# West Coast Junction Users Group Meeting
# "USJ Formation for 32nm Node"

# Single Wafer Implantation Process Matching

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- KyungWon Lee



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# Outline

- Implanter Scanning Architectures
- Beam and Ion Flux Differences
- Thermal Modeling and Measurements
- Process Effects
- Case Study
- Conclusions



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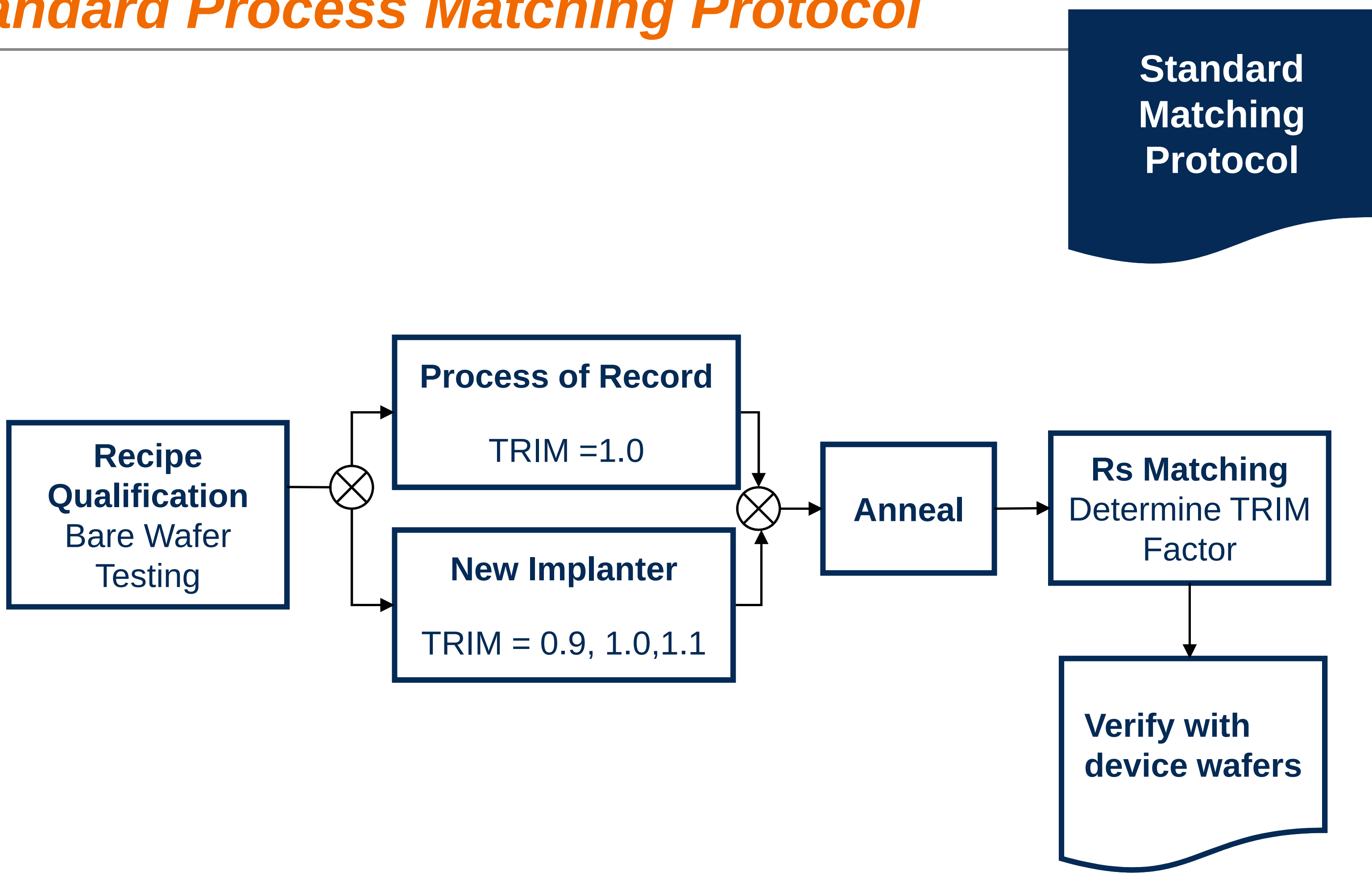
# *Introduction*

- Successful implanter architectures exist for high current implantation; spot (stationary) and ribbon beam systems
- There are differences in the beam scanning mechanisms and in the ion beams for each architecture
- The combination of scanning and beam properties directly affect:
  - Damage Accumulation Rate
  - Thermal Properties - ranging from $10^{-9}$ sec. to several seconds
  - Amorphous Layer Formation
- Understanding these variables is critical for process control, as well as for matching results across platforms
  - Successful strategies have been developed

# *Standard Process Matching Protocol*



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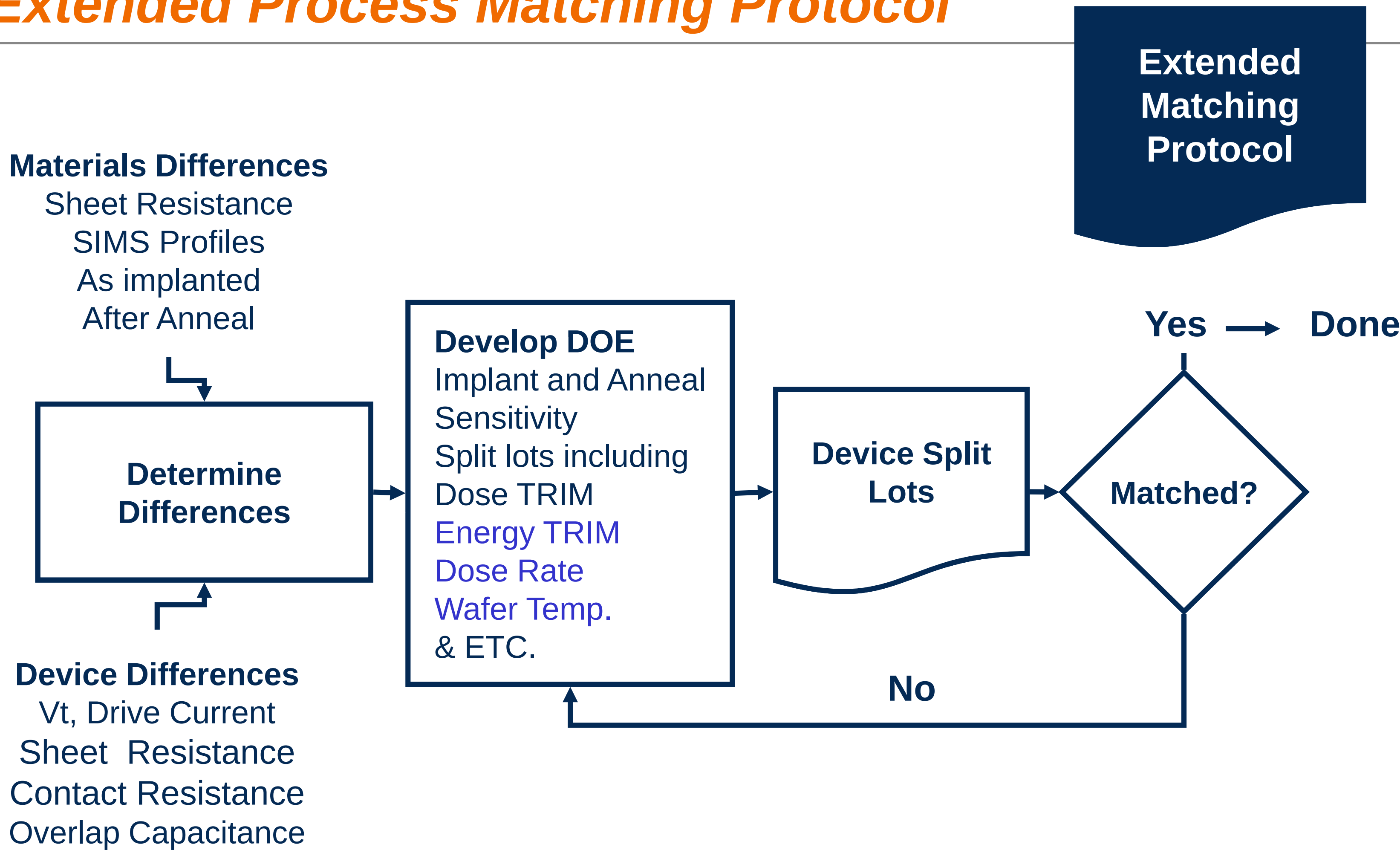
# *Extended Process Matching Protocol*



