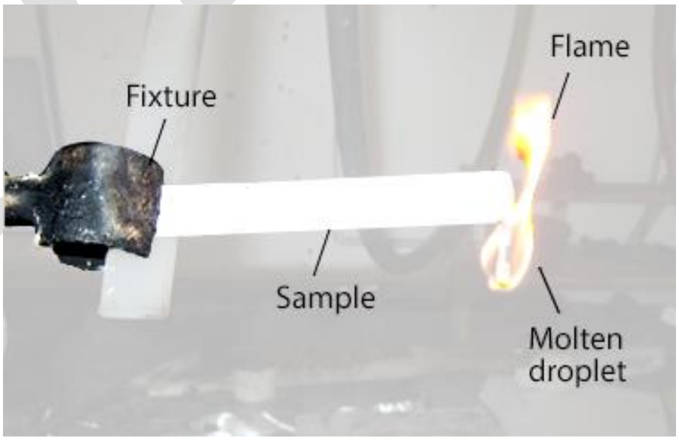

Fig. 8. Burning PLA sample in the horizontal fixture (HB test)

CA and PLA materials both generated burning droplets of molten sample particles, however PLA was more critical from this aspect. Figure 9 presents a quantitative comparison between the HB burning rates of CA and PLA, where the values are presented in [mm/min] units.

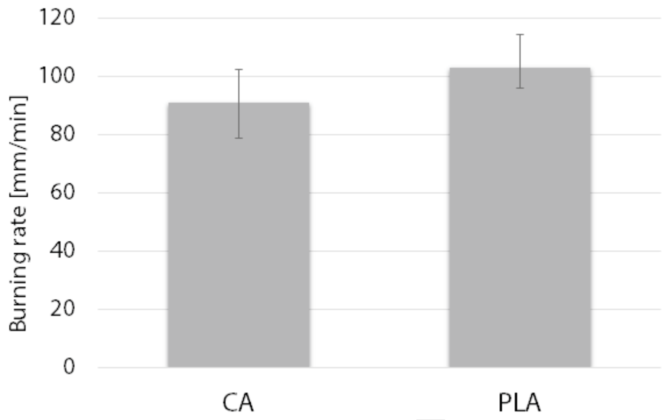

Fig. 9. Averaged HB test results with min and max values

Both materials fall out of the HB test specification, which means that they are fast burning materials (where both values have larger than 75 mm/min burning speed). According to the min max observations and the averages PLA is considered to be the fastest burner. It has to be noted, that FR4 materials could not be evaluated this way, while the flame extinguished after each removal of the test flame.

Additional investigation involved vertical burning tests as well [26], however CA and PLA materials failed to fit into the upper class V0 and V1 verifications.

The results of burning tests are consequential from the fact that the biodegradable, sustainable materials do not have any flame-retardant addition, nor non-flammable reinforcements in their structure.

IV. Conclusions

The paper presents the results of different tests to obtain extended information about mechanical performance of the sustainable PLA and CA materials. The experiments also involved industry standard FR4 material for a reference during the comparisons.

It was found with dynamic mechanical analysis, that the PLA material is avoidable from the aspect of soldering or any other assembling technology, where elevated temperatures are required (such as conductive adhesive [28-30] curing). The glass transition temperature of the material is considerably lower than the T_g of the FR4 and even the CA material, which may cause considerable deformation on the materials (similar to what was shown previously during soldering experiments [16, 18]). The glass transition temperature may be improved by the application of selected additives. From another aspect, processes with lower, moderate temperatures (such as soldering with low temperature alloys) is a possibility with the use of CA.

Three-point bending tests highlighted the fact that the mechanical stress performance of these materials is much weaker than the glass-fiber reinforced FR4 boards. CA material slightly exceeds the performance of PLA however. With the plans of the application of fiber-reinforcements, the mechanical stress performance can be improved.

Burning tests showed that both CA and PLA materials inhere fast burning characteristics. Flame-retardant additives may improve the results of burning test classifications compared to the FR4 substrate.

