High Resolution Dry Film Photo-imageable Dielectric Enabling Dual-side Panel Level Fine Line RDL

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Presented by Dr. Christine B. Hatter

March 5, 2025

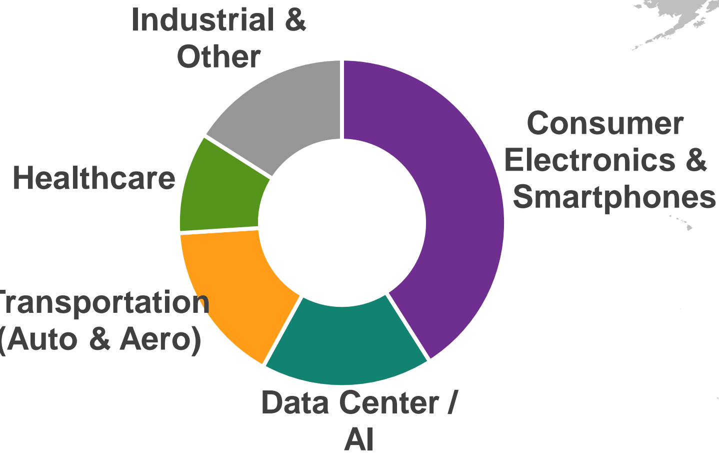
Advanced Circuits & Packaging

Interconnect Solutions

Electronics & Industrial

Electronics & Industrial: At a Glance

End-Market Exposure*



*Net sales and operating EBITDA as reported for FY23. All other metrics as of year-end 2023.

22%
12%
64%
2%

2023 net sales by geography*

$5.4B*
2023 Net Sales

~12,000
Colleagues

~60
Manufacturing Sites

15
Major R&D and Application Centers

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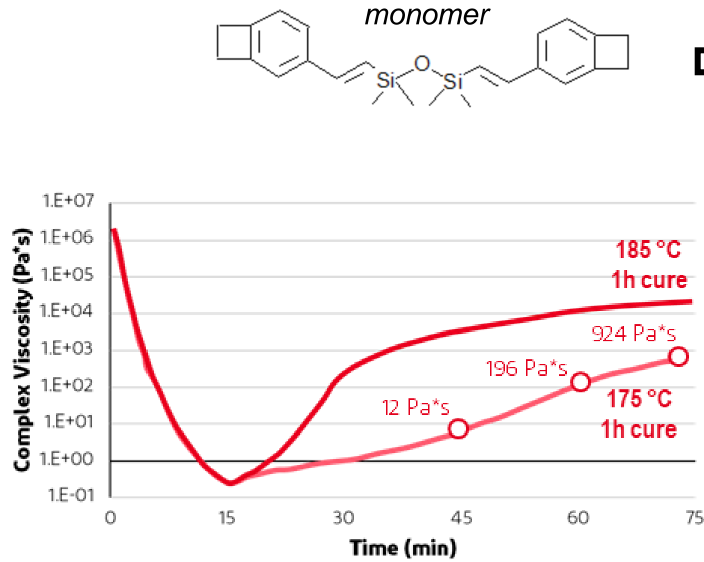
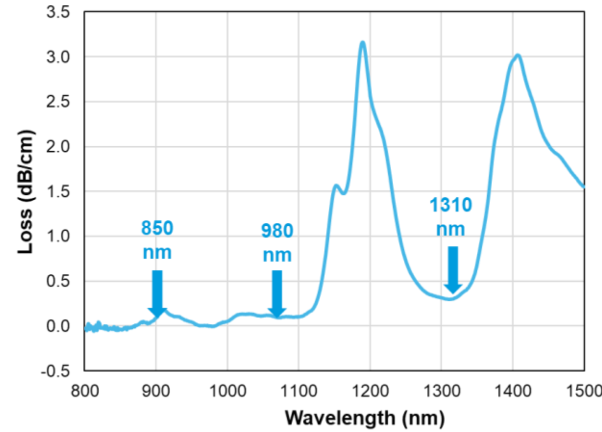
BCB Possess Unique Material Properties

monomer ⇨ polymer

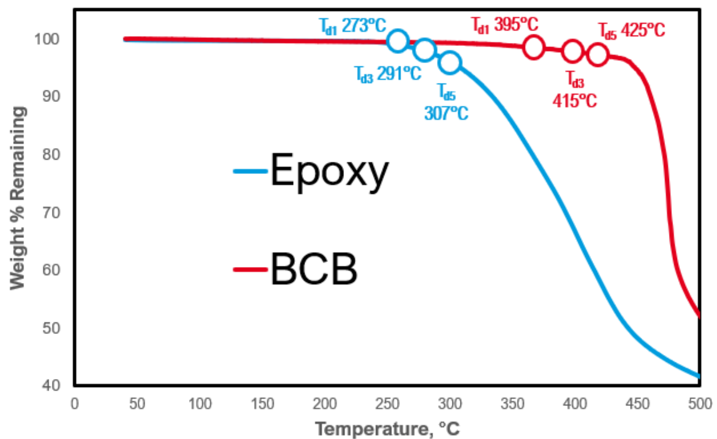
- Excellent Rheological Properties (comparable to Epoxy)
- Very controllable cure extent





- Exceptional optical characteristics
- Low absorbance at key wavelengths, isotropy, stability

- Excellent Thermal Stability Compared to Many Materials
- (comparable to PI)



CYCLOTENE™ Dielectric Product	>39 GHz	
	D_k	D_f
3000 series (non-photo)	2.5	0.001
4000 series (Photo)	2.6	0.002
XP80 Series (Higher Resolution)	2.6	0.003
Epoxy Comparison	>3.0	>0.020

- Exceptional electrical characteristics
- Good stability at high frequency

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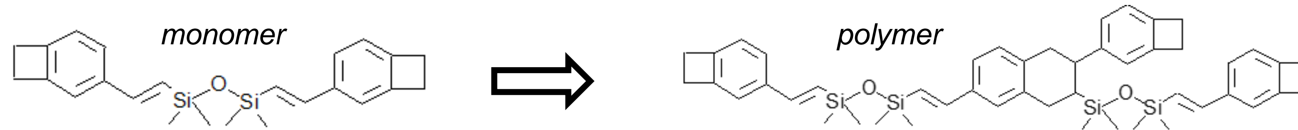
DuPont CYCLOTENE™ BCB Dielectric Materials

Low loss polymers originally developed as wafer-level packaging dielectrics with ultra-low D_k/D_f.



BCB Base Resin

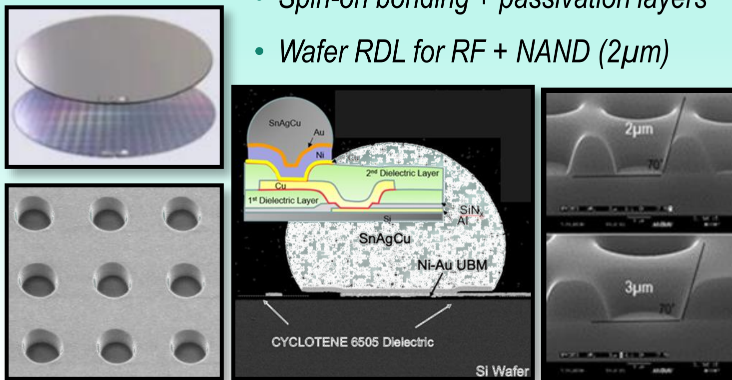
CYCLOTENE™ 3022
+ High thermal stability, low CTE

CYCLOTENE™ 4000 PID
+ Lowest D_f (<0.002)
+ High thermal stability, low CTE

CYCLOTENE™ 3300
+ Lowest D_f (<0.003)
+ High thermal stability, low CTE
+ Self-Priming liquid

