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Self-healing encapsulation material for auto-repairable power module architectures

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Abstract

A self-healing polymer intended to printed circuit boards (PCBs) insulation has been implemented. The applicability of this new material to PCB manufacturing and recovery of properties on mechanical and electrical standpoints are investigated. The research points to enhanced reliability for future architectures of integrated power modules.

Keywords — *Self-healing, vitrimers, epoxy, printed circuit board, power module, integration*

1 Introduction

During their lifetime, power modules encounter several types of damages that can be critical for their operation. One of the most identified sources of damage is thermomechanical stress generated during thermal cycling, resulting from different thermal expansion coefficients between components, the substrate and the encapsulant. This leads to typical failure mechanisms, like bond wire lift-off, wire fatigue and solder degradations that drive the end of life of the device [1-3].

Several studies have explored the role of the encapsulant in such failure mechanisms in order to mitigate their impact on the reliability of power modules. These results show that, in comparison with silicone gel, having a stiffer encapsulation material such as epoxy compounds has a beneficial effect on lifetime [4-7].

Another path to explore hard encapsulation is the embedding of dies into printed circuit boards (PCBs). These architectures offer numerous advantages, such as better cooling solutions, higher efficiency and integrability [8,9]. For this purpose, existing materials are not always suitable, creating new types of defects during production and operation [10,11].

Indeed, having a stiffer encapsulation leads to greater interfacial stresses during heat cycles. Ultimately, devices designed with stiffer embedding materials will develop interfacial cracks in the dielectric and eventually fail.

Finding a way to mitigate the prevalence and consequences of such mechanical damages is highly desirable. The solution may not be necessarily in making stiffer encapsulation, but instead design materials capable of accommodating mechanical stresses and restoring from induced damages. Hence, for the first time to our knowledge the development of materials with self-healing capabilities is explored with application to power integration and lifetime extension of power electronics devices in mind.

Intrinsic self-healing is the inherent ability of a material to recover from damages without the help on an external structure or reagent. These materials rely on chemical equilibria to dynamically reform their network on a molecular level by exchanging chemical bonds across the fracture plan.

Most of intrinsic self-healing solutions are based on weak intermolecular bonds and often exhibit very low mechanical and thermal properties that aren't suitable for an embedding substrate application [12-15]. However, higher energy bonds can also be used to create dynamic networks that show much higher mechanical and thermal properties. [16,17].

Fitting of these materials to the needs and requirements of integrated power modules deserves to be further studied as the ability to unite two surfaces back to a continuous volume seems very valuable for electrical insulation reliability, both from an early life and an end-of-life point of view.

Besides self-healing capabilities, a broad panel of properties will need to be assessed, ranging from processability, thermal stability, thermomechanical properties, dielectric strength and adhesion among others. Mechanical and thermomechanical properties of materials can often be accommodated by smart design. In the present work, we focus on some decisive aspects that are the processability, the thermal stability and the dielectric strength. The thermal stability is especially important at the manufacturing step. For instance, soldering operations can involve solder bath at up to 290°C in lead-free processes [18].

As the main electrical insulator, the dielectric also needs to exhibit a high breakdown strength to avoid insulation failures in high voltage applications. This becomes especially true when aging occurs or when cracks propagate inside the encapsulation, decreasing the actual thickness of the insulator [19].

Our goal with this paper is to present the implementation of intrinsic self-healing materials suitable for PCB die embedding. Firstly, the material compatibility with the PCB application is investigated. Then, a PCB demonstrator will be produced from a developed Resin Coated Copper (RCC). Finally, recovery of the mechanical integrity and electrical insulation properties are achieved. The ultimate goal is to use this technology with embedded power die.

2 Vitrimers in PCB manufacturing

2.1 Choice of self-healing material

Vitrimers are a new family of polymers that rely on strong covalent bonds to achieve self-healing, often using trans-esterification reactions [20]. Trans-esterification involves ester and alcohol groups, reacting with each other and changing the crosslink distribution in the network. This reaction is reversible, theoretically allowing infinite reorganizations of the crosslinked network [21].

One of the simplest ways to obtain these chemical groups is to cure conventional epoxy resins with carboxylic acids in presence of a catalyst. This can be done with many epoxy resins already used in the electronics field.

Additionally, these polymers do not require depolymerization to activate their healing properties but on the contrary, rely on a state where all the chains are linked together in a metastable equilibrium before rearranging their structure and split. Maintaining a coherent network with a degree of stability during healing seems very valuable for such a technical field.

