Characterization of Dopant Activation, Mobility and Diffusion in Advanced Millisecond Laser Spike Annealing

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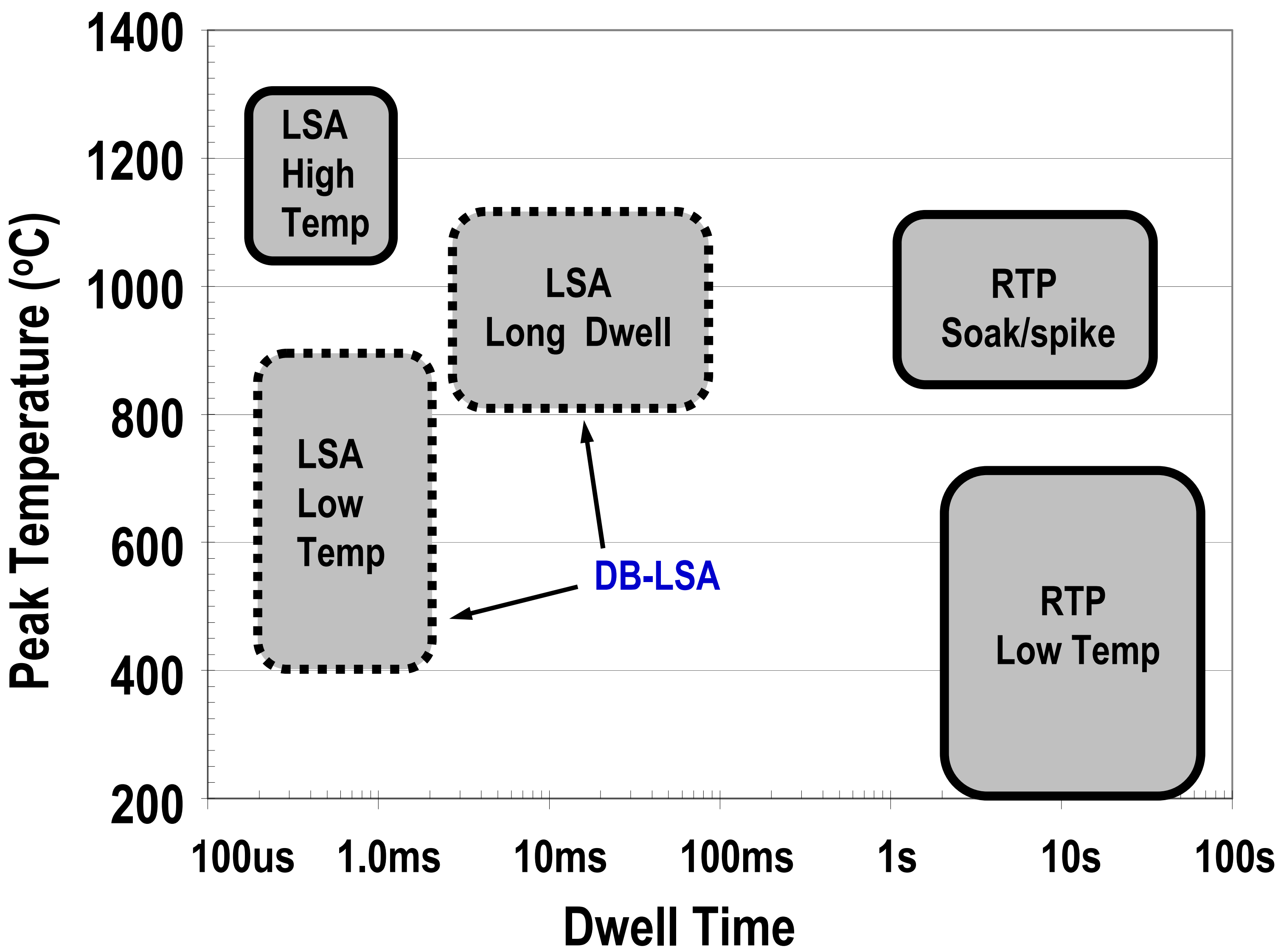
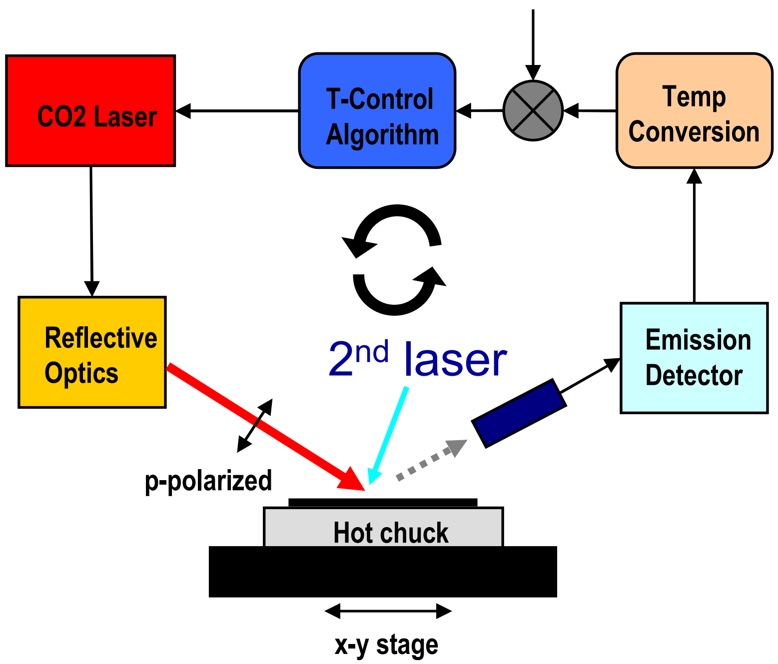
Outline

