New Low Dielectric Constant,
High Tg, Printed Circuitry Substrates

Randy Bissell, Jeff Conrad, Eric Holman, Paul Reichenbacher
Isola

Abstract
The electronics packaging industry is expending tremendous resources to develop materials which meet the requirements of the next generation electronic applications, e.g., wireless communications infrastructure, satellite communications, and powerful, desktop work-stations. One of the key areas where our industry has been unsuccessful to date is producing materials which meet both electrical performance and cost criteria. Recent advances in polymer technology, coupled with laminate process technology now are yielding materials which address both issues.

AlliedSignal developed a new family of fiberglass reinforced substrates (FR408) using a specially formulated epoxy resin to achieve a robust combination of performance and processing characteristics. These substrates are low dielectric constant (Dk or ε_r), low loss (Df or tan δ) laminates with high glass transition temperatures (Tg) which allow standard FR4 printed circuit fabrication processes. Their electrical properties are relatively insensitive to frequency, making these materials suitable for demanding communications, computing, and instrument applications.

This paper will discuss these new technologies presenting results of PCB fabrication techniques for these materials as well as the benefits to the end users. Other products which address these needs have proven to be more difficult to process than standard FR4 materials. Comparisons of fabrication techniques of this product to FR4 processes will be discussed. End user requirements such as dielectric performance in the giga-hertz frequency range (GHz) will be compared to industry standard products.

Why New Substrates?
Traditional FR4 laminates and prepregs economically meet many printed circuit board (PCB) needs, but new equipment implementations demand substrates with better dielectric and thermal reliability properties.

High end, desk-top computers (work stations), test equipment, and other instruments often operate at frequencies where standard FR4 PCBs limit operating performance. Pentium-II™, K-6, and faster processors, may not achieve full potential with most FR4 PCB materials and designs. PCBs with lower relative permittivities (ε_r), i.e., lower dielectric constants (Dk), are needed to permit faster signal speeds in these and future work stations, test instruments, oscilloscopes, and similar devices. Increasing processor speeds and increased functionality in these devices result in higher processor operating temperatures. PCBs with improved heat tolerance are needed.

PCBs with lower inherent loss, i.e., with lower dissipation factors (Df or tan δ), run cooler, since less power is dissipated into the dielectric substrate.

Telecom and communications switches, network servers (LANs & WANs), satellite communications, modems, and similar applications also may be limited by Dk. While processing speed is important, many of these applications must handle faint signals without loss of fidelity. In these situations, low Df PCBs may be crucial to ensure operation.

Present Options

Designers facing these challenges often specify PCBs made from materials with Dk and Df values[1, 2] significantly lower than FR4 laminates. Substrates made with resins such as cyanate ester, BT-epoxy, or thermoplastics blended with epoxy resin are used. See Table 1. Unfortunately, the costs of these materials and their PCB fabrication are significantly higher than FR4.

Table 1. Multilayer-PCB Laminates[a]

Resin	Tg, °C	Dk[b]	Df[b]	FR4 Fab.
FR4 Di-Epoxy	130	4.2	0.022	yes
FR4 Hi-Perf Epoxy	170	4.2	0.018	yes
BT-Epoxy	180	4.0	0.012	no
Epoxy-PPO Blend	180	3.8	0.010	mod.
Cyanate Ester	240	3.6	0.007	no

[a]Woven E-glass cloth reinforcement; 45 wt% resin.
[b]Dk & Df at 1.5-2.0GHz.

Requirements for a New Substrate

Based on these assessments and working with several original equipment makers (OEMs) and fabricators, it became clear new substrates are needed. Table 2 identifies key criteria and why each is important.

There are some laminate and prepreg systems available meeting the first four criteria, but each requires modified FR4 PCB fabrication processes. Longer multilayer lamination cycles with higher temperatures than used for most FR4 materials are needed. This translates to lower PCB fabrication productivity and higher costs.