# Definitions

## Peak Dose Rate

- The instantaneous rate of arrival of ions to the surface, ions/cm$^2$/s

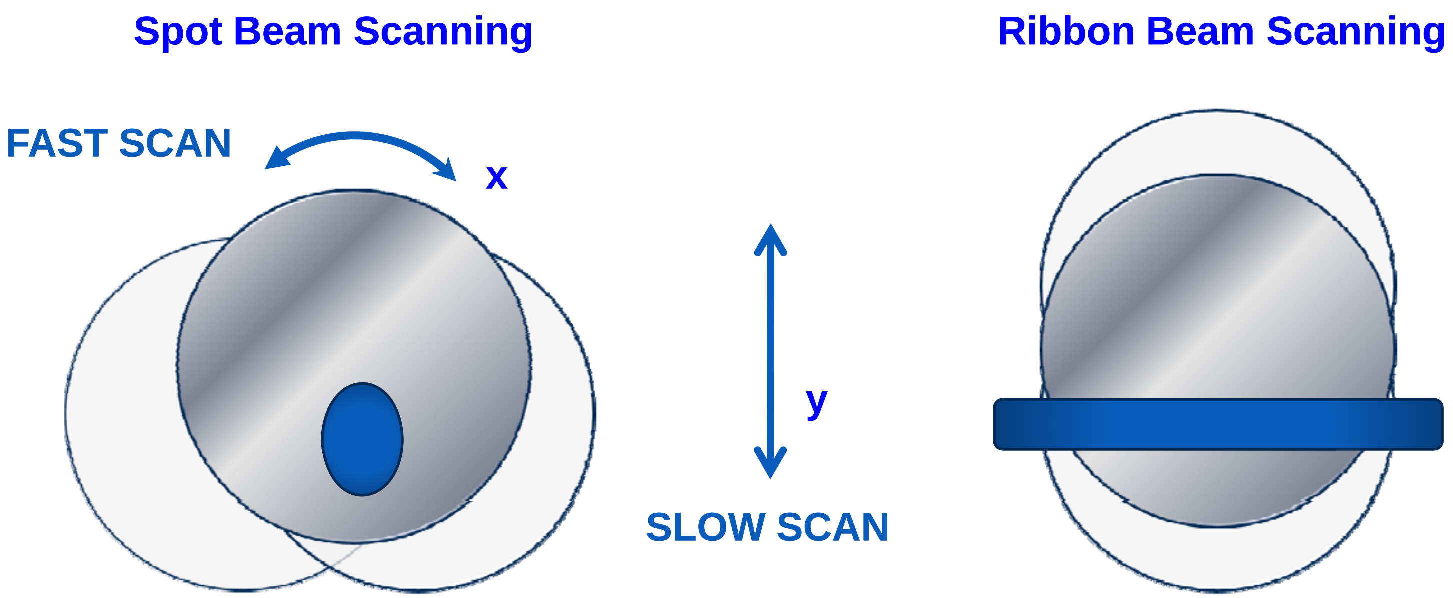
## Effective Dose Rate

- The dose rate averaged over an entire wafer, or a spot on the wafer

## Duty Cycle

- Beam time on the wafer (or spot) ÷ Beam time off the wafer (or spot)

# Description of Scanning Dynamics




| Parameter | SYMBOL | 2D mechanical | 2D mechanical | 1D mechanical |
|---|---|---|---|---|
| | | 13w batch | single wafer | single wafer |
| Beam Current (mA) | $I$ | 15 | 15 | 15 |
| Beam X-Width at 3σ (mm) | $W$ | 70 | 50 | 350 |
| Beam Y-Width at 3σ (mm) | $H$ | 50 | 70 | 70 |
| Fast Scan Speed, X-direction (cm/sec) | $V_f$ | 5600 | 200 | NA |
| Slow Scan Speed, Y-direction (cm/sec) | $V_s$ | 5 | 5 | 5 |