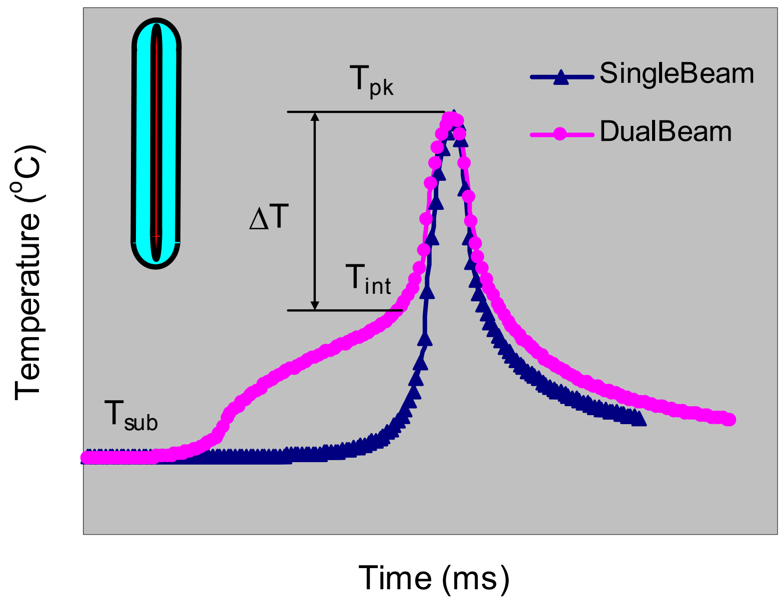
- **Advanced Dual-beam LSA system**
- **Effect of dwell time and multiple anneals**
  - Dopant diffusion
  - Sheet resistance
  - Junction leakage
- **Dopant activation & mobility study**
  - Sheet resistance
  - Mobility & active sheet concentration from Hall measurement
  - Model analysis
- **Conclusions**
- **Acknowledgement**

Annealing Technology and Time Scale



Advanced Dual-Beam LSA System



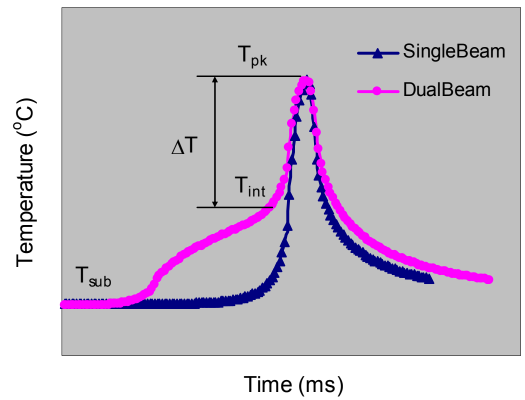


- A 2nd laser is introduced to the conventional SB-LSA system as a pre-heat laser

DB-LSA Advantages and Applications

DB-LSA offers great process flexibilities:

- T_{sub}, T_{int} & T_{pk}
- CO_2 dwell time
- Pre-heat laser dwell time
- CO_2 only process
- Pre-heat laser only process
- Dual-beam process



DB-LSA Applications

	Low T (Silicide Formation)	Stress Reduction (Junction Formation)	Long Dwell (Defect Annealing)
T_{sub}	< 250°C	~400°C	~400°C
T_{int}	Minimal	Low-Mid	High
Thermal budget	Negligible	Small	Large
T_{pk}	500-900°C	1100-1350°C	1100-1350°C

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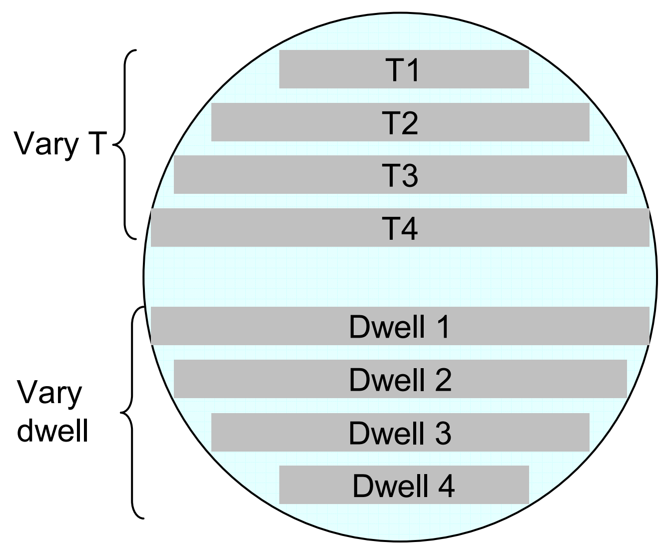
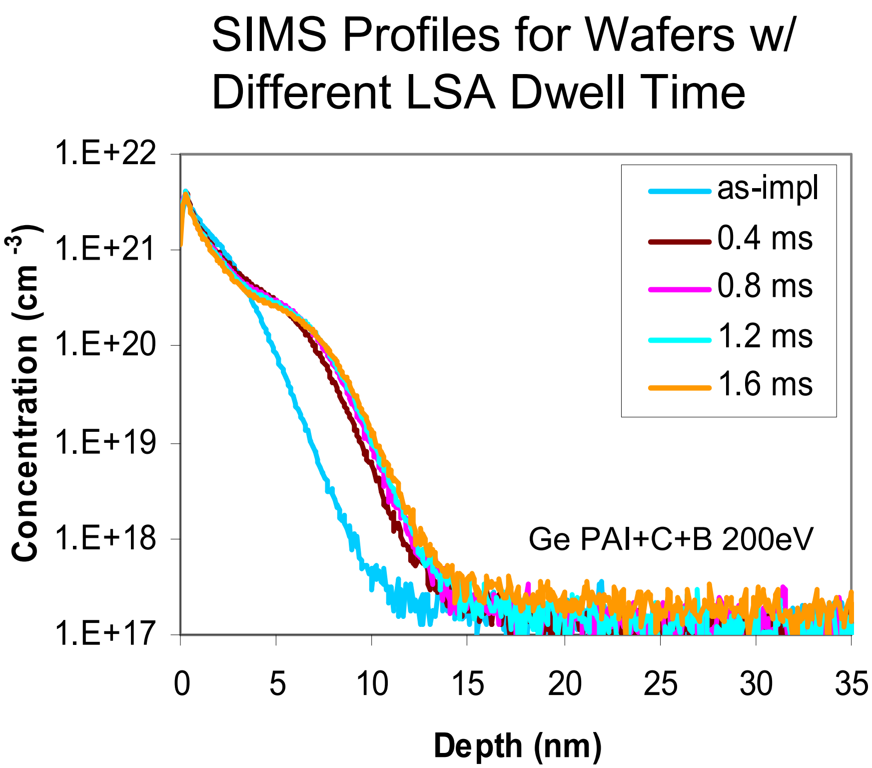
Design of Experiments for Dwell Time & Multi-Anneals Study