For these reasons, trans-esterification based vitrimers have been selected as the main strategy to produce self-healing samples and demonstrators.

2.2 Material elaboration

Vitrimers are greatly aligned with the requirements of PCB manufacturing. They can be easily based off commercial epoxy resins, widely used in the electronic field, by curing them using carboxylic acids and an appropriate catalyst (Figure 1).

The elaboration process is based off Altuna et al.'s procedure [22]. Epoxy groups were introduced with a 10% excess regarding acid groups to ensure completion of the reaction and the catalyst content was set at 5% molar compared to acid groups.

Diglycidyl ether of bisphenol A (DGEBA, D.E.R. 332 – Epoxy equivalent = 178g.eq-1) and sebacic acid (99% purity – Acid equivalent = 101g.eq-1) were used as the main precursors and 1-Methylimidazole (99% purity) was selected as the catalyst. All reagents were purchased from Sigma-Aldrich and used without further purification.

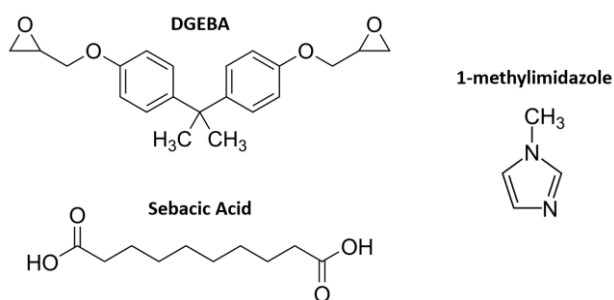


Figure 1 Precursors and catalyst used in this work

Epoxy resin and fatty acids were heated to 150°C in disposable aluminium pans before being mixed and reacted for a few minutes. The low viscosity liquid was taken out of the convection oven and slightly cooled down (near 130°C) before addition of the catalyst and further mixing by hand, avoiding formation of bubbles in the resin.

The liquorish liquid was then casted and shaped by press-molding to produce different kinds of samples (bulk, films, resin coated copper RCC). The curing process was carried out in the mold at 150°C for 1h under 1MPa of pressure.

The reaction was separately followed by Differential Scanning Calorimetry (DSC) and showed no heat generation after 25 minutes and a complete return to baseline after 1h. This indicates that the majority of the reagents have reacted and that seldom modifications of the network should happen afterwards.

The final polymer was also analysed by Fourier-Transform InfraRed spectroscopy (FTIR) to assess the chemical nature of the end-product. Consumption of epoxy and acid groups could be observed while formation of ester and alcohol groups could be confirmed (Figure 2), which validates the formation of a vitrimer self-healing network.

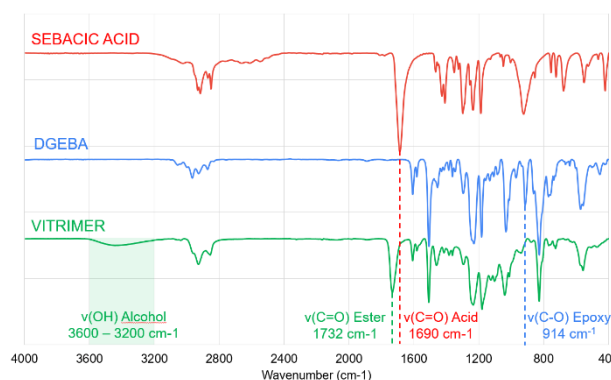


Figure 2 FTIR spectra of precursors and the elaborated vitrimer

2.3 Compatibility with PCB applications

Thermal degradation was assessed by Thermo-Gravimetric Analysis (TGA) using a NETZSCH TG209 TGA/DTA analyser, performed at 10°C/min from room temperature to 700°C. A drying step was introduced, stalling at 150°C for 15min before continuing the heating ramp. Measurements were achieved both in pure nitrogen and in dry air (Figure 3).

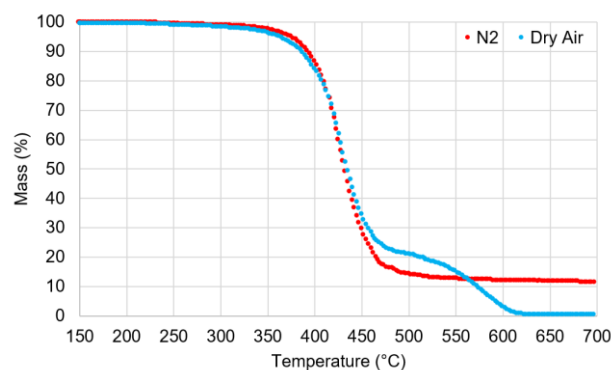


Figure 3 Vitrimer thermal degradation in nitrogen and dry air

Gathered in conditions close to the ASTM D3850, both curves show a very high thermal stability, with a 5% mass loss recorded at the temperature of 373°C in pure nitrogen and 362°C in dry air. Considering the temperature of 288°C used for delamination tests in IPC-TM-650 2.4.24.1,

a mass loss of about 1% was registered in dry air, including the drying step. These figures demonstrate the high stability of this vitrimer at the temperatures encountered in the normative tests of this application field.