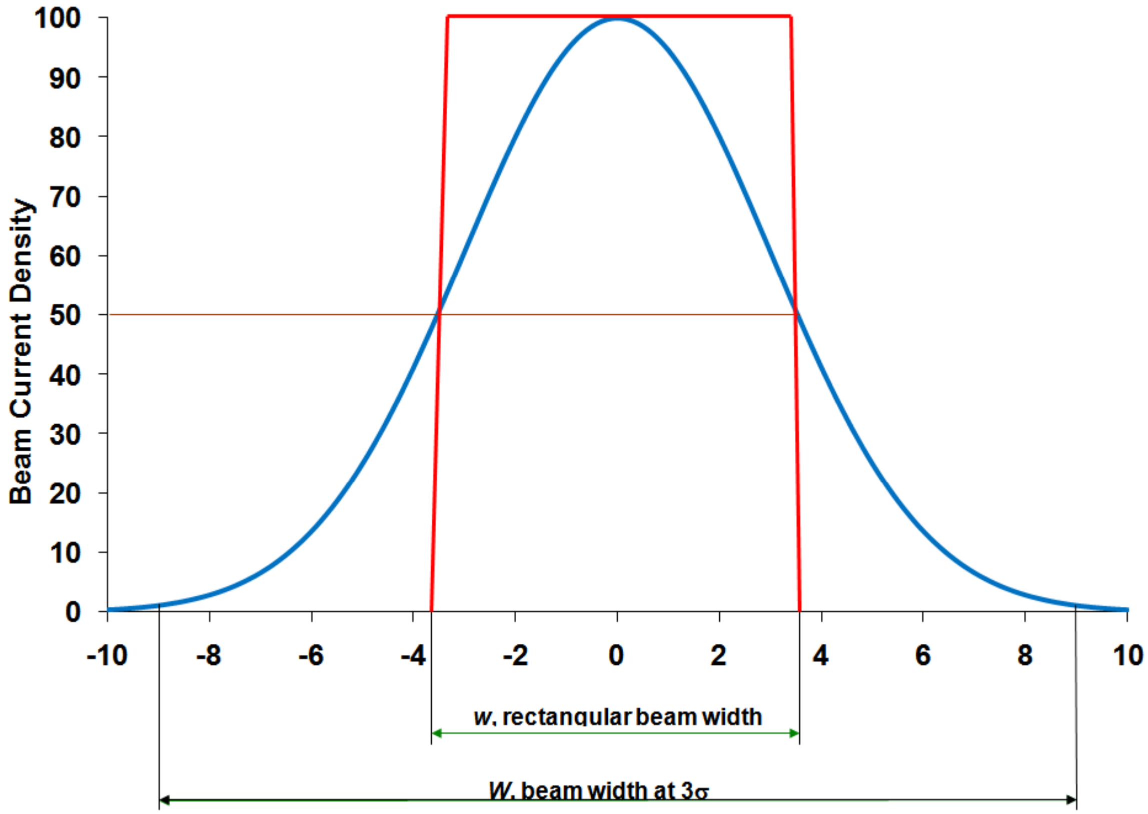
# Beam Representation

## For Comparison Purposes

**Assume a Gaussian beam (blue) and model as a rectangular beam (red)**

**It is of interest to examine the period the beam is on the wafer:**

- **Fast Scan Direction for spot**
- **Slow Scan Direction for ribbon**

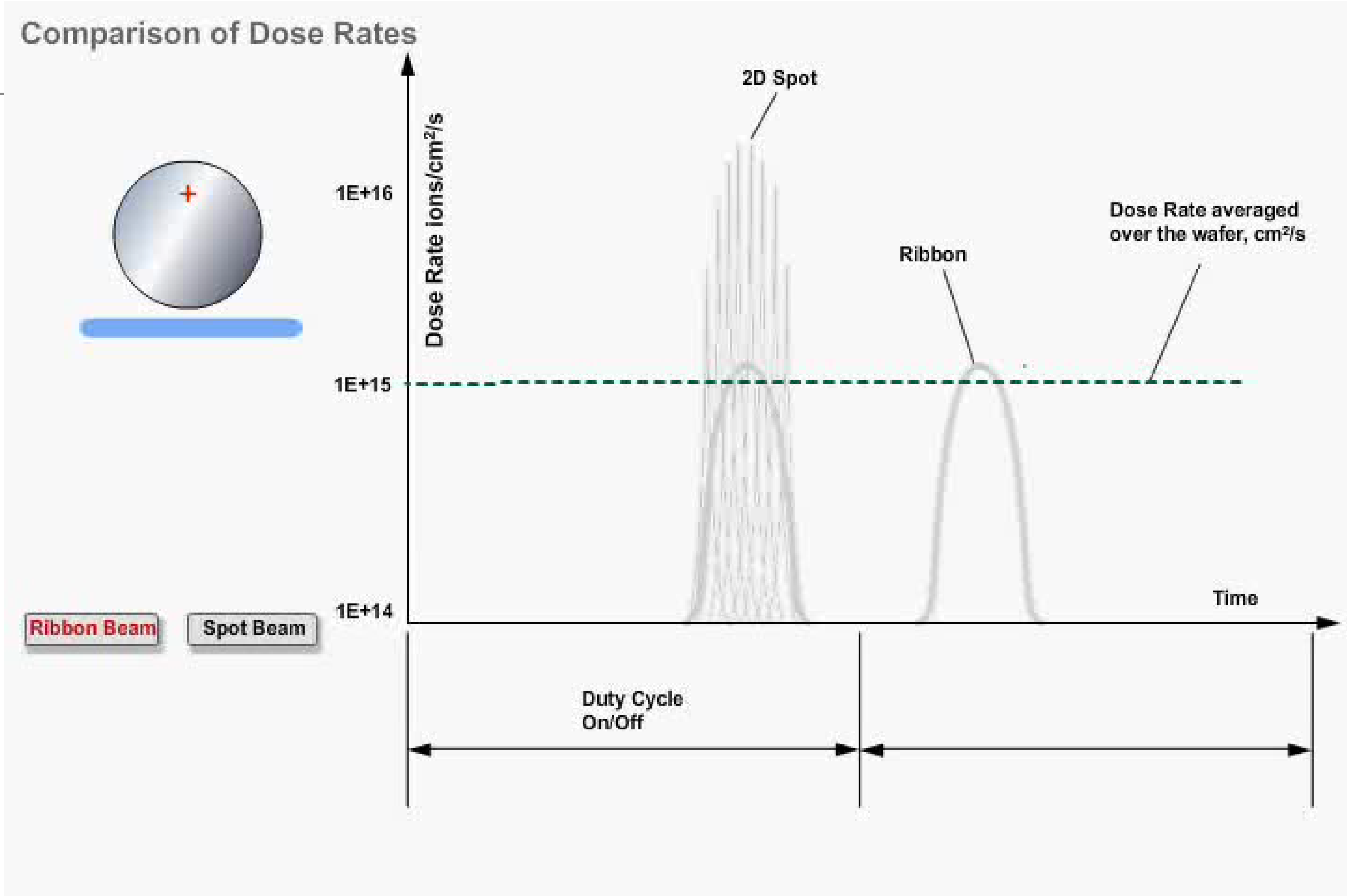


# Beam Parameters in Scanning Dynamics

## Parameter is normalized to 1 for each row

| Parameter | SYMBOL | 2D mechanical | 2D mechanical | 1D mechanical |
|---|---|---|---|---|
| | | 13w batch | single wafer | single wafer |
| Ion Beam | | spot | spot | ribbon |
| Rectangular Beam Density (uA/cm$^2$) | $j = I / (wh)$ | 1 | 1 | ~.06 |
| Ion Flux (ions/cm$^2$/sec) | $J = j / qe$ | 1 | 1 | 0.1 |
| Average Ion Flux (ions/cm$^2$/sec) | $J_{avf} = J \tau_f$ | 0.1 | 1 | 1 |
| Scan Duty Cycle (Fast Scan) | $\tau_f = T_{onf} / T_f$ | 0.007 | 0.06 | 1 |

1. Beam density is higher for the spot beam systems
2. Ion Flux is 10X for the spot beam system
3. “Average Ion Flux” is approximately the same
4. Duty cycle varies widely depending on scanning mechanism



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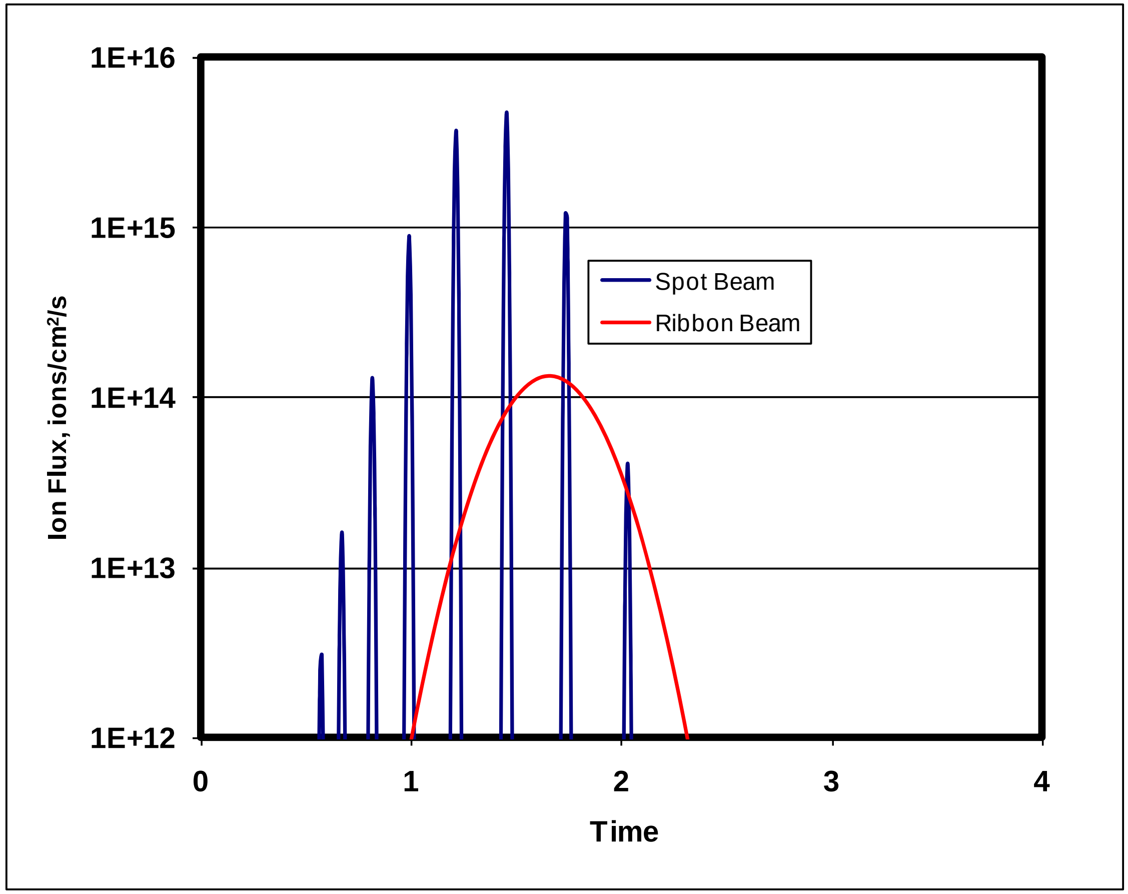
# Peak Dose Rate for Stationary and Ribbon Beam Systems

**The "Effective" dose rate of each system is nearly identical**

**The "Peak" dose rate for a spot beam is over an order larger**



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# Thermal Signatures
# Fast Scan Duty Cycle

