Laser Drilling For Electrical Interconnection in Advanced Flexible Electronics Applications

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Acknowledgement:
Frank Egitto
Outline

• Introduction: Motivation for laser processing and advanced electronics

• Laser Fundamentals

• Laser/Material Interactions

• Types of lasers, laser drilling systems, and drilling techniques

• Laser-enabled high-performance electronic components

• Extensions of laser processing technologies
**Levels of Interconnection**

*Flip Chip Assembly*
- Chip
- Underfill
- Chip Carrier
- Conductive Joint

*Wirebond Assembly*
- Chip
- Encapsulant Wire
- Chip Carrier

**Functions of Rigid and Flexible Electronic Packaging**
- Mounting and physical support of electronic components
- Protection of devices from environment
- Removal of heat from devices
- Electrical interconnection of components
  - Signal distribution
  - Power distribution

**Wafer**

**IC Chip**

**System**
Traditional Application of Laser Processing to Flexible Electronics

- Annealing of conductors to control electrical properties
- Exposure of photosensitive materials (e.g., photoresists) for pattern formation
- Singulation
- Repair of circuit traces
- Skiving
- Labeling
- Holemaking for electrical interconnection

1. Low $T_{\text{melt}}$
2. Low Cost

- Sintering of nanoparticle with controlled thermal diffusion length
- Low temperature & non-vacuum process
- Additive process

Laser thermal lab., UC Berkeley

Endicott Interconnect
High density electronic components are composed of multiple layers of circuit traces.
Electrical interconnection between layers is made with drilled and plated holes.
For decades, *mechanical drilling* has been the conventional means of hole formation and is still a mainstay for most printed circuit board applications.

*Mechanical punching* has been used extensively for hole formation in thin, flexible, homogeneous materials. Hole diameters on the order 0.002" are achievable, but the process is highly sensitive to material properties.
"Smaller, Lighter, Faster, Cheaper"

The demand for high-performance, lightweight, portable computing power is driving the industry toward miniaurization of many electronic products and the components that comprise them.

Common examples are
- laptop computers
- personal digital assistants
- digital cameras
- cellular phones
Microelectronics Advanced Interconnections
Semiconductors versus Package
Smallest features: “parallel paths” for how long?

Laser via / thin film / z-interconnect based interconnect technology
needed to reduce the IC to PWB interconnect gap

HyperBGA® Interconnect technology
Z-interconnect technology
Reduced Interconnect Gap

HyperBGA is a registered trademark of Endicott Interconnect Technologies, Inc.
Traditional Approaches to Increasing Circuit Density

- Smaller lines and spaces
- Smaller vias
- Blind and buried (controlled-depth) vias
- Added wiring layers

Use of blind vias increases wiring density.

Adding layers increases wiring density.
To incorporate a greater degree of electronic function into a smaller volume, circuit traces and the holes used to connect them must have smaller physical dimensions.

**Microvias** are defined as holes used for electrical interconnection and having a diameter less than 0.006 inch (150 μm).
Hole diameters affect wiring density.

- hole diameter, \( d \)
- capture pad diameter, \( c = d + x \)
- line width, \( l \)
- line space, \( s \)
- line-to-pad space, \( p \)
- hole pitch, \( h \)
Increase in Wiring Density
With Reduction in Hole Diameter

Increased Number of Lines Per Channel

Reduced Pitch

Land on larger hole

Land on smaller hole
Top View

- Hole diameter, $d$
- Capture pad diameter, $c = d + x$
- Line width, $l$
- Line space, $s$
- Line-to-pad space, $p$
- Hole pitch, $h$
Hole Diameter and Wiring Density

hole diameter, $d$
capture pad diameter, $c = d + x$
line width, $l$
line space, $s$
line-to-pad space, $p$
hole pitch, $h$, at one line per channel

$$h = l + 2p + x + d$$

hole pitch, $h$, at two lines per channel

$$h = 2l + s + 2p + x + d$$

hole pitch, $h$, at three lines per channel

$$h = 3l + 2s + 2p + x + d$$

In general, for $n$ lines per channel, where $n \geq 1$, and $n$ is an integer, the hole pitch is

$$h = nl + (n-1)s + 2p + x + d.$$
Increase in wiring density with decrease in hole diameter by way of reduced pitch (lines per channel constant).