The polymer response to cyclic heat treatments was monitored by Differential Scanning Calorimetry (DSC), using a TA DSC 2010 with a heating rate of 5°C/min from 0 to 300°C for a total of 4 successive cycles (**Figure 4**).

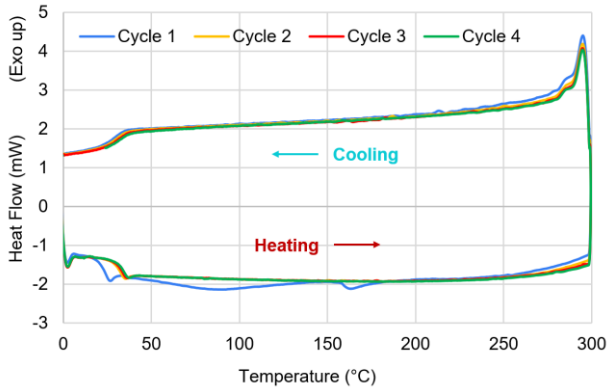


Figure 4 DSC thermograms of the vitrimer during heat cycles

These thermograms confirm the thermoset nature of the polymer and provide insight on the glass transition temperature (T_g), evaluated near 35°C. On the first cycle, one can observe endothermic events (downwards) attributed to recovery of physical aging as T_g is very close to the ambient temperature. Once energy has been provided to the system however, superposition of the curves can be observed and no reaction or significant modification of the glass transition were detected. These results ensure that the material will experience minimal change during its life cycles regardless of heat generation of power devices, that is usually capped below 150°C for most applications.

Breakdown strength determination was performed on a 300 μm thick film at 50 Hz with a Baur DPA-75C system, in a sphere-to-sphere configuration (1/2" diameter) immersed in a fluorinated dielectric liquid (Galden HT55). The electrical field is considered uniform in the material. A voltage ramp of 2kV/s was selected to obtain breakdown between 10 and 20 seconds, thus limiting the electrical aging of the material.

The breakdown strength was evaluated over 28 measurements at 67 ± 1.9 kV/mm at room temperature. These results show a very high breakdown strength, suitable for PCB insulation in high voltage applications such as power modules.

3 Manufacturing of a self-healing PCB

3.1 RCC manufacturing

To produce a self-healing PCB, it is necessary to first produce an object with several insulating and conductive layers, that can later be etched with the desired printed pattern. One way to do that is to prepare a Resin Coated Copper (RCC), that will be composed of two conductive copper layers, insulated by a dielectric coating resin.

Using press-molding as the main manufacturing technique, a sacrificial mold was designed using 35 μm thick copper sheets for top and bottom covers and a 300 μm thick spacer for the sides of the mold. The copper sheets were received surface-treated on one side (brown oxidation) to improve resin adhesion.

This mold receives the in excess liquid hot pre-polymer and is closed before going into the press for curing at 150°C for 1h under 1MPa of pressure. Once cooled down, the mold is removed from the press and directly cut to size, removing the spacer and the excess of copper and resin in the process (**Figure 5**).

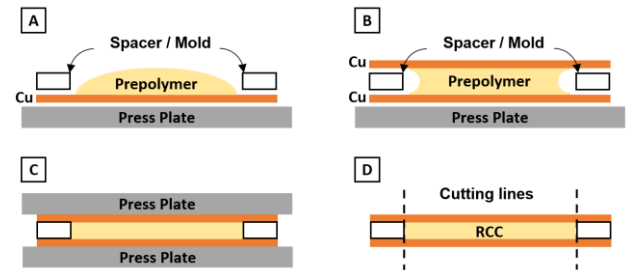


Figure 5 A) Pouring resin into the mold, B) Closing with copper foil, C) Pressing and curing, D) Cutting the RCC

The obtained end-product is a cured RCC (15 x 10 cm²) with a self-healing insulating material that can be further processed into a PCB (**Figure 6**). At this stage, it is also possible to drill the RCC and perform the electrodeposition of copper to make through-hole or filled vias.