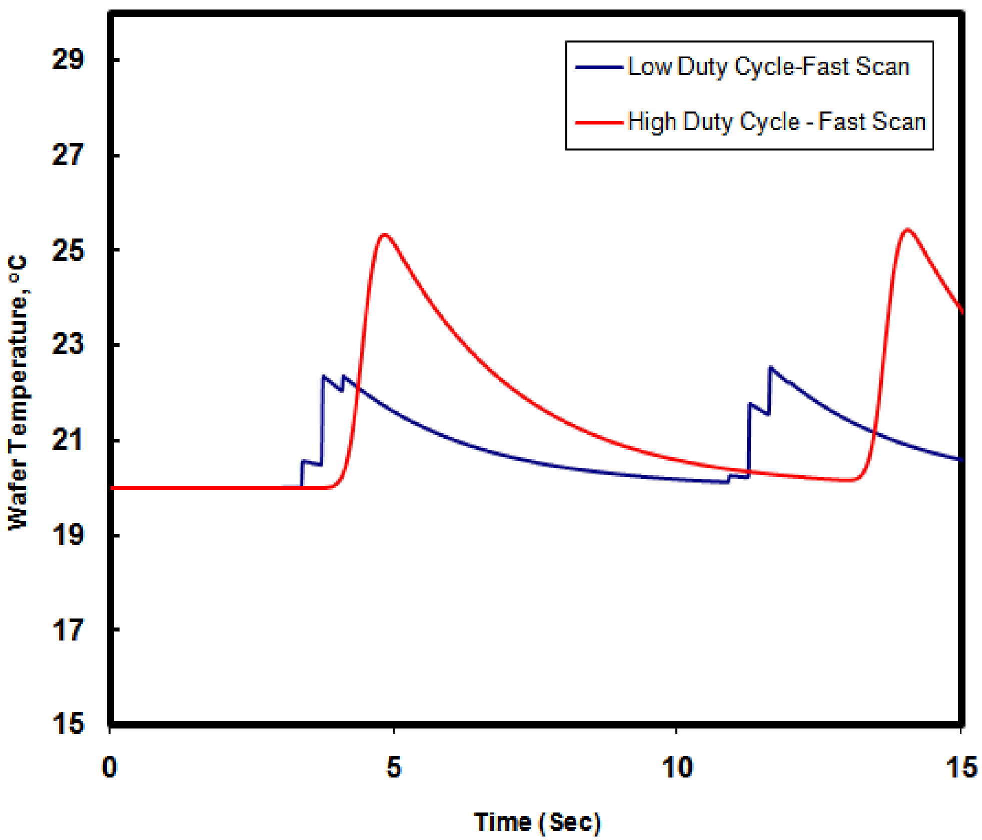
**Assumptions**

**1. Slow scan speeds are the same**

**2. Coefficient of heat transfer is the same (wafer returns to baseline when beam moves off a spot)**

**Longer Dwell Time results in higher temperature rise**

**In this case, Duty Cycle is >20X**



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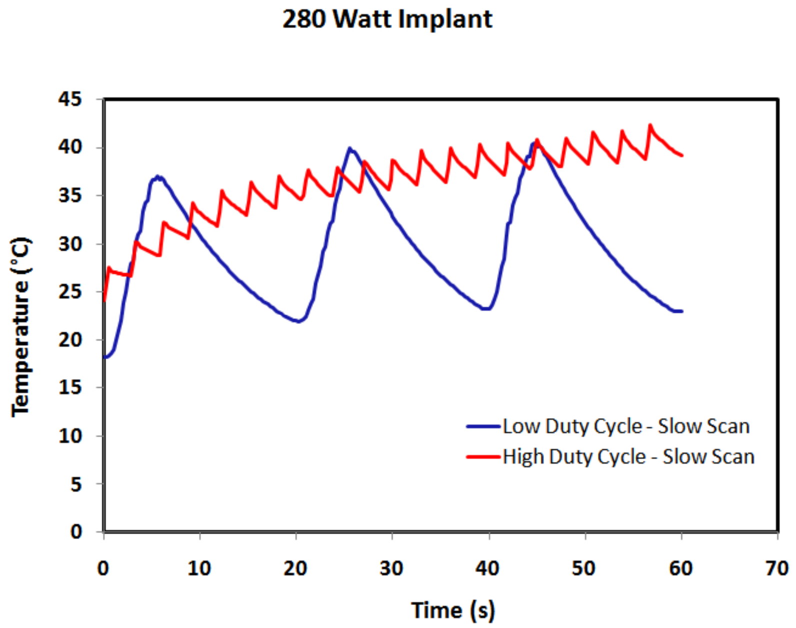
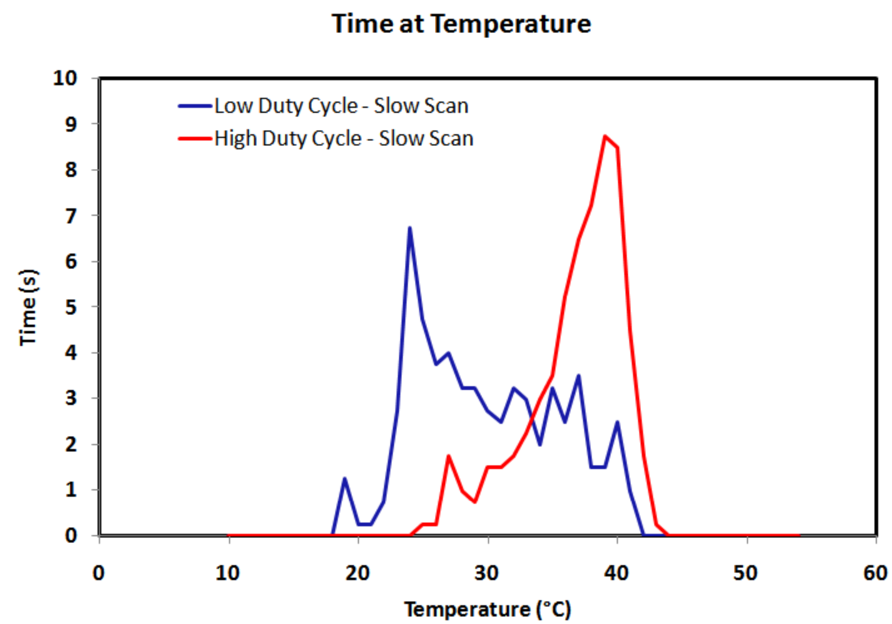
# SenseArray Measurements – Slow Scan Duty Cycle




**Duty Cycle in Slow scan affects bulk (macroscopic) thermal response**

**Peak temperatures are similar during the implant**

**High scan speed has a larger thermal budget in this case.**



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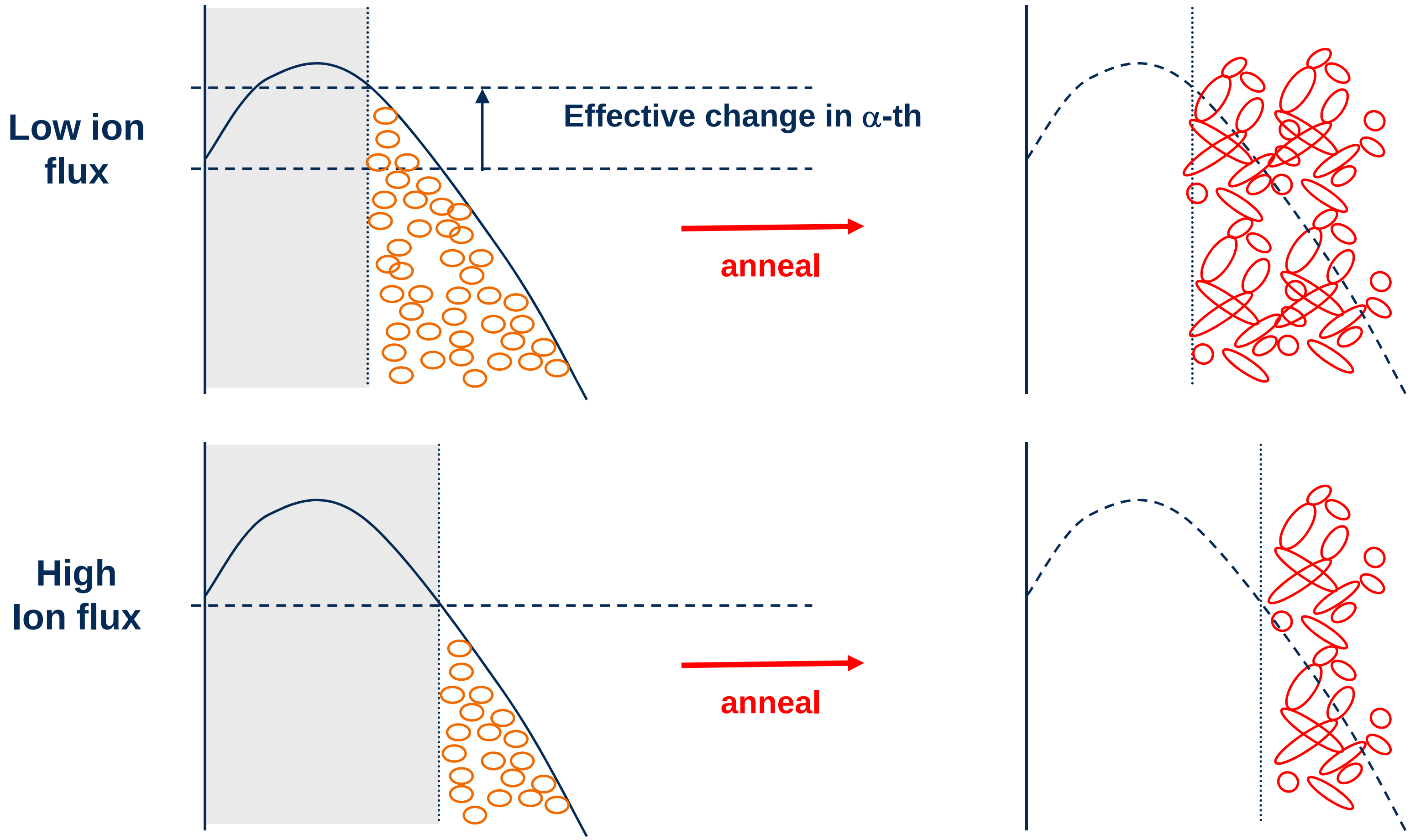
# Damage Accumulation