Liquid Dielectrics + Adhesives

- *Spin-on bonding + passivation layers*
- *Wafer RDL for RF + NAND (2μm)*



TMAH-Developed BCB for RDL

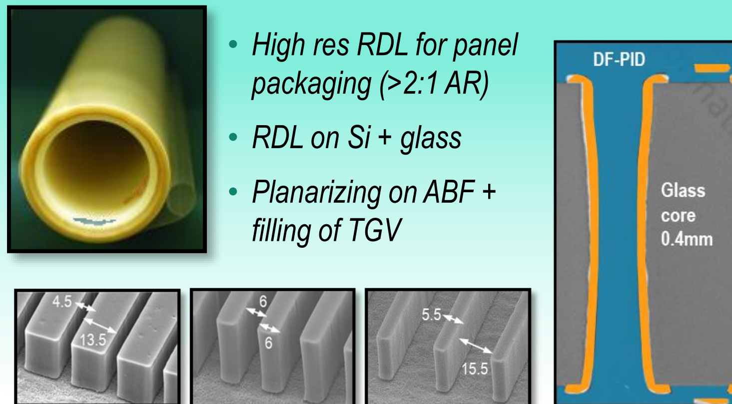
CYCLOTENE™ 6505 PID
+ Positive Tone liquid
+ High Resolution

CYCLOTENE™ DF-6000 PID
+ Negative Tone dryfilm laminate
+ Good Planarization

CYCLOTENE™ DF-6800 PID
+ Negative Tone dryfilm laminate
+ High Resolution

Dryfilm Dielectrics + Encapsulants

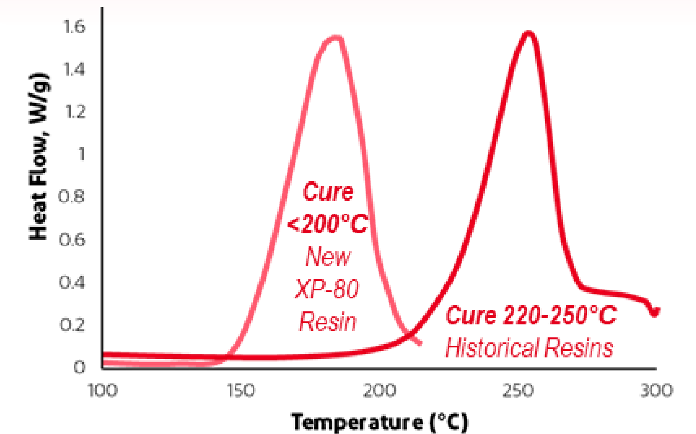
- *High res RDL for panel packaging (>2:1 AR)*
- *RDL on Si + glass*
- *Planarizing on ABF + filling of TGV*



Low Temp Cure BCB for RF

Developmental XP-80
+ Self-priming
+ Ultra-low high frequency D_f (<0.003 @ 50GHz)
+ High Resolution (5μm, 1:1 AR)

Developmental XP-81
+ Self-priming
+ Calibrated for automotive reliability standards
+ Low D_f (0.003)



Next-gen BCB offers reduced cure temp without sacrifices to dielectric properties seen in PI + epoxy

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Dry-film CYCLOTENE™ Enabling Advanced Substrate + RDL

(1) Hybrid Substrate

Fine Vias Formation

IC Chip
DF-PID
Build-up Substrate

Conventional BUF

>40um
>40um

DF-PID

<20um
<20um

Mask: 5μm Via, 1:2
10μm
4.9μm

- ✓ High via resolution
- ✓ Filler-free, ultra-low roughness (<10nm)

(2) Glass Core Substrate (a) / FOPLP (b)

TGV filling & RDL build-up

a Glass Core Substrate

Top view
X-SEM
DF-PID
300μm

- ✓ Good TGV filling capability
- ✓ Excellent planarization

b FOPLP

DF-PID

- ✓ Dry-film material creates better planarization & uniformity than liquid spin-on for multi-layer build
- ✓ Film lamination makes panel app. easier

(3) Embedded Die Substrate

Embedded Die Cavity & High Aspect Ratio Trench Filling

DF PID
Organic core
Chip
Organic core

Planarization

Dryfilm PID
15 μm
22 μm
85 μm
Wide Trenches

15 μm
Dryfilm PID
10 μm
6.5 μm
10μm
Bilayer
10μm
6.50μm
Fine Features

20 μm
Dryfilm PID
400 μm
50 μm
Deep Narrow Gaps

- ✓ Good cavity filling capability
- ✓ Excellent planarization

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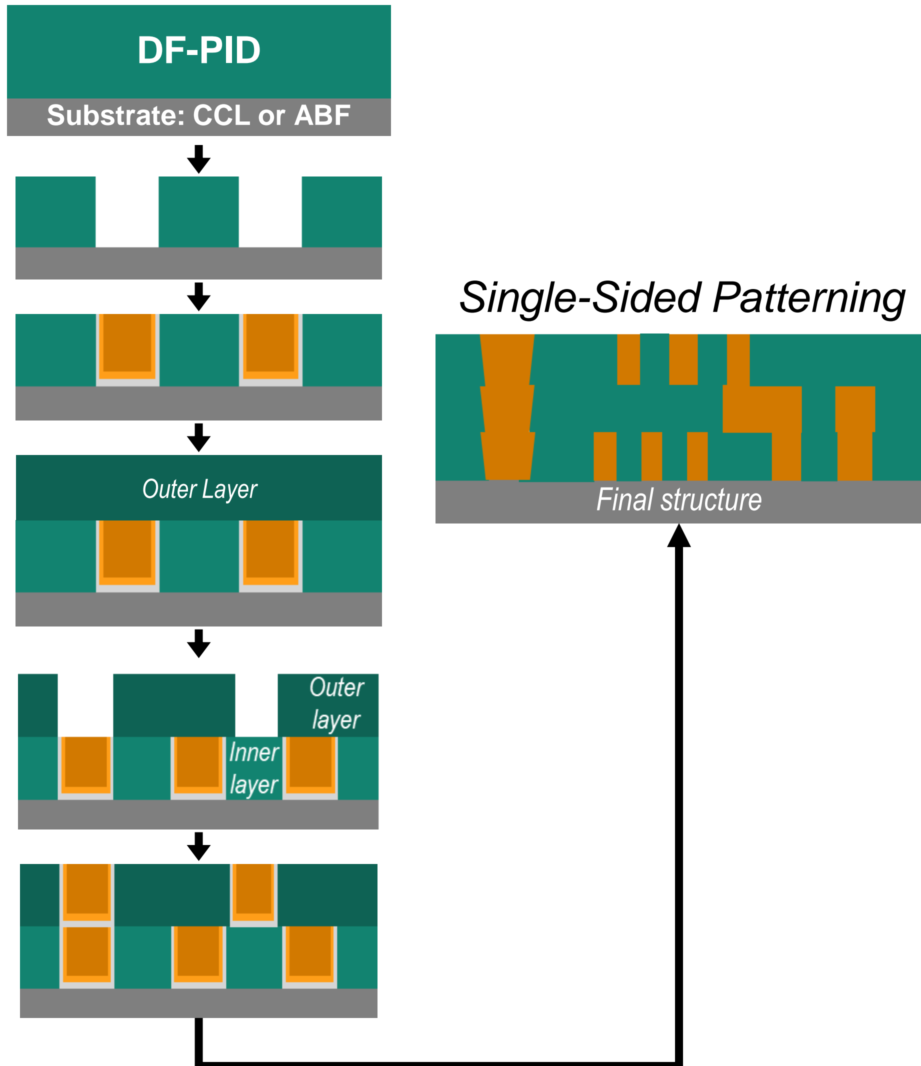

DuPont CYCLOTENE™ DF-6800 PID Single-Sided PET-off Patterning

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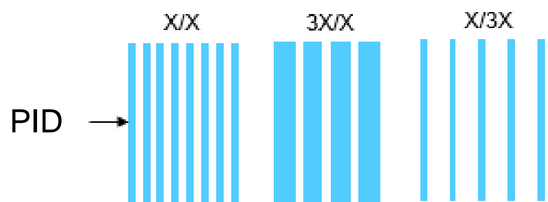
DF6800 PID Delivers High Resolution PET-off Patterning

- DF6800 PID delivers single-side build capabilities
- Good resolution at 20µm film thickness
  - >2.5:1 (line)
  - 1.7:1 (via)
  - Good sidewall profile

