LXA: Nanosecond Laser Anneal for sub-10nm

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Ultratech

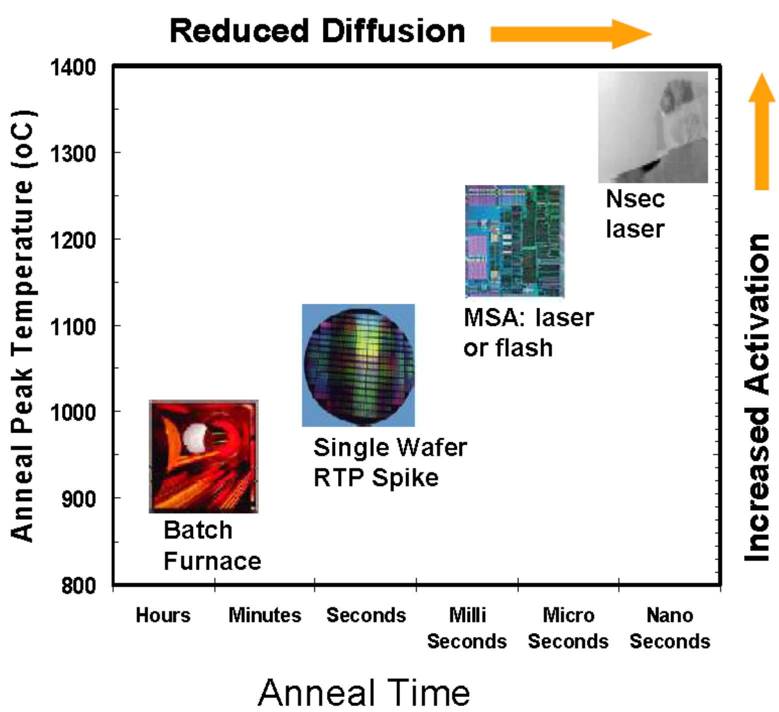
History of Laser Technology at Ultratech

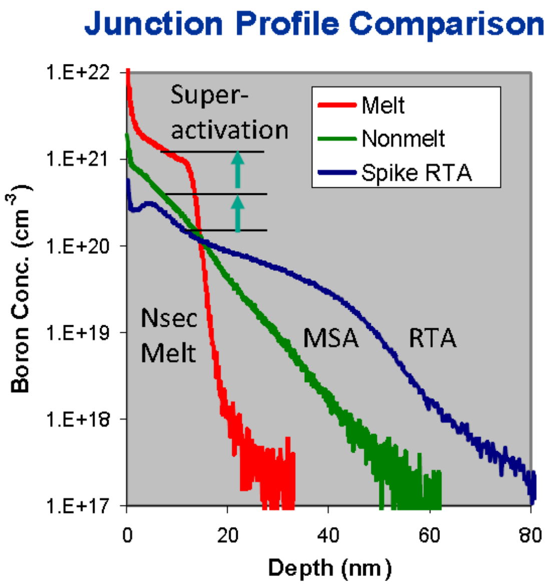
94	Acquire PGILD Patents and initiated laser processing program
97	Delivery of laser PGILD melt system
99	Begin sub-melt technology research
00	License laser technology to leading equip. supplier
05	Delivery of first LSA production system
06	LSA100 in 65nm logic production
08	LSA100 in 45nm logic production
10	LSA101: POR for 28nm at all logic foundries
12	Ship 50th LSA System
13	Ship LSA201 w/ ambient control
15	LSA101/201 "Turbo" and "A"
16	**Ship LXA beta system**

Intellectual Property:

Ultratech has over 1000 patents and patent applications in all technologies with 250 in laser processing technology

Thermal Annealing Evolution





Trend to shorter time-scale spike anneal continues and is driven by a combination of

- Scaling
- Materials
- New Architectures and Structures (e.g., Nanowire, 3D IC)

NSA – Nanosecond Anneal

- The next frontier for laser thermal annealing (LTA) is extension to nanosecond time scales.
  - Anneal time scales on the order of 50-100ns
- Primary driver has been melt anneal for junction formation.
  - Additional material-modification applications are likely.
- Traditional approach to NSA uses pulsed laser system for the nanosecond exposure.
  - UV (e.g., Excimer)
  - Visible (e.g., Frequency doubled YAG:Nd^+)

