New Thermal Management & Flexible Heater Laminate Materials for Electronics

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Abstract

As electronics continue to become more compact and complex, controlling heat remains a growing challenge for circuit performance and durability. DuPont is continuously innovating new Kapton® film and Pyralux® laminate materials that can better manage these challenges by increasing or reducing heat dissipation or assisting in heat generation within a system. This combination of material capabilities allows for a thin, flexible or rigid circuit that can alleviate hot spots and promote more efficient heat control within electronic systems.

DuPont has introduced two innovative laminate materials to enhance thermal management in electronics. Temprion™ ODBC is a thermally conductive laminate that complements the Pyralux® laminates product family, showcasing a Kapton® film dielectric with three times the thermal conductivity of traditional Kapton® film at 0.65 W/m-K while maintaining a dielectric strength of 6 kV/mil. It also offers twice the thermal conductivity and a 12% reduction in thermal resistance compared to traditional Pyralux® AP and TFH laminates. Alternately, Pyralux® ML is a metal-clad laminate that incorporates Kapton® all-polyimide technology and various metal alloys, such as copper-nickel and Inconel®, to address unique challenges in heat generation while providing controlled heat transfer and tailored electrical resistance properties.

The information highlighted here will explain the advantages of these new thermal management and heat generating laminate materials for use in electronics supported with data and end-use application examples.

Key words

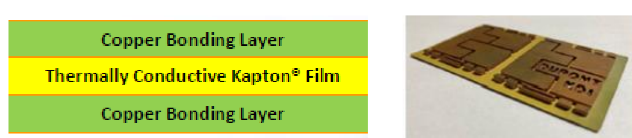
Heat Dissipation & Generation, Flexible Circuits, Flexible Heaters, Power Electronics, Thermal Management

I. Introduction

As the trend toward miniaturization and increased functionality in electronics continues, effective heat management has emerged as a critical factor impacting circuit performance and longevity. DuPont is at the forefront of this advancement, developing innovative Kapton® film and Pyralux® laminate materials designed to address these thermal management challenges. This integrated approach not only supports the latest industry designs but also ensures the reliability of complex electronic systems.

Temprion™ ODBC (Organic Direct Bond Copper) is a thermal management material from DuPont that offers a high-quality, reliable choice for managing heat and reducing thermal resistance in a wide variety of electronic assemblies. This laminate system is a thermally conducting, electrically insulating material that exhibits low thermal resistance, high heat dissipation, and improved thermal stability during continuous operation.

A typical construction of Temprion™ ODBC features a thermally conductive Kapton® polyimide film core bonded to copper, as shown in Fig. 1 (a). A sample part is shown in Fig. 1 (b).



(a) (b)

Fig. 1. (a). Typical DuPont™ Temprion™ ODBC construction. (b) Sample Temprion™ ODBC part.

The copper layer thickness may be between 12 µm to 5.0 mm and is bonded to a thermally conductive Kapton® film layer at elevated temperatures and pressure under vacuum or inert atmosphere. The high dielectric-to-metal bond strength of Temprion™ ODBC allows it to maintain its electrical and thermal performance after 5,000 thermal shock cycles from -40 °C to 200 °C without delamination [1].

In certain electronic devices, heat generation is also essential for functions like temperature control, warming, or maintaining performance in extreme environments. Thin and lightweight heaters are often needed in these applications to ensure maximum efficiency and quick response times.

Pyralux® ML is DuPont's newest laminate offering that can be used for heat generation through resistive element heating. It is a double-sided metal-clad laminate featuring an all-polyimide dielectric layer. Specialty metal alloys, including copper-nickel (CuNi), Inconel®, and other non-copper alloys, are selected to provide excellent conductivity, resistivity, and thermal resistance. The different specialty alloys allow designers, fabricators, and OEMs flexibility when targeting a specific resistance for a heating circuit. Double-sided circuits with additional functionality, like temperature control, are also feasible.

A typical Pyralux® ML construction is shown in Fig. 2. The metal alloy thickness will depend on the specific material selected but can range between 12 µm to 152 µm. Typical properties for Temprion™ ODBC and Pyralux® ML are listed in Table I with Pyralux® AP as a comparison.

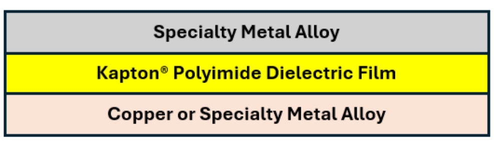


Fig. 2. DuPont Pyralux® ML construction

Table I. Typical properties for Temprion™ ODBC, Pyralux® ML, and Pyralux® AP materials.