Table 2. Criteria for New Substrates

Criteria	Benefit
Dk < 4.0	Signal Speed
Df $\leq$ 0.01	Signal Integrity
Tg $\geq$ 180°C	Reliability
Low H_2O Abs	Reliability
FR4 Fabrication	Productivity
Costs $\approx$ FR4	Economics

The New System – FR408

Technologists at AlliedSignal worked closely with suppliers and customers to develop materials for laminates and prepregs which meet the key criteria listed above. A new line of laminates and prepregs resulted, now called FR408.

FR408 laminates and prepregs are reinforced with normal E-glass fabrics and clad with standard copper foils. The FR408 resin makes all the difference. It is a homogeneous, flame retardant, thermoset epoxy system which does not use dicyandiamide (dicy) as a cross-linking agent. Dicy is replaced with a less polar cross-linking molecule which provides better thermal, dielectric, and moisture absorption properties than even high performance FR4s.

Industry Approvals – UL

FR408 laminates and prepregs are recognized by Underwriters Laboratories as ANSI FR4 materials suitable for PCB applications.

FR408 also is qualified to UL's Metal Clad Industrial Laminate program (MCIL). Because of FR408 thermal stability, 4-layer MCIL boards passed UL's higher temperature 10-day MCIL protocol, negating the need for lower temperature 56-day thermal aging. PCB fabricators now are adding FR408 to their UL files.

UL recognition of these laminates and PCBs is important, because it facilitates their quick acceptance and implementation as recognized FR4 components.

Thermal Performance

Table 3 compares key thermal, expansion, and moisture resistance properties of FR408 and high performance FR4 laminates. In each case, the new product demonstrates measurably better performance. These

Table 3. Thermal Performance

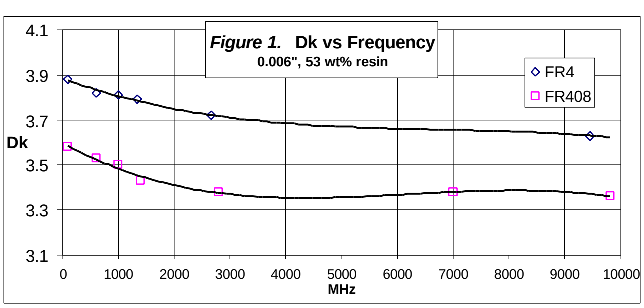
Property[a]	FR4	FR408
Tg (DSC)	170^{o}C	180^{o}C
Tg (DMA)	172^{o}C	195^{o}C
Z-CTE, RT-Tg	70 ppm/^{o}C	65 ppm/^{o}C
Z-CTE, Tg-288^{o}C	240 ppm/^{o}C	200 ppm/^{o}C
Expansion, RT-288	3.7%	3.2%
Solder, 288^{o}C	>60 sec	> 300 sec
H_2O Abs, D-24/23	0.20%	0.15%

[a]0.028" laminates; 40 wt% resin.

data predict increased PCB reliability, especially for thick, high layer-count boards.

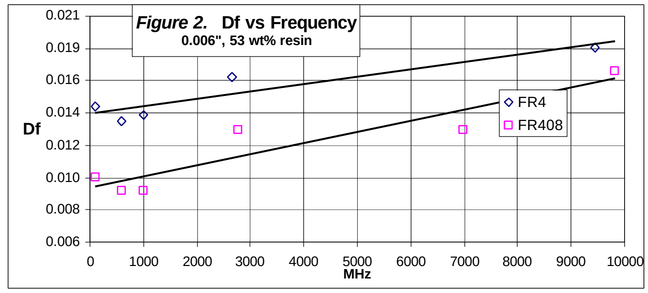
Dielectric Performance

Figures 1 and 2 compare the dielectric properties of laminates with 53 wt% resin contents at various frequencies, 50MHz to 10GHz.[1, 2]



Three observations are evident:

1. FR408 Dk and Df are superior to typical FR4 performance.

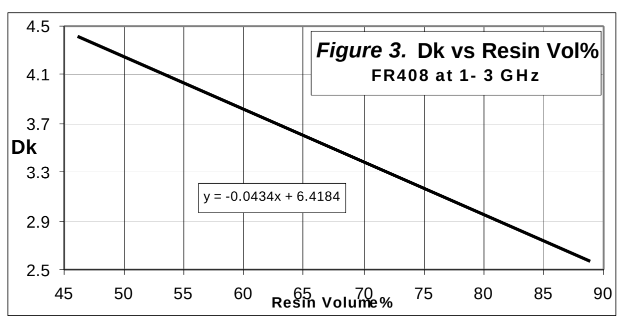


2. The Dk of both laminates are "flat" from 1 to 10 GHz, with FR408 being 0.3 Dk units lower (better) than FR4.

3. Df for both laminates increases with frequency. Df for FR408 is 0.003 Df unit lower (better) than FR4.

Resin content affects dielectric properties, since E-glass cloth has a higher Dk and lower Df than epoxy resin.[3] Laminates with low resin contents have higher Dk and lower Df values than those in Figures 1 and 2. The Dk of FR408 laminates is linearly related to resin volume %; see Figure 3.

Table 4 identifies six FR408 laminates



and shows their resin contents, the

fiberglass cloth styles used, and the resulting Dk of each. PCB designers need to understand the implications of selecting laminate constructions.

Table 4. Dk vs Resin%

FR408 Laminates		Resin %		
Thickness	**Constr.**	**wt%**	**vol%**	**Dk**
0.002"	106	67	80	3.0
0.007"	2113+2116	47	64	3.6
0.008"	2x2116	43	60	3.8
0.010"	2x1652	42	59	3.8
0.015"	2x7628	40	57	3.9
0.020"	3x7628	37	54	4.1

Laminates can be made in several ways. By selecting different glass cloths and resin contents one can make laminates with the same thicknesses, but with different dielectric (and other) properties. Thus, selecting a low resin content construction to minimize Df and maximize dimensional stability will increase Dk.

Significance of Dk & Df

Dk and Df are laminate characteristics which impact signal speed and integrity in electronic circuits.

Signal propagation speed is inversely proportional to the square root of Dk, so PCBs with lower Dk values cause less signal delay. Compared to FR4 PCBs, the Dk values of Tables 1 and 4 predict small but significant signal speed improvements for BT-epoxy (2.5%), epoxy-PPO (5.1%), FR408 (5.1%), and cyanate ester PCBs (8.0%). These advantages coupled with placing critical components closer to each other, i.e., denser PCB designs, allow many circuits to be driven at faster speeds.

Circuit performance may be degraded by slow signal propagation between chips and by distortion of signal pulses. Major distortion sources are unintentional resistances, inductances, and capacitances in the circuits between chips. These factors distort signals and slow their rise times.

Df is directly proportional to signal loss and distortion. PCB substrates with low Df absorb a smaller percentage of high speed electromagnetic waves than those with higher Df values. This is particularly important as signals are processed at higher frequencies. Figure 4 shows signal loss, expressed in dB/cm, is more affected by Df at high frequencies.

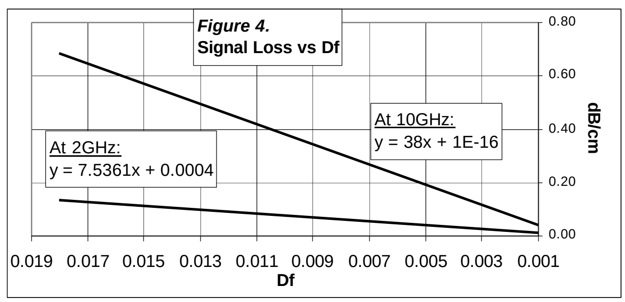


Figure 4.
Signal Loss vs Df

One also may calculate the percentage improvement in signal loss as a function of Df. This "improvement metric" is independent of frequency. Figure 5