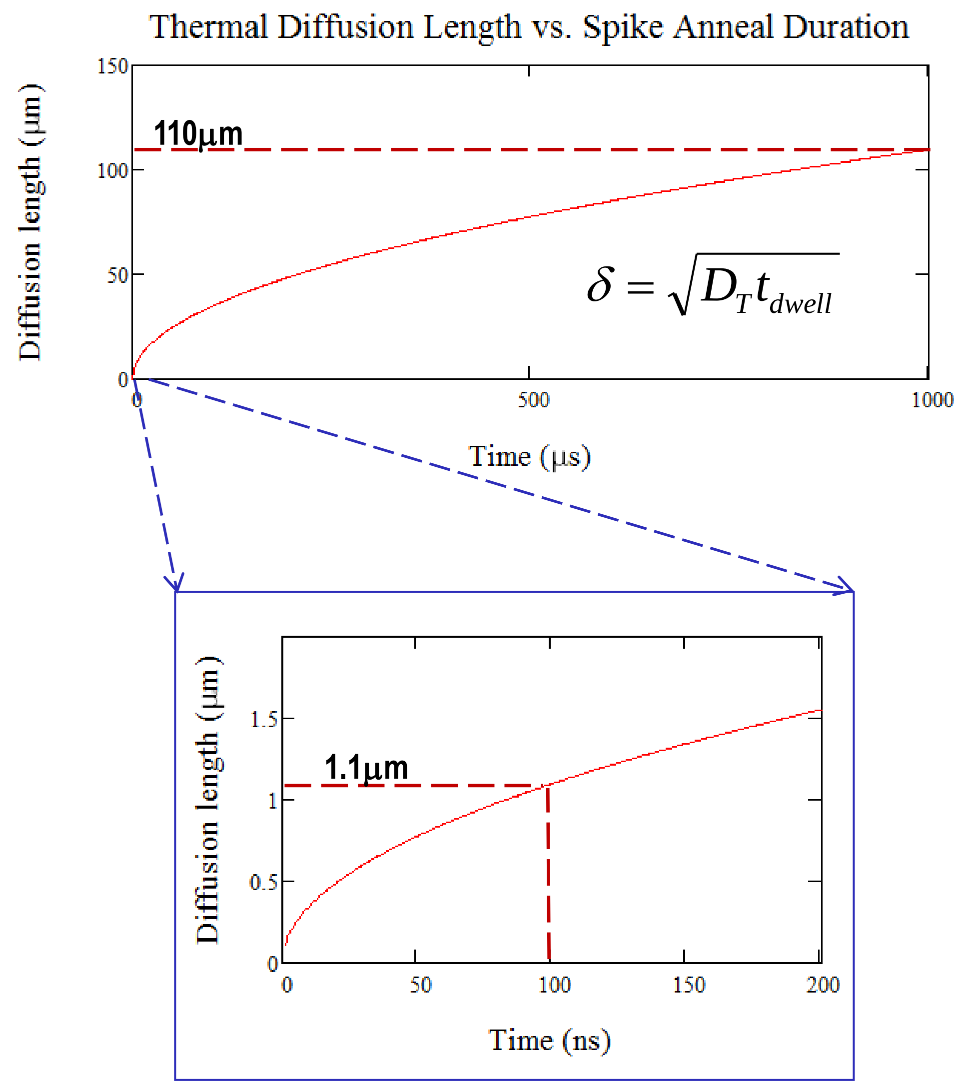
Challenges with NSA

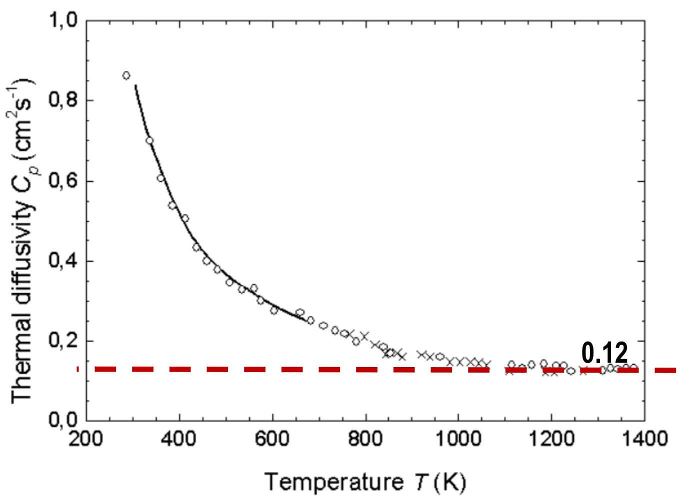
- **Approaching NSA system design using a traditional step-and-repeat pulsed-laser based architecture has a number of challenges.**
  - **Thermal pattern loading effects.**
  - **Within-field uniformity.**
  - **Pulse-to-pulse repeatability.**
  - **Scribe line exposure (test structures).**
  - **High pulse energy requirement.**
    - Drives cost, limits throughput.
- **Ultratech has developed a novel NSA architecture (LXA) that addressed these challenges.**

Thermal Pattern Loading Effect

- **During laser spike annealing, thermal averaging occurs over a distance scale given by the thermal diffusion length, δ.**

- **δ is a function of material properties (thermal diffusivity, D_T) and the duration (dwell time) of the laser anneal, t_{dwell}.**

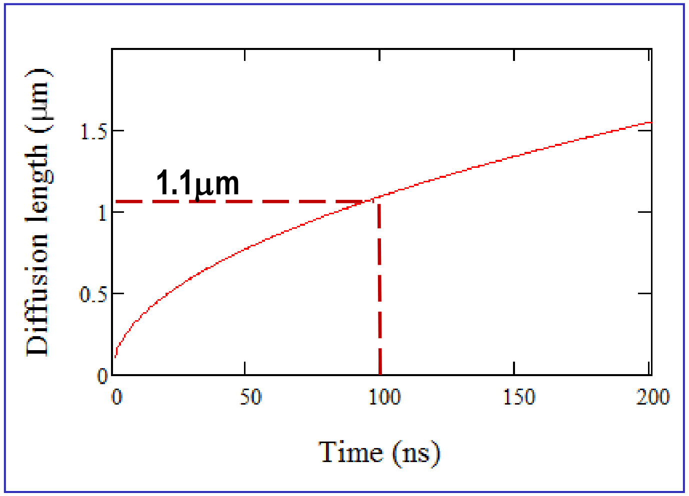




Shanks, H. R., P. D. Maycock, P. H. Sidles, and G. C. Danielson, *Phys. Rev.* 130, 5 (1963) 1743-1748.

Thermal Pattern Loading Effect

- The thermal diffusion length establishes the length scale over which areas with different optical absorption will arrive at the same temperature due to thermal diffusion.
- Changing anneal time scale from millisecond regime to ~100ns time scale reduces the thermal diffusion length by two orders of magnitude.



