How High-Frequency PCB Fabrication Materials Are Driving Advanced Applications

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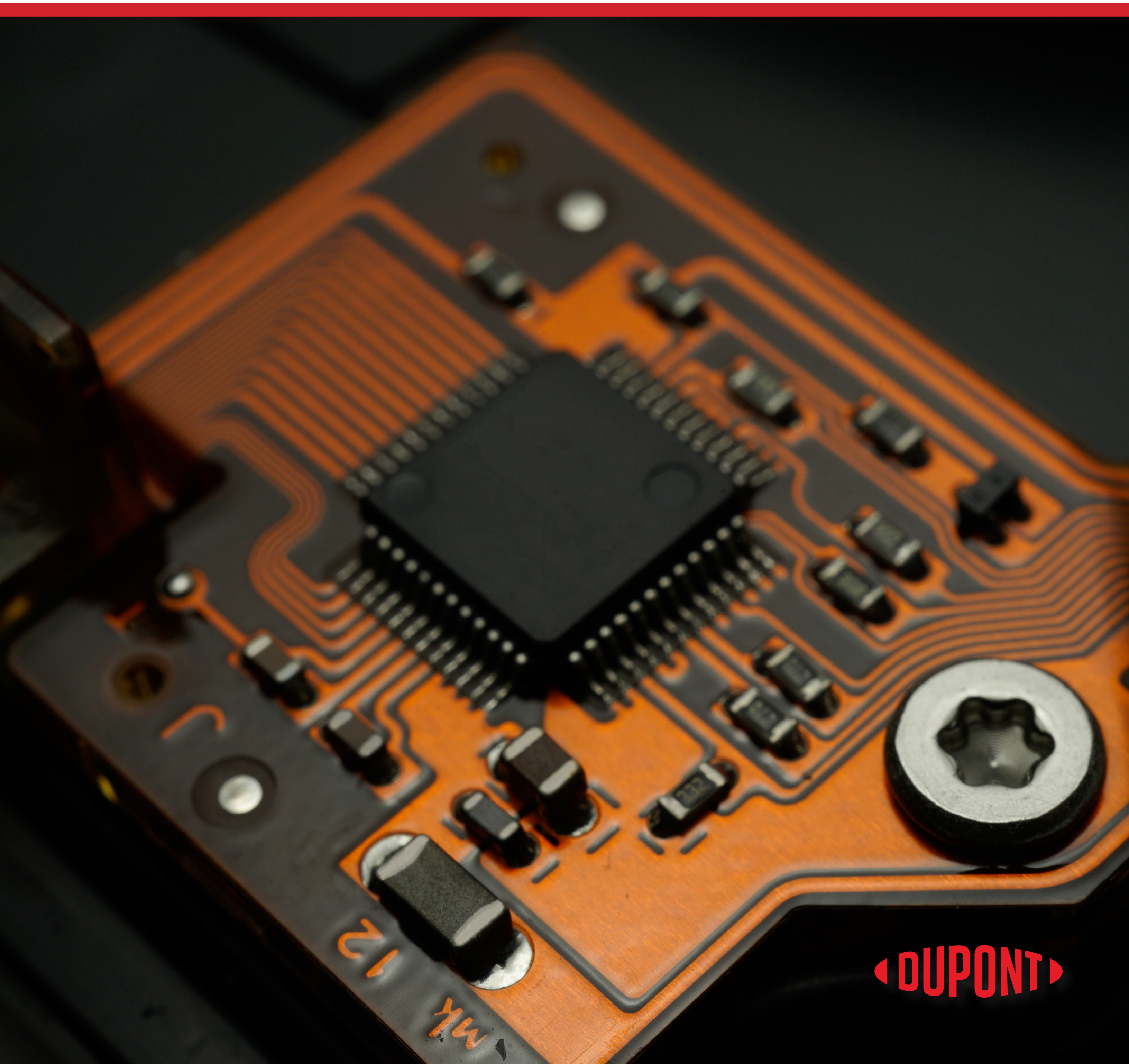

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Linewidths are becoming much smaller and feature densities are rising as electronics become smaller, faster, and thinner. High-frequency PCB materials are most often associated with microwave and mmWave systems to support low-loss signal propagation between components on a PCB, as well as into antenna modules and modem packages in mobile devices. The material systems used in PCBs for the most advanced electronics are key enablers of system performance, and they should be chosen carefully at the beginning of the design process.