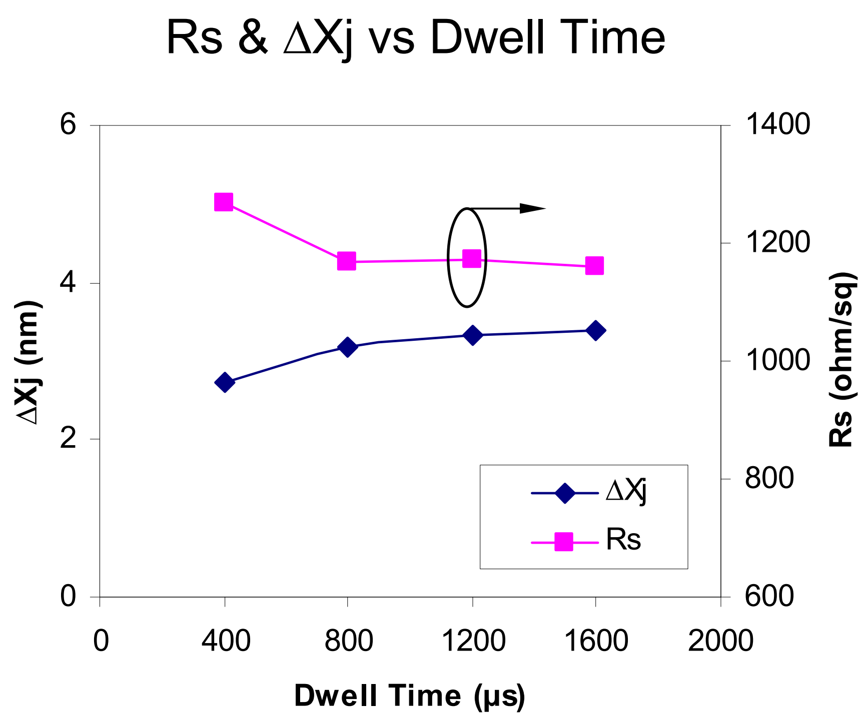
	Implant	Dwell (ms)	# of Anneals	LSA T (^{o}C)	Metrology	
Short-mid dwell regime	Ge PAI+C+B 1E15 200eV	0.4~1.6	1~4	1150~1250	**SIMS**	**RsL**
	Ge PAI+C+B 1E15 500eV	0.4~1.6	1~4	1150~1250		
Long dwell regime	Ge PAI +B 2E15 500eV	10~20	1	1100~1225		