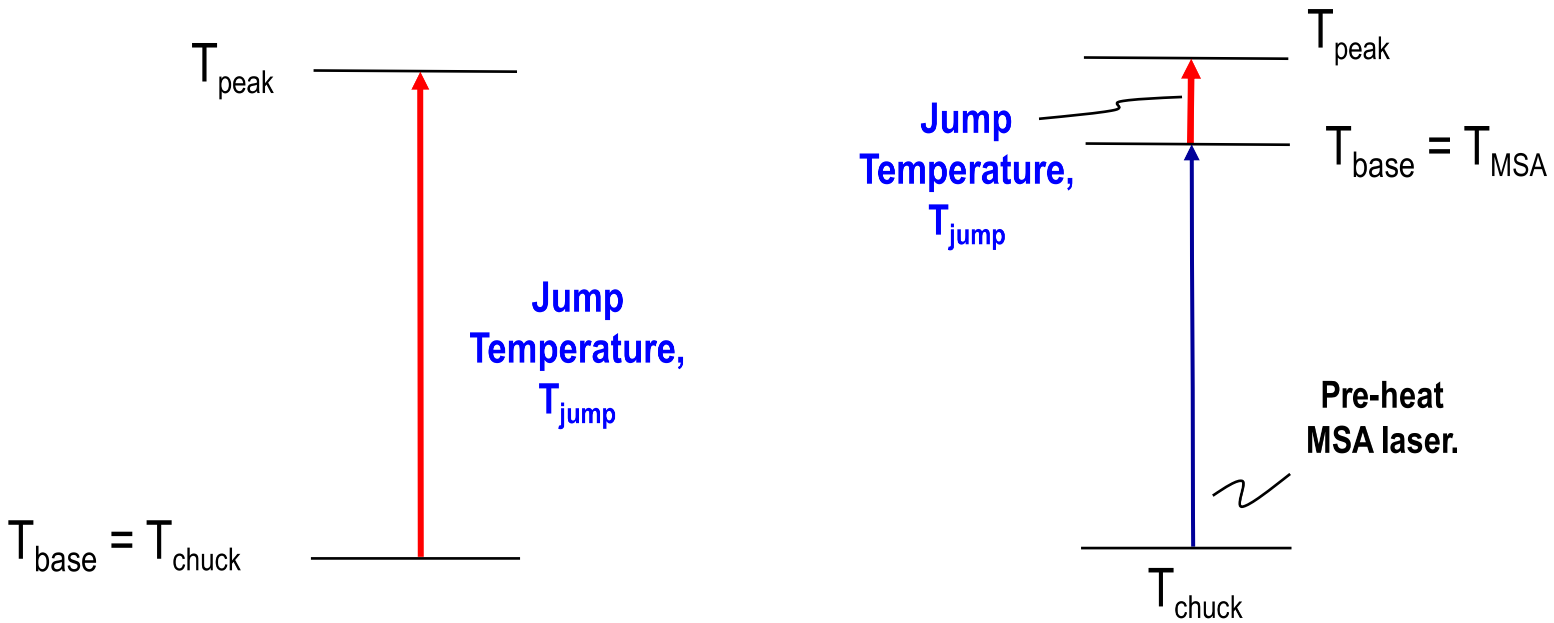
- Differences in optical absorption spatially separated by >1μm range are no longer thermally “connected” during the anneal, and will come to their own, local temperature based on local absorptivity.
- This has process implications for laser spike annealing in the NSA regime.
  - Dumification becomes more complex
  - Capping layer adds process complexity and cost.

LXA Design Concept

Conventional Melt vs. LXA

Conventional Melt

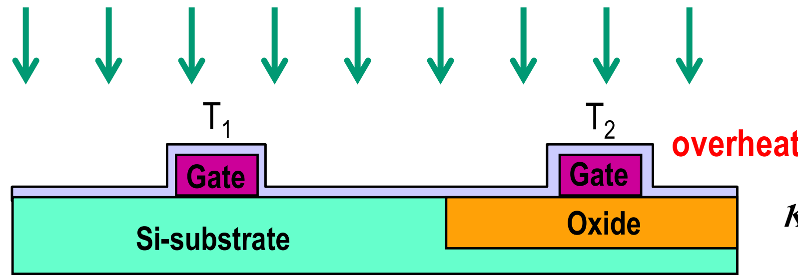
LXA



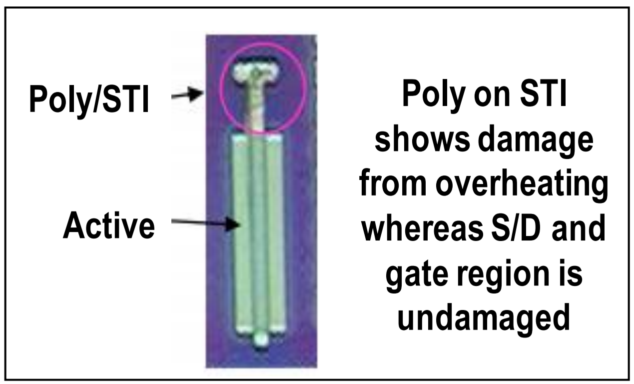
- **Basic LXA concept: Perform NSA in combination with MSA.**
  - **A pre-heat laser providing MSA**
  - **A second laser provides the NSA.**
- **NSA Jump temperature is an order of magnitude smaller compared to conventional.**
- **MSA laser preheating + nanosecond laser enables nsec anneal with reduced pattern effects, and eliminates the need for absorber layer.**