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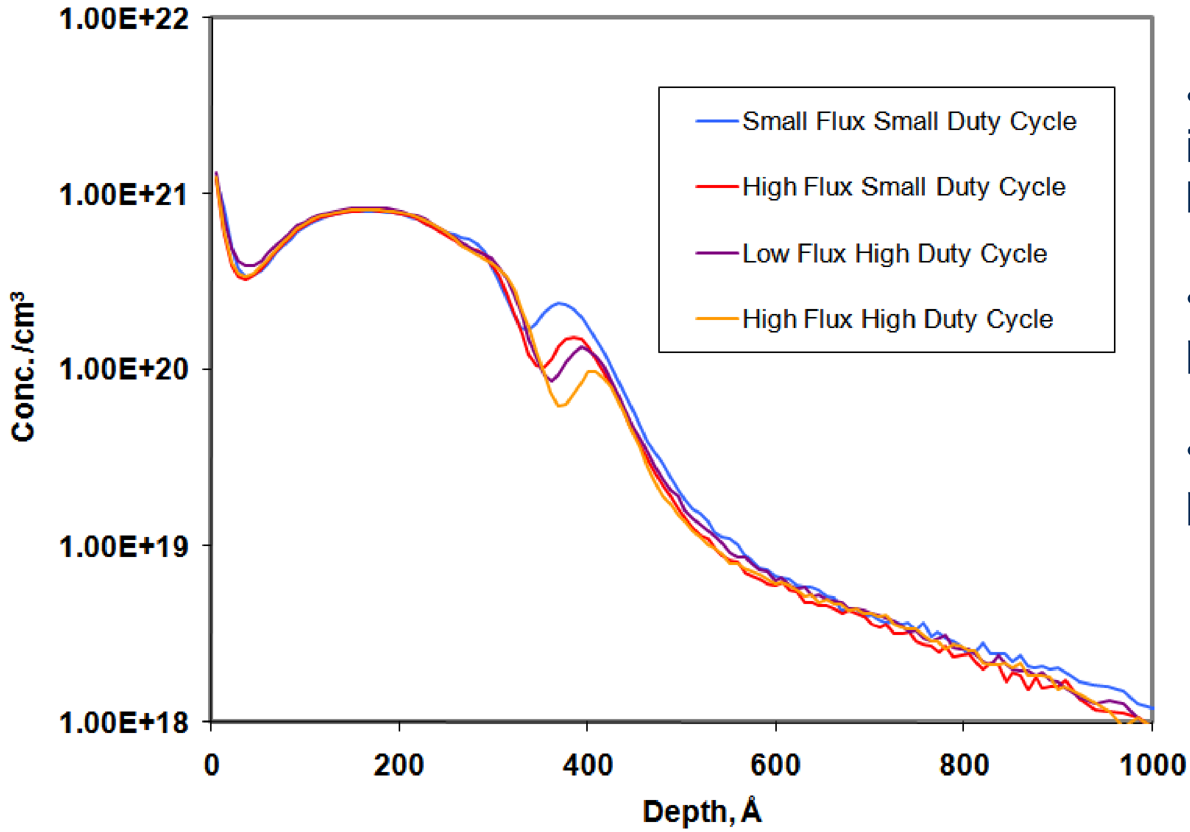
# *Interaction of Ion Flux and Temperature*

- **There is a complex interaction of the Ion Flux and Wafer Temperature during the implant process**

- **The Ion Flux governs damage accumulation rate**
  - **Peak Dose Rate coupled with duty cycle are the primary factors**
  - **Beam Current is the primary factor for a given architecture**

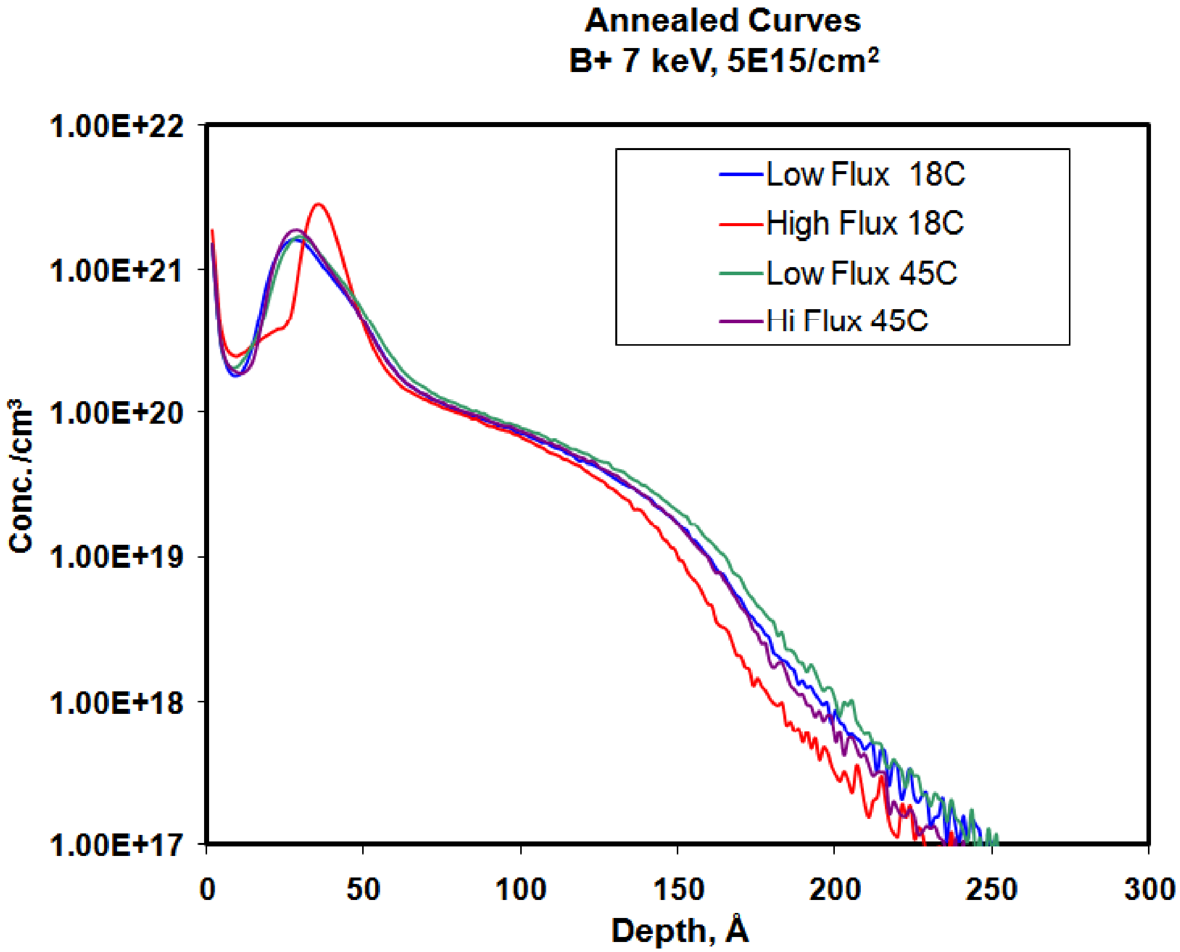
- **Thermal Profile determines the rate of damage annihilation during an implant**
  - **Duty Cycle in the fast scan direction is primary factor**
  - **Coefficient of heat transfer is dependent on system design and governs the cooling rate when the beam is off the wafer**

# *Effect of Duty Cycle and Ion Flux*
# *$BF_2$ 10 keV $5x10^{15}$ ions/cm²*




- **Second peak indicative of pile-up in EOR region**
- **Sensitive to thermal profiles as well**
- **Case Study will present device details**