Property	UoM	Temprion™ ODBC	Pyralux® ML	Pyralux® AP
Thermal Conductivity	W/m-K	0.65	0.25	0.20
Breakdown Voltage	kV/mil	6.3	5	5
Cu Adhesion	lb./in	>8	>6	>8
Metal Alloy Adhesion	lb./in	N/A	>2.5	N/A
Tensile Strength	MPa	89	350	345
Young's Modulus	GPa	4.7	>7	4.8
Elongation	%	42	40	50

II. Heat Dissipation

Thermally Conductive Copper Clad Laminates

Traditional copper clad laminates often utilize acrylic, epoxy, or polyimide dielectric materials. While these materials have excellent electrical properties, they are not thermally conductive. When used in electronic components, they often result in elevated temperatures. DuPont™ Temprion™ ODBC copper clad laminates solve this problem, as demonstrated by a comparative study between this new material and traditional Pyralux® laminates. The collected data in Fig. 4 shows that the Temprion™ ODBC material provides improved thermal conductivity when compared to the traditional Kapton® dielectric-based Pyralux® laminates. The Temprion™ ODBC laminates exhibit a 2x increase in thermal conductivity and a 12% reduction in thermal resistance as compared to traditional Pyralux® AP and TFH laminates. This thermal dissipation improvement enables faster cooling and lower temperatures in electronic devices.

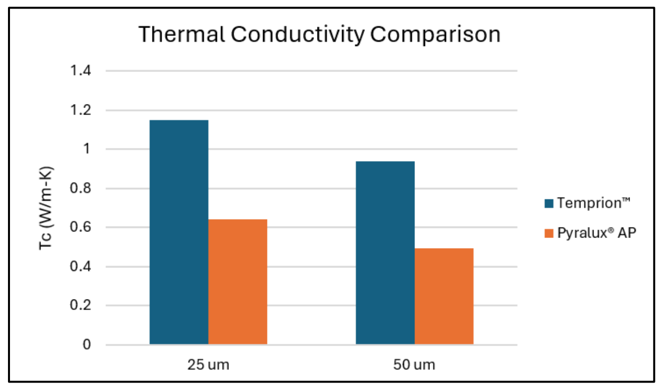


Fig. 4. Thermal conductivity of Temprion™ ODBC laminate compared to Pyralux® AP laminate.

Thermal Management in Flexible Circuits

Flexible copper clad laminates (FCCLs) are often used in flexible printed circuit boards in electronic devices. FCCLs act as the electrical connection between various parts of the electronic device, carrying the current or voltage through the copper traces etched into the laminate material. However, as the current or voltage is transferred through the flexible circuit from one part of the device to another, the resistivity of the FCCL also generates heat. This heat generation in the FCCL can limit the power output in the electronic device to avoid excessive temperatures that will ultimately damage the electronic components in the device.

One pathway to enabling larger power outputs in electrical devices is to reduce the temperature within the electrical components. Accomplishing this requires materials that dissipate that heat faster without negatively impacting the transmission of the electrical signals. The new Temprion™ ODBC thermally conductive laminates fill this need.

Temprion™ ODBC laminates allow for greater heat dissipation as demonstrated in Fig. 5. When compared to DuPont™ Pyralux® laminates, the Temprion™ ODBC laminates demonstrate an almost 12% reduction in the thermal resistance of the FCCL. This reduced thermal resistance allows the heat to dissipate faster, avoiding excessive heat buildup in the electronic component and potentially reducing temperatures by >10 ºC.

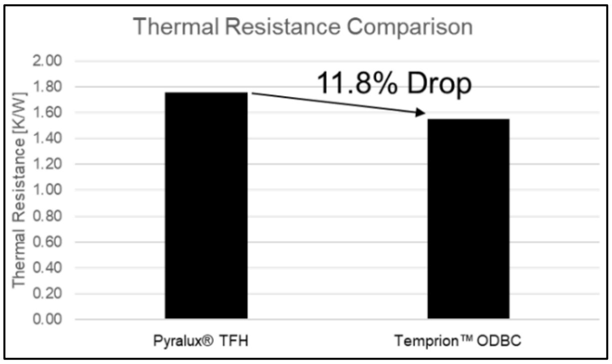


Fig. 5. Thermal resistance of Temprion™ ODBC laminate compared to Pyralux® TFH laminate.