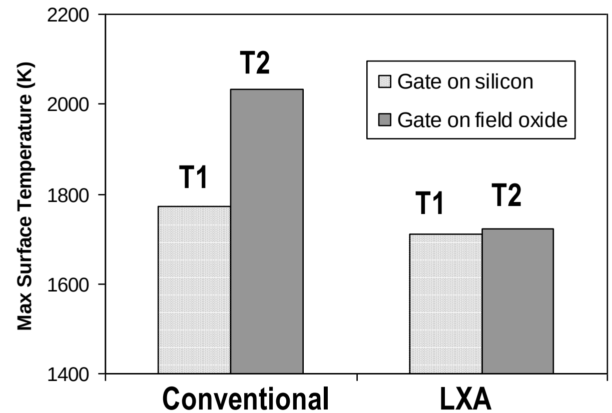
MSA = Millisecond Anneal

Pattern Effect In nsec Annealing



$$\kappa_{ox} << \kappa_{si}$$



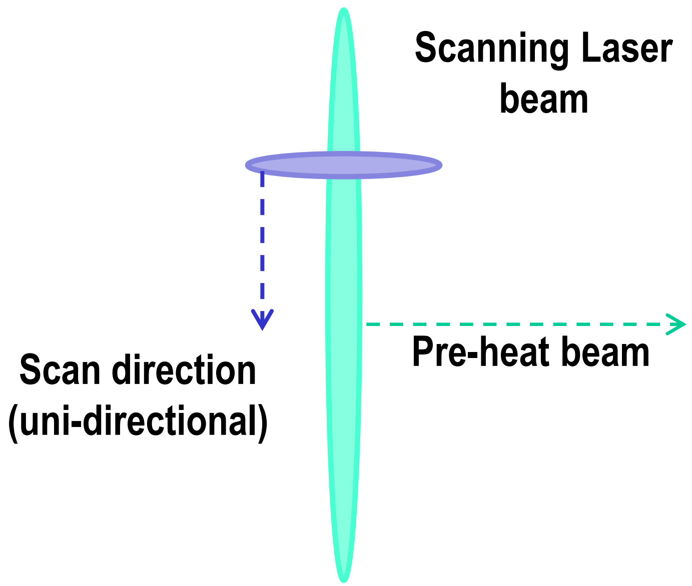


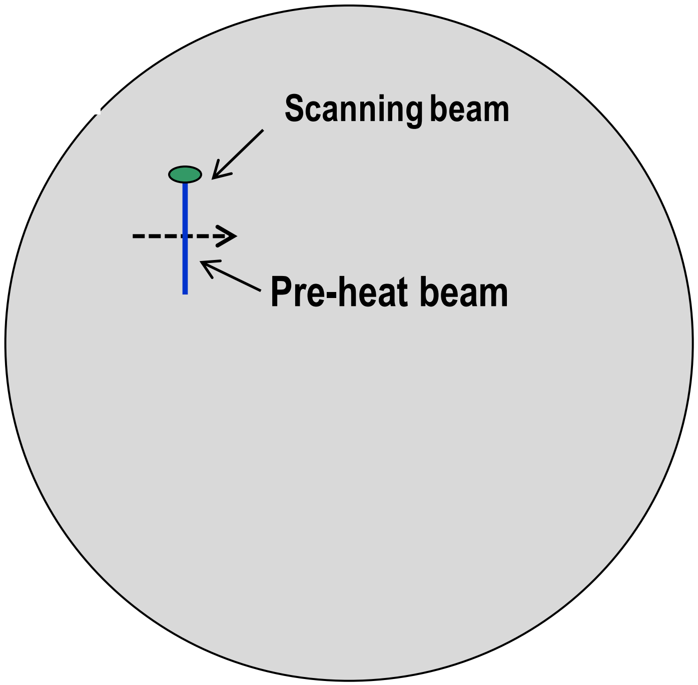
- Pattern effects in nsec dominated by inhomogeneous thermal property →may be difficult to dummify due to smaller heat diffusion length.
- msec preheating + nsec laser significantly reduces pattern effects.

LXA w/o a Pulsed Laser

- Basic LXA concept provides advantage in terms of thermal pattern effects.
- Most of the other NSA challenges listed result from use of a pulsed laser for the nanosecond-scale exposure.
- Ultratech developed LXA alpha using pulsed laser for NSA.
- Now developing an LXA architecture that avoids use of a pulsed laser.
  - Achieve nanosecond exposure using a CW laser with a laser scanner.
  - “Flying spot” provides nanosecond-scale thermal anneal.
- Alpha-II system using “Flying Spot” was completed earlier this year.
  - Beta system delivery targeted end of 2016.

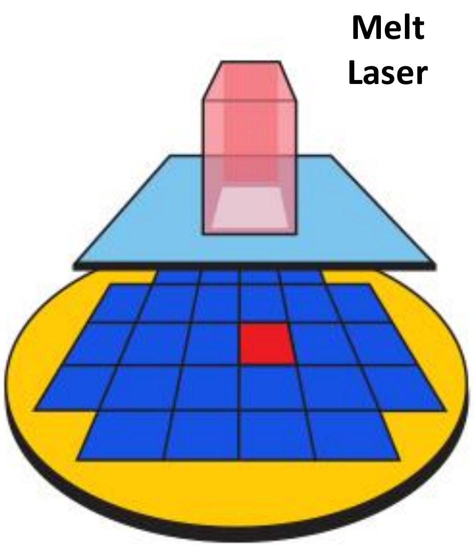
Scanning Laser Concept





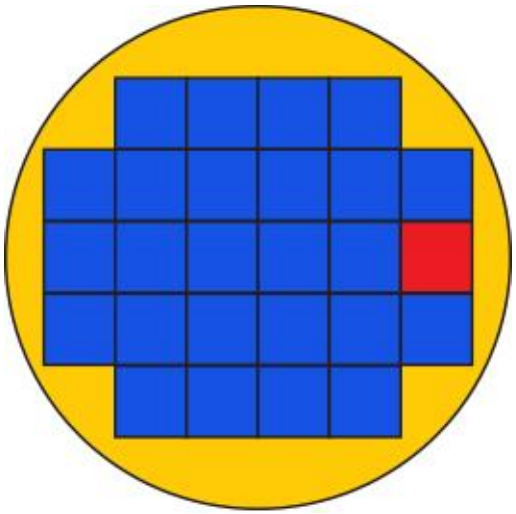
- MSA beam profile is top-hat in long axis, Gaussian in short axis.
- The NSA beam is a Gaussian-Gaussian ellipse and scanned (uni-directional) along a MSA pre-heat beam.
- MSA beam raster's across wafer similar to traditional LSA.
- Size of NSA spot and speed of scan provide exposure of 75-200ns
  - Adjustable NSA exposure by changing scan rate.
- Wafer is on a heated chuck.
  - $T_{substrate}$ range is 150C – 400C