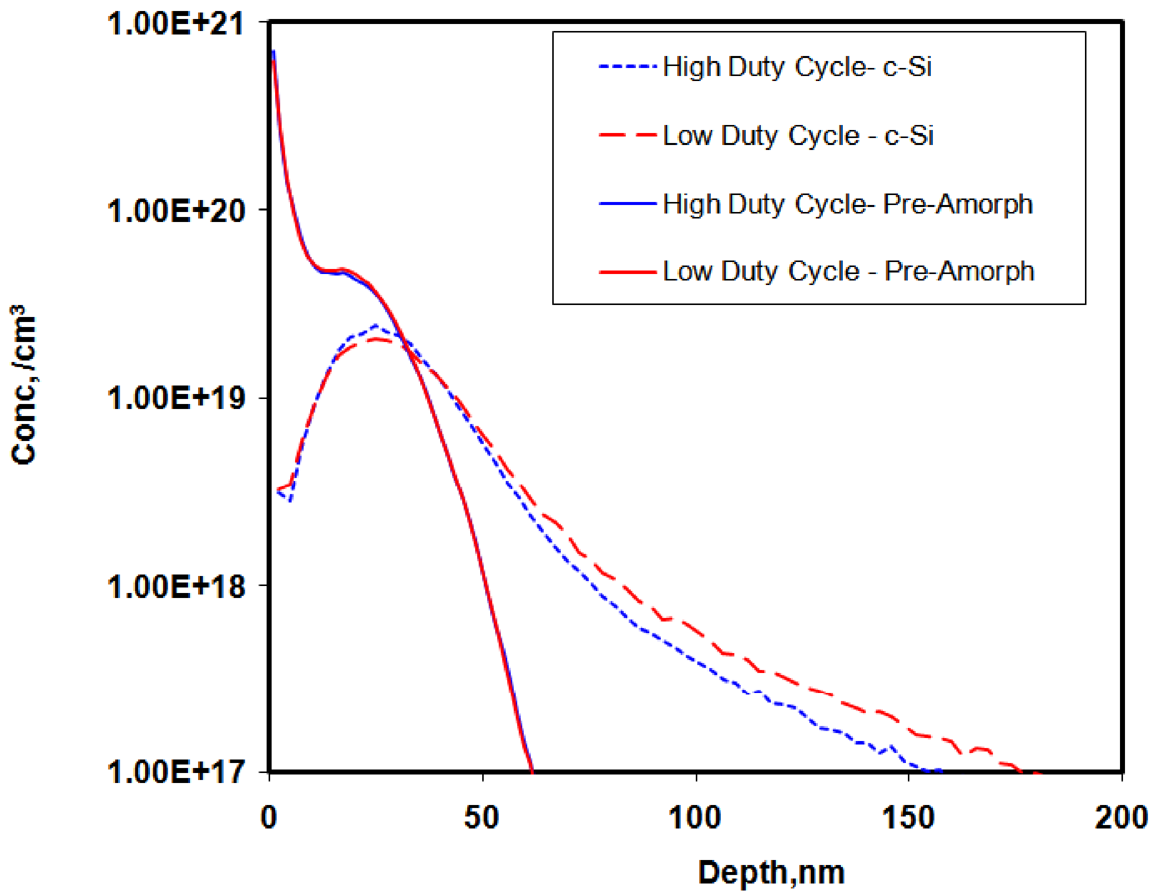
# *Implant Temperature Interaction with Ion Flux*




**Red curve has been pushed into amorphous layer formation**

**Altered diffusion and activation characteristics**

# *Ion Flux Effect on Channeling Profiles*
# *As 15 keV $8x10^{13}/cm^2$*




- **Higher Duty Cycle leads to faster damage accumulation rate**
- **Channeling is suppressed sooner**



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# Case Study
# $BF_2$ Implant into c-Si



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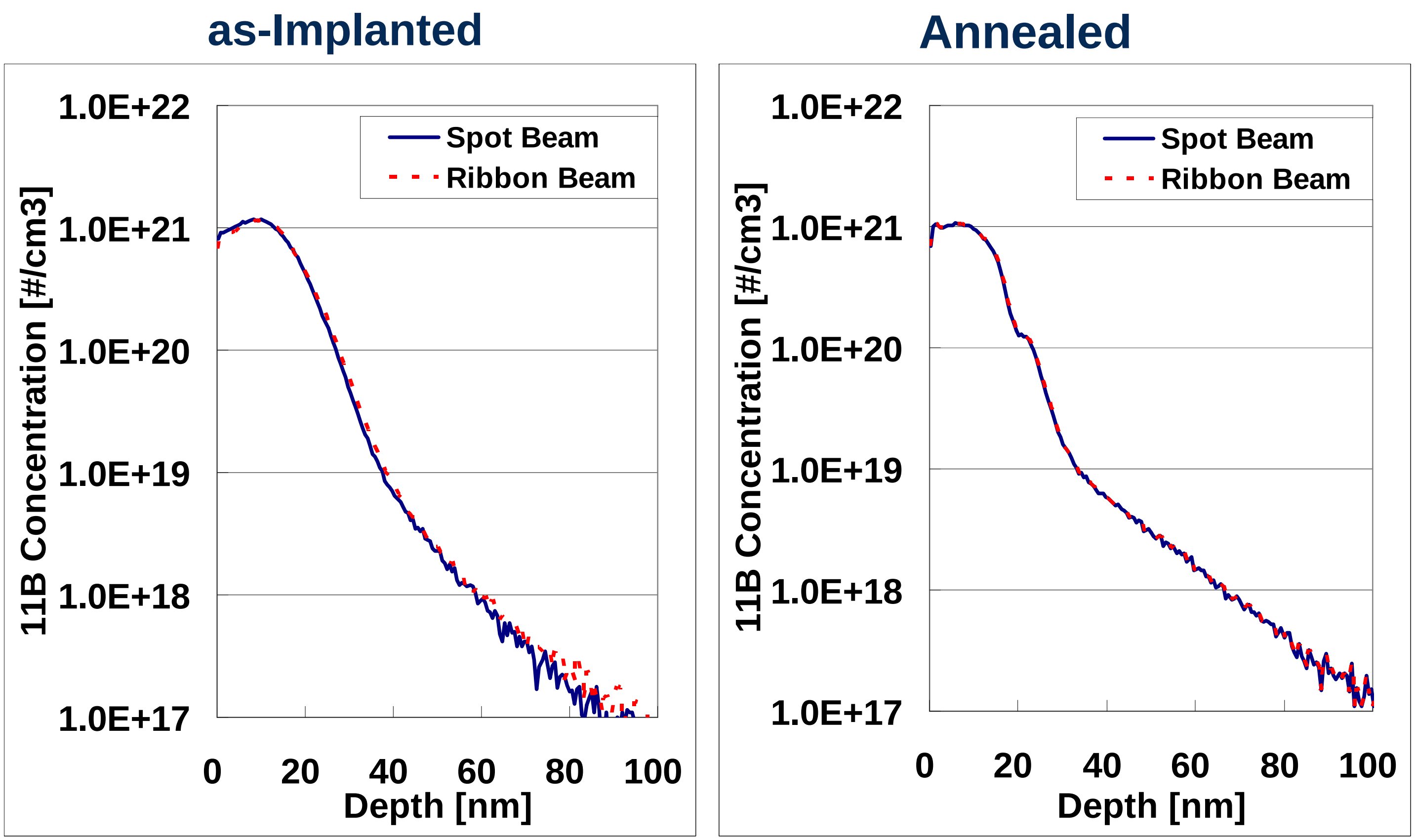
# Initial Data
# SIMS Profile Comparison ($BF_2$, 10keV)




***The SIMS profiles were well matched for both as-implanted and annealed samples***



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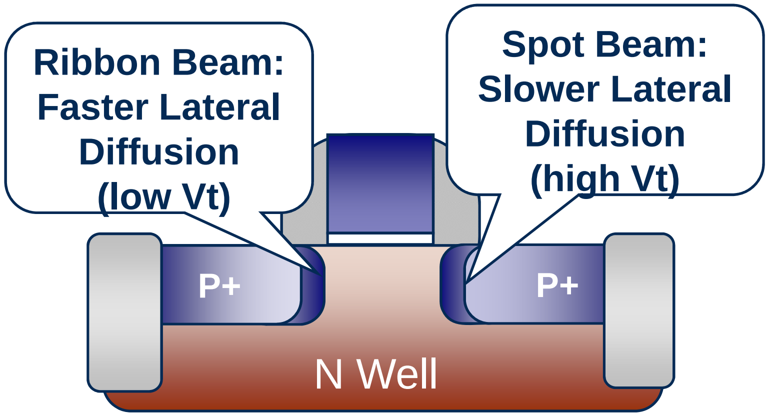
# Initial Data
# Device Test Results

- **Device Test Results [Normalized]**

| | PMOS Vt | Active Rs |
|---|---|---|
| Ribbon Beam | 100 | 100 |
| Spot Beam | 103 | 100 |

**Higher PMOS Vt on Spot Beam**
**→ Longer Channel Length?**

- **Schematic of PMOS Device**




***The observed values of PMOSFET parameters such as drive current, off current, junction capacitance, junction leakage, etc. suggested that the transistor channel lengths from the spot beam implanter were <u>longer</u> than those from the ribbon beam implanter.***