Ultratech

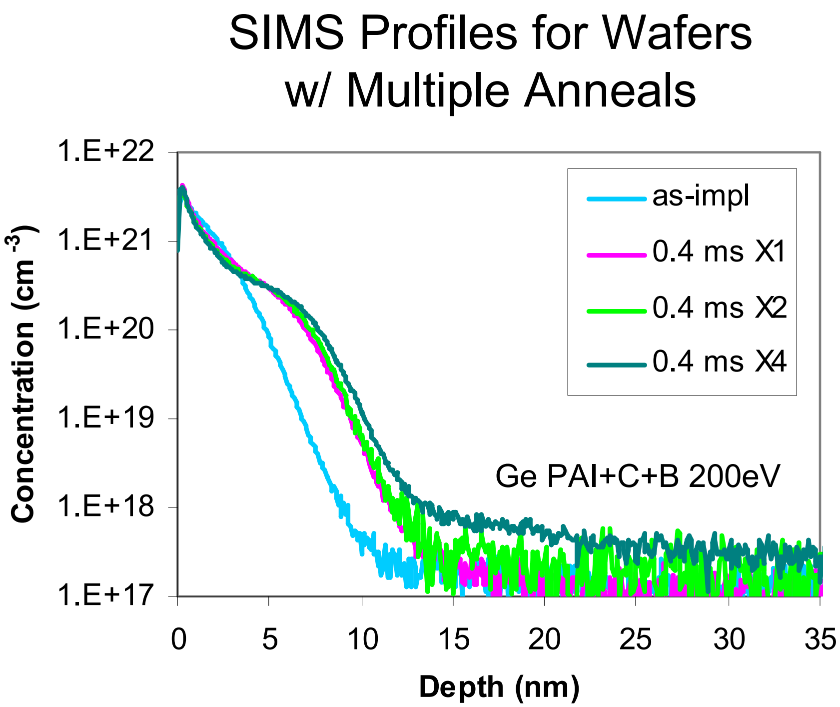
Effect of LSA Dwell Time

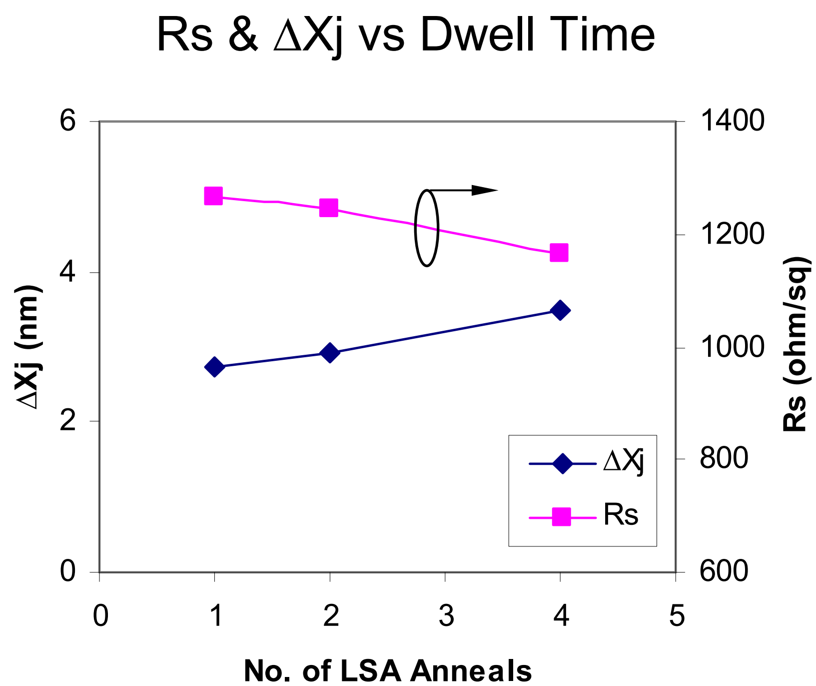




- Rs decreases with dwell time
- Xj increases mildly with dwell time

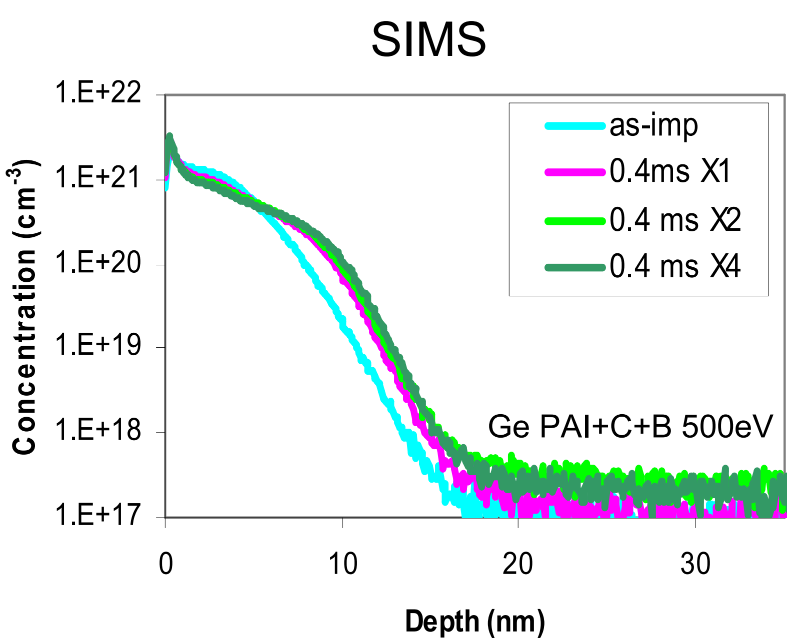
Effect of Multiple LSA Anneals

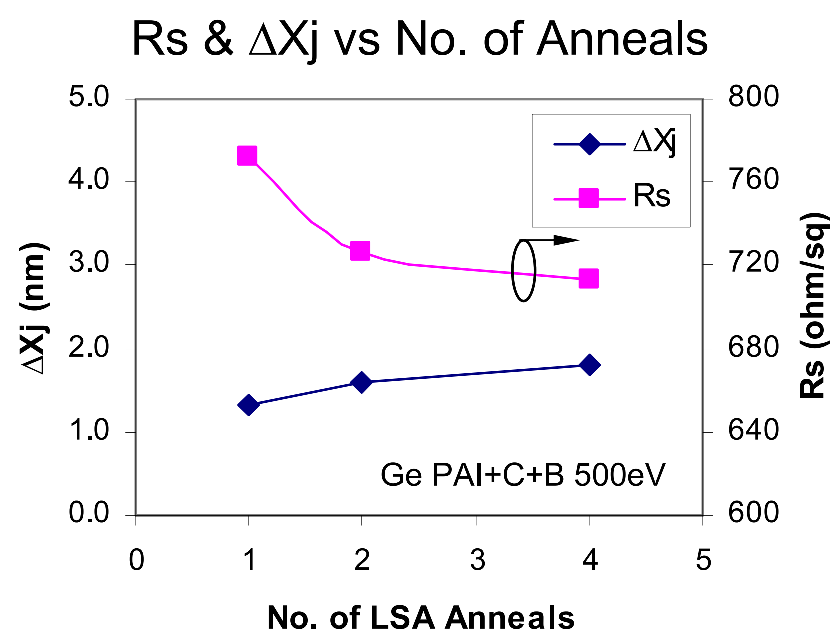




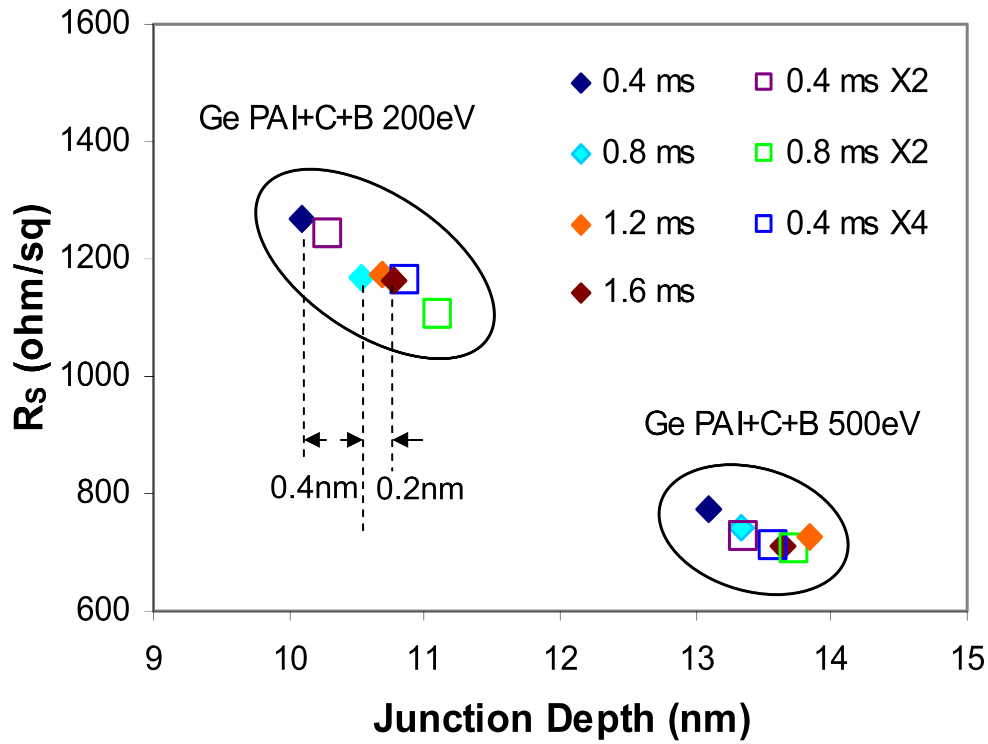
- Majority TED occurs at 1st anneal
- Subsequent anneals slightly deepens Xj