NSA Hardware Implementation



(a) Conventional Pulsed Melt

NSA Hardware Implementation

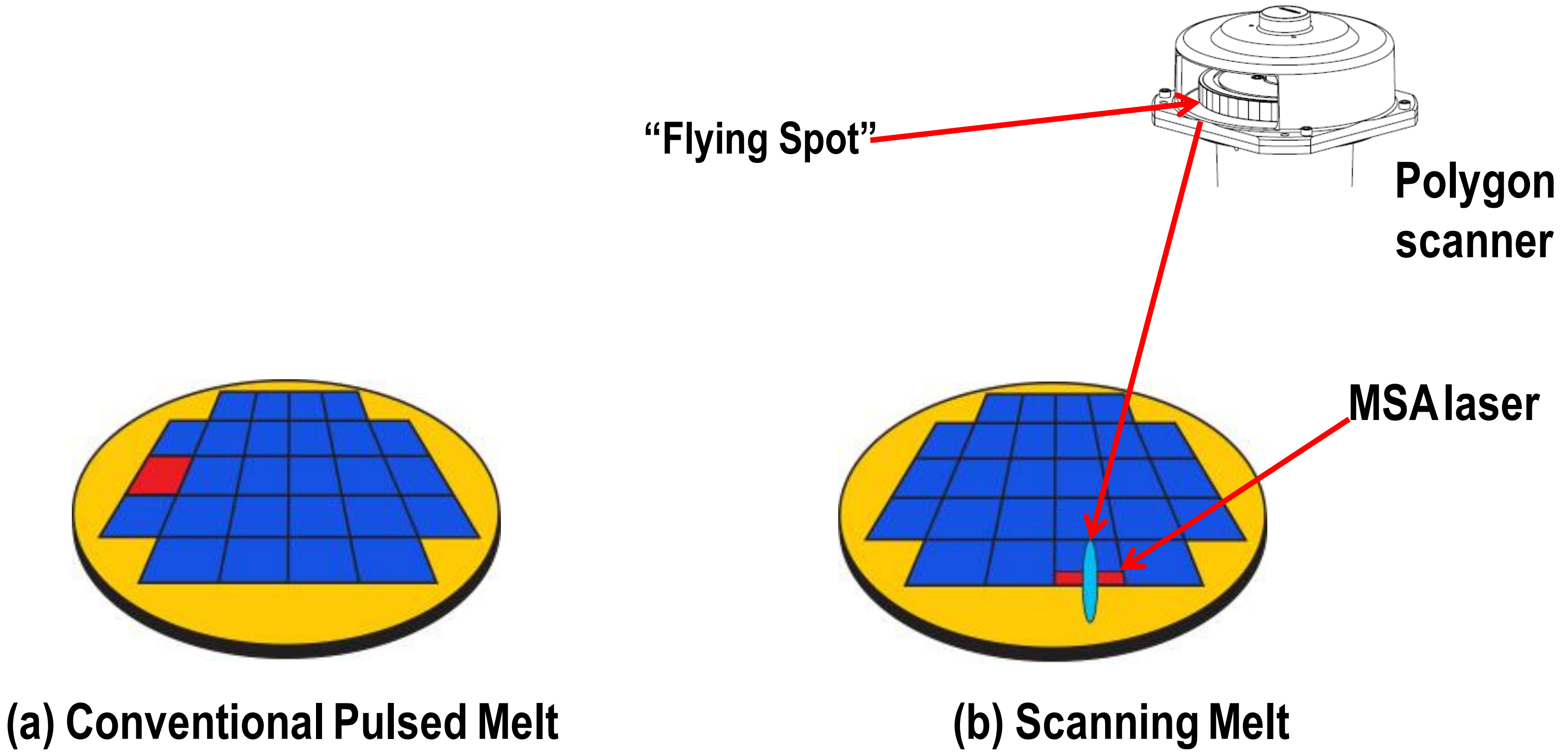


(a) Conventional Pulsed Melt

Pulsed Melt Issues:

1) Full field illumination uniformity
2) Pulse to pulse repeatability
3) Pattern effects
4) In-situ temperature measurements are impossible
5) Scribe line exposure (test structures)

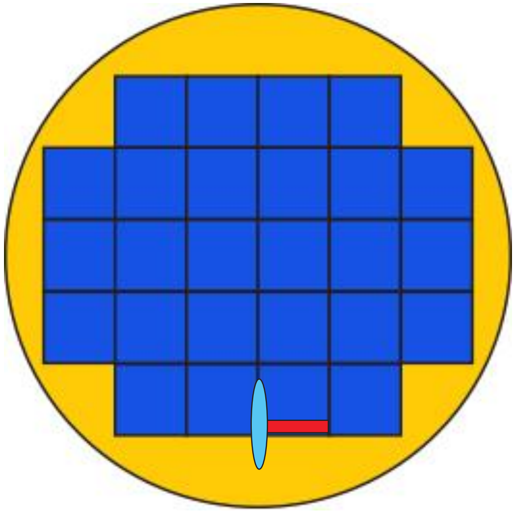
NSA Hardware Implementation



NSA Hardware Implementation

Advantages of LXA w/ CW laser "Flying Spot"

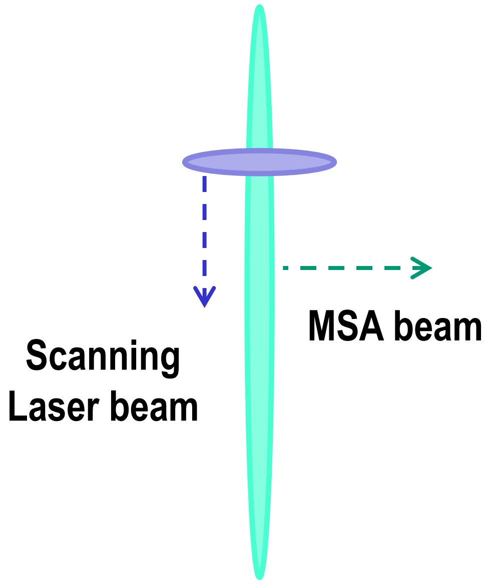
1) More stable beam profile
2) More stable laser intensity
3) Fewer pattern effects
4) In-situ temperature measurements are possible