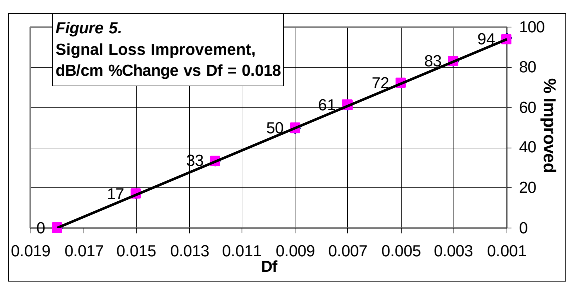
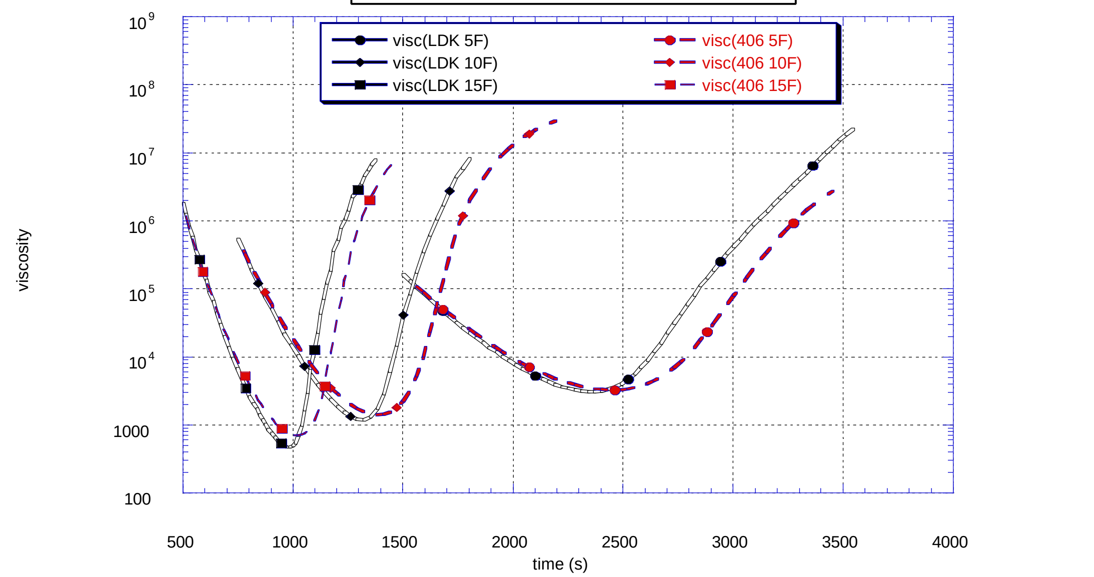


Figure 5.
Signal Loss Improvement, dB/cm %Change vs Df = 0.018

predicts switching from FR4 laminate materials with 0.018 Df to FR408 (Df 0.010) reduces signal loss by 45%.

Thick, high layer-count PCBs are difficult to manufacture with good yields and may be unreliable during thermal cycling. Laminates with lower Dk allow designers to call out thinner cores, while holding impedance (Z_o) constant.

***Figure 6.* Prepreg Rheology**
LDK = FR408; 406 = FR4



Thus, one may redesign an FR4 PCB with 50Ω impedance, 4.2 Dk, and 4 mil thick cores to 3.5 mil cores by selecting laminates with 3.8 Dk. Impedance will remain unchanged. Overall PCB thickness is reduced by more than 10%. Reducing board thickness, along with choosing materials with greater thermal stability and lower inherent expansion can dramatically improve PCB yields and thermal reliability.

Fabrication Experience

To date, FR408 laminates and prepregs have been evaluated for various applications, from 0.028" double-sided PCBs to 0.093" thick, 16-layer boards. These were made using normal FR4 processing. Standard compensation factors; normal image, etch, and strip materials and methods; standard drilling settings; and normal hole plating chemistries were employed.