The Temprion™ ODBC laminates accomplish this enhanced heat dissipation without impacting electrical performance of the flexible circuit. The thermally conductive dielectric material can be bonded to a wide variety of metal conductors to control current or voltage transfer between components in the device. Furthermore, this new dielectric material maintains excellent electrical insulation, as seen in Table I. Therefore, the Temprion™ ODBC material can enhance thermal dissipation without impacting the required electrical performance.

Thermal Management in Power Electronics

In the power electronics sector, insulating layers in a module are important for separating circuits from thermal management components. High power density packaging uses rigid boards as thermal substrates for mounting semiconductor dies. These substrates provide mechanical support and electrical isolation for the circuit and die, while promoting effective heat dissipation. To meet the needs for conduction and insulation, thermal substrates are made of multiple layers that combine conductive materials, like metals, with insulating materials, such as ceramics or polymers, allowing heat to escape from the dies [1].

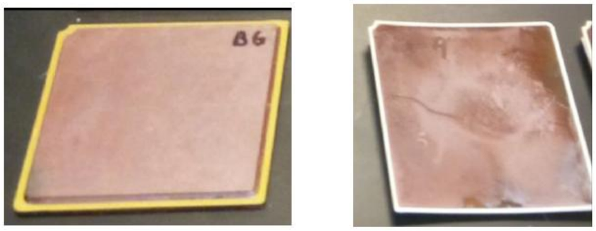
The most prevalent structures utilized for thermal substrates are direct bond copper (DBC) components, created through a high-temperature bonding method between copper and a highly thermally conductive ceramic, such as Al_2O_3, AlN, or Si_3N_4. In a typical DBC configuration, layers of metal and ceramic are fused together in a high-temperature controlled environment, resulting in a thermally conductive yet electrically insulating ceramic layer situated between two layers of copper. However, the significant differences in the coefficients of thermal expansion (CTE) between the metal and ceramic layers lead to considerable thermomechanical stresses at the bonding interface, which can cause degradation when exposed to high temperature gradients during the operation of power modules. Furthermore, the bonding processes used for attaching copper layers to the ceramic restrict the thickness of the copper layers to below 1000 µm, with common DBC designs featuring 300 µm copper layers and a 380 µm ceramic layer. The high elastic modulus of ceramics can also lead to delamination of the DBC under thermal cycling. [1]

Temprion™ ODBC addresses many of the known issues with traditional DBC components and provides similar or better thermal and electrical performance when compared to Al_2O_3, AlN, or Si_3N_4 substrates. In one example, the issue of CTE mismatch between copper and dielectric in DBC constructions is significantly reduced for Temprion™ ODBC constructions as the CTE of the polyimide film core is much closer in value to that of copper. The CTE values of these DBC and ODBC materials are shown in Table II [5].

Table II. Typical CTE properties for DBC and ODBC laminate materials.

Material	CTE (ppm)
Aluminum	24.0
Temprion™ ODBC polyimide	20.0
Copper	16.5
Al_2O_3	7.1
AlN	4.3
Si_3N_4	3.2

To understand the thermal reliability advantages of Temprion™ ODBC to DBC substrates, a set of samples are exposed to repeated thermal cycles between -40 °C to 200 °C at 5-minute dwells. The ODBC sample consists of DuPont thermally conductive all-polyimide Kapton® film with 0.8 mm thick copper. The DBC sample consists of an Al_2O_3 substrate with 0.3 mm thick copper. After 100 cycles, the DBC samples experienced severe warpage and breakage, while the ODBC sample surpassed 5,000 cycles without any visual damage or high potential (HiPot) failures. Fig. 3 (a) and Fig. 3 (b) show the respective samples after testing. Results confirm that Temprion™ ODBC has very high thermo-mechanical reliability [1].



(a) (b)

Fig. 3. (a) Temprion™ ODBC sample with 0.8 mm thick copper after 5,000 thermal cycles showing no signs of degradation. (b) DBC sample with AL_2O_3 substrate and 0.3 mm thick copper showing signs of warpage and breakage after only 100 thermal cycles.

A comparison of material properties for common ceramic substrates to Temprion™ ODBC is shown in Table III. Although the polyimide film used in the Temprion™ ODBC has lower thermal conductivity than ceramics, its higher dielectric strength and ductility enable thin layers, as low as 25 µm, to be used. This, along with the thick metallization, reduces the thermal resistance and makes the ODBC a viable candidate for power modules [2].