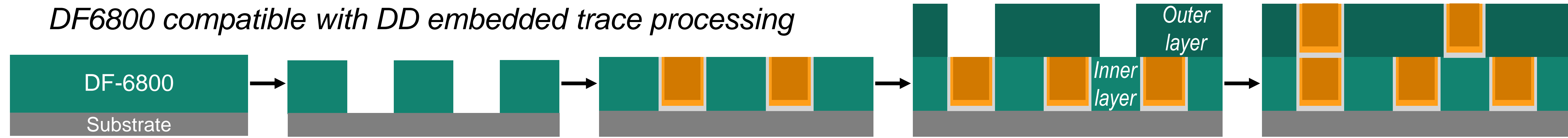


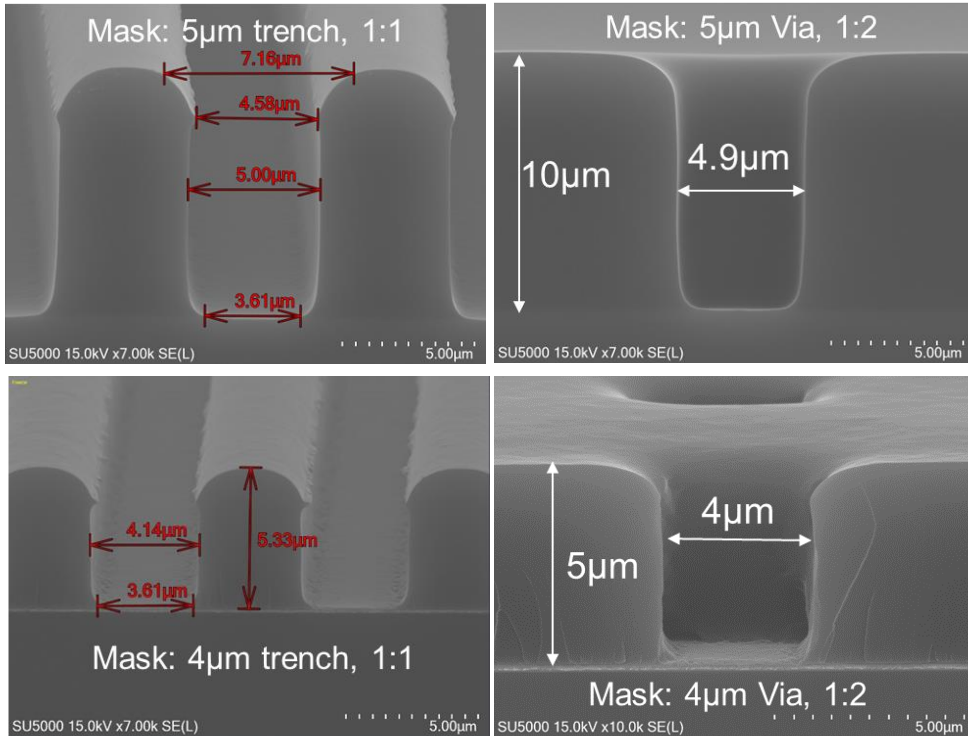
- Film thickness achieved
  - **5, 10, 15, 20, 25, 30 and 40µm**

PID		DF6820
PET on/off		**PET off**
Substrate		**CZ8401**
Exposure		Low NA stepper, PED 2.5-3hr
Developing		TMAH develop, BP 35
Design value	L/S=3x/x	7 µm
	L/S=x/3x	9 µm
	L/S=x/x	8 µm
	Via=x/x	11 µm
SEM	L/S 45° SEM	
	Line top CD	Design: 10µm, measure: 9.12µm
	Taper ratio	**0.73**
	Via X-SEM	
	Via top CD	Design: 11µm, measure:12.24µm
	Taper ratio	**0.75**

DF6800 Performance Suitable for Advanced Substrate

DF6800 compatible with DD embedded trace processing



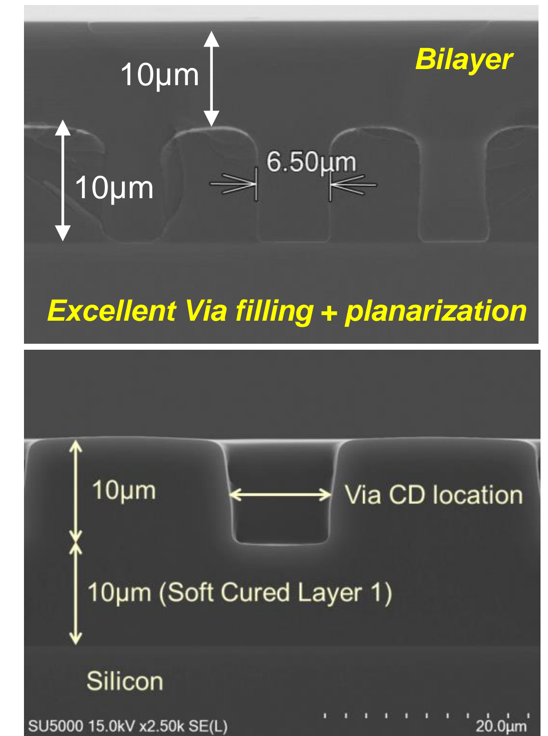


1st layer achieves 2:1 AR for 10µm film
- 4µm trench and via for 5µm film

2nd layer achieves 7µm trench for 10µm via

Layer	Inner layer	Outer layer
Curing condition	Soft cure: 200°C,1hr, N_2	Hard cure: 220°C,1hr, N_2
Self-adhesion	Yes	Yes to inner layer
Peel strength to PVD Ti/Cu	**>0.4 kgf/cm**	**>0.4 kgf/cm**
Chemical resistance	Pass	Pass

Curing profile, plasma/PVD condition tuned for best inner + outer layer performance



Excellent via filling as top layer and retention of high AR & straight side profile

- ✓ Compatibility with plating and CZ chemistry
- ✓ Reliability tests to date shows positive results

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DuPont CYCLOTENE™ DF-6800 PID Dual-Sided PET-on Patterning

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DF6820 Resolution with PET-on Patterning

PET condition	PET-off	PET-on	PET-on
PED Condition	No delay	No delay	4 hours delay
Via: 10 µm			
Via: 15 µm			
Via: 20 µm			

**DF6800 20um film*
**SÜSS Aligner 180 mJ/cm^2*

PID		DF6820	
Substrate		CZ8100	
PET on/off		PET on	PET off
Exposure		170 mJ/cm^2 on stepper	170 mJ//cm^2 on stepper
PED		3.5hr	3.5hr
Developing		TMAH	TMAH
CD	**L/S=3x/x**	>12 µm	7 µm
	L/S=x/3x	>15 µm	7 µm
	L/S=x/x	>10 µm	8 µm
	Via=x/x	>30 µm	11 µm
SEM L/S 21/7µm	**Front view**	N/A	
	Side view	N/A	

- ➢ Decreased resolution observed with DF6800 PET-on patterning
- ➢ Increasing PED also shows negative effect on PET-on processing