For \( n, p, x, l \), and \( s \), constant,

\[ h = d + k \]

where \( k = nl + (n-1)s + 2p + x \).

That is, the pitch can be reduced by the same amount that the hole diameter is reduced such that \( h_1 - h_2 = d_1 - d_2 \)

Wiring density expressed as the number of lines per micron is given by \( n/h \). Percentage increase in wiring density, \( D \), with reduced pitch is given by

\[ \frac{(n/h_2 - n/h_1)}{(n/h_1)} = \left[\frac{(d_1 + k)}{(d_2 + k)}\right] - 1 \]

For \( k \ll d_1, d_2 \).

\[ D = \frac{d_1}{d_2} - 1. \]

For \( k \gg d_1, d_2 \).

\[ D = 0. \]
Increase in wiring density with decrease in hole diameter by way of increased number of lines per channel (pitch constant).

For $h, p, x, l, s$, constant,

\[
h = nl + (n - 1)s + 2p + x + d
\]

\[
n(l + s) = -d + q, \text{ where } q = h + s - 2p - x
\]

\[
n_2(l + s) = -d_2 + q, \text{ where } d_2 \text{ is the smaller diameter hole}
\]

\[
n_1(l + s) = -d_1 + q, \text{ where } d_1 \text{ is the larger diameter hole}
\]

\[
(n_2 - n_1)(l + s) = d_1 - d_2
\]

\[
n_2 - n_1 = (d_1 - d_2) / (l + s).
\]

That is, the increase in the number of lines per channel, $n_2 - n_1$, is equal to the ratio of the change in hole diameter, $d_1 - d_2$, to the line pitch, $l + s$. Again, $n_2 - n_1$ must be an integer. For example, if $d_1 - d_2 < l + s$, there is no increase in wiring density. If $(l + s) < (d_1 - d_2) < 2(l + s)$, lines per channel increase by 1. If $2(l + s) < (d_2 - d_1) < 3(l + s)$, lines per channel increase by 2, and so on.
PTHs consume real estate, blocking channels that could be used for wiring.
Increase In Wiring Density With Blind Vias

- PTH
- Blind Via
- Space available for wiring
Increase In Wiring Density

Blind Via vs PTH

Use of blind vias Increases wiring density.

Mechanical drills and punches are not suited to formation of blind microvias.
Microvia

A blind, buried, or through via that is on the order of 150 $\mu$m or smaller in diameter.

Definition often limited to blind vias for high density interconnect structures (HDIS).
Layer Interconnection with Plated Thru Holes

Lines must go around PTH's

Layer Interconnection with Controlled-Depth Vias

Controlled-depth vias don't block lines
Sequential Build-Up Process (SBU)
Benefits of Blind Vias and Added Layers

1. Fabricate Core
2. Fabricate 1st Build-up Layers on Core
3. Fabricate 2nd Build-up Layers on Existing Layers
   (Etc.)

Options:
- Stacked Blind Vias
- Staggered Blind Vias
Parallel Process for Z-Axis Interconnect
As Alternative to SBU

Fabricate All Layers Separately

Join & Interconnect Layers

A means of forming electrical joints between adjacent cores is required.
Advantages of Parallel Lamination for Z-Axis Interconnect vs SBU

- **Shorter cycle time**
  Individual layers (cores) built in parallel

- **Higher yield**
  Opportunity to inspect and sort cores, prior to lamination, to optimize composite yield
Increase in Wiring Density With Controlled-Depth Vias