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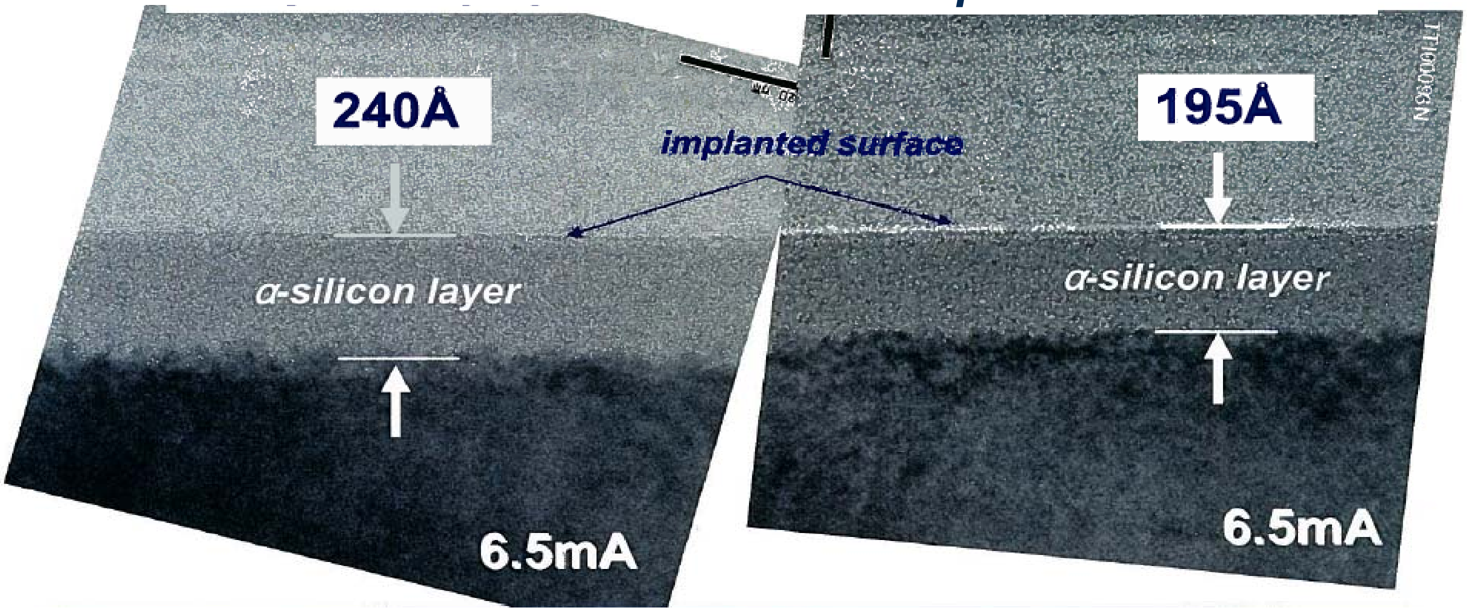
# Results
# Amorphous Layer

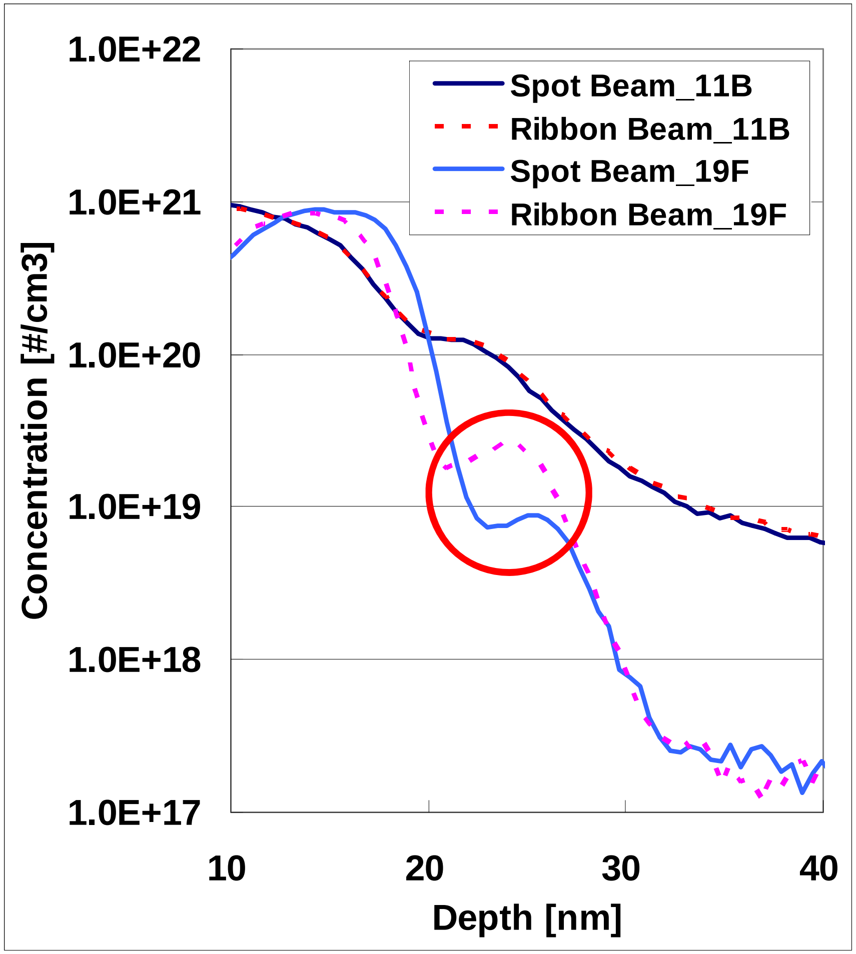
**Optima HD**
**Higher peak dose rate**

**Ribbon Beam**
**Lower peak dose rate**




***Higher Dose Rate & Lower Wafer Temperature Produce Thicker Amorphous Layer.***

# Fluorine Segregation at Amorphous/Crystalline Interface (Second F Peak)




- ***Higher dose rate & lower wafer temperature of spot beam produces:***
  - ***Deeper second fluorine peak***
  - ***Lower residual damage (reduced F segregation)***

# *Experimental Approach to Simulate Ribbon Beam with Spot Beam*

- Dose Rate Effect
  - Dose Rate should be Decreased.
  - Variables: Fast and Slow Scan Speed
- Wafer Temperature Effect
  - Wafer Temperature should be Increased.
  - Variables: Wafer Chuck Temperature & Cooling Gas Pressure
- Test Matrix

| # | Fast Scan Speed [m/s] | Slow Scan Speed [mm/s] | Wafer Chuck Temperature [°C] | Remark |
|---|---|---|---|---|
| 1 | ~ 1.0 | ~ 25 | 15 | |
| 2 | ~ 2.0 | ~ 45 | 15 | Normal Operation |
| 3 | ~ 3.0 | ~ 45 | 15 | |
| 4 | ~ 2.0 | ~ 45 | 45 | |



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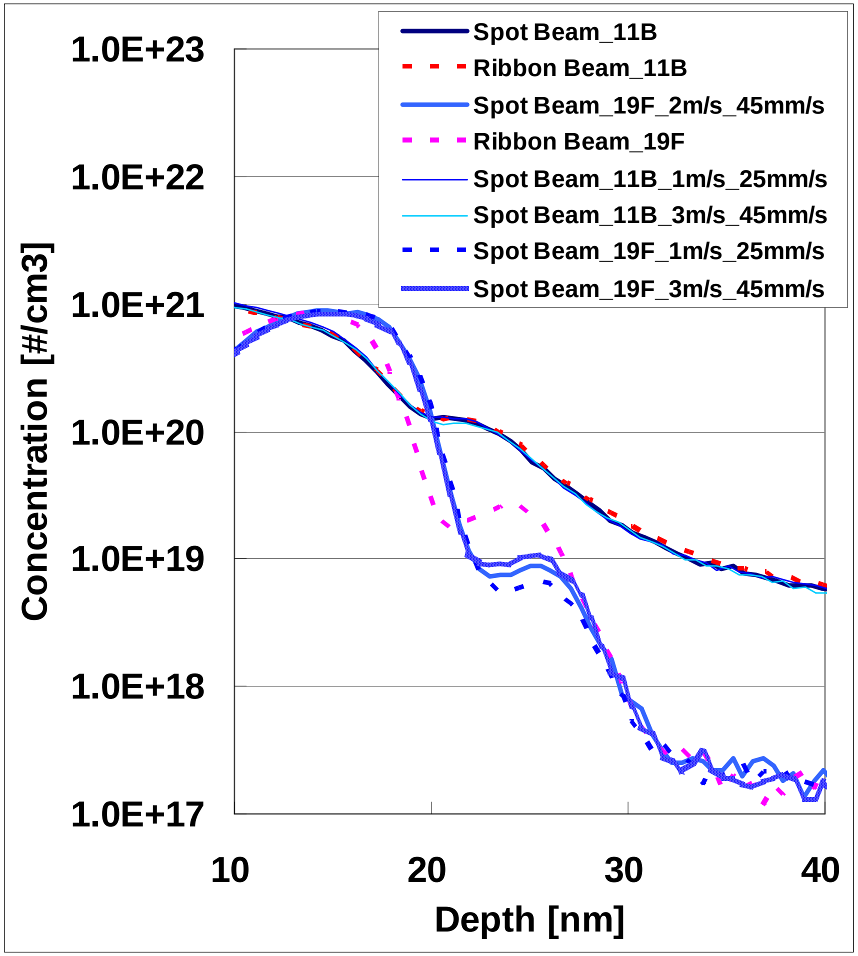
# Results
# Dose Rate Effect




