Picosecond laser processing of semiconductor and thin film devices

Brian Baird
Summit Photonics LLC
January 26, 2010

Topics

- **Introduction and Source Architectures**
- Semiconductor Micromachining
- Memory Processing
- Thin Film Device Microprocessing
- c-Si and Thin Film Solar Cells
- Emerging Technology and Processes
Pulsed lamp-pumped Nd:YAG lasers entered the trimming and marking laser systems markets in the 1970s.

Pulsed diode-pumped Nd:YLF lasers entered the commercial systems market in 1988 (Spectra-Physics Model 7950 employed on the ESI Model 9000)

In the mid 1990s, 266 nm and 355 nm pulsed harmonic solid state lasers achieved wide adoption.

Over the past decade, ps DPSS, hybrid, and fiber lasers have begun to enter the industrial laser processing market.
ps Materials Processing

- **Seed Sources**
  - Bio-Medical

- **High speed processing**
  - Medical, Polymers, Scribing...

- **Ultrafast Fiber lasers**
  - Comfort Zone Now
  - Fianium - UVP 355 Fibre

- **Coherent DPSS**
  -特朗普 TruMicro
  - Lumera, TBP, HIQ DPSS

**Pulse Energy**
- 1mJ
- 100uJ
- 10uJ
- 1uJ
- 100nJ
- 10nJ
- 1nJ

**Average Power**
- 1mW
- 1W
- 10W
- 100W
Ultrafast Process Timescales


ps Solid State Photonic Source Architectures

- DPSS MOPAs and regenerative amplifiers
- Hybrids (tandem amplifiers) employing fiber front end coupled to solid state amplifiers
- All fiber
Time Bandwidth ps DPSS Lasers

Amplifier domain low speed

- 1 mJ
- 100 µJ
- 10 µJ

Repetition rate

- 1 kHz
- 10 kHz
- 100 kHz
- 1 MHz
- 10 MHz
- 100 MHz

Pulse energy

- 1 µJ
- 10 nJ
- 1 nJ

Oscillator domain low energy

- 100 nJ
- 10 nJ
- 1 nJ

FORTIS™
FUEGO™
DUETTO™
ARGOS
CHEETAH™

Summit Photonics
Tandem Amplifier Concept

A Hybrid Approach to Peak Power Scaling

- Employ DPSS amplifier to boost peak power and output energy per pulse while producing well defined *tailored temporal* pulse output
- Match gain spectrum of fiber and solid state medium to allow stable harmonic operation
Tandem Amplifier 32 Experimental Setup

2-Stage, single pass Nd:YVO₄ Amplifier

Amplifier Concept

**New:** Single or double pass
Low Input Power Module **LP**

Standard Module **MP**

**New:** High Power Module **HP**

Flexible power scaling (10-100W) by type and number of modules
cw to ps-pulse regimes

 Summit Photonics
MP-Module CW Single Pass Results

![Graph showing output power vs input power for different numbers of stages.](image)
Talisker - Picosecond Industrial Hybrid Laser
The Promise of All-Fiber ps Lasers

- Traditional ultrafast lasers have often been bulky, complex and expensive
- Benefits of fiber lasers – compactness, reliability, and reduced maintenance
- Improvements in DPSS and emergence of fiber lasers enables industrial applications
Fianium FP1060 ps MOFPA

- Flexible repetition rates
  - > 1 MHz for high throughput
  - Energy per pulse > 10 uJ
  - Excellent beam quality
  - Single shot and burst mode for flexibility and control
  - Peak powers up to 500 KW → 4 MW
Topics

- Introduction and Source Architectures
- **Semiconductor Micromachining**
- Memory Processing
- Thin Film Device Microprocessing
- Processing of c-Si and Thin Film Solar Cells
- Emerging Technology and Processes
Scribing Results in Ultra-Low k Devices

Results:

- No delamination after laser grooving and blade dicing:

  After grooving

  After dicing

Very low debris, minimal HAZ, High die fracture strength

Summit Photonics
Silicon Micromachining – Lumera Hyper-Rapid

Hyper Rapid 50, 1064 nm, constant average power of 50W

- High rep. rate + burst: 14x removal rate

Eff. ablation rate: HYPER-RAPID 50
> 20 mm³/min

Summit Photonics
Wafer Scribing – FP1060-HE

- 1064 nm
- 10 ps
- 5 MHz
- 600 mm/sec
- 1.1 uJ

- Scribing Low-K region
- High repetition rate, low energy – pulse overlap
- No Delamination, low debris – very clean scribe
ps laser Marking of Silicon wafers