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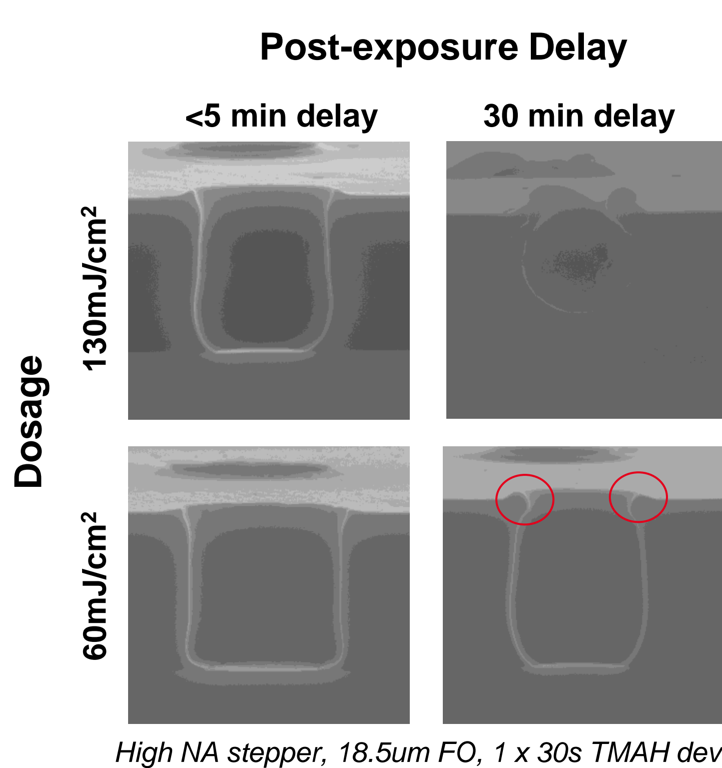
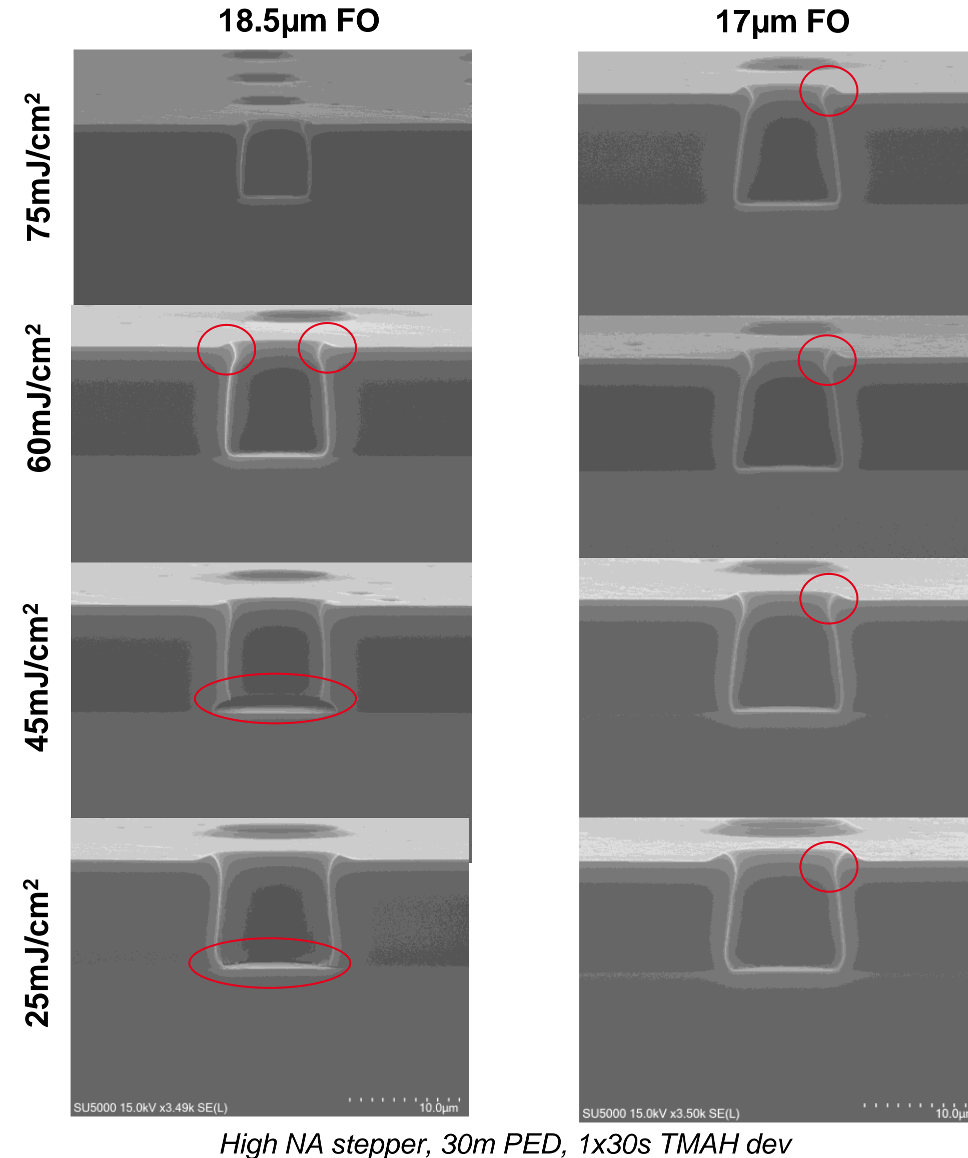
DF6810 Resolution with PET-on Patterning



High NA stepper, 18.5um FO, 1 x 30s TMAH dev



High NA stepper, 30m PED, 1x30s TMAH dev

- Dosage and focus adjustments fail to improve 10µm via PET-on patterning

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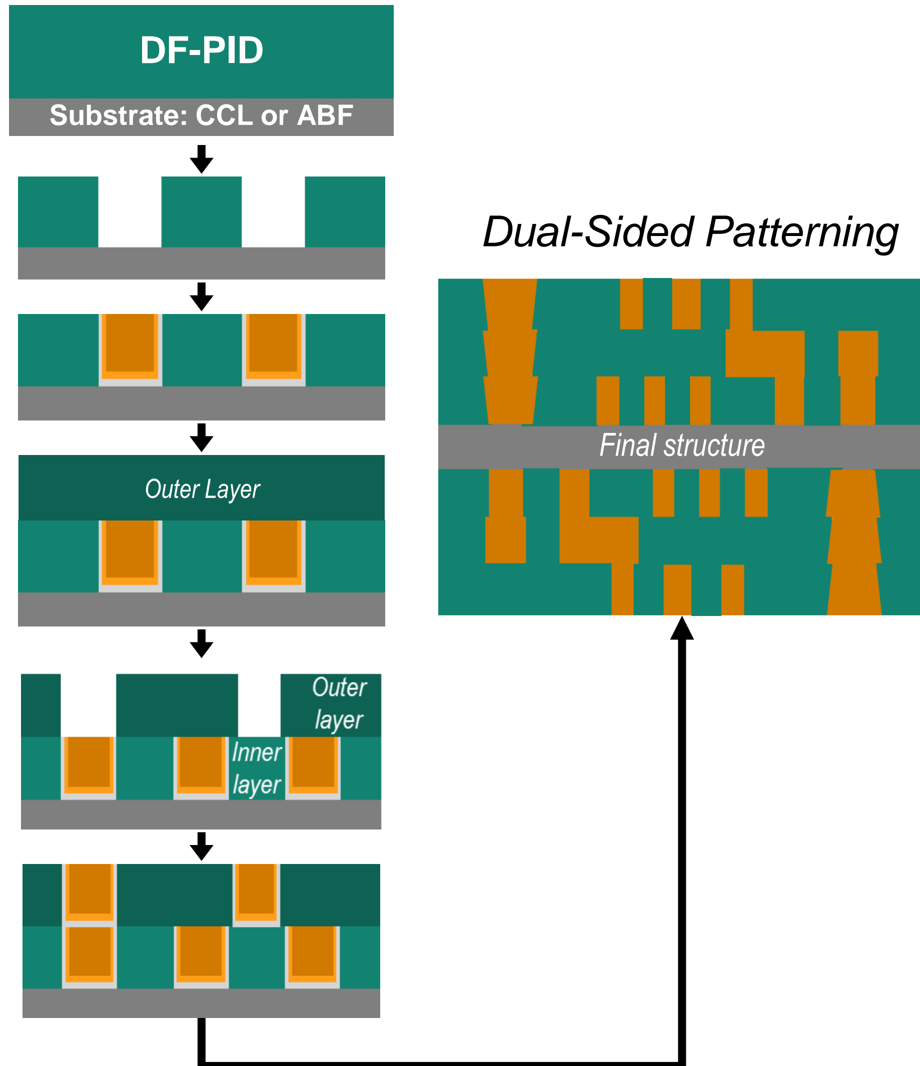