Table III. Comparison of material properties

Property	UoM	Temprion™ ODBC	AL_2O_3	AlN	Si_3N_4
Thermal Conductivity	W/m-K	0.65	24	170	90
Dielectric Strength	kV/mm	164	20	20	20
Minimum Dielectric Thickness	mm	0.025	0.32	0.63	0.25
Maximum Metallization Thickness	Mm	> 0.5	0.3	0.3	0.8

III. Flexible Heaters for Electronics

The global flexible heater market is anticipated to grow from USD 1.2 billion in 2022 to USD 1.7 billion by 2027, growing at a CAGR of 7.2% during this forecast period [3]. The electronics and semiconductor segment accounts for the largest market share, 31% in 2023, and is projected to grow at the highest CAGR for this forecast period [3],[4].

Flexible heaters find widespread use in numerous electronic applications for efficient temperature management. These heaters are crafted from a range of materials, including Kapton® polyimide film, silicone rubber, butyl, and mica. Among these, silicone rubber and Kapton® polyimide heaters are particularly favored due to their flexibility, excellent thermal transfer properties, and quick warm-up times [6]. Despite their advantages, these technologies do come with certain limitations. For instance, silicone rubber heaters are typically thicker and heavier than polyimide heaters, which can make them unsuitable for applications where heating efficiency is critical. Similarly, Kapton® polyimide heaters that utilize copper as the resistive trace material may have limited uses due to copper's high conductivity. As a result, manufacturers often need to create custom laminate materials using specialized resistive metal foils to meet the resistance requirements for a given application.

DuPont™ Pyralux® laminate material offers an innovative alternative to traditional silicone and polyimide-based heaters. Pyralux® ML features an all-polyimide core laminated to specialized resistive metal foils, removing the necessity for fabricators to create their own custom laminates, which can be both costly and time-consuming. It is currently being evaluated for use in high performance computing and flexible heater applications. Like existing market products, Pyralux® ML can be fabricated into circuits to generate heat by passing electric current through the circuit, reaching maximum temperatures up to 200 °C in less than 60 seconds when operated as a standalone heater. Fig. 5 shows an example of a heater made with Pyralux® ML.

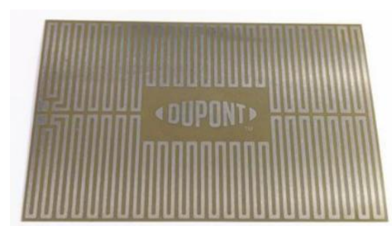


Fig. 5. Pyralux® ML heater circuit with CuNi foil

Pyralux® ML can control heat transfer by using metal alloys with significantly lower thermal conductivity than traditional copper-based laminates. Copper has a thermal conductivity of 400 W/m-K, but Pyralux® ML may be constructed with copper-nickel (CuNi) and Inconel® alloy foils that have thermal conductivity <30 W/m-K. The properties of these specialty alloys allow for more design flexibility, and they eliminate the need for custom lamination by fabricators, ultimately reducing the complexity and cost to manufacture.

In an example power test, a heater made with Pyralux® and Kapton® film bonded to CuNi metal foil is powered at three set voltages: 1) 30V, 2) 35V, and 3) 40V. Temperature and current of the circuit is monitored throughout the test. The test setup can be seen in Fig. 6 (a) with power connected to the circuit, an external thermocouple placed on the circuit to record temperature, and two multi-meters to measure voltage and current. Results of the test are shown in Fig. 6 (b) in which the heating circuit becomes temperature-stable in less than 60 seconds of operation. As expected, an increase in voltage input yields an increase in temperature output.

Fig. 6. (a). Pyralux® ML heater powered with attached thermocouple and multi-meter devices.

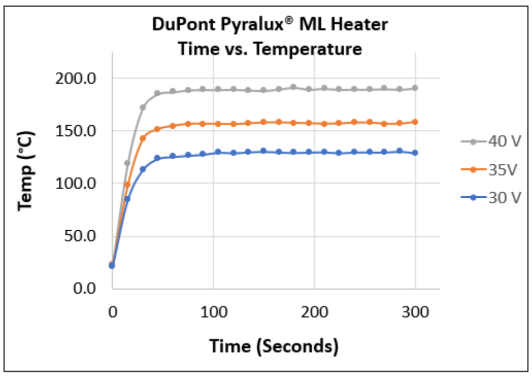


Fig. 6. (b). Time vs. temperature plot of the heating circuit at 30V, 35V, and 40V input.