Standard one-size-fits-all PCB fabrication materials that may be appropriate for simpler systems are not likely to work in high-frequency systems. Products with high feature density such as mobile devices, mmWave systems, and aerospace systems need more specialized material systems that are specifically designed for operation at high frequencies. Several material factors greatly influence the performance of PCBs operating at RF frequencies, including:

- Dielectric properties of PCB laminates
- Pairing of copper foils with dielectrics
- Plane capacitance in a PCB stack up
- Surface plating and solder mask selection

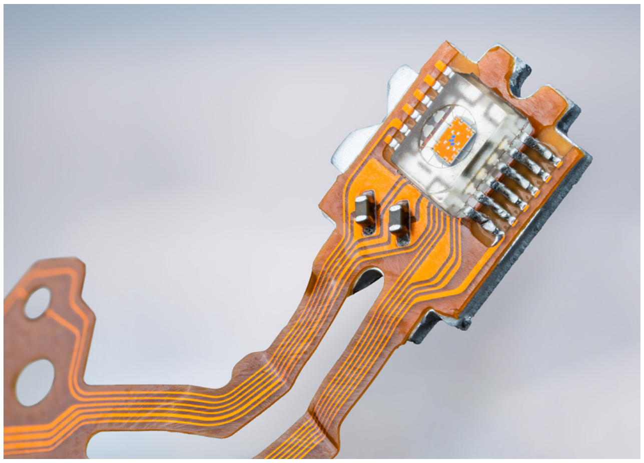
This document gives a thorough overview of these material systems and what PCB designers and engineers can expect in terms of performance and design requirements.

Overview of High-Frequency PCB Materials

Materials used in high-frequency PCBs are broadly classified as either flexible or rigid materials, with some products mixing both types of materials in rigid-flex PCB designs. There is a much greater diversity of rigid materials with diverse dielectric, thermal, and mechanical properties. DuPont has developed a broad range of dielectric materials designed for both rigid and flexible PCBs.

Flexible Layer Stackup Materials

Many portable devices such as mobile devices and wearables have limited space, yet they still implement an RF front end and a high-speed digital chipset, both of which require low-loss materials. Space may be limited in these devices, so it can make sense to use a flexible substrate material to mount components and



route traces. Materials such as Kapton® polyimide films are often used in these PCBs to build a flexible layer stack up, which can be used to route traces and mount components in space-constrained devices.

Flexible layer stacks include the following material sets to support static or dynamic flex applications:

- Polyimide-based films
- Copper foil (typically rolled-annealed) bonded onto the base film
- Adhesives for bonding these materials into a layer
- A polyimide coverlay layer that protects etched copper

Copper-clad polyimide films also come in an adhesiveless variety. These materials come in an assortment of thicknesses and with lower Dk/Df properties than standard FR4-grade PCB laminates. These layer stacks are also lighter than rigid materials, featuring strong trace adhesion and long-term environmental stability that results in a highly reliable material system for high-speed/high-frequency electronics. **Table 1.** shows several high-frequency materials available from DuPont with their respective Dk and Df material attributes.

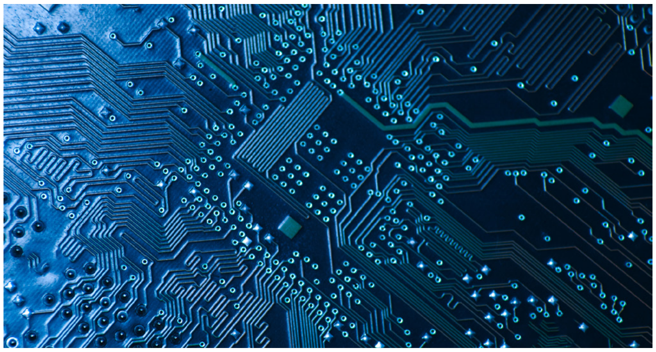
Table 1. DuPont's high-frequency dielectric materials and important material properties

