FABRICATION AND RELIABILITY OF ULTRA-FINE RDL STRUCTURES IN ADVANCED PACKAGING BY EXCIMIER LASER ABLATION

NCCAVS Joint Users Group Technical Symposium
San Jose, June 7th, 2017

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Corona, CA 92880, USA
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<th>Advanced Packaging Trends</th>
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<td>Reliability of Embedded Laser RDL Patterning for Advanced Packaging</td>
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OPPORTUNITY & NEED FOR NEW INVESTMENTS IN RDL PATTERNING TECHNOLOGIES

No dominant HVM solution available

Current Cost Effective Solutions Limited to 5um L/S and 10um Via Diameters

Source: Babak Sabi, Corporate VP Intel, 2016
COMMON REQUIREMENTS FOR ADVANCED PACKAGING

Application:

- **Flip Chip: 200/300mm** (Cu Pillar, Micro Bumping, Solder Bumping)
- **WLCSP: 200/300mm** (RDL, Integrated Passive Devices)
- **Fan out WLP: >300mm** (eWLB, RCP, other)
- **Embedded IC: >300mm** (FCBGA, FCCSP)
- **2.5D Interposer, 3DIC: (200)/300mm**

**Challenges Facing RDL Patterning Process**

- New package designs to meet the changing market requirements
  - Small Thin Light Form Factor (micro via’s, 2/2um L/S RDL) and Higher I/Os
- Seed Layer Etch is difficult due to fine pitch of RDL traces
  - Fine RDL traces becoming unstable
- Consumer electronic devices driving the need for process cost reductions (5G, AR, Automotive, …etc)
- Enhancements in Package Performance
  - Improved Material Choices: Thermal, Mechanical and Electrical Properties
  - Loss of pattern integrity through curing after patterning
  - CTE mismatch

**Alternative Patterning Solution: Excimer Laser Enabled RDL Formation**

- Fine features: micro vias and 2/2um L/S RDL
- RDL structure is embedded; Seed Layer Removal and RDL trace stability not a concern anymore
- Direct Laser Patterning (dry etching) with curing before patterning – maintain pattern integrity
- More Dielectric Material Choices through use of non-photo dielectrics
- Significant Reduction of Cost of Ownership
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<th>Outline</th>
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Laser ablation is the process of removing material (subtractive process) from a solid surface by irradiating it with a laser beam.

The ablation of polymer is a photo physical process: mixture of photo-chemical and photo-thermal processes.

Rather than burning, enough energy is added to disrupt molecular bonds at the surface, disintegrating the broken material bonds into the air.

Ablation occurs with almost no heating or change to the underlying material.

Materials suitable for Excimer ablation:

- Most organic materials
  - Polymers/Organic Dielectrics (PI, PBO’s, BCB’s, Epoxy etc…)
  - Epoxy Mold Compounds (EMC – filled and unfilled)

- Some in-organics
  - Dielectrics (SiNx - < 1µm thick with 248nm only)
  - Thin metals (Ti, TiW, TaN, Ta, Cu, Ag, Al, etc…); <600nm thick on organic material
  - Conductive materials (ITO, IZO, CNT); <1µm thick on organic material
# Laser Ablation

What is Laser ablation?

- Direct Material Removal by laser irradiation
- Common Laser Types: CO2, DPSS (Diode Pumped Solid State), Excimer
- Various characteristics for different applications and purposes