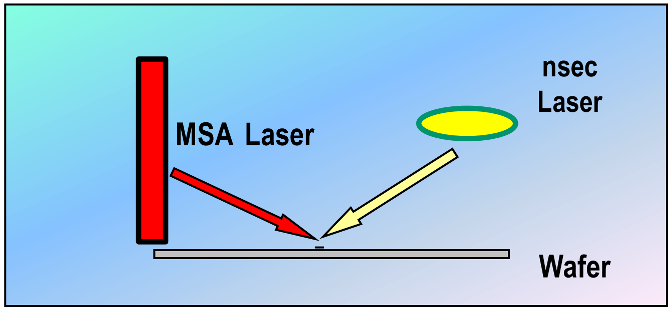
(b) Scanning Melt

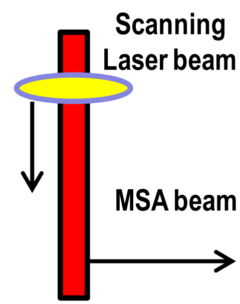
Overview of Scanning LXA

- Use CW laser for NSA source.
  - Focused to a spot at wafer.
  - Spot is scanned using commercial scanner system.
- Superimpose scanning spot on MSA laser stripe.
  - Forms a Gaussian-Gaussian ellipse at wafer plane.
  - Long axis is > than MSA short axis (alignment tolerance).
  - MSA laser has real-time temperature feedback to maintain stable pre-heat temperature.
    - Similar to Ultratech LSA101 temperature feedback system.
- Integrated metrology built into scanning system.
  - Emission detection system designed in, field of view follows the spot.
- Process Flexibility
  - Can vary NSA exposure time.
    - Scan rate is variable.
  - Can vary the MSA pre-heat temperature.
  - Can vary the substrate temperature
    - 150C to 400C

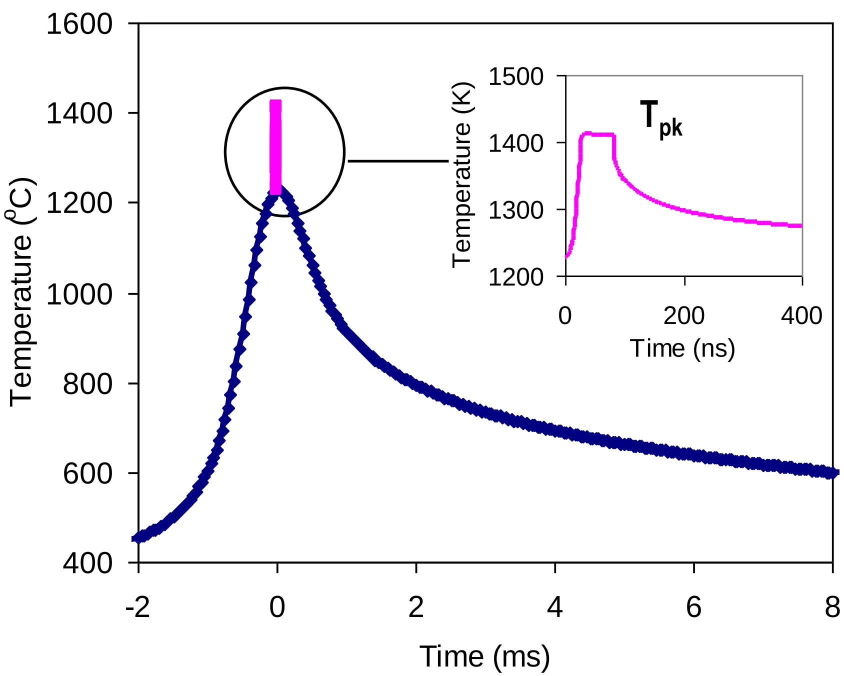


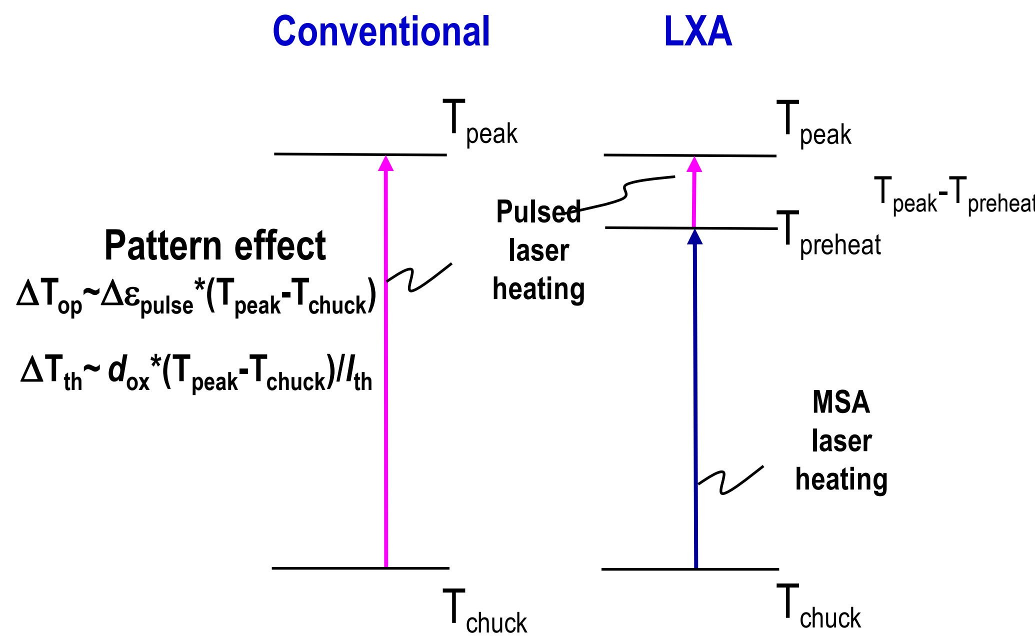
LXA: nsec LTP with MSA Preheat





- Wafer is pre-heated by MSA beam.
- Nanosecond exposure by a second scanning, or "flying spot", laser.
- Exposure time determined by flying spot velocity and width.