It must be noted that any applied non-degradable (or harmful) additive material may increase the environmental impact of the generated assembly. So practically the improvements should be considered with bio-based substrates or biodegradable materials. While PCB substrates from the presented sustainable materials may show weaker performances compared to the industry standard FR4 boards, their degradability and environment friendly nature may render them as important substitutes for circuit substrates in the near future, where their weaker mechanical performance is not a critical factor from the aspect of usability (e.g. sensor electronics carriers, disposable electronics, etc.).

Acknowledgment

This research was realized in the frames of TÁMOP 4.2.4. A/1-11-1-2012-0001 „National Excellence Program – Elaborating and operating an inland student and researcher personal support system”. The project was subsidized by the European Union and co-financed by the European Social Fund. This work is connected to the scientific program of the "Development of quality-oriented and harmonized R+D+I strategy and functional model at BME" project. This project is supported by the New Széchenyi Plan (Project ID: TÁMOP-4.2.1/B-09/1/KMR-2010-0002).

REFERENCES

[1] Hogue, C. Growing Piles of Toxic Trash, Chemical and Engineering News, ISSN 0009-2347, 88(9) (2010)

[2] Zs. Illyefalvi-Vitéz, J. Pinkola, G. Harsányi, Cs. Dominkovics, B. Illés, L. Tersztyánszky, Present Status of Transition to Pb-free Soldering, Proceedings of 28th IEEE-ISSE conference 2005, pp. 72-77.

[3] Illyefalvi-Vitéz, Krammer O, Pinkola J "Testing the Impact of Pb-free Soldering on Reliability" 1st Electronics Systemintegration Technology Conference, Dresden, Németország, pp. 468-472. (2006)

[4] Staat, A., Hohlfeld, T., Standau, T., Weimann, I., Bauer, R., Harre, K., Substrates based on renewable resources for printed circuit boards, IEEE ISSE (2014), pp. 50-53.

[5] Staat A, Vogt M, Harre K, Bauer R, Effect of Incorporation of Different Additives in sustainable Polymers on Selected Electrical and Mechanical Properties, IEEE ISSE, 2015. 21-25.

[6] Albrecht Georg Staat, Hardi Köhler, Maximilian Vogt, Reinhard Bauer, Kathrin Harre , Effect of Incorporation of Additive Combinations in Polylactic Acid on Selected Electrical Properties, European Polymer Federation Congress, Dresden, Germany, 2015.

[7] Ohki, Y., Hirai, N.; Electrical Conduction and Breakdown Properties of Several Biodegradable Polymers, IEEE Transactions on Dielectrics and Electrical Insulation, 2007 (14), 1559 – 1566.

[8] Hirai, N., Ishikawa, H., Ohki, Y.; Electrical Conduction Properties of Several Biodegradable Polymers, Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2007.

[9] Mattana G., Briand G., Marette A., Vásquez Q. A., F. de Rooija N., Polylactic acid as a biodegradable material for all-solution-processed organic electronic devices, Organic Electronics, Volume 17, February 2015, pp. 77–86.

[10] Vásquez Quintero, A., Frolet, N., Marki, D., Marette, A., Mattana, G., Briand, D., de Rooij N.F., Printing and encapsulation of electrical conductors on polylactic acid (PLA) for sensing applications, 2014 IEEE 27th International Conference on Micro Electro Mechanical Systems (MEMS), 2014 pp. 532 - 535.

[11] Haroon, Ullah, S., Flint, J.A., Electro-textile based wearable patch antenna on biodegradable polylactic acid (PLA) plastic substrate for 2.45 GHz, ISM band applications, 2014 International Conference on Emerging Technologies (ICET), 2014, pp. 158 – 163

[12] A. Géczy, L. Gál, L. Dudás, G. Horváth, B. Kovács, D. Nagy, I. Hajdu, Experimental 13.56 MHz RFID cards on biodegradable substrates, IEEE 38th International Spring Seminar on Electronics Technology, 2015. pp. 52-56.