<table>
<thead>
<tr>
<th>Laser</th>
<th>CO2</th>
<th>DPSS (Solid State)</th>
<th>DPSS (Solid State)</th>
<th>Excimer</th>
<th>Excimer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>10.6mm (long)</td>
<td>1.06um</td>
<td>355nm</td>
<td>308nm</td>
<td>248nm (short)</td>
</tr>
<tr>
<td>Photon Energy (eV)</td>
<td>0.12</td>
<td>1.7</td>
<td>3.5</td>
<td>4.08</td>
<td>5</td>
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<tr>
<td>Primary Ablation</td>
<td>Thermal</td>
<td>Thermal</td>
<td>Thermal</td>
<td>Photochemical</td>
<td>Photochemical</td>
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<tr>
<td>Mechanism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capable of Ablating</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>or Cutting Metal Pads?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu - Natural Stop</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Layer?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Laser Heat</td>
<td><strong>HOT</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>COLD</strong></td>
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<tr>
<td>Classification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Affected Zone</td>
<td>Large</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Small to none</td>
<td>Small to none</td>
</tr>
<tr>
<td>(HAZ) &amp; Recast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In Production for</td>
<td>Yes – Large Vias</td>
<td>Yes – Med Vias</td>
<td>Yes – Med Vias</td>
<td>Yes – small vias</td>
<td>No - Qualifying</td>
</tr>
<tr>
<td>Advanced Packaging?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concerns of</td>
<td>No – even though</td>
<td>No – even though</td>
<td>No – even though</td>
<td>Logically No –</td>
<td>Logically No –</td>
</tr>
<tr>
<td>Pad/Dielectric Damage?</td>
<td>Thermal</td>
<td>Thermal</td>
<td>Thermal</td>
<td>Less Thermal + Cu stop layer</td>
<td>Less Thermal + Cu stop layer</td>
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<tr>
<td></td>
<td><strong>Excimer Laser Ablation</strong></td>
<td><strong>Solid State Laser Ablation</strong></td>
<td></td>
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</tr>
<tr>
<td>---------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Imaging Type</strong></td>
<td>Mask based projection</td>
<td>Maskless, direct ablation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Patterning area</strong></td>
<td>Field area, up to 50x50mm. 1000’s of features at a time</td>
<td>Single spot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Patterning Mode</strong></td>
<td>Direct bond breaking</td>
<td>Melting and evaporation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Available wavelength</strong></td>
<td>(193nm), 248nm, 308nm</td>
<td>Various: 355nm, 532nm, 1064nm, etc...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Throughput</strong></td>
<td>+++ (not dependent on pattern density)</td>
<td>- (pattern density and shape dependent)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Typical applications</strong></td>
<td>Complex structures: <strong>Ablation of complex structures</strong> <em>(i.e. RDL trench and vias)</em></td>
<td>Low density patterning, scribing, drilling: <strong>Laser drilling</strong> <em>(i.e. through glass vias)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SCAN BEAM ABLATION

Scanning Laser beam

Process can be performed on wafers or substrates

Substrate moves under projection lens to ablate next unit site
Typical setup of an Excimer Laser stepper:

- Laser beam is made uniform and shaped through the optics train.
- The laser beam hits the mask, and the resulting image is projected through a reduction projection optics on the substrate.
- The system operates like a normal stepper, with a laser source instead of a UV lamp.
Physical process of ablation is the generation of debris.

Process breaks down the material molecular structure and debris is generated, simulating dust. To maximize debris removal, a Debris Cell is used.

- Debris collection system sucks air around the ablation area
- Debris exhausted out of the building or through a filter
- Laminar flow of HEPA filtered air across the substrate.

Precious metals can be reclaimed!
In addition to the debris cell, post-laser ablation cleaning is needed. Depending on the ablated material, several options are available:

**O2 plasma cleaning: Recommended**
- Most common cleaning method
- Successful cleaning of wafer with PBO (HD8820)

**Sacrificial layer for debris removal:**
- Successful removal process shown for FCPi 2100 (Fuji Film) Sacrificial layer removed using high-pressure CO2 ionized water
OUTLINE

1. Advanced Packaging Trends
2. Excimer Laser Ablation Technology
3. Via and RDL Patterning in novel material
4. Reliability of Embedded Laser RDL Patterning for Advanced Packaging
EXCIMER LASER APPLICATIONS IN ADVANCED PACKAGING

**Via Drilling**
- Small Vias: 5um
- Cost Reduction
- New materials
- Photolith & mtl limits
- DPSS limits

**RDL Trench**
- Smaller RDL 2/2um
- Better PI’s
- Cost Reduction
- Photolithography resolution limits

**Seed Layer Removal**
- Tighter Cu pitch
- Smaller RDL < 5um
- Cost Reduction
- Wet process limits

**Debonding**
- No mechanical stress
- No thermal stress
- High throughput

Trends:
- Excimer Laser Release (248nm or 308nm)
- Remove Carrier (No Lift-Off Force)