Multi-Anneals for 500eV B Implants





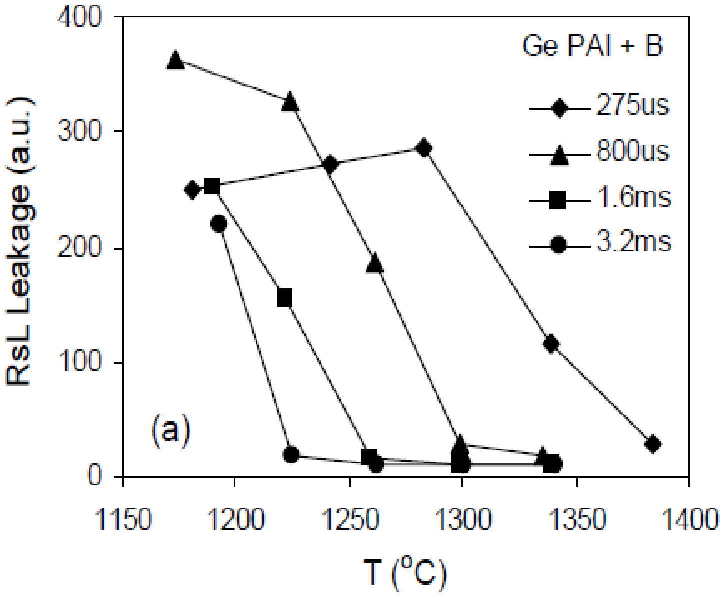
Rs vs X_j for LSA w/i Short-Mid Dwell & Multiple Anneals



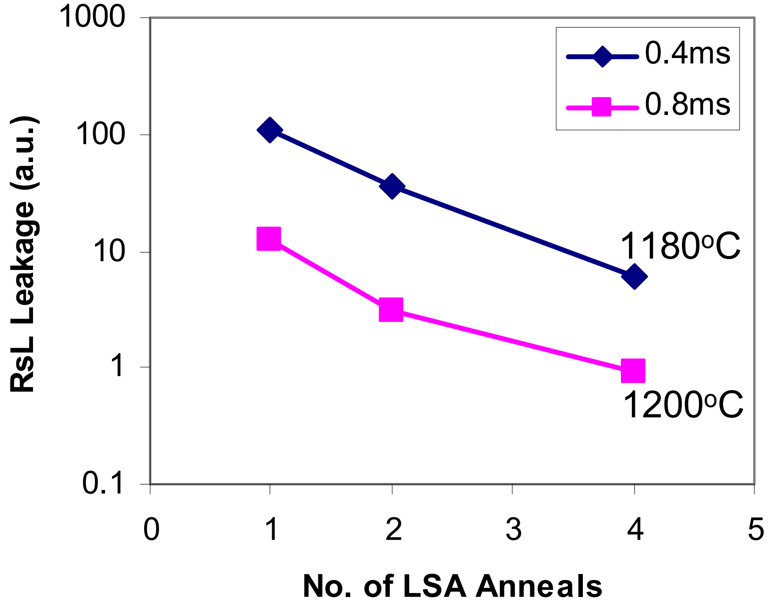
- Capability of fine-tuning of Xj with sub-nanometer precision
- Beneficial for junction engineering & device optimization

RsL Leakage Measurement

RsL Leakage vs LSA Temperature
[Wang et.al. IWJT 2010]