[13] Schramm, R. Reinhardt, A., Franke, J., Capability of Biopolymers in Electronics Manufacturing, IEEE ISSE (2012) pp. 345-349.

[14] Baecker Matthias, Schusser Sebastian, Leinhos Marcel, Poghossian Arshak, Schoening Michael J., Sensor system for the monitoring of degradation processes of biodegradable biopolymers, Sensors and Measuring Systems 2014; 17. ITG/GMA Symposium; Germany, 2014.

[15] B. Medgyes, I. Hajdu, R. Berenyi, L. Gal, M. Ruszinko, G. Harsanyi, Electrochemical migration of silver on conventional and biodegradable substrates in microelectronics, 37th International Spring Seminar on Electronics Technology (ISSE), 2014, pp. 256 – 260.

[16] Geczy, A. Lener, V. Hajdu, I. Illyefalvi-Vitez, Zs. Low temperature soldering on biopolymer (PLA) Printed Wiring Board substrate IEEE ISSE, (2010), 57-62.

[17] Geczy, A. Kovacs, M. Hajdu I. Conductive layer deposition and peel tests on biodegradable printed circuit boards, IEEE SIITME (2012) 139-142

[18] Geczy, A, Gal, L. ; Hajdu, I. ; Kovacs, B. ; Nagy, D. ; Ruszinko, M., Optimizing solder joints on biodegradable PCBs with vapour phase soldering, IEEE ISSE, (2014), 33-38

[19] A. Pietrikova, J. Durisin, "VPS and reliability of solder joint", IEEE SIITME 15th International Symposium for Design and Technology of Electronics Packages, 2009. pp. 395-398.

[20] B. K. Synkiewicz, A. Skwarek, K. Witek, (2014) "Voids investigation in solder joints performed with vapour phase soldering (VPS)", Soldering & Surface Mount Technology, Vol. 26 Iss: 1, pp. 8 – 11.

[21] O. Krammer, T. Garami, "Investigating the Mechanical Strength of Vapor Phase Soldered Chip Components Joints" IEEE SIITME 16th International Symposium for Design and Technology in Electronic Packaging, 2010. pp. 103-106.

[22] O. Krammer "Comparing the Reliability and Intermetallic Layer of Solder Joints prepared with Infrared and Vapour Phase soldering", SOLDERING AND SURFACE MOUNT TECHNOLOGY, Vol. 26, Issue 4., pp. 214–222. (2014)

[23] Tamás Hurtony, Attila Bonyár, Péter Gordon, Microstructure comparison of soldered joints using electrochemical selective etching, MATERIALS SCIENCE FORUM 729: pp. 367-372. (2013)

[24] Niedermann P., Szebényi G., Toldy A.: Characterization of high glass transition temperature sugar-based epoxy resin composites with jute and carbon fibre reinforcement. Composites Science and Technology, 117, 62-68 (2015)

[25] A. Elkamel, L. Simon, E. Tsai, V. Vinayagamoorthy, I. Bagshaw, S. Al-Adwani, K. Mahdi, Modeling the Mechanical Properties of Biopolymers for Automotive Applications, Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management Dubai, United Arab Emirates (UAE), March 3 – 5, 2015

[26] DIN EN ISO 178 : 2003-06: Plastics, Determination of flexural properties, June 2003

[27] Test for Flammability of Plastic Materials for Parts in Devices and Appliances (5th ed.); Underwriters Laboratories Inc. (UL); ISBN 0-7629-0082-2, July 10, 1998 – UL 94

[28] David Busek, Study of Modern Materials of Electrically Conductive Joints in Electronics, PhD Thesis, Czech Technical University in Prague, Faculty of Electrical Engineering, February 2012

[29] Pavel Mach, David Bušek, Radek Polanský, Thermomechanical analysis of electrically conductive adhesives, 3rd IEEE Electronic System-Integration Technology Conference (ESTC), 2010

[30] David Busek, Pavel Mach, Electrical connection network within an electrically conductive adhesive, IEEE ISSE 31st International Spring Seminar onElectronics Technology, 2008, pp. 184-188.