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**Wafer**

**Substrate**
Excimer ablation allows us to control many things…

**Side-wall Angle Control (WPR5100):**
- Higher fluence: Steeper wall-angle
- Lower fluence: Shallow wall-angle
- Wall angles to < 82°

**Depth Control - by No. of Pulses:**
- Each pulse removes a certain amount of material
  + Etch-rate = material removed/pulse
- With a known etch-rate – the number of pulses to reach a desired depth can be predicted and controlled

**Example:**
- Assume Typical Polyimide Etch-rate = ~0.30μm / pulse
- Desired Depth for Trench & Pad Pattern = ~5μm

**Selective Material Removal:**
- Metal pads >1μm thick are a Stop Layer

**Pulse Estimate Calculation:**
5μm Depth / 0.30μm Etch-Rate = 16.667 = ~17 pulses
VIA PATTERNING LIMITATIONS - UV EXPOSURE PHOTO PI

+ Photolithography
  + Limited Pitch and Via Wall Angle Control (UV Imaging)
    • Flexibility desired to address tighter via pitches, wall angles for Cu sputtering or higher aspect ratios where thicker dielectrics are desired.

Photolithography

- Wall to steep
- BCB after UV expose
- BCB after Cure
- HD4000 – UV Imaged

+ Excimer Ablation
  + Ablation performed after cure. Provides ability to flexibly alter the wall angle to the desired requirement.

Demonstration of via wall angle control: WPR5100 (7µm). Wall angle altered with fluence change

- 376mJ/cm² - 45 pulses
- 822mJ/cm² - 15 pulses
- 1200mJ/cm² - 12 pulses

- ~85°
- ~74°
- ~81°

- 9µm thick HD4000. Via wall angle 45 & 78 degrees
- 9µm thick HD4000 & 17µm via. Wall angle ~45 degrees
Unique Characteristic of Excimer Laser Ablation:

- Thick (>1μm) Traces, Bumps & Pillars are Natural Stop Layers:
  - Consider the cross-section of the 1μm tall Cu feature, below.
  - The conductive metal immediately disperses the laser energy throughout the structure with its sea of free electrons.
  - Any energy or heat that reached the Metal-Dielectric Interface is insufficient to break bonds via photochemical or thermal action – so No melting or Ablation takes place – even with multiple pulses.

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**Excimer Laser Pulse #1**

**Excimer Laser Pulse #2**

**1μm tall feature**

- Photon Energy absorbed and dispersed

**Ti/Copper Layer (400nm)**

**Polymer Layer (4μm)**

**Silicon Wafer**

**RDL Feature on Copper Seed Layer on Polymer Dielectric**

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**No Ablation or Damage to RDL Structures Thicker than 1μm - Readily apparent through Laser Seed Layer Removal Ablations**

- Thin Seed Layer ablated off of Polymer
- Thick Cu Bumps Not Ablated or Damaged
**Photo vs. Non-Photo Dielectrics**

- Non-Photo Dielectrics cost up to 50% LESS than Photo-Dielectrics
- Photo Dielectrics have a higher Shrinkage Rate – increased cost and less pattern fidelity
- Many Non-Photo Dielectrics have better thermal, mechanical and chemical properties
- Non-Photo Dielectrics increase the material choices => better CTE

### PHOTO DIELECTRIC

**Assuming 45% Shrink Rate**

$$ + 0.45 \times \$ $$

**Total Cost = \sim 3.0 \$**

**Almost 3X Cost**

### NON-PHOTO DIELECTRIC

**Assuming 15% Shrink Rate**

$$ + 0.15 \times \$ $$

**Total Cost = \sim 1.15 \$**

Some Non-Photo Dielectrics have 30% less Shrinkage vs. Photo
Excimer Ablated 5µm Via in 15 thick BCB:
- Result: 4.7µm top and 2.8µm bottom
- Aspect Ratio: 4~5
LASER ABLATION OF BCB MATERIAL

BCB Ablation KrF 248nm

Fluence [mJ/cm²]

Etch rate [µm/shot]

0.30
0.25
0.20
0.15
0.10
0.05
0.00

0
100
200
300
400
500
600
700

Number of pulses

Depth of ablation [µm]