40 μm and 75 μm laser-drilled vias in cores
Increase in Wiring Density with Controlled-Depth Vias

40 \mu m and 75 \mu m laser-drilled vias in cores
Mechanically-Drilled Through Via

75 \( \mu \text{m} \) diameter

170 \( \mu \text{m} \) clearance hole
Laser-Drilled and Plated Through Hole
Nd:YAG 355 nm Gaussian Beam
Drilled Through Epoxy-Glass and Cu Foil (Top and Bottom)

Epoxy-Glass
3.0 mil diameter
6.0 mil thickness
Laser Micromachining of a Human Hair
Using an Excimer Laser at 193 nm

Source: Lambda Physik
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• Laser Fundamentals

• Laser/Material Interactions

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• Laser-enabled high-performance electronic components

• Extensions of laser processing technologies
**Light Amplification by Stimulated Emission of Radiation**

1. R=100%
   - Lasing Medium

2. 2
   - Direction of light propagation

3. 3
   - Light amplification by stimulated emission of radiation

4. R<100%
   - Source: Engineering Technology Institute

5. 4
   - Source: Engineering Technology Institute

6. 6
   - Source: Engineering Technology Institute

Source: Engineering Technology Institute
Laser Wavelengths For Processing

**Laser Type**

- **Excimer**: 248 nm
- **Nd:YAG**: 1064 nm
- **CO2**: 10,000 nm

**Wavelength**

- **ULTRAVIOLET**: 100 nm - 400 nm
- **VISIBLE**: 400 nm - 750 nm
- **INFRARED**: 750 nm - 10,600 nm
Elements of a Laser

Lasing Medium  Pumping Mechanism  Laser Beam Out

Continuous Wave (CW) or Pulsed (High Energy Bursts) Outputs

Pulsed Mode Used For Clean Holemaking With a Minimum of Thermal Damage
Excitation of Atoms

by collision with free electron

by absorption of light

$E_\phi = h\nu = E_1 - E_0$
Emission of Light

spontaneous emission

$E_\phi = h\nu = E_1 - E_0$

stimulated emission

coherent, amplified light
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Laser Holemaking

Beam Shaping and Delivery

Photon (Energy) Absorption
By Material

Breaking of Chemical Bonds
Photochemical Processes
Photothermal Processes

Vaporization (Ablation)
Laser Material Interaction

- **Homogeneous**
  - Consistent material cross-section
  - No Cu planes
  - No glass fillers

- **Non-Homogeneous**
  - Fiber reinforced
    - FR4 typical circuit board material
  - Particle filled
    - Build-up materials for HDI packaging
  - Cu planes
  - Mixed materials
Absorption Curves

248 nm - KrF excimer
308 nm - XeCl excimer
355 nm - Nd:YAG 3rd Harmonic
532 nm - Nd:YAG 2nd Harmonic
1064 nm - Nd:YAG Fundamental

Absorption

Wavelength (nm)

Source: ESI
Laser Beam Delivery

Mask Imaging

Contact or Conformal Mask

Focused Spot
\[ I_x = I_0 \exp^{-ax} \]

Ablation ceases when \( I_x < I_{th} \)
\[ I_x = I_0 \exp^{-ax} \]

- \( I_0 = I_1 \) (shallow absorption)
- \( I_0 = I_2 > I_1 \) (moderate absorption)
- \( I_0 = I_3 > I_2 \) (deep absorption)

**Rate**

(Endicott Interconnect)
\[ I_x = I_0 \exp^{-\alpha x} \]
\[ I_{th} = k \left( \frac{1}{\alpha^n} \right) \]

- low \( \alpha \)
- little or no absorption
- low rate

- moderate \( \alpha \)
- deeper absorption
- high rate

- high \( \alpha \)
- strong but shallow absorption
- low rate

\( I_0 \) (Etched Depth Per Pulse)