Material	Material Type	Dielectric Thickness †	Copper Thickness †	Dk*	Df*
Pyalux® TFH	D/S Laminate	25, 45, 50 (um)	12, 18 (um)	3.2	0.003
Pyralux® TFHS	S/S Laminate	12, 25, 45, 50, 70 (um)	12, 18 (um)	3.3	0.0025
Pyralux® AP	D/S Laminate	1-6 (mil)	9, 12, 18, 35, 70 (um)	3.4	0.003
Pyralux® TK	D/S Laminate	50, 75, 100 (um)	12, 18, 35 (um)	2.5	0.002
Pyralux® AG	D/S Laminate	12, 25, 50 (um)	12, 18, 35 (um)	3.2	0.007
Pyralux® GFL	Adhesive	15, 20, 25, 30, 35 (um)	N/A	2.5	0.0017
Pyralux® GPL	Adhesive	15, 25, 30 (um)	N/A	2.8	0.0035
Pryalux® HXC	Coverlay	12, 25 um PI/15, 20, 25um Adhe-sive	N/A	5	0.1
Pyralux® HP	Coverlay	12, 25, 50um PI/12, 25, 50um Adhesive	N/A	3	0.0045

† More information is available in Product Data sheets
* Please refer to product data sheets for Measurement method and frequency

Rigid Dielectric Materials

Standard FR4-grade fabrication materials are not recommended for high-frequency, high-reliability systems as these materials as can have excessive signal losses at frequencies exceeding 5 GHz. High-speed, high-frequency systems and designs require low-loss interconnects, consisting of two commonly used in high-frequency PCBs:



- PTFE with ceramic filler
- PTFE with ceramic and glass-reinforcement (spread glass)

When selecting materials for high-frequency products, it is important to consider the material's dielectric constant (Dk) and loss tangent (Df). High-Dk PTFE-based materials can provide much lower losses than standard FR4-grade materials.

Copper Foils

The dielectric material sets listed above are generally supplied as copper-clad laminates with a particular copper foil applied to the material. For high-frequency operation, the important material property of copper foil is its surface roughness, which will increase the skin effect resistance experienced by a signal propagating on an interconnect. Copper foils are formed through an electrodeposition process or are annealed in a rolling process to smooth out the copper film. Surface treatments may also be used to further reduce the roughness profile of a copper film.

When selecting a copper-clad laminate, the designer must pay attention to the type and thickness of copper foil used in the laminate material. High-frequency designs generally aim for materials with the smoothest possible copper foil to minimize skin effect resistance at high frequencies. The surface roughness of copper foils depends upon several factors, including processing parameters, microscopic grain structure, pre and post-processing surface treatments, and material composition. The surface plating can also contribute to losses in the copper foil, as is discussed in a later section.

Is a Low-Dk Material Required?

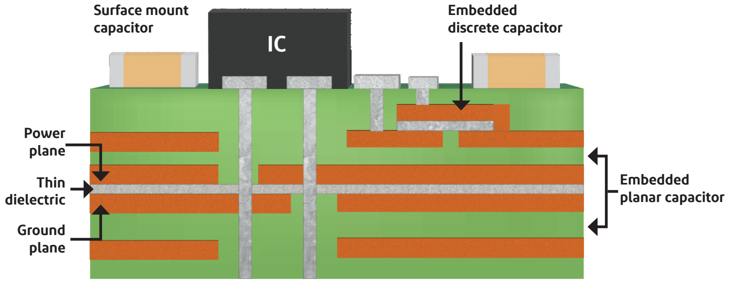
Typical approaches to building advanced digital systems tend to focus on using low-Dk dielectric materials. There are several reasons for this, which relate to the losses experienced by propagating waves and digital signals, as well as the transmission line design required to hit particular impedance targets. Some design guidelines will give blanket statements that specify low-Dk materials for all high-speed/high-frequency PCBs, but this is not a strict requirement.