0,000
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000

4µm lines
10.6µm lines
4 µm vias

30P 20P 15P 10P 5P 1P

9/19/2016 2:36:50 PM dwell HV HFW mag det tilt
30 µs 5.00 kV 121 µm 1716 x TLD 52 °

Kaletta @ Fraunhofer IZM / TU Berlin
5UM AND 10UM VIAS IN 9UM THICK NON-PHOTO ABF MATERIAL
FINE TRENCHES IN 5.6UM THICK HD4100: 2.0UM AND 2.5UM TOP OPENING

2um top via

2.12um
1.14um

2.5um top via

2.43um
1.21um
**EFFECT OF FILLER SIZE ON FINE PITCH TRENCH FORMATION**

- Large filler in polymer dielectrics leads to side erosion
- Small/no filler material enables high resolution trench formation

**ABF GX92**
- Large filler

**ABF GY50**
- Small filler

**Fujifilm Polyimide**
- No filler

**Surface Topology**

**4µm L/S Trench**

(a) 5µm
(b) 5µm
(c) 5µm
Material: ABF GY50, Fujifilm Polyimide
- Target: 4.5µm depth
- Mask: 2µm – 4µm line and space

- Aspect ratio of trench ~ 1:1 for small filler ABF, 1:1.5 for non-filled
- SUSS R&D project to develop new projection optics for higher resolution and aspect ratio
Fine pitch embedded RDL trench wiring by Excimer Laser ablation

ABF GX92
Large filler
5/5µm L/S in GX92
10µm

ABF GY50
Small filler
3/3µm L/S in GY50
6µm

Fujifilm Polyimide
No filler
2/3µm L/S in Polyimide
5µm

10µm pitch in GX92, 6µm pitch in GY50 and 5µm pitch in PI demonstrated
Fine pitch embedded RDL trench wiring by Excimer Laser ablation

Fujifilm Polyimide (FFEM)

No filler

6/6, 5/5, 4/4, 3/3, and 2/2um L/S in PI demonstrated
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EMBEDDED LASER RDL FORMATION SCHEME

Starting substrate

Coat and cure polymer

Laser ablate RDL trenches

Laser ablate Vias

Overplate Cu

Metal reduction

Sputter seed metals
### EMBEDDED LASER RDL FORMATION VS. CURRENT PROCESS

<table>
<thead>
<tr>
<th></th>
<th>Semi-additive</th>
<th>Embedded trench</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross section</strong></td>
<td><img src="image" alt="Cross section diagram" /></td>
<td><img src="image" alt="Cross section diagram" /></td>
</tr>
</tbody>
</table>
| **Advantage**   | - Current POR in industry  
- Lots of industry development                                                                                                                                                  | - No photo-lithography material required  
- Line & via formation in one Step  
- No wet seed removal required  
- Via pattern integrity                                                                                                                                  |
| **Challenge**   | - RDL Undercut and erosion during seed etch  
- Surface non-planarity                                                                                                                                                                   | - Planarization of Cu overburden                                                                                                                   |
| **Fine line**   | - Erosion of the Cu during seed layer removal  
- ![Fine line images](image)                                                                                                                                                           | - No Cu erosion                                                                                                                                 |

- **BU Layer**: 3 μm L/S
SURFACE PLANARIZATION

- Trench formation by excimer laser
- Trench filling by Cu plating
- Cu overburden removal by surface planarization
XSEM OF EMBEDDED RDL STRUCTURE IN FCPi 2100 (FUJI FILM)

Courtesy of Fujifilm US

40 micron pitch 52° tilt after FIB

40 micron pitch 90° tilt after FIB, high resolution detector
XSEM OF EMBEDDED LASER RDL IN PHOTO AND NON-PHOTO MATERIALS (VIA FIRST PROCESS)

- Material: LTC9320 low T cure (Fujifilm)
- 4/4/4um L/S/via
- Sputtering seed: 100nm Ti 600nm Cu
- Cu Plating 4.7µm overburden
- CMP for planarization (stop on seed layer)
- Seed layer removal using Excimer Laser
- No leakage observed post seed layer removal
- No plating voids in via!