**Rate**

Endicott Interconnect
Absorbance of PTFE and Polyimide

Doping of PTFE With Polyimide

PTFE

$\alpha \sim 10^2 \text{ cm}^{-1}$

$\text{CF}_2-\text{CF}_2$

Etch Rate (um/pulse)

% Polyimide in PTFE

BPDA-PDA Polyimide

$\alpha \sim 10^5 \text{ cm}^{-1}$

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EXCIMER LASERS

LASER
- Gas lasing medium
- Ultraviolet (UV) emission
- e.g., 308 or 248 or 193 nm
- Several hundred pulses per second

LASER SYSTEM
- Broad beam
- Laser spot is shaped using a projection mask

TYPICAL ATTRIBUTES
- Best suited to etching of polymers
- Not well-suited to removal of metals
- Tapered wall profile

75 µm via in polyimide made with an excimer laser at 308 nm.
Example of Excimer Laser System
Used With Projection Mask

Mask Imaging

stationary

Excimer Laser

Prism Beam Expander

Beam Homogenizer

Turning Mirror

Turning Mirror

Turning Mirror

Mask

X-Y Positioning Stage

Substrate

Vacuum Chuck / Rotational Stage

Objective Lens

Lens

Turning Mirror

Mask
Example of Excimer Laser System
Used With Projection Mask
Stationary Beam, Scanning Mask and Substrate
Example of Excimer Laser System
Used With Contact Mask
**CO₂ LASERS**

**LASER**
- Gas Lasing Medium
- IR emission (around 10.6 µm)

**LASER SYSTEM**
- Focused beam (50-75 µm minimum diameter) or metal contact mask

**TYPICAL ATTRIBUTES**
- Highest power
- Best suited to drilling of polymers, some thermal damage
- High reflectance from metal surfaces
- Best when speed (not small size) is important
- Used in about 80% of microvia applications

*CO₂ Laser Processing of Woven Glass/Epoxy Resin Using a Conformal Mask. Cu-Plated 6 mil Via.*
Nd:YAG LASERS

LASER
- Solid Lasing Medium
- Infrared (IR) Fundamental Emission (1064 nm)
- Visible (532 nm) or UV (355 or 266 nm) emission with nonlinear crystals
- Up to 100,000 pulses per second

LASER SYSTEM
- Focused beam (12 to 25 μm diameter, depending on wavelength and optics) or shaped beam for blind via drilling.
- Trepanning for holes having diameters greater than beam diameter

TYPICAL ATTRIBUTES
- Capable of drilling variety of materials (polymers, glass, metals)
- Most versatile
- Well-suited to holes with small diameter, high aspect ratio
- Used in about 20% of microvia applications
355 nm Laser Rail Layout

HR Mirror → Q-Sw → Nd:YAG → BBO 2nd → BBO 3rd → Output Coupler Splitter Beam Dump

Source: ESI
Beam Profiles

Gaussian

Trepanning

Via

Punching

"Top Hat"
multiple revolutions (programmable)
laser beam turns on and off

Trepan Tool

Spiral Tool

Radial Pitch
Bite Size
Beam Diameter
Bite Size
Beam Diameter
**Rep Rate.** The number of laser pulses delivered to the workpiece per unit time.

**Focus Height** (or Z Offset). Positions the beam out of focus relative to the surface of the part by the specified amount.

**Average Power.** The energy per pulse multiplied by the rep rate.

**Tool Diameter.** The desired final diameter of the via.

**Pulses.** The number of times the laser fires into a given hole in the punch mode.

**Bite Size.** The distance between laser pulses, center to center, in the trepan or spiral mode.

**Velocity.** The speed at which the beam moves across the work surface, in the trepan or spiral mode.

**Repetitions.** The number of times the path of the beam is traced, in the trepan or spiral mode.

**Effective Spot Size.** What the computer believes the diameter of the beam on the material to be. A large value for effective spot size prompts the laser software to trace a tighter spiral or trepanning loop.