- **Decreasing the dose rate by increasing both scan speeds increased the secondary fluorine peak height, but not to the level of the ribbon beam implanter.**



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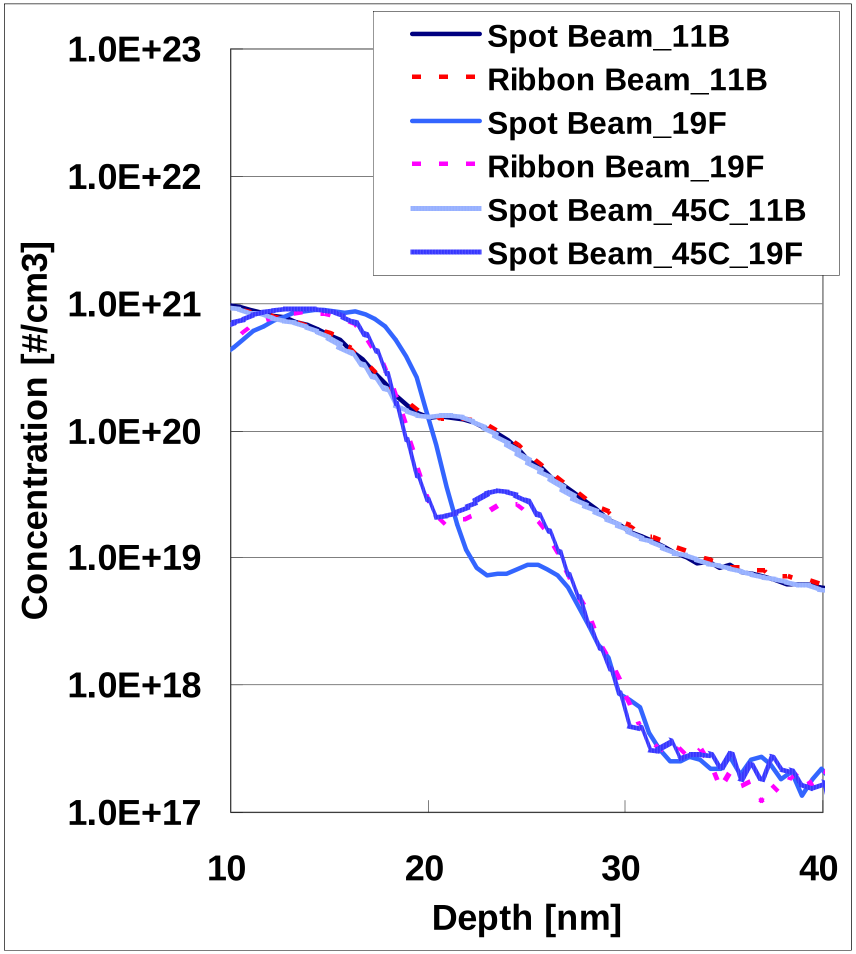
# Results
# Wafer Temperature Effect




- Increasing the wafer temperature up to 45ºC increased the fluorine secondary peak to a level higher than that of the ribbon beam reference
  - The normal wafer temperature is 15ºC



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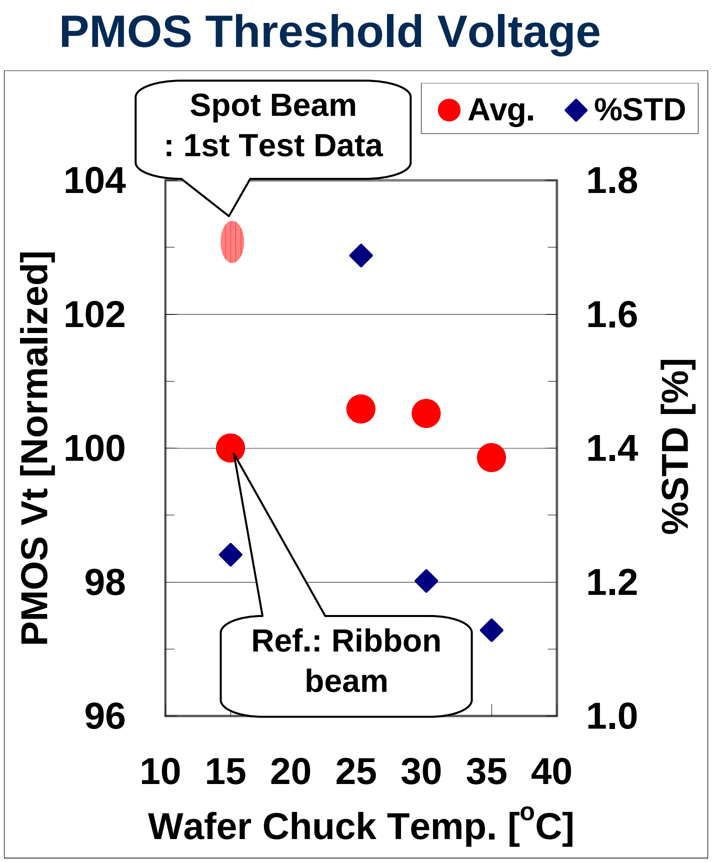
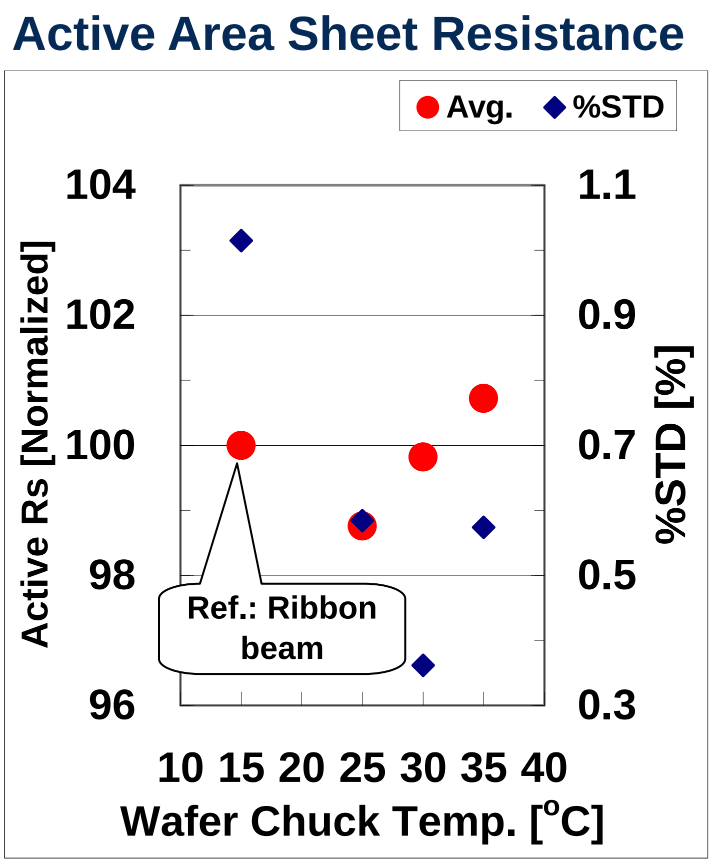
# Device Test Results




*30 ℃ is a good matching condition for both $V_T$ and $R_S$*



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# Conclusions

- Average Ion Flux governs primary damage accumulation rate
  - Very different between multi-wafer systems and single wafer systems
  - This causes significant variance in amorphous layer thickness; matching results across platforms is problematic
  - Though the beams and scanning systems are quite different, average ion fluxes are similar for ribbon and spot single wafer systems
- Thermal Properties are strongly governed by beam scanning dynamics
  - Subtle effects on self-annealing which are related to baseline temperature and the duty cycle
  - Control of temperature through chuck design and cooling systems can be used as a method to fine tune the process results
- Process matching can be accomplished through straightforward adjustments to wafer temperature or average ion flux