<table>
<thead>
<tr>
<th>Product</th>
<th>Tangerine fs</th>
<th>Tangerine ps</th>
<th>Tangerine sp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy</td>
<td>&gt; 10 µJ</td>
<td>&gt; 10 µJ</td>
<td>&gt; 0.5 µJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>2 MHz</td>
<td>2 MHz</td>
<td>30 MHz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&lt; 700 fs</td>
<td>10 ps</td>
<td>&lt; 100 fs</td>
</tr>
<tr>
<td>Footprint (cm)</td>
<td>120x40</td>
<td>120x40</td>
<td>120x40</td>
</tr>
</tbody>
</table>

16x16 DataMatrix marking
Processing time
72ms
Dimensions
0.5x0.5mm
2µJ @2MHz
100pls/point

Summit Photonics
Topics

- Introduction and Source Architectures
- Semiconductor Micromachining
- Memory Processing
- Thin Film Device Microprocessing
- c-Si and Thin Film Solar Cells Processing
- Emerging Technology and Processes
Laser Repair System Fab Installation

~ 100 laser memory repair systems are produced and installed annually
Absorption Contrast is Key

Professor Schawlow, an early proponent, demonstrates how to employ laser absorption contrast to selectively process a work piece.
1 μm Compared to 1.3 μm

Aluminum Links

1047 nm: Energy level just below damage threshold

1343 nm: Energy level centered in the process window
Picosecond pulse and Thresholding

Thresholding on Si substrate
ps Laser Link Processing Results

57ps IR laser pulse

35ps IR laser pulse

Summit Photonics
Topics

- Introduction and Source Architectures
- Semiconductor Micromachining
- Memory Processing
- Thin Film Device Microprocessing
- c-Si and Thin Film Solar Cells Processing
- Emerging Technology and Processes
Thin film removal for Flat Panel Displays

- Patterning of ITO on SiN for flat panel displays.
- 532nm, 5µJ, 200kHz, scan speed = 3m/s.
Topics

• Introduction and Source Architectures
• Semiconductor Micromachining
• Memory Processing
• Thin Film Device Microprocessing
• c-Si and Thin Film Solar Cells Processing
• Emerging Technology and Processes
Comparison of ns and ps Edge Isolation laser processing

**ns-system**
- Thermal regime: $6.6 \text{k}\Omega \text{cm}^2$

**ps-system**
- Thermal regime: $\leq 16 \text{k}\Omega \text{cm}^2$
- Optical regime: $\geq 24 \text{k}\Omega \text{cm}^2$

**Results:**
- Higher shunt resistances
- 1 s laser processing time
- Less damages

Summit Photonics
ps Edge Isolation of c-Si PV cells

Typical ablation behaviour for a ps-laser

Laser fluence $H_p (\text{J/cm}^2)$

Av. ablation depth per pulse $a_p (\mu\text{m/pulse})$

$H_{\text{trans}} = 1 \text{ to } 1.1 \text{ J/cm}^2$

thermal penetration zone

optical penetration zone
532 nm ps MOFPA ablation of SiN on c-Si

Speed: 4000 mm/s
Ablation threshold ~0.1 J/cm²

Goal: Remove SiN to produce metallization “streets”
Thin film removal – solar cells

- Selective removal of SiO$_2$ from silicon.

355nm
Fluence $\sim$0.11 J/cm$^2$ ($\sim$1.5 times laser ablation threshold)

532nm
Fluence $\sim$0.27 J/cm$^2$ ($\sim$2 times laser ablation threshold)

- No melt visible when using 355nm close to the laser ablation threshold.
- Some melt is visible on the silicon when using 532nm (note higher fluence).