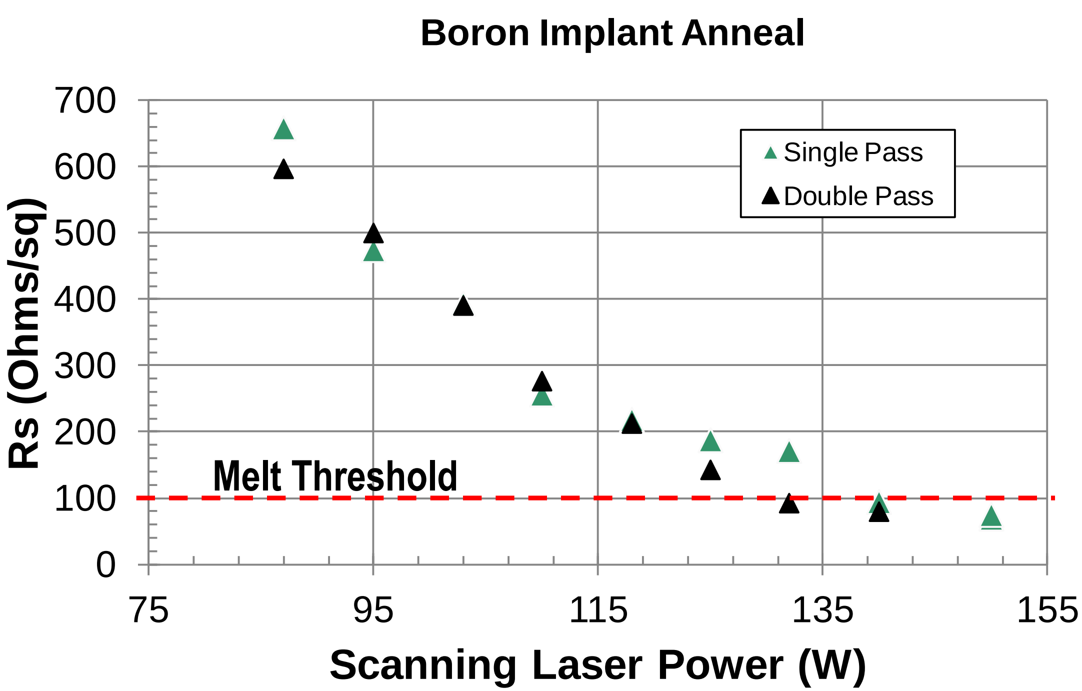




Full Field Melt Tool vs. LXA

	Full Field Melt Tool	LXA
Approach	Full Field (Full Die) Step-and-Repeat Melt	Raster scanning over entire wafer with non-melt laser; melt laser provides additional power to melt small regions.
Pre-melt Wafer Temperature	Chuck temperature (typically 400°C)	LSA "spike" temperature (range 850°C to 1100°C)
Temperature Rise Due to Melt Laser (ΔT)	Approximately 850°C	Approximately 150°C
Temperature Non-Uniformity (Pattern Effects)	$= \Delta R * \Delta T$ ~ 30% * 850°C = 255°C	$= \Delta R * \Delta T$ ~ 30% * 150°C = 50°C
Test Devices in Scribe Lines	Due to the beam roll-off, the test devices in scribe lines are not annealed similarly.	With raster scanning, all test devices are annealed similarly.
Laser Repeatability	Pulse to pulse laser repeatability is typically ~5%, adding 40°C to die-to-die temperature non-uniformity.	No pulse-to-pulse variations. CW scanning laser: ~1% stable (~1-2°C)
Beam Uniformity	Making a flat top beam from a coherent source: typical 5% peak to valley. Will add another 40°C temperature non-uniformity	Gaussian beam is stable and well defined.
Total Temperature Non-uniformity	~325°C	~50°C

LXA Prototype Test Results

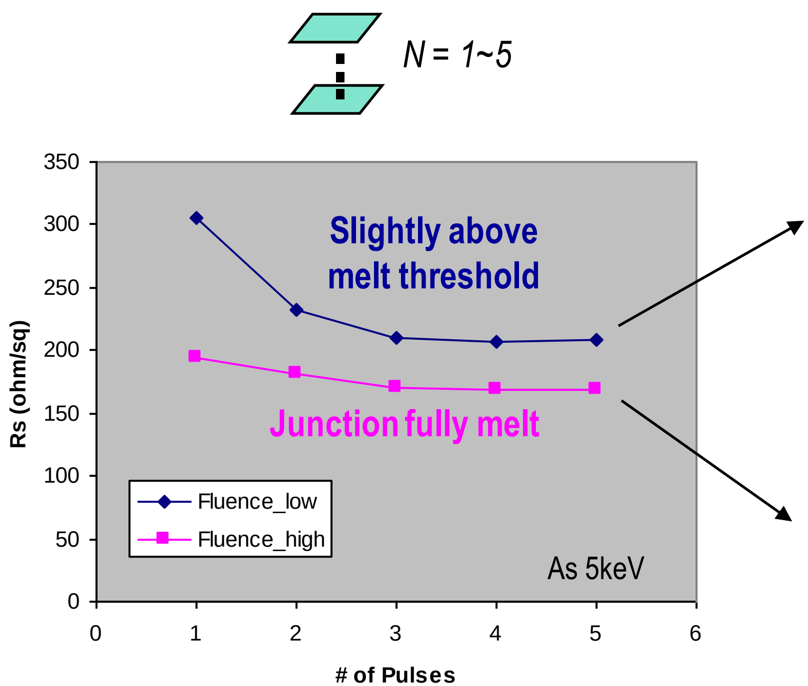


- **Boron Implant Anneal.**
- **Conditions:**
  - **Scanning laser:**
    - 75ns exposure
    - Power varied
  - **MSA laser:**
    - 400µs dwell time
    - 950C pre-heat condition.