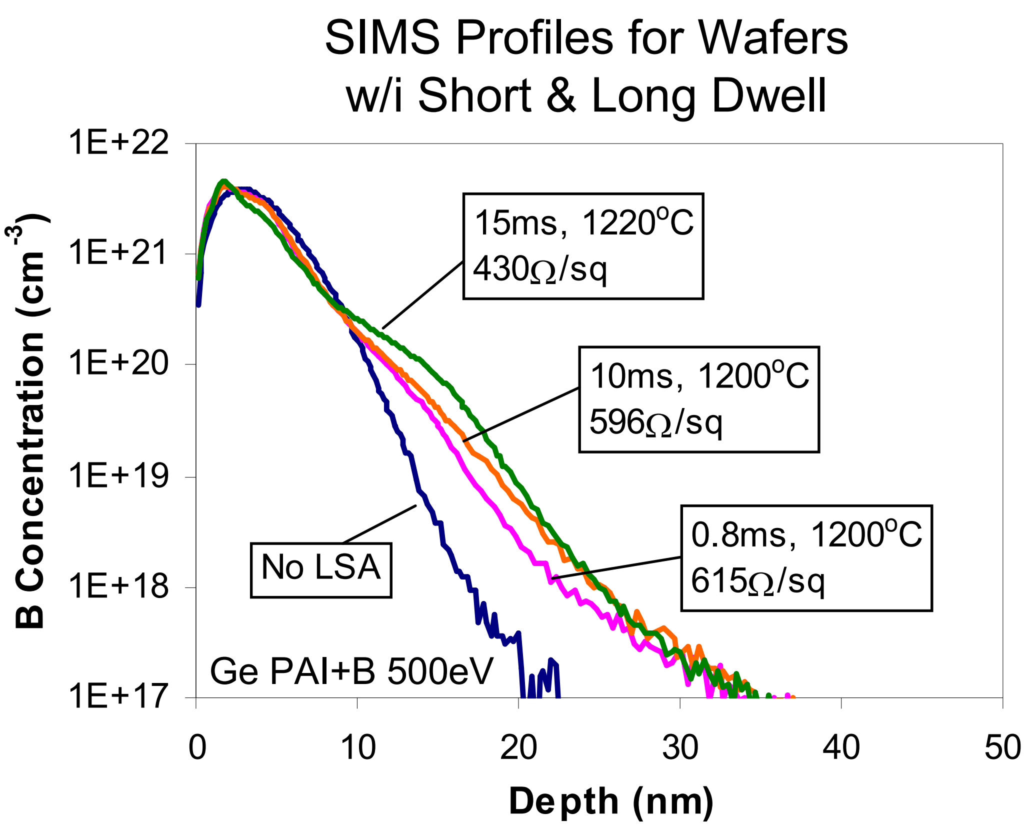


RsL Leakage vs No. of LSA Anneals



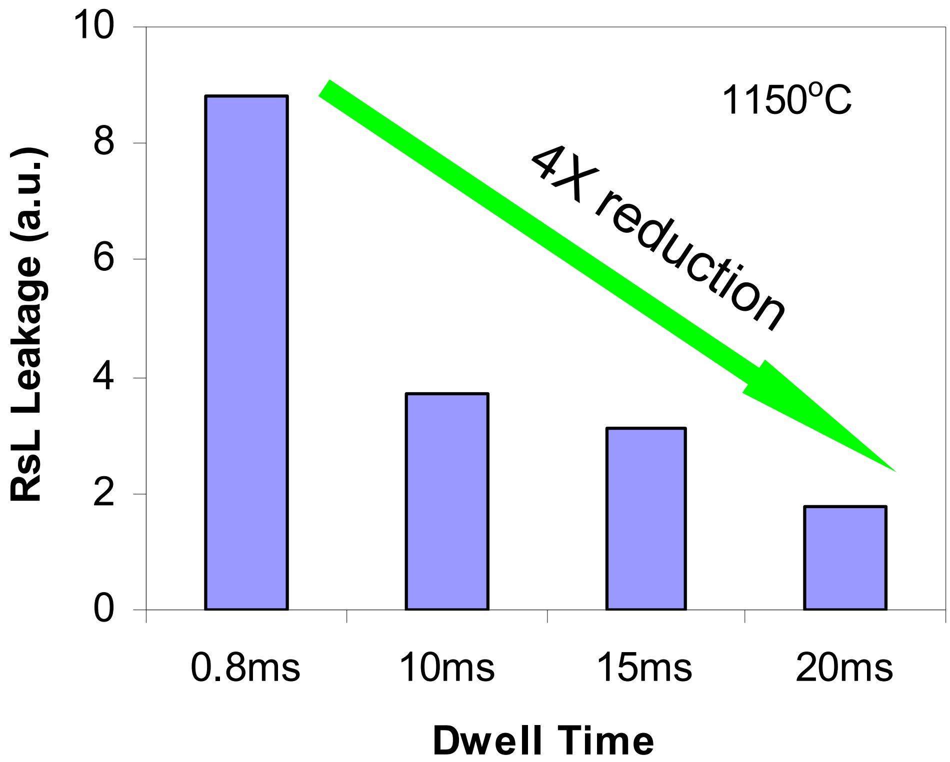
- Junction leakage can be reduced by
  - increasing LSA temperature or dwell time
  - additional LSA anneals

Dopant Diffusion w/i Long Dwell Time



ΔXj ~ 4nm for 0.8ms
ΔXj ~ 6nm for long dwell

Dwell Time Effect on Junction Leakage



- At the same annealing T, junction leakage can be improved w/i long dwell time

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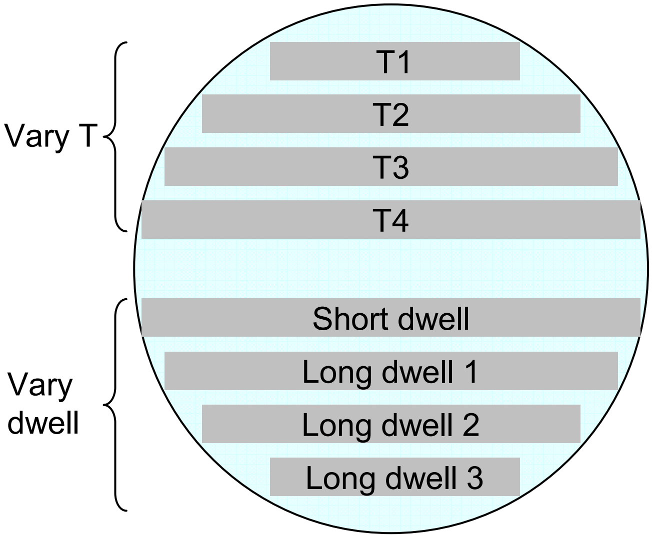
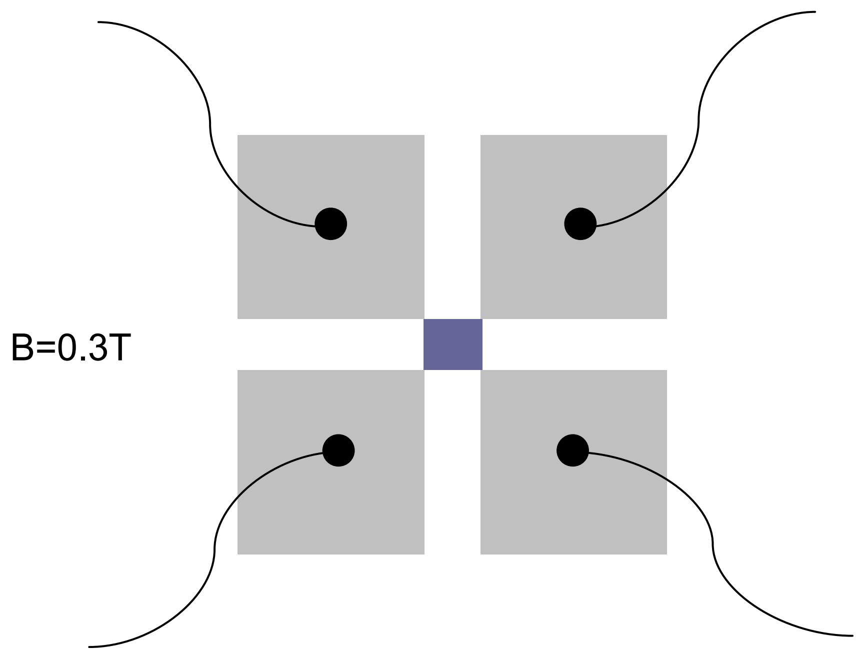
Design of Experiment for Dopant Activation & Mobility Study