**Inner Diameter.** The inside diameter of the first spiral.

**Revolutions.** The number of spiral revolutions per hole.

**Radial Pitch.** The distance between spiral revolutions.

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**Trepan Tool**

**Spiral Tool**
Compound Beam Positioner
Beam Positioning

Blind Via Drilling

Through Via Drilling

Laser μVia Drilling

Beam Positioning
Registration Requirements

- Blind via on pad
- Buried via through clearance hole
- Clearance hole
Toolpath File

% (ESI 5100)
T1 8
T0 996 G0
X112710.0 Y94580.0
X112710.0 Y661160.0
X504510.0 Y661160.0
X504510.0 Y94580.0
T1 1
T0 101 G0
T2 101.6
X71119.0 Y80690.0
Y83230.0
Y85770.0
Y88310.0
Y90850.0
X80010.0 Y89580.0
X78739.0 Y80690.0
X76199.0
X73659.0
X81279.0
X118109.0 Y88310.0
X72389.0 Y128950.0
X214629.0 Y88310.0
X237490.0 Y89580.0
X261644.9 Y102852.0
Y104122.0
Y105303.0

Four Point Alignment

Measured Alignment Targets

Design Alignment Targets

Design Data Locations

Drilled Hole Locations

Designed location of alignment markers

Hole Diameter in \( \mu \text{m} \)

Designed location of drilled holes

Toolpath File Border

Panel Border
Registration

X-Ray Image of 75 \text{\textmu}m Vias Through 125 \text{\textmu}m Clearance Holes
**Blind Via Formation**

Various Blind Via Structures

- Typical microvia
- Skip microvia
- Multilayer via
- Via on via with conductive fill
- Staggered via

Source: TechSearch International, Inc.
Blind Via Drilling:

**Cu surface mask**

- Cu surface mask
- Dielectric

or, without Cu mask

- Dielectric
- Lens
- Etched Metal Foil
- Contact or Conformal Mask
- Mask Imaging
- Focused Spot
Laser-Drilled and Plated Blind Via
Nd:YAG 355 nm Gaussian Beam, Trepanned, No Surface Cu Mask
(Similar hole quality possible using shaped beam in punching mode)

Top Diameter = 4.2 mils
Bottom Diameter = 3.0 mils
Control of Etch Selectivity
By Adjustment of Fluence or Wavelength

Through Metal

In Focus, High Fluence*
For High Intensity

Out of Focus or Low Fluence For Low Intensity

Stop on Metal

OR

“Shaped” UV or IR to Reflect From Metal

* fluence = energy per unit area per pulse
Nd:YAG Laser........Two-Pass Process

Gaussian Beam Profile

Pass 1: Remove surface Cu.

Pass 2: Remove dielectric.
160 μm Laser-Drilled Blind Via In Epoxy/Glass
Using 355 nm Nd:YAG Gaussian Beam
Spiral Mode, Two Pass Process
CO₂ Laser..........Two-Step Process

Chemically etched copper "mask"

Ablate dielectric with IR beam
Combination Nd:YAG & CO$_2$ Laser Process

Trepan or Spiral
Photosensitive Dielectrics

1. Apply
2. Expose
3. Develop

Positive

Negative
Photolithography

Apply Resist

Expose

Develop
**Chemical Etching**

**Plasma**
- Photoresist
- Plasma Etch
- O*, CO, CO₂, etc.

**Wet Chemical**
- Immerse In or Spray With
  Wet Chemical Etchant
- Strip Photoresist
Panel Throughput: Photo-vias vs Laser

Number of Sides / (Day - Machine)

Via Count / Side
Thousands

- Laser, 300 vias/sec
- Laser, 80 vias/sec
- Photo process
Laser Drilling vs Plasma Etching

Relative Cost

Cost Per Panel vs Number of Vias Per Panel

- Laser
- Plasma

Cost Per Panel

Number of Vias Per Panel

50,000 100,000 150,000 200,000 250,000

0 50,000 100,000 150,000 200,000 250,000
Laser Drilling vs Mechanical Drilling
Relative Cost