DuPont CYCLOTENE™ DF-6800M PID Development and PET-on Patterning

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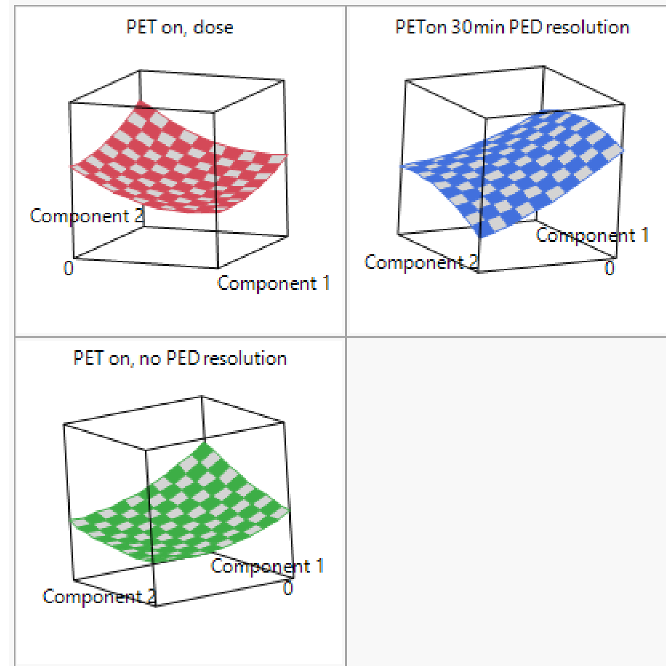
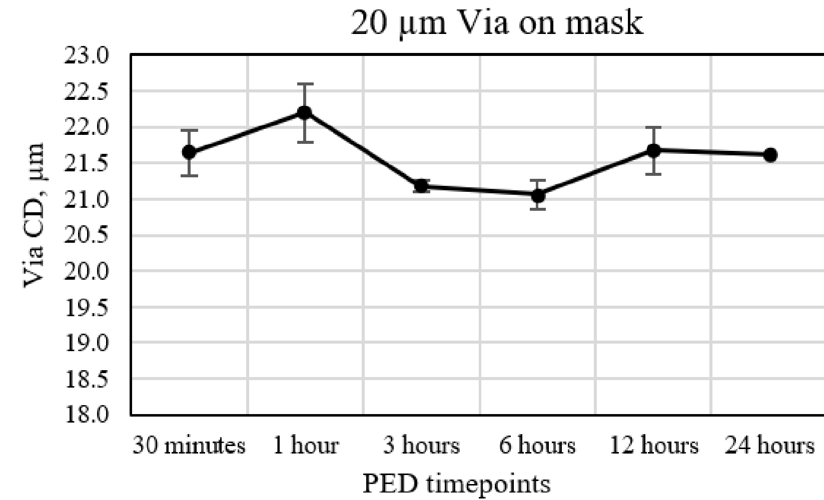
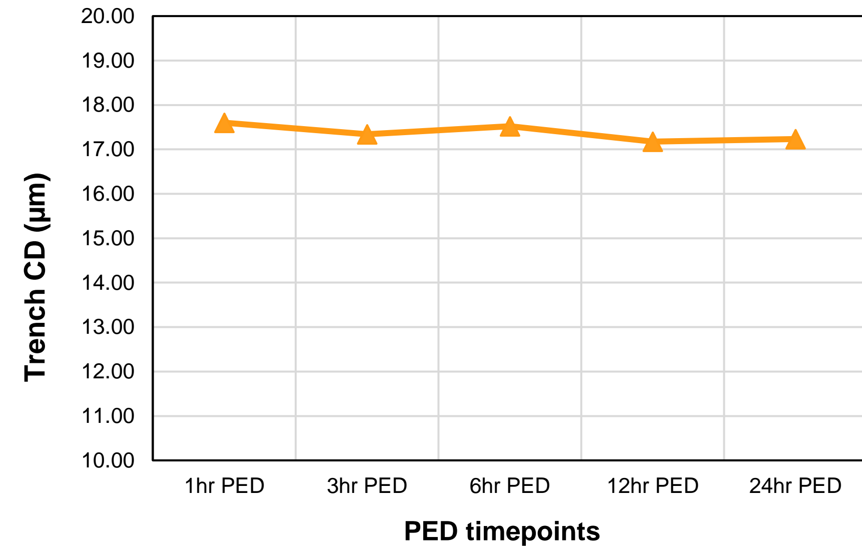
PET-on Patterning of DF6800M

Formulation	Components
Material	*Low D_k Polymer*
	Cross-linker
	Photo-initiator
	Stabilizer
	Leveling Agent
Solvent	*Solvent A*
	Solvent B







- Updated photo-package improves spatial uniformity of crosslinking density
- Optimization Complete using multivariate experiment design
- DF6800M shows stable CDs of via up to 24h PED

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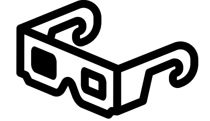
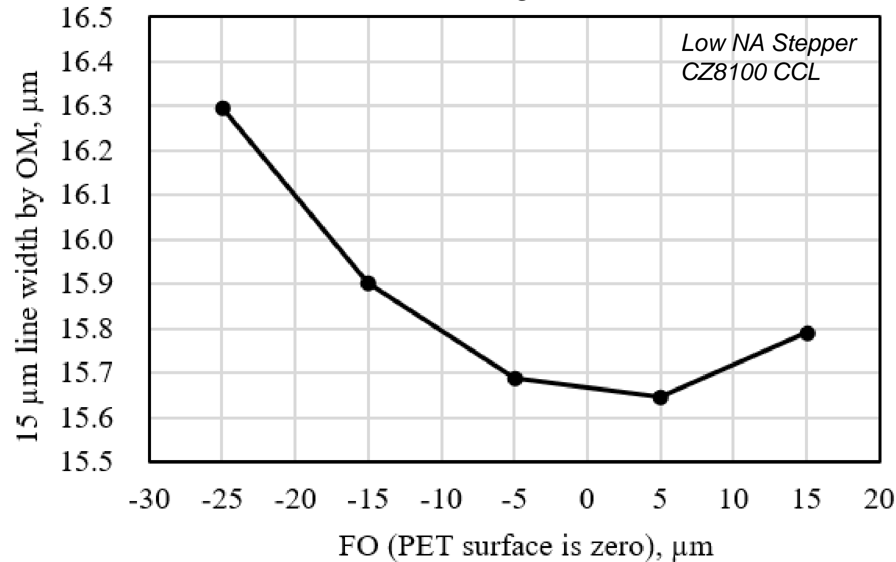
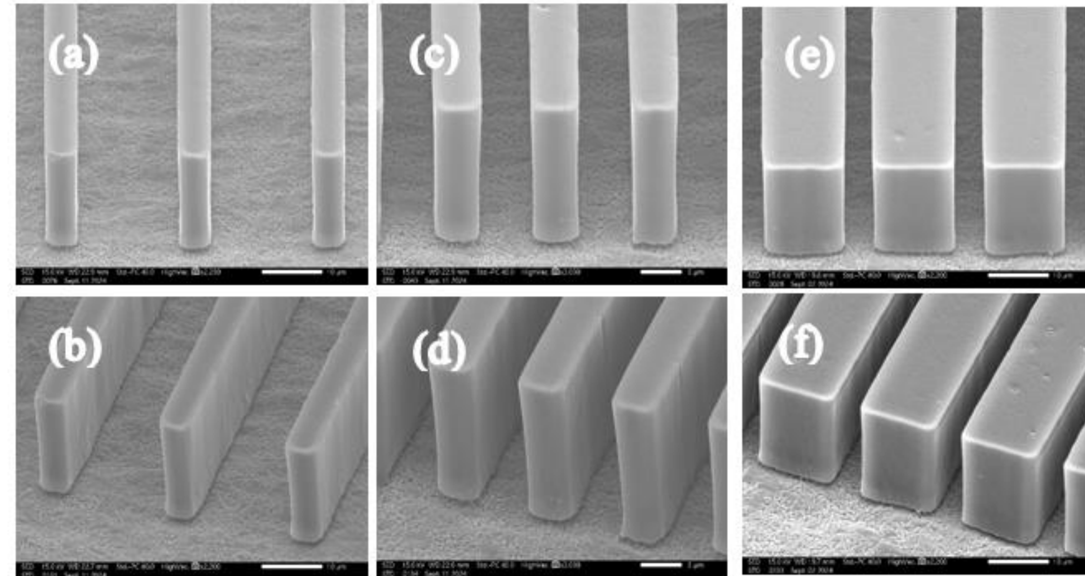
PET-on Patterning of DF6800M

Type	Composition		
	Polymer	Crosslinker	Photo-package
DF6000	AD-BCB	M1	P1
DF6800	AD-BCB	M1	P2
DF6800M	AD-BCB	M1	P3

Trench / Via Resolution		
	DF6800	DF6800M
Patterning	PET-off	PET-on
L/S = 1/3	21 µm trench	16.5 µm trench
L/S = 1/1	8 µm trench	6 µm trench
L/S = 3/1	7 µm trench	4.5 µm trench
Via = 1/1	11 µm via	8µm via