Implant	Dwell (ms)	# of Anneals	LSA T (^oC)	Metrology		
				Van der Pauw	Hall Measurement	SIMS
B 2E15 5keV	0.8~20	1	1150~1300	Rs	Ns, μ	carrier concentration



Van der Pauw Hall Measurement



Van der Pauw & Hall Measurement sample patterning

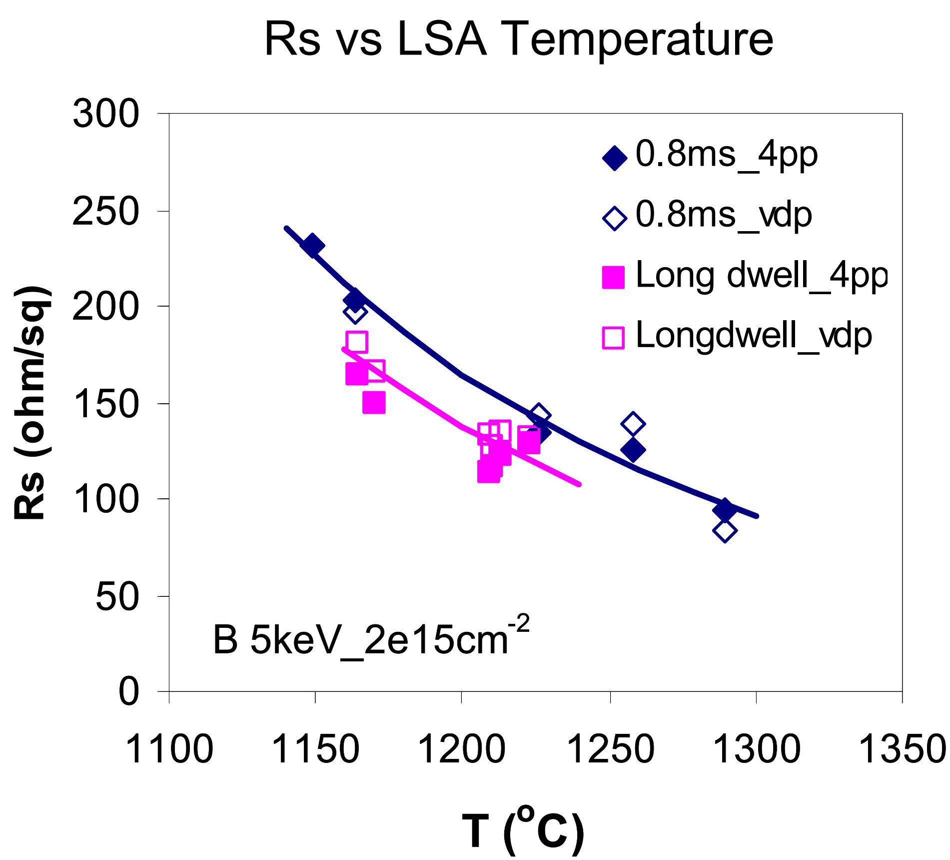
$$Ns = \frac{I \cdot B}{q|V_H|} \times r_H$$

$$\mu = \frac{1}{q \cdot Ns \cdot Rs}$$

Hall scattering factor $r_H = 0.74$

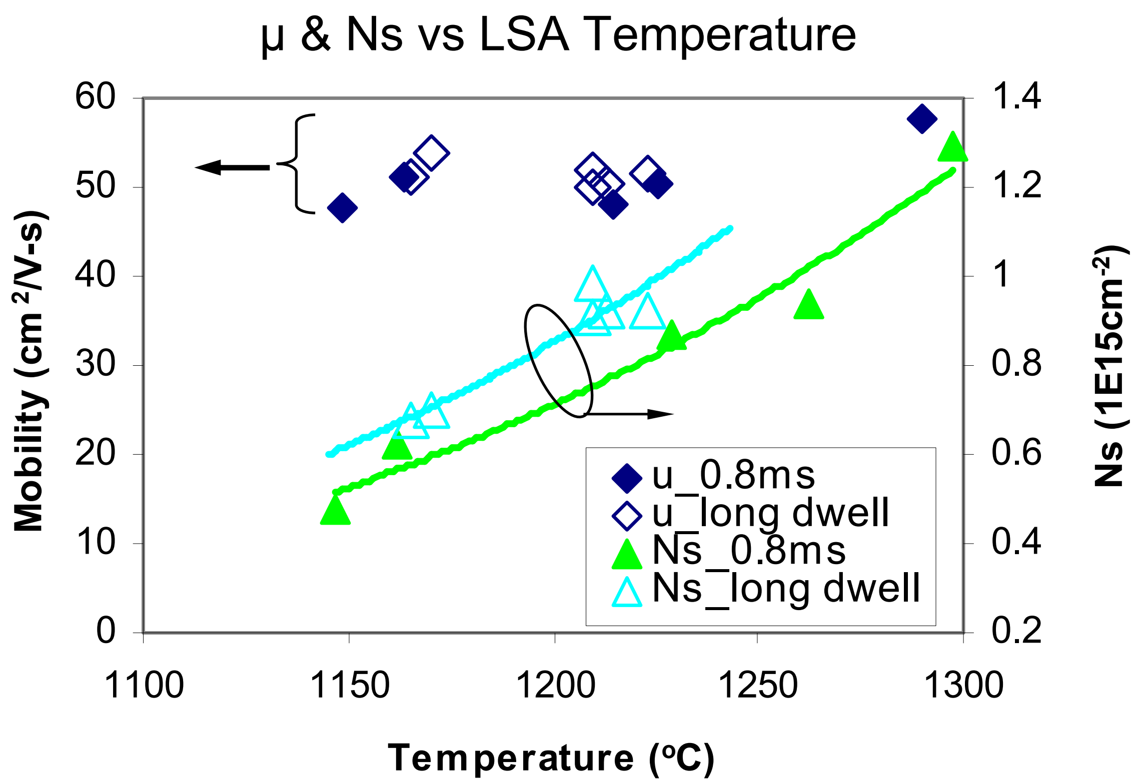
A. T. Fiory et. Al. *Appl. Phys. Lett.*, vol. **74**(18), p. 2658, 1999.