- Material: ABF GY50 (Ajinomoto)
- 6/6/6um L/S/via
- Sputtering seed: 100nm Ti 600nm Cu
- Cu Plating 4.7µm overburden
- CMP for planarization for Cu, seed layer and stop on ABF
- No leakage observed post CMP
- No plating voids in via!

Courtesy of IZM Fraunhofer
Excimer ablation over Cu and Al pads:
- 3rd party tests have been performed showing no damage to the underlying materials
- Case study:
  - Si/SiOx/SiNx/TiTiN/AlCu(1.4um)/dielectric(8.5um)
  - Over pulsed 40 and 50 with no damage to the low k dielectrics

Summary: No increase of crack rates after laser impact

3rd party confirmation of no damage to Cu pads
Excimer Laser Micro-via Reliability

- Build-up + excimer + Eless seed SAP -

- 8µm diameter, 20/40µm pitch micro-vias in 10µm build-up layer with excimer laser
- Coupon number: 6 coupons in one panel
- 8 daisy-chain lines in a coupon for 40µm pitch, 6 lines for 20µm pitch

**Thermal cycle**

- 40µm pitch coupons
- 20µm pitch coupons

**bHAST**

- 40µm pitch coupons
- 20µm pitch coupons

**Preconditioning:** MSL3
**TCT condition:** -55°C, 15min → 125°C, 15min

- No resistance increase for 4300 cycles

- **B-HAST condition:** 130°C, 85%RH, 5.0V

- No Conductance increase for 2000 hr

No reliability failures observed with single layer micro-via chains
RELIABILITY OF EMBEDDED TRENCH (5/5UM)

Multilayer RDL structure in ABF GX92 with 8um via diameter 20, 30 and 40um pitch daisy chain structure
Thermal shock test
liquid to liquid: 125°C 1min and -55°C 1min

No failure observed after 1000 cycle of thermal shock test
QUALITY CHECK OF LASER DUAL DAMASCENE RDL

Daisy-Chain contains over 900 vias
~150 Ohms

Low temperature polyimid (Fujifilm LTC 9320)
14x14mm package (10x10mm die), 10um via in 20um dielectric, 10/10um L/S RDL*

**Photolithography Process**

<table>
<thead>
<tr>
<th>Process</th>
<th>Cost/wafer ($USD)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>44.64</td>
<td>60%</td>
</tr>
<tr>
<td>Labor</td>
<td>1.37</td>
<td>2%</td>
</tr>
<tr>
<td>Material</td>
<td>27.93</td>
<td>38%</td>
</tr>
<tr>
<td>Total</td>
<td>73.93</td>
<td>100%</td>
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</tbody>
</table>

**Excimer Laser Process**

<table>
<thead>
<tr>
<th>Process</th>
<th>Cost/wafer ($USD)</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital</td>
<td>35.39</td>
<td>68%</td>
</tr>
<tr>
<td>Labor</td>
<td>0.86</td>
<td>2%</td>
</tr>
<tr>
<td>Material (non-photo dielectric)</td>
<td>15.45</td>
<td>30%</td>
</tr>
<tr>
<td>Total</td>
<td>51.70</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Savings**

- 59%
- 30%

**Cycle Time**

- Photolithography: 5.80 hours
- Excimer Laser: 2.38 hours

- Savings: 59%

*Collaboration with SavanSys
Excimer Laser Ablation is a Valuable Enabling Technology:

- Enables Finer Resolution Patterning in Photo-Polymers (Dielectrics)
- Enables Direct Dry-Etch Patterning of Non-Photo Polymers
- Enables Higher-Density Via Drilling
- Enables Multilayer RDL integration at lower cost
- Enables Complex Patterns, More Uniform Feature Shape, Placement and Quality on thin metal surfaces
- Enables Selective Dry-Etch Thin Seed-Layer Removal
- Enables Cost-Effective Patterning of Large Surfaces

Next GEN Device Patterning Challenges

1. Fine Photo-Dielectric Patterning
2. Direct Non-Photo Dielectric Patterning

Excimer Laser Ablation

Photolithography Limitations
UV Lasers Limitations

BARRIERS
Thank you!

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