FR408 prepregs have resin melt viscosity profiles like those of traditional FR4 prepregs. See Figure 6. Because of this, no change in multilayer PCB lamination cycle is needed when switching from most FR4 materials to FR408, unlike some other materials designed to provide low Dk and low Df.

In these evaluations, FR408 boards and traditional FR4 boards were laminated in the same press load. No post-lamination bakes were required to achieve full multilayer PCB cure. The press cycle recommended for most FR408 multilayer PCBs includes:

- Preheat press to 350-360°F.
- Adjust heat rise to 8-12 °F/minute.
- Hold at 350-360 °F for 50 minutes.
- Cool; no post-bake required.

Hole Drilling & Tool Wear

In one experiment, 8-layer, 0.048" FR408 and FR4 PCBs of identical design were drilled in one and two high stacks. Hole diameters of 9.8, 13.5, and 18.0 mils were drilled with standard feeds and speeds. See Table 5 below. After 2,000 hits, hole quality remained good, and tool wear was identical from the FR408 and FR4 PCBs.

Table 5. Drilling Evaluation
8-layer 0.048" MLBs, FR4 & FR408

Drill Dia., mils	9.8	13.5	18.0
Stack-Up	1 & 2	1 & 2	1 & 2
Speed, rpm	105	100	85
Feed, inch/min	70	100	152
Chip Load, mil/rev	0.7	1.0	1.8

In other trials, thicker FR408 boards were drilled at various machine settings. The PCB fabricator concluded “we can’t drill a bad hole in FR408.”

Table 6.
Analyses of 16-Layer, 0.093" PCBs

	units	FR4	FR408
Tg (DSC)	^{o}C	168	184
Z-CTE, RT-Tg	ppm/^{o}C	78	78
Z-CTE, Tg-288^{o}C	ppm/^{o}C	302	277
Z-CTE, RT-288^{o}C	ppm/^{o}C	177	157
3xSolder, 288^{o}/20sec		pass	pass
H_2O, as received	%	0.14	0.09

PCB Properties
Several 16-layer, 0.093” thick FR408 and FR4 PCBs, made to identical designs, were sent to AlliedSignal for characterization. As predicted, in each case FR408 boards out-performed the 170^{o}C Tg FR4 PCBs; see Table 6.

Conclusion
FR408 laminates and prepregs are new tools for PCB designers, fabricators, assemblers, and end users. PCBs can be fabricated and assembled with normal FR4 processes, while providing interconnect systems with improved thermal, dielectric, and moisture resistance performance.

Until now, reaching these performance levels meant using materials which process differently than FR4, limiting PCB supply to a few shops. FR408, with its *homogeneous*, thermoset polymer system, and FR4 processing characteristics now opens the door to fabricators and assemblers whose processes are well-tuned to traditional FR4 materials. FR408 PCB laminates and prepregs provide a new performance/cost benchmark for PCB materials:

- Low Dk over a wide frequency band
- Low Df over the same band
- Outstanding thermal reliability
- Low expansion characteristics
- Very low moisture uptake
- Normal FR4 fabrication & assembly

FR408 is a commercially available product combining the thermal and dielectric advantages of high performance substrates with the processing ease and costs of FR4.

References

[1]Dk and Df values were obtained using a Hewlett-Packard impedance analyzer, model 4291A, or from analyses of strip-line resonator circuits.

[2]Ivan Araktingi, Randy Hoard, and Markus Jansons, "Development of a New Test Method to Measure Laminate Dielectric Properties into the GigaHertz Region," IPC Expo, March 1997, San Jose, CA.

[3]Joel Murray, Clark-Schwebel Corp., data from OCF, PPG, and NEG Corp, E-glass dielectric properties at 1MHz and 1GHz, respectively: Dk = 6.5 and 6.1 & Df = 0.002 and 0.004.