SEM images courtesy of Nanogram

Summit Photonics
Monolithic interconnection in CIGS solar modules

Mo back contact deposition by sputtering

ZnO:Al Front contact deposition by sputtering

Scribing of Mo by laser beam

Patterning of buffer/CIGS by laser scribing

CIGS absorber deposition by vacuum evaporation

CdS or ZnS buffer deposition by chemical method

Patterning of front contact & wiring

ZnO:Al (1 µm)
CdS or ZnS (0.03 µm)
CIGS (2 µm)
Mo (1 µm)
Substrate

Summit Photonics
CIS P1 by ps ablation, low overlap

- Ps-front side and ps back side ablation
- Process speed of 2 to 20 m/s possible
- Galvanic separation perfect
- Groove width of ca. 30 µm, depth 400 nm
- No damage on the ablation ground → barrier layer functional

Summit Photonics
CIS P3 by ps ablation

- Process speed 2 m/s possible
- Groove depth of 3.6 µm → Complete separation of the ZnO-CIS-film.
- ZnO-layer (green) is chipped-off without thermal influence and micro cracks, CIS-film (turquoise) exhibits faint rims on both sides of the groove, Mo-surface (blue) is free of CIS
- Functionality has still to be validated
Laser Shipment Projections for Thin Film Scribers

Key Assumption: 0.25 Lasers/MW
Topics

- Introduction and Source Architectures
- Semiconductor Micromachining
- Memory Processing
- Thin Film Device Microprocessing
- c-Si and Thin Film Solar Cells Processing
- **Emerging Technology and Processes**
Laser Processing of Nontransparent Materials

Summit Photonics
Laser Processing of Nontransparent Materials

disordered surface layer

1 μm
Optical Hyperdoping Responsivity
LIPSS Processing of Stainless Steel

Typical processing parameters:
- Power: 10’s of mW
- Raster pitch: 5um
- Scan speed: 5-600mm/sec
Silicon scribing and LIPSS texturing

11 µm width groove – depth 6 µm

Parallel grooves

Crossed grooves

Silicon Texturing (black silicon)
Flexible Pulsewidth ps fiber oscillator

- Narrow spectrum: < 1 nm
- Linearly polarized
- 1064 nm central wavelength

- Adjustable pulse duration: 30 ps < τ < 300 ps
- Repetition rate: > 5 MHz
- Oscillator output pulse energy: 1-10 nJ.

US Patent application No 12/498,072
Amplification limits of ps pulses in silica fibers @ 1064 nm

**SRS** → Maximum peak power

Amplitude noise on the optical pulses as a function of their peak power normalized to the effective area of the amplifying fiber.

**SPM** → Spectral broadening

Spectral broadening of the pulse as a function of their peak power normalized to the effective area of the fiber.

\[
\Delta \lambda_{FWHM} [nm] \approx 300 \frac{P_{peak} [kW]}{\Delta t_{FWHM} [ps] A_{eff} [\mu m^2]}
\]
Summit is a provider of **Photonics Engineering Services**

- Founded June, 2008
- Office and lab facility in Portland metro area
- Laser processing system architecture design and system selection and evaluation
- Laser source evaluation, design, and selection
- Advanced laser process development and evaluations
- Photonics intellectual property evaluation and creation
  - IP rights assignment
- Photonics “gap” engineering solutions
Summit Laser Application Lab
Summary and Outlook

• Industrial picosecond laser processes are being adopted for semiconductor and solar cell manufacturing.
• LIPSS applications represent an important area of research and emerging industrial applications.
• High pulse energy applications will continue to be dominated by ps laser solutions employing solid state power amplifiers.
• All fiber ps lasers will compete successfully in the thin film (PV and display) and semiconductor IC markets.
Acknowledgements

- Bob Hainsey (ESI)
- Sean Peng (ESI)
- Jeff Albelo (ESI)
- Joohan Lee (GSI)
- Kurt Weingarten (TBP)
- Eric Mazur (Harvard)
- Mark Keirstead (Coherent)
- Colin Moorhouse (Coherent)
- Robert Braunschweig (A-S)
- John Clowes (Fianium)
- Pascal Deladurantaye (INO)
- Yves Taillon (INO)
- Maik Frede (LZH)
- Dietmar Kracht (LZH)
- Viktor Schuetz (LZH)
- Heinz Huber (HiQ)
- Uwe Stute (Trumpf)
- Peter Herman (U. Toronto)
- Ralf Knappe (Lumera)
- Dirk Muller (Lumera)
Thank You!

Questions?

Summit Photonics