In another sample test, a heater circuit made with Pyralux® ML is powered at ~42V input and held for 15 minutes to verify the stability of the heat output. As shown in Fig. 7, the heater quickly reaches a peak temperature of ~200 °C in 60 seconds. After 15 minutes of continuous operation, no abnormal readings are observed with the heater. Once power is removed from the circuit, the heater returns to < 30 °C in approximately 90 seconds. This test confirms the ability for Pyralux® ML to provide rapid, on-demand heating when desired, and quick cooldown when heat is no longer required.

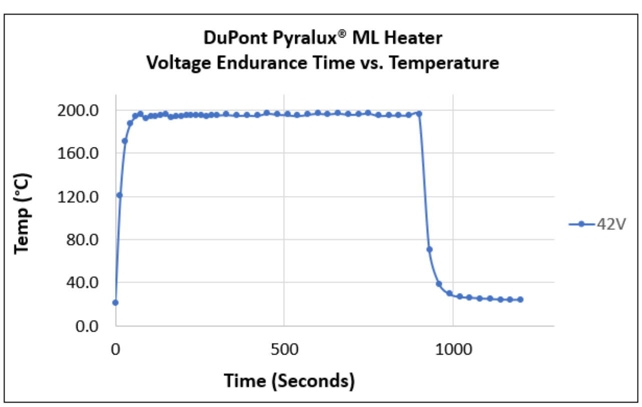


Fig. 7. Time vs. temperature plot of the Pyralux® ML heating circuit when powered for 15 minutes continuously.

The thermal properties of Pyralux® ML allow for faster heat transfer than traditional materials. This means heaters using Pyralux® ML can reach their desired temperatures more quickly and use less energy to maintain them in operation. The laminate material also allows for the design of heaters with complex shapes and through-holes, giving designers the ability to create customized solutions. This flexibility is particularly useful in applications where space is limited, or unique shapes are needed.

Another feature of Pyralux® ML is that the polyimide core can withstand temperatures up to 260 °C, making it ideal for environments where conventional materials would degrade, such as in semiconductor manufacturing and aerospace.

In the semiconductor industry, Pyralux® ML is well-suited for high-temperature applications where the material's thermal mass and electrical properties are critical. With its low thermal mass, Pyralux® ML enables faster heat-up and cooldown cycles, improving processing times and reducing energy consumption by up to 10%. In addition, the material's dielectric properties minimize signal loss and interference, which is essential for high-frequency applications.

The automotive industry is another area where Pyralux® ML heaters may be used, specifically in electric vehicles (EVs). In cold weather environments, for example, preheating lithium-ion batteries before charging or discharging is important to maintain the high performance and lifetime of the battery [7]. As outside temperatures drop below freezing, an EV's average driving range drops by 12% compared to its range at 24 °C [8]. By preheating the EV battery, improvements to the battery function, charging speed, and driving range are all possible. Pyralux® ML may be utilized as a heating solution for battery management while providing a 15-20% weight reduction when compared to traditional copper-based laminates. This improved thermal management can lead to a 5-10% increase in battery life by ensuring more unform operating temperatures.

IV. Conclusion

The ongoing efforts to decrease the size, weight, and power consumption of electronic devices are resulting in higher heat generation within their circuits. This elevated heat can create performance difficulties and durability concerns for both the circuits and nearby components. To address this issue, DuPont has developed Temprion™ ODBC and Pyralux® ML laminate materials. These materials are designed with optimized thermal conductivity, enabling them to manage heat effectively while fulfilling electrical insulation requirements, ultimately enhancing the reliability and efficiency of the circuits.

The Temprion™ ODBC thermally conductive laminates can impact thermal management in multiple ways. First, this new thermally conductive material enables flexible circuits to become dual purpose. They can now act as an electrical connector as well as a thermal dissipator. This dual functionality will enhance the performance of electronic devices and allow for greater power output without increasing temperatures. Furthermore, Temprion™ ODBC laminates enable power modules to handle higher voltage designs due to the enhance temperature reliability of the polyimide substrate. This will lead to higher performance power electronics for the next generation electrical vehicles.

Pyralux® ML represents a significant advancement in non-copper-based laminates, providing OEMs with a new tool to solve their most challenging heat management problems. By establishing a new industry standard with its specialty metal foil laminate, DuPont has created a material that is both reliable and customizable, meeting the specific needs of high-performance markets. As Pyralux® ML continues to be adopted, its impact across industries will likely expand, reinforcing its position as a vital solution for future electronic and thermal management applications.

Acknowledgment

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