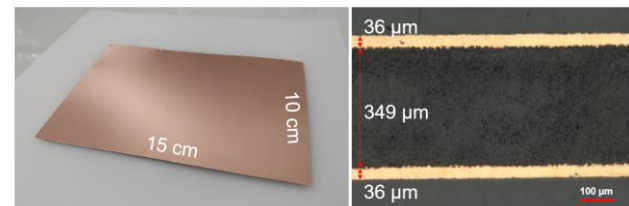


Figure 6 Left) End product, Right) RCC cross-section

3.2 PCB etching process and conformity assessment

To ensure the dielectric material can withstand the complete manufacturing procedure, a cured RCC followed a conventional PCB etching process.

First the RCC was cut to size and laminated with a photoresist dry film in a Eurolam M300 laminator. This film polymerizes under UV light and resist chemical revealing and copper etching operations. The negative mask was printed and applied on the dry film before exposure of the film for several minutes. After revealing the pattern by dissolving the unpolymerized dry film, the exposed copper was etched in a Sprint 3000 Bungard chemical etcher, using a commercial iron perchloride solution. Then, the exposed dry film was removed in a dilute solution of sodium hydroxide (stripping). The final product was obtained after rinsing and drying (**Figure 7**).

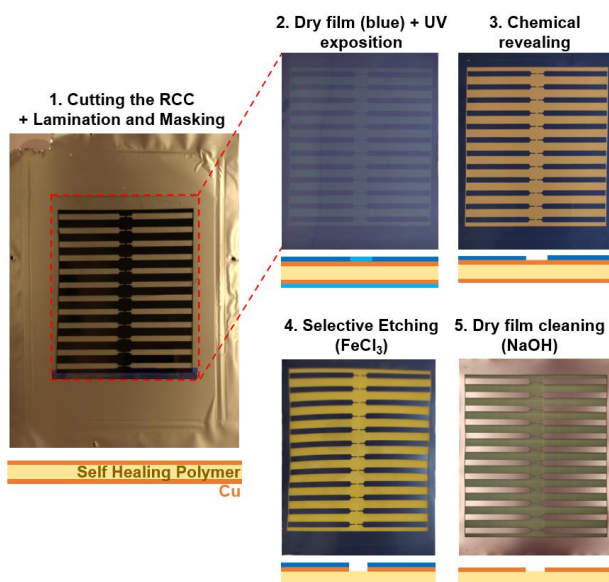


Figure 7 Developed PCB etching process on the self-healing RCC

Visual conformity was assessed: the polymer didn't seem to suffer any degradation following the procedure and its apparent adhesion to copper remained very strong despite the numerous chemical baths and manipulations it was exposed to. A slight roughness is revealed since the polymer totally replicated the topography of the surface-treated copper sheets.

FTIR spectra of the polymer before and after this process showed no modification in the chemical nature of the material, which ensured conservation of self-healing properties of the printed circuit board throughout the whole manufacturing process.

4 Material recovery

4.1 Recovery protocol

Recovery of fracture is very dependent of the conditions in which the recovery takes place.

Many studies use pressure in conjunction with temperature during the whole healing process to help surfaces match and merge together or to completely reform a new sample. This procedure dramatically helps chemical groups to enter into intimate contact and even helps diffusion and interlacing of mobile chain ends [23,24].

However, externally applying pressure to an operating power module is not realistic. Therefore, pressure application during the healing process was not used in this work. Instead, the shape memory properties of the material were used to ensure a good match of the fracture plans in 3D.

In the case of a completely severed sample, heating the material for 1min at 150°C recovers from plastic deformations, yielding perfectly matching surfaces. In addition, when a sample is not totally severed, shape memory can also help realigning and pressing the pieces together, without external help. In both cases, a very good match could be obtained.

Afterwards, the matching surfaces are put into contact with minimal force if necessary and are set free to heal for

1h at 150°C before being cooled down. This is therefore the worst-case scenario in this configuration, as confinement and thermal expansion could be used as a way to press the crack borders together by creating internal pressure.

4.2 Demonstration of mechanical properties recovery

Mechanical recovery was assessed using a Mecmesin Multitest-i in tensile configuration, performed at a strain rate of 20mm/min at room temperature (**Figure 8**). Dumb-bell shaped bulk samples were designed by scaling down the type IV design proposed in the ASTM D638-14 standard to 85mm length. Samples were pre-heated for 10 min at 150°C to recover from physical aging naturally occurring at room temperature, before being cooled down and broken on the tensile bench. After the recovery process, the same samples were tested again on the same bench.