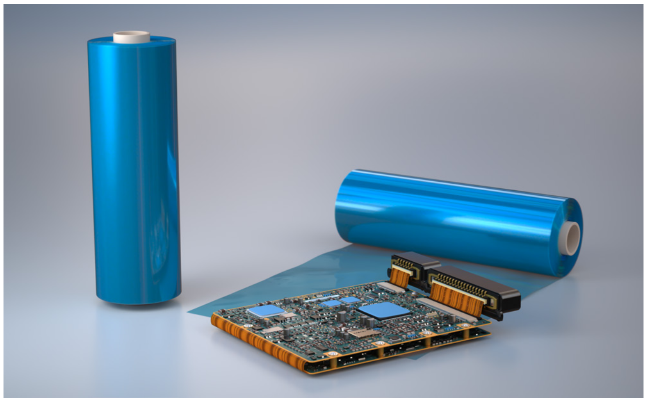
In high-layer count systems with thin dielectrics, the layers will be very thin. The main motivation for using a low-Dk material is to allow for slightly larger linewidths. While this can reduce trace density on PCB, it is beneficial for manufacturability and lowering conductor loss. Thinner, lighter and flexible PCB stack ups can be enabled with low Dk material.

Other systems operating in areas like aerospace and defense may carry the same preference for low-Dk materials, like in backplane and daughtercard systems. When layer counts are high (24 layers is typical) and board thicknesses are not too large, the layer thickness will still be low enough that a low-Dk material may be preferable. In larger format backplanes, the interconnection distance can also be so great that only the lowest loss tangent materials with minimal dielectric dispersion can hit attenuation and distortion targets. When the board size is thicker, a higher Dk value is still acceptable as linewidth/spacing targets can still be met for single-ended and differential channels.

Some specialty RF systems operating at intermediate frequency ranges (sub-GHz, WiFi, and ISM bands) might prefer higher Dk values because they allow circuit sizes to be smaller when operating at these lower frequencies. These systems might implement printed components that exploit coupling or structural resonances, and the frequencies at which these effects arise strongly depend upon the physical size of the printed elements relative to an RF signal's wavelength. When the dielectric constant is larger, a signal's wavelength will be smaller for a given frequency, and thus the system will be made physically smaller.

Overall, high speed, high frequency (HSHF) low loss dielectrics play a vital role in the production of wireless communication systems, radar systems, and satellite communications. These materials possess unique properties like high thermal stability, low dielectric constant, and low dissipation factor that enable them to transmit signals at high frequencies with minimal loss, thereby maintaining signal integrity and reducing EMI. As the demand for faster, more advanced electronics grows, the continued development and use of high speed, high frequency low loss dielectrics will remain a key factor in manufacturing success.





Embedded Planar Capacitance Materials

High-speed PCBs with high layer counts will generally use plane layers to provide ground between signal layers, as well as one or more power plane layers. Power planes can be split into large rails providing multiple core voltage levels, or multiple planes could be used when the total current requirements are high. In either case, adjacent power and ground layers provide planar capacitance that is pivotal in supporting power integrity in high-speed digital PCBs.

This planar capacitance stores energy that will be supplied to digital integrated circuits whenever they switch logic states, and the stored energy is proportional to the laminate Dk value between the power and ground layers. Embedded planar capacitance materials provide lower inductance than discrete capacitors which is critical for power integrity applications.

To provide additional capacitance and maintain stable power delivery in smaller PCBs, embedded planar capacitance materials can be used between power and ground layers. These materials are very thin with a high Dk value, so they can provide very high capacitance. Standard processing steps can be used to integrate these materials into a PCB stackup and they do not appreciably change the end cost of the product.

DuPont Interra® embedded planar capacitor laminate is used to make thinner, more efficient power and ground planes within a multilayer printed wiring board. Interra® HK04J provides very low impedance at high frequency, power bus decoupling, and electromagnetic interference reduction. It replaces surface mount by-pass capacitors and their plated-through-holes, which improves the reliability, design flexibility, packaging size and cost of the PWB. Interra® HK04J is an all-polyimide dielectric laminate that offers the best mechanical properties, reliability and capacitance stability on the market

Other Materials and Components Metallization

Both flexible and rigid circuit board manufacturing relies on metallization processes, with electro/electroless plating being a popular method for depositing a uniform layer of metal onto a flexible substrate through electrochemical or chemical reactions. This technique is well-suited for high-density flexible circuits that require precise conductive features and can be easily adapted for high-volume production. Manufacturers can use electro/electroless plating to produce high-quality, high-performance circuits that meet the exacting standards of modern electronic devices.