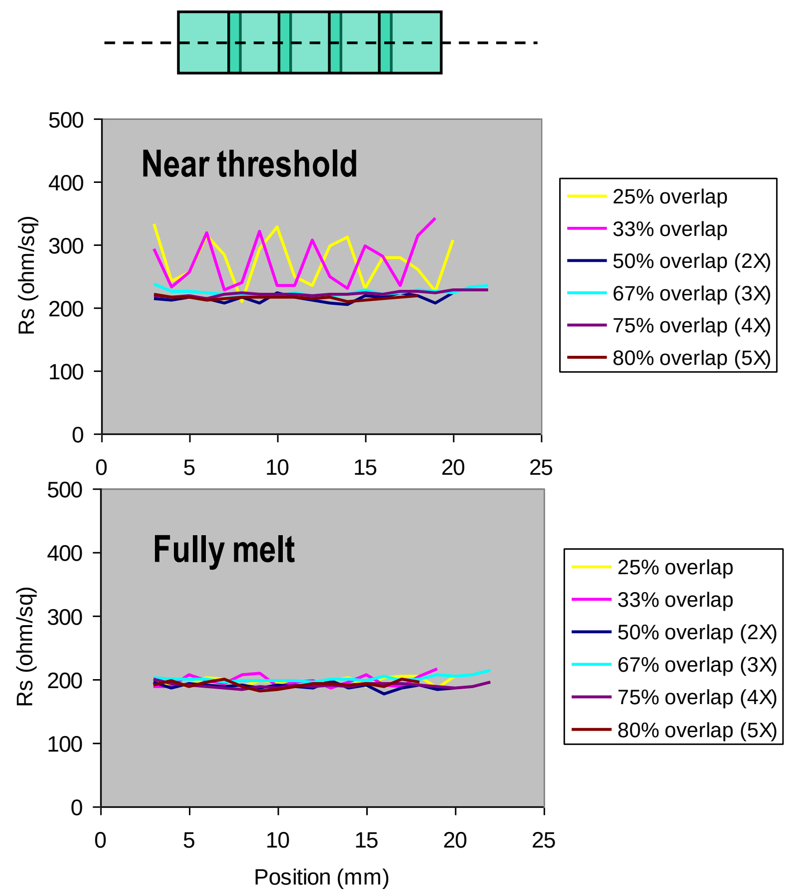
Stitching Experiments

This work was done using Ultratech “alpha system”.
Diode laser preheat and pulsed laser used for ns anneal.

(a) Same location multiple pulses



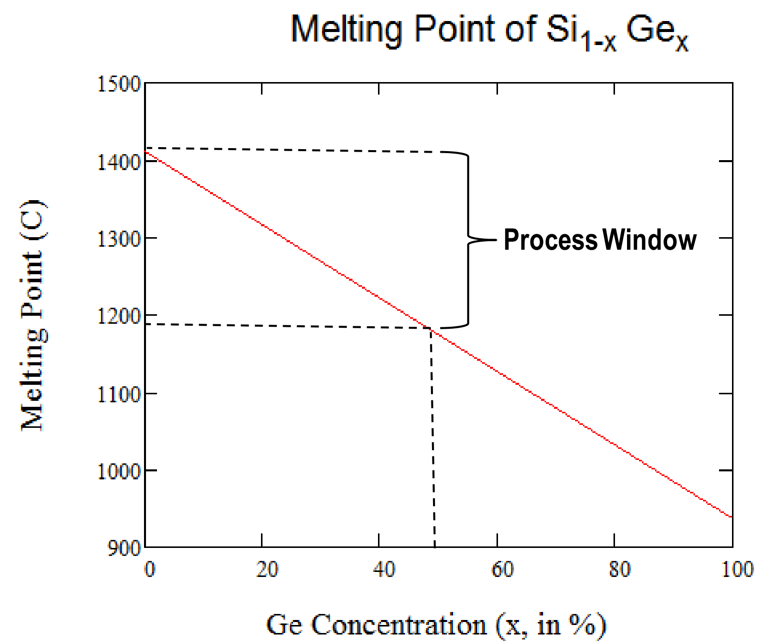
(b) Different overlap



- **Effects of stitching can be optimized by pulse overlap & fluence**

Process Window Example

- NSA will be used to change material properties via a melt anneal of a specific structure/material.
- In all of these cases, the melt temperature for the desired process is less than the melt temperature for the surrounding Si substrate.
- The difference between the target melt temperature and the melt temperature of the Si establishes the process window.
- Example: $Si_{1-x}Ge_x$
  - 50% Ge melt temperature ~1200C
  - Bulk Si melt temperature is 1414C
  - Process window ~200C



Summary

- Ultratech is the industry leader in laser thermal annealing technology.
  - More than 20 years experience developing LTA technology and processes.
  - First to deliver melt technology to the industry.
  - Strong IP position for both melt and sub-melt LTA.
- Sub-melt MSA has been main market for LTA since 65nm
  - But NSA LTA is emerging as a requirement for 10nm and below.
- Ultratech has a novel approach to NSA LTA
  - LXA concept, with NSA in conjunction with MSA pre-heat.
- Alpha versions of the LXA concept have been developed over past several years.
  - Many customer demos run on these systems.
  - Feedback is positive.
- Currently developing LXA beta system based on "Flying Spot" architecture.
  - Target delivery to our beta partner end of this year.