Results show an almost perfect recovery of the elastic modulus as well as a complete recovery of strength at yield. However, strain profiles show a shift in failure mode, from a ductile type of failure to a fragile one. Indeed, recovery of the fractured surface isn't perfect and once plastic deformation occurs, the fracture plan acts as a guide for new crack propagation, testing the toughness of the adhesive joint that abruptly yields.

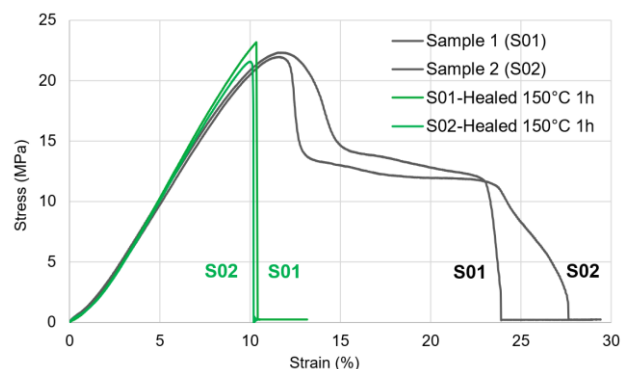


Figure 8 Tensile test of bulk samples before and after healing

4.3 Demonstration of dielectric strength recovery

Recovering from a proper breakdown isn't really feasible as the high energy plasma of the spark degrades the chemical groups of the polymer and most often transform it into carbon, which is not self-healing by itself. However, recovery can be expressed for any property following any damage, as long as the damage is in fact reducing or preventing the expression of the said property.

In the case of integrated power modules, mechanical damages can decrease the breakdown strength of the insulating material, by reducing the overall thickness or by creating initiation sites for partial discharges, which will trigger breakdown after some time. Therefore, the purpose of this test is not to repair a dielectric breakdown but to evaluate the rate of recovery of the breakdown voltage in repaired volumes, following a mechanical damage.

For breakdown voltage recovery evaluation, novel samples had to be designed, concentrating both mechanical

and electrical stresses in the same area. Embedded electrode patterns were produced with a controlled 1mm gap using the PCB etching process before being encapsulated in a new batch of the polymer. A CO₂ laser ablation was then used to remove some of the polymer for electrical contacts and cut notches for mechanical stress concentration (Figure 9).

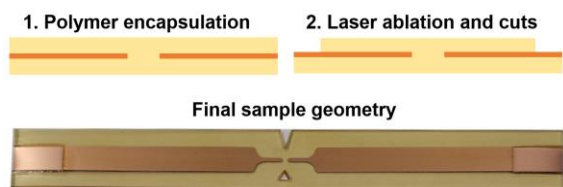


Figure 9 Tensile/breakdown tests sample manufacturing and geometry

Crack propagation was channelled in between the electrodes using notches and stopped using an open void. This allowed to keep a small portion of the polymer intact and take advantage of the polymer shape memory to precisely self-realign the electrodes during the recovery process (Figure 10).

Mechanical damages were produced with a Deben Microtest tensile stage at a strain rate of 1mm/min at 20°C. After healing, breakdown strength tests were performed in a fluorinated dielectric liquid bath using a 2kV/s voltage ramp at 50Hz.

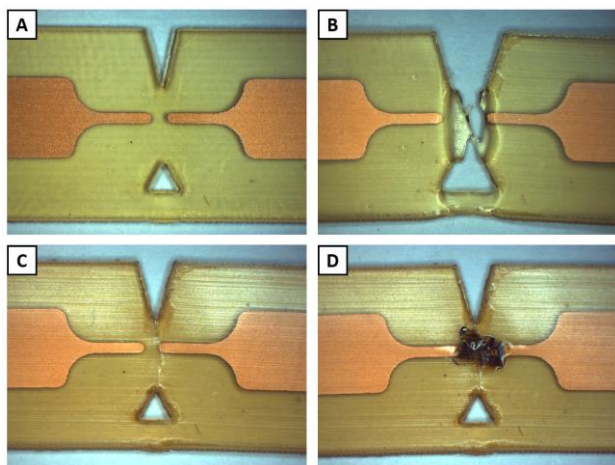


Figure 10 Stress concentration region. A) Pristine, B) Mechanical damage, C) Healed for 1h, D) After breakdown

Results in Figure 11 compare the breakdown voltages of unbroken samples (Reference) with broken and repaired samples (Healed) that experienced different recovery times (5 min to 60min) at 150°C.