- ➢ Modified photo-package (P3) successfully mitigates time sensitive dark reactions (T-topping, re-entrant profiles)
- ➢ 5µm FO identified for best DF6800M PET-on patterning

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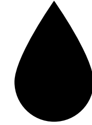
Development Optimization for DF6820M PET-on Patterning on CCL

	DF6820M				
Substrate	CCL Cu, Ra 0.33 µm				
SST = x/41	10.5				
FO (PID surface as 0)	5µm				
BP	25	35	**45**	55	65
L/S=3x/x	4.5	4	**4.5**	5	5.5
L/S=x/3x	7	6	**5.5**	6	5
L/S=x/x	7	7	**6**	6	6
Via=x/x	6	7	**9**	9	9
SEM Front view 3x/x	L/S=13.5/4.5	L/S=12/4	L/S=13.5/4.5	L/S=13.5/4.5	L/S=13.5/4.5
Top width (µm)	13.79	12	**13.36**	13.43	13.49
Bottom width (µm)	13.62	11.27	**12.40**	12.64	12.70
Taper ratio	1.01	1.06	**1.07**	1.06	1.06



- Development time has limited impact to DF6800M resolution
  - 3:1 L/S and via
- Increasing BP, 1:3 resolution improves (better line adhesion)
- BP35-45 generates optimal balance between via resolution and L/S adhesion.

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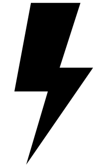
Dosage Optimization for DF6820M PET-on Patterning on CCL

	DF6820M				
Substrate	CCL Cu 18 µm, Ra 0.33 µm				
SST=x/41	x	x	**11**	x	15
Dose	127	159	**200**	251	315
FO (PID surface as 0)	5µm				
BP	45				
L/S=9/9 — Front view					
L/S=9/9 — Side view					
Top width (µm)	7.34	8.60	**8.93**	9.29	9.83
Bottom width (µm)	7.43	8.42	**8.66**	8.73	9.06
Taper ratio	0.99	1.02	**1.03**	1.06	1.08



- Dosage increase shows improvement in L/S
- SST 11/41 (200mJ/cm2) generates optimal balance between L/S and via resolutions

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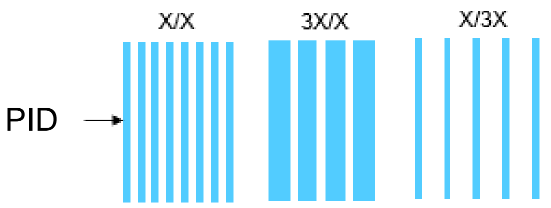
DF6800M Delivers High Resolution PET-on Patterning

- DF6800M extends from DF6800 generation and delivers
  - **PET-on** patterning capability
  - Improved L/S and Via **resolution**
  - At least 24hr **PED stability**
  - Good sidewall profile
  - Expected comparable dielectric and mechanical properties

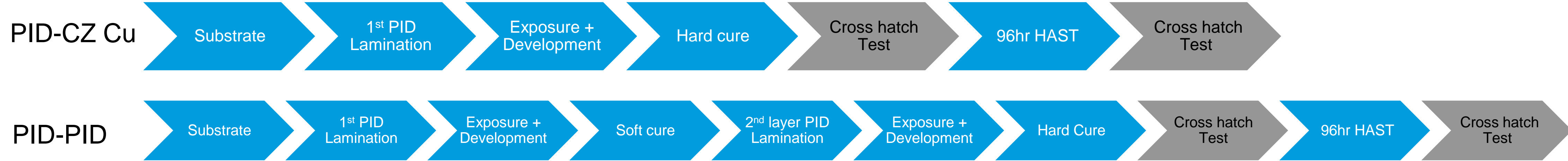


- Film thickness
  - **10, 15, 20, 25μm**
  - Possible to extend to 5μm and 40μm in future

PID		DF6820	DF6820M
PET on/off		**PET off**	**PET on**
Substrate		**CZ8401 Ra 0.17 μm**	
Exposure Ushio aligner (UX-44101)		PET-off, -5μm FO, PED 2.5-3hr, no PEB	PET-on, 5μm FO, PED 2.5-3hr, no PEB
Developing		TMAH spray development, BP 35	TMAH spray development, BP 45
Design value	L/S=3x/x	7 μm	4.5 μm
	L/S=x/3x	9 μm	5.5 μm
	L/S=x/x	8 μm	7 μm
	Via=x/x	11 μm	8 μm
SEM	L/S 45° SEM		
	Line top CD	Design: 10μm, measure: 9.12μm	Design: 7μm, measure: 6.77μm
	Taper ratio	**0.73**	**0.97**
	Via X-SEM		
	Via top CD	Design: 11μm, measure:12.24μm	Design: 8 μm, measure: 7.66μm
	Taper ratio	**0.75**	**0.95**

DF6800M shows comparable adhesion performance as DF6800

Process flow:



	PID-CZ Cu		PID-PID	
Film	**DF6800**	**DF6800M**	**DF6800**	**DF6800M**
Substrate	CZ8401 treated CCL	CZ8401 treated CCL	Soft cured self	Soft cured self
Before HAST	**5B**	**5B**	**5B**	**5B**
After 96hr HAST	**5B**	**5B**	**5B**	**5B**

- DF6800M passes adhesion test on CZ8401 pre- and post-HAST treatment
- DF6800M shows same PID-PID adhesion result as DF6800 following 1st layer soft cure, then both layers hard cure process.

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Cyclotene™ Dry Film Property Table

Property	DF6800	DF6800M	Instrument & Method
Film Thickness	40, 30, 25, 20, 15,10, 5µm	25, 20, 15, 10µm	TMI 49-86 Digital Micrometer
Lithography Performance			
Application Type	Single-Sided Patterning	Double-Sided Patterning	Integration Preference
Exposure Dose	~170 mJ/cm^2, PET-off	~200mJ/cm^2, PET-on (20µm)	Ushio stepper UX-44101 on CZ8100
Develop Time (for 20µm film)	BP35	BP45	TMAH spray Developer
Aspect Ratio	2.5:1 trench, 1.4:1 via	3:1 trench, 2:1 via	Hitachi 9380 SEM (top down) and Amray 4200
Mechanical Properties			
Tg	>250°C	>250°C	TA Instruments Q400 TMA: 10°C/min, Nitrogen, CTE measured at 25°C
CTE (ppm/°C)	67.5	61	
Modulus (GPa)	2.7	2.5	
Elongation	10% ave (16% max)	10% ave (15% max)	Instron 33R-4464 Tensile Tester: 2kN load cell, 5mm/min
Tensile strength at break (MPa)	92	87	
Moisture Uptake	0.84%	0.83%	TA Instruments Q5000SA Moisture Sorption Analyzer:23°C, 45% RH, 60min
Thermal Stability	359˚ C for 5% wt loss	330°C for 5% wt loss	TA Instruments Q5000 Thermogravimetric Analyzer: 10°C/min, nitrogen
Electrical Properties			
Dielectric Constant @ 10 GHz	2.87	3.05	Cylindrical Cavity Resonator
Dissipation Factor @ 10 GHz	0.019	0.018	

- ➢ DF6800M enables PET-on patternability through post exposure delay
    - ➢ DF6800 PET-off patternability for single-sided multi-layer builds

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Appendix

DF-6800 Dielectric + Adhesion Properties

Sample Preparation	
Sample Preparation	• DF-6800 15µm film was laminated via hot roll laminator on test substrate • The films were subsequently flood exposed and developed, then cured at 220˚C for 60min
Pressure Cooker Test (PCT)	Temperature = 121˚C; %RH=100% Pressure = 2 atm; Time = 48hr
HAST	Temperature = 130˚C; %RH=85% Time = 96hr

Adhesion: cross-hatch & tape test, by ASTM D3359 standard

Substrate	Before PCT	After PCT	Conclusion
CZ-treated CCL	5B	5B	**Pass**
ABF	5B	5B	**Pass**

bHAST test:

Dielectric	Pattern Space: Cu line/space (µm)	Resistivity with bias		Optical inspection after bHAST	Bias	Result
		Before HAST	After 96hrs HAST			
DF6020	30/100	>$10^{12}\Omega$	>$10^{12}\Omega$	No dendrites detected	5V	**PASS**
DF-6800, 15µm	30/100	>$10^{12}\Omega$	>$10^{12}\Omega$	No dendrites detected	5V	**PASS**
DF-6800, 15µm	13/9	>$10^{12}\Omega$	>$10^{12}\Omega$	No dendrites detected	5V	**PASS**

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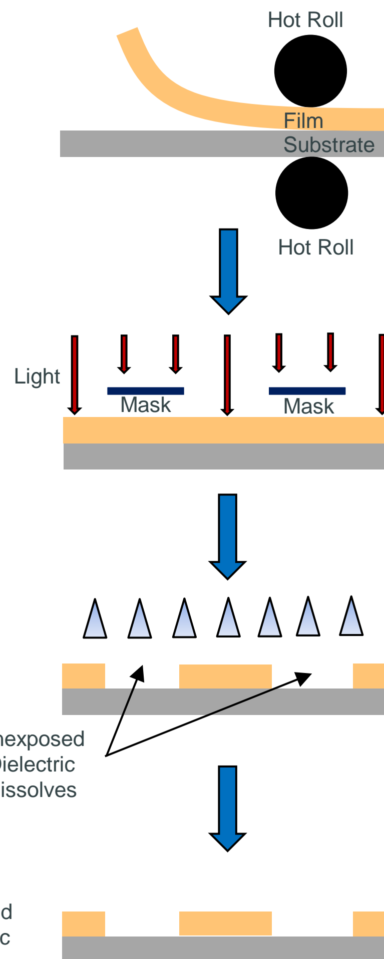
General Lithography Process Flow for Dry Film

Dry Film Construction

19 µm Polyethylene Cover Sheet
5-45 µm BCB-Based Dielectric
23 µm Polyester Backsheet

CYCLOTENE DF68XY: XY µm thickness

➢ PE removed before lamination



1) Lamination

- Adhesion Promoter Application (optional on CZ-Cu, ABF)
- Hot Roll or Vacuum Lamination

2) Patterning of Acrylic

- UV Exposure with Broadband or I-line
  - Negative Working/Tone
  - Stepper, aligner, LDI compatible

3) Development of Unexposed Areas

- Puddle or Immersion
  - Aqueous Base Developer
  - Water Rinse

4) Curing of BCB

- Hard Cure at Elevated Temperature
  - N_2 Purged Oven (<100ppm O_2)
- Plasma Descum

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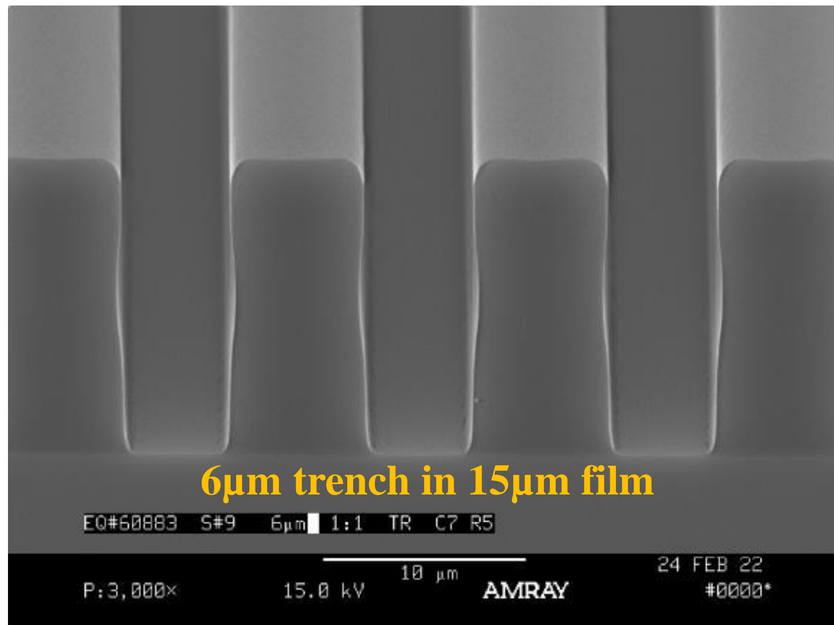
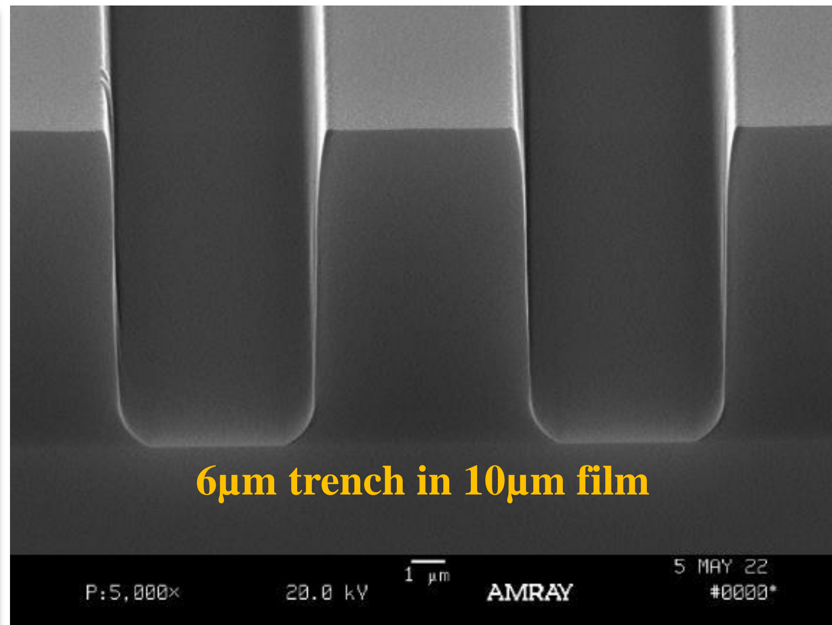
DF6800 Lithography Performance

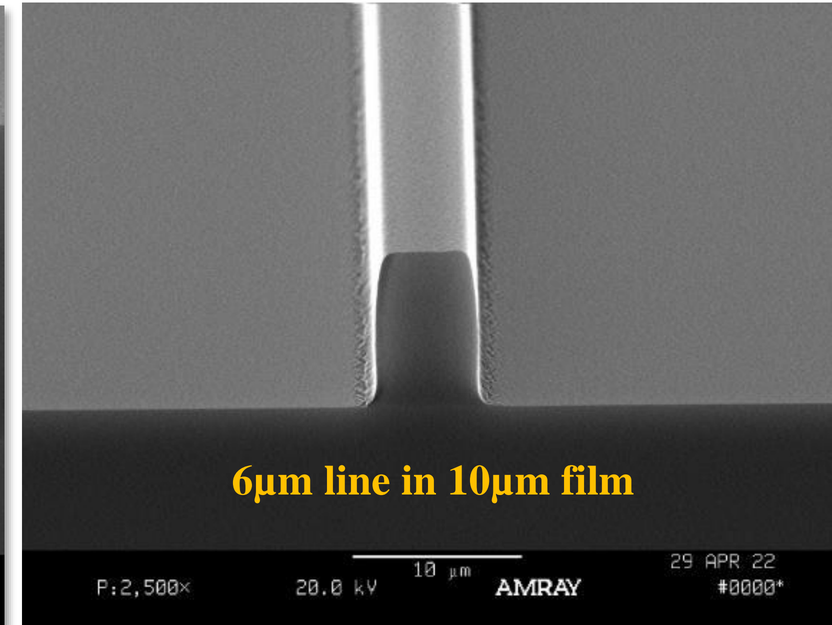
i-line Stepper



i-line Mask Aligner



Laser Direct Write



➢ Excellent lithography performance (PET-off patterning)

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Excellent Fill/Planarization Due to Superior Rheology, Suitable for 3DIC and Fine L/S