Dryfilm Photoresist

Dry film photoresist is a popular method for producing high frequency circuit boards due to its excellent resolution, uniformity, and adhesion properties. The process involves coating the substrate with a layer of dry film photoresist, exposing it to ultraviolet light through a photomask, and developing the image by removing the unexposed areas of the film.
This results in a precise circuit pattern that can be etched or plated to create the desired circuit features. The use of dry film photoresist is particularly well-suited for high frequency circuit boards, as it can provide the necessary resolution and accuracy to ensure the signal integrity of the circuits. Additionally, the dry film photoresist can be easily stripped and developed, which minimizes the risk of damage to the substrate and ensures high process yields. Overall, the use of dry film photoresist is an effective method for producing high quality, reliable high frequency circuit boards.

DuPont has developed the Riston® FX Series of photoresists to help fabricators address increasing challenges to produce fine lines at high yields, while cost effectively handling harsh selective metallization processes.

Table 2. Metal surface platings and important properties

Immersion Tin (ImSn)	• Moderate loss • RoHS compliant
Hot air solder leveling (HASL)	• Moderate loss • Lead-free RoHS compliant HASL also available
Electroless nickel immersion gold (ENIG)	• High loss • RoHS compliant
Electroless nickel/electroless palladium/ immersion gold (ENEPIG)	• High loss • RoHS compliant
Organic solderability preserve (OSP)	• Low loss (comparable to bare copper) • Short shelf life
Immersion silver (ImAg)	• Low loss (comparable to bare copper) • Tarnishes over time

Surface Plating

Exposed conductors on a PCB will have an applied surface plating that helps prevent corrosion, provides solderability, and resists physical damage. The application of surface plating is a regular part of the standard PCB manufacturing process. Surface plating options used in PCBs are outlined in **Table 2.**

For RF systems, nickel-free surface platings are preferable for two reasons. First, the roughness of these electroplated films can be much higher than the underlying copper, which increases the skin effect resistance. The other reason is that nickel is ferromagnetic, and it will create additional losses during propagation. Both factors make ENIG and ENEPIG undesirable in high-frequency PCBs operating well into the GHz range.

Solder Mask

This material is used in standard and advanced PCBs to protect the surface layers during the soldering process. This material serves an additional use in that it defines solder pads and holds molten solder in place during the assembly process. Standard liquid photo-imageable (LPI) solder mask materials are available for use in rigid and flexible PCBs, although it is customary for flex PCBs to omit the solder mask due to the presence of a coverlay in flexible PCB layer stackups.

In high-performance devices, the solder mask is often removed from loss-sensitive interconnects to minimize signal attenuation. For example, in many RF PCBs, the copper on the surface layers carrying high-frequency signals will be exposed, while other areas of the PCB will be covered in a solder mask. This is because typical solder mask materials have Df = 0.02 in the MHz range, which is unacceptably high for systems operating in the GHz range or higher. Appropriately applied surface plating protects exposed conductors from environmental degradation, which also ensures low loss (nickel-free plating).

Conclusion

High-performance product designs on flex or rigid substrates require an advanced material set that can ensure low loss, power stability, and signal integrity. A comprehensive design process starts by considering the available materials for circuit boards operating at high frequencies, starting from copper-clad laminates and PCB stackup construction. Many design failures can be traced back to improper stackup design, so it is important to consider any material options before beginning the physical layout.

DuPont's Silicon Valley Technology Center, in the heart of Silicon Valley, is a hub for research and support with state-of-the-art engineering labs and customer meeting spaces that foster collaboration. DuPont engineers can help you design a comprehensive high-speed or high-frequency system, from chip to board. With computer modeling and advanced testing capabilities, DuPont helps customers find the best solutions for their most challenging applications.

No matter what high-performance design challenge you face, DuPont's experts can address your specific needs and improve the performance of your electronic products.

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