The rate of recovery seems very satisfying as it only requires 5 minutes of healing to achieve at least 85% of the pristine breakdown voltage value. After one hour, the recovery increased to about 100%. These results seem ideal, however, there is a great dispersion of data points with the shortest healing times. Given the complexity and numerous steps required for providing these results, not so many samples could be tested to improve the statistics. Regardless, the lowest data point for any of these sets showed at least 65% recovery which is still a great figure for such large damages.

With this in mind, it appears that breakdown voltage recovery happens very quickly in the healing process, as long as the network has been reformed to some extent and that no gaps or thinned sections remained.

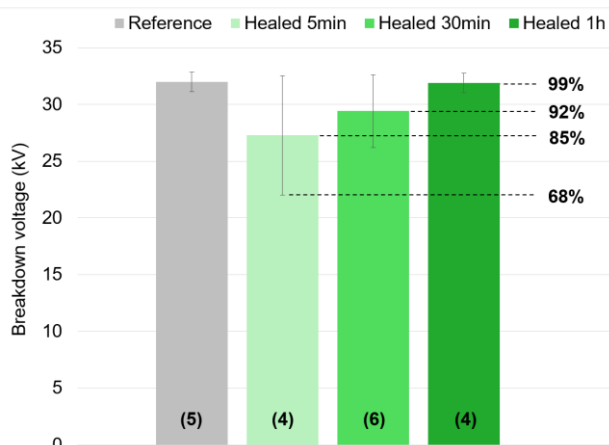


Figure 11 Breakdown voltage recovery after mechanical damage and healing. Number of measurements in brackets

5 Discussion

While investigating such self-healing materials, the intent is not to entirely replace existing solutions but rather propose new design options that can be compatible with the same domain of use. Using these materials in conjunction with typical materials like FR-4 could be valuable as a strong interaction is expected with any epoxy/alcohol/ester group. Excellent bonding with most metals has also been observed but no quantitative data have been produced yet. Associating these materials with fillers/fibres is achievable and surface functionalization can even integrate the filler into the self-healing mechanism to increase bonding strength/repairability [25].

Conventionally, high-T_g thermosets are strongly favored for PCB manufacturing to reduce thermomechanical stresses, mostly because polymers often have a lower coefficient of thermal expansion (CTE) below their glass transition, thus reducing mismatches with other components such as copper or silicon. However, glassy polymers also exhibit a rather high and stable elastic modulus which is also a factor of thermal stress. In this regard, having a softer material capable of reducing the overall thermal stress above T_g could be suitable for strategies, from which self-healing solutions emerge.

Indeed, vitrimer self-healing will only occur once chain mobility is achieved (above T_g) [26] and their mechanical moduli dramatically decrease near T_g. Overall, lower stress concentration could be expected above T_g.

Additionally, the ability of the network to reform dynamically can provide stress-relaxation above the topology freezing transition temperature (T_v) [22]. A smart behaviour could therefore be obtained, with a stiff low CTE material below T_g, a soft high CTE material above T_g, and a self-healing, stress-reliever material above T_v.

6 Conclusion

In this work, the applicability of a self-healing polymer (vitriimer) to the manufacturing of highly technical PCBs was investigated.

The vitriimer was successfully produced and its compatibility with the field of application was assessed. Results have shown that very high thermal stability and breakdown fields can be expected from such materials, two properties that are key in PCB design and manufacturing.

The ability to produce several semi-finished products (bulk samples, films, RCCs, PCBs) with satisfying conformity using press-molding was also demonstrated.

Self-healing of mechanical damages at 150°C for 1h was very efficient with most of the elastic properties recovered. Longer times or higher temperatures could help going a step further by recovering plastic properties.

Demonstration of dielectric breakdown voltage recovery after mechanical damage was provided. Longer heating times could increase the confidence on the self-healing up to 99% of recovery after 1 hour against 85% after 5 minutes healing compared to a non-broken reference. This is encouraging for using these materials in a preventive strategy against voids formation that can trigger electrical events.

To complete this study, chemical formulation and implementation of fillers/fibres in the vitriimer matrix would allow to tune properties and thus improve the flexibility for the application field.

The creation of vias or multi-layered stacks are further steps for future PCB integration using these self-healing materials.

A study about healing of more relatable electrical events such as partial discharges has already been started.

Finally, gathering of more data could prove valuable to increase statistical power.

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