DF6800

Si

434µm

SU5000 1.2kV x180 SE(L) 300µm

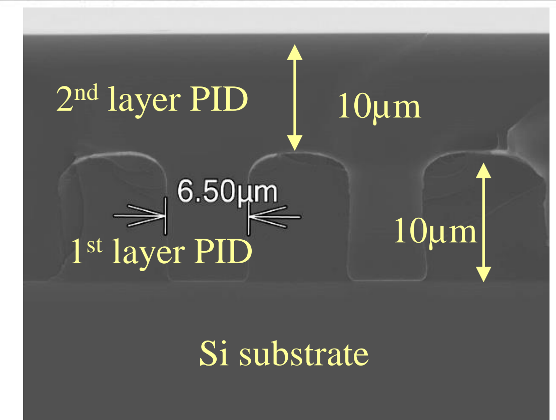
24.5µm 25.1µm 24.5µm

46.0µm

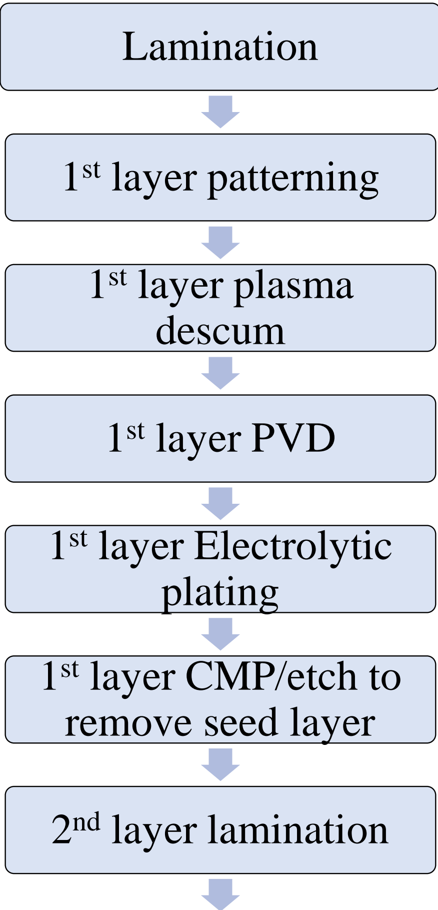
SU5000 1.2kV x300 SE(L) 100µm

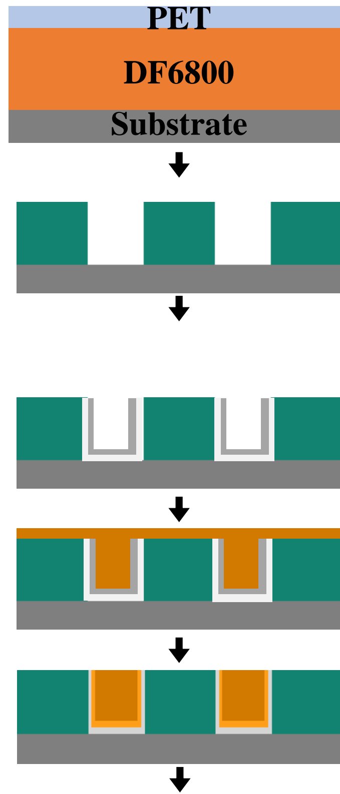
- Excellent fill and planarization on high aspect ratio features. Example below: filled silicon trench depth = 434um, width = 46um, dimple = 600nm

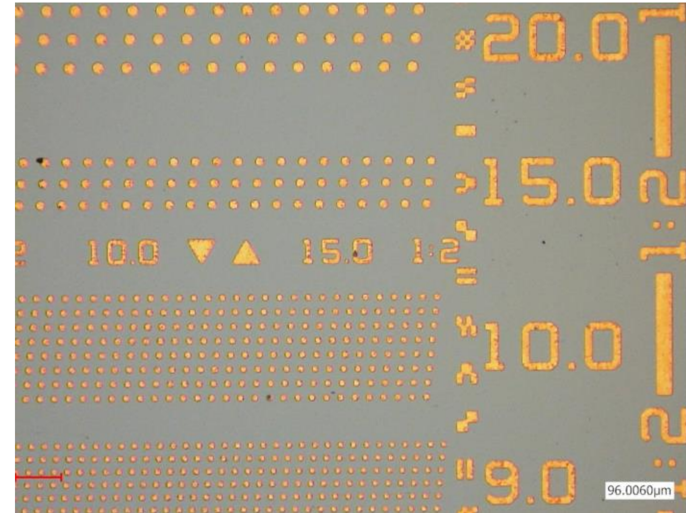
- Excellent fill and planarization on micro-patterned features: pattern trench depth = 10um, width = 6.5um, dimple undetectable.

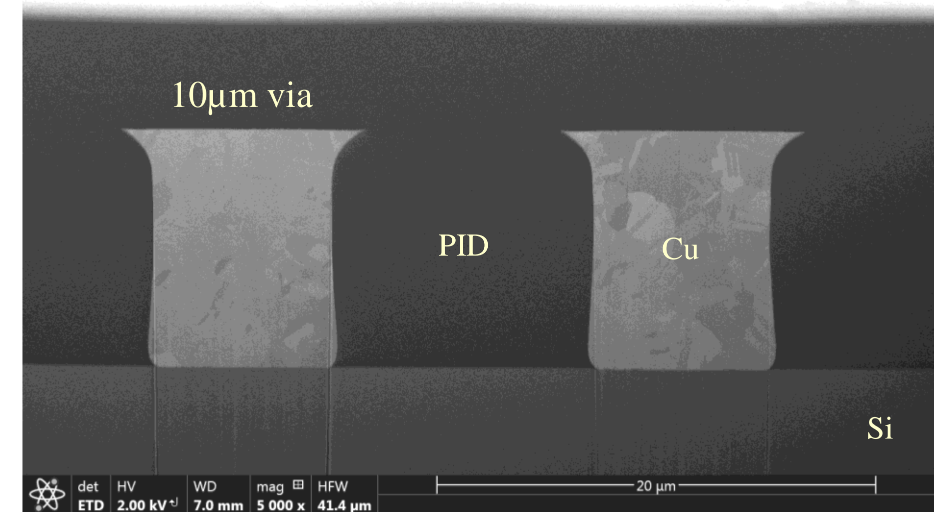


Successful Multilayer Build DF6800









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Plasma Treatment, PVD Seed Layer Deposition and Adhesion Test

Plasma Treatment Recipe

Etch process step 1				Etch process step 2			
CF4/O2 (sccm)	Pressure (mTorr)	Power (watts)	Time (sec)	O2 (sccm)	Pressure (mTorr)	Power (watts)	Time (sec)
75/75	85	200	20	75 O2	85	200	10

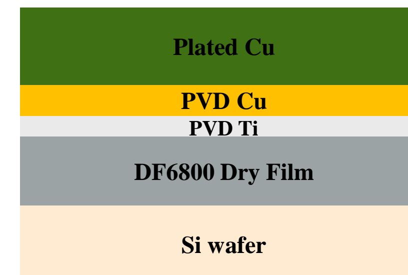
PVD Seed Layer Deposition Recipe

Sequential Sputter Process			
	Bias	Ti	Cu
Power	100 W	350 W	400 W
Pressure	10 mTorr	3 mTorr	3 mTorr
Dep Time	60s	250s	441s
Dep Rate	n/a	2.0 Å/s	3.4 Å/s
Gas Type	Ar	Ar	Ar
Gas Flow	~140 sccm	~35 sccm	~35 sccm
Pre-Sputter Time	n/a	300s	60s
PS Type	DC	DC	DC
Cathode	n/a	2	3

Adhesion Test

Peels were done at several stages: Soft cure → peel, then hard cure → peel, then HAST → peel OR hard cure → peel, then HAST → peel.

Testing Vehicle Structure



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Excellent Adhesion to PVD Metal

Best SC PS
Best HC PS
Best Post-HAST PS

Implemented 2nd O_2 plasma step

Performance target

Implemented degas & argon preclean

Peel Strength (kgf/cm)

0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

Round 1 Round 2 Round 3 Round 4 Round 5

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Successful Pass Bias-HAST Test

Dielectric	Cu Line/Space (µm)	Resistance		bHAST 130°C/85%RH/ 96hrs	Bias	Result
		Before HAST	After 96hrs HAST			
DF6815	30/100	$>10^{12}\Omega$	$>10^{12}\Omega$	No dendrites	5V	**PASS**
DF6815	13/9	$>10^{12}\Omega$	$>10^{12}\Omega$	No dendrites	5V	**PASS**

- DF6815 passed the bias-HAST test at 5V for 30/100µm & 13/9µm L/S
- **No Cu ion migration.**

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