Cost Per Via

Via Diameter

0.002" 0.004" 0.006" 0.008" 0.010"

Mechanical

Laser
Packaging and HDI Production

December 1996

- Drill: 9.0%
- Plasma: 3.0%
- Laser via: 43.0%
- Punch: 3.0%
- Photo-via: 42.0%

August, 1998

- Drill: 4.0%
- Plasma: 1.0%
- Laser via: 60.0%
- Punch: 1.0%
- Photo-via: 34.0%

Laser vias used for 90% of HDI applications in 2002.


2 The Electronics Industry Report 2002, Prismark Partners LLC.
ESI's Via Technology Roadmap

Source: Electro Scientific Industries, Inc.
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HyperBGA®
Both packages use 50blind vias
CoreEZ core vias are 4x smaller
CoreEZ is ½ as thick
Core EZ’s core is 6 times as dense
CoreEZ can fully route signals on both sides of the core
✓ 2 times the wiring density with fewer layers
HyperZ®

- Coreless structures for maximum wiring density
  - 40um and 65um vias
GE Power Overlay

Fig. 1 Pictorial cross-section on a two chip POL module mounted onto a baseplate.

Fig. 4 POL Via Process Steps: a. Laser Cut Via Plug and b. Cover Sheet and Via Plug Removal.

Direct Metallurgical Contact: Chip on Film

- Bare Chip Bonded to Flex with adhesive
- Vias formed over chip pads
  - laser ablation
  - plasma, RIE etch
- Sputter/electroplate processes used to electrically connect chip pads to flex interconnect

Example: GE Chip-on-Flex (COF)

Source: GE

Ray Fillion, GE Global Research - Slide 24
On-Flex Integral Passive

Passives Integration with Flex Circuitry

- Polyimide
- Ta$_2$N or DLC
- Cu
- Through hole Via
- Capacitor
- Interconnect
- Inductor
- Through hole Via
- Resistor

Passives on Flex Capability

- > 99% Yield, < 5% Tolerance Demonstrated for Ta$_2$N (25 to 100 Ohms/Sq.) Resistors on Flex (up to 30K Ohms Possible)
- > 99% Yield for DLC (20 nF/cm$^2$) and TaOx (100 nF/cm$^2$)
- Capacitors up to Values of ~2nF meeting application required $V_{dd}$ & $J_L$
- Single and double sided spiral inductors up to 400 nH demonstrated
- High Frequency Performance up to 10 GHz
  Demonstrated for R’s, L’s, C’s on Flex

Electronic Packaging Applications

- Wire Bond Attach
- Flip Chip Attach
- Direct Bond Chip on Flex

Integrating R, L, C Structures Demonstrated on Flex
(US patent Allowed)

Major Impact of Technology

- Reduced Size and Weight with Superior Electrical Performance and Reduced Cost

Ray Fillion
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Embedded Resistor Trimming

- Resistors formed through etching thin film resistor foil
- Resistor value designed low for etching process
- Laser used to trim up to nominal value
- Tighter control
Laser Direct Imaging

- Laser Direct Imaging of Photoresist
  - Real-time registration adjustment
  - Mask savings v. traditional photoprocessing
  - Falls inline with existing equipment infrastructure

15µm Lines/Spaces with 25 µm thick resist
Laser Direct Ablation of Dielectric

- **Laser Direct Ablation**
  - Laser system used to form trenches in dielectric
  - Trenches are plated with via fill plating technology
  - Surface material is removed leaving circuit traces embedded in dielectric
Summary

• Laser processing is key to providing portable and high performance computing power.

• Technology is changing rapidly with new enabling applications being consistently being discovered.

• Abundant opportunity for process control through variation of laser beam parameters (e.g., wavelength and fluence) and material properties.

Thanks for your attention.

QUESTIONS?