Rs Measurement Results



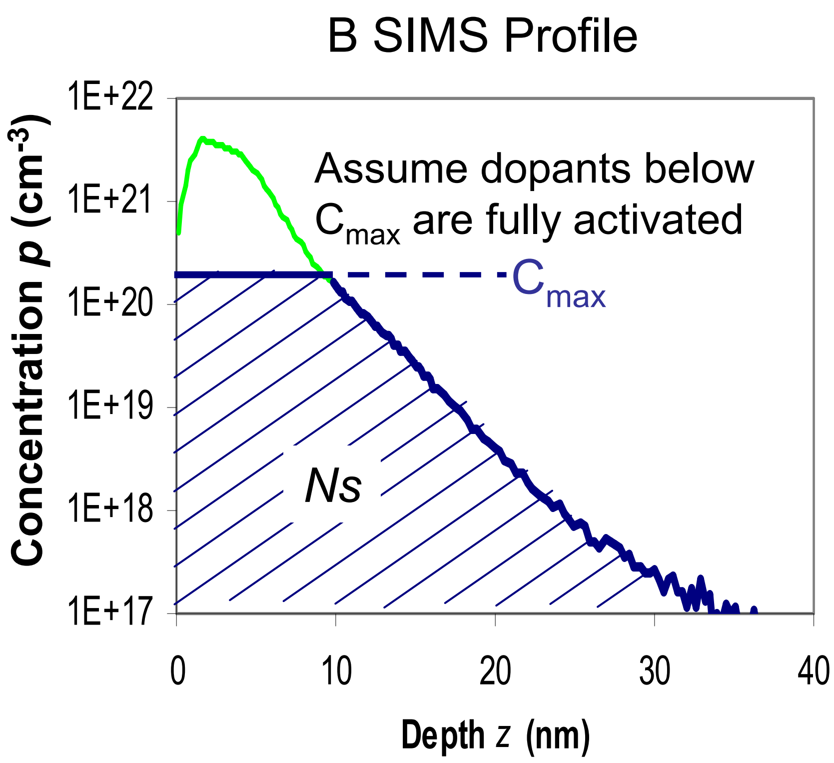
- Rs decreases with LSA temperature

Hall Measurement Results



- μ has weak dependence w/ LSA temperature
- Ns increases dramatically w/ LSA temperature

Modeling of Dopant Activation



From SIMS profile, μ and n_s can be obtained:

$$\mu = \mu_0 e^{\frac{-p_c}{p}} + \frac{\mu_{max}}{1+(p/C_r)^{\alpha}} - \frac{\mu_1}{1+(Cs/p)^{\beta}}$$

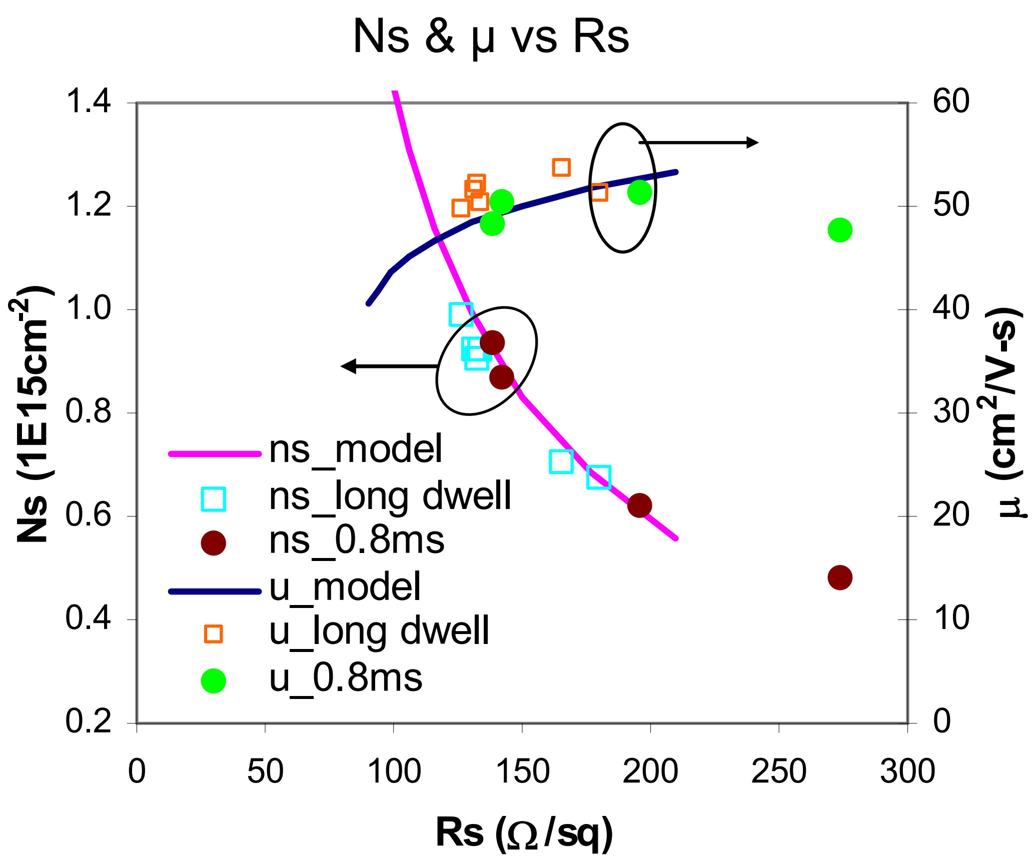
(Masetti mobility model)

C_{max} can be obtained by solving

$$Rs = \frac{1}{q\int^{C_{max}} p \cdot \mu(z)dz} \quad \text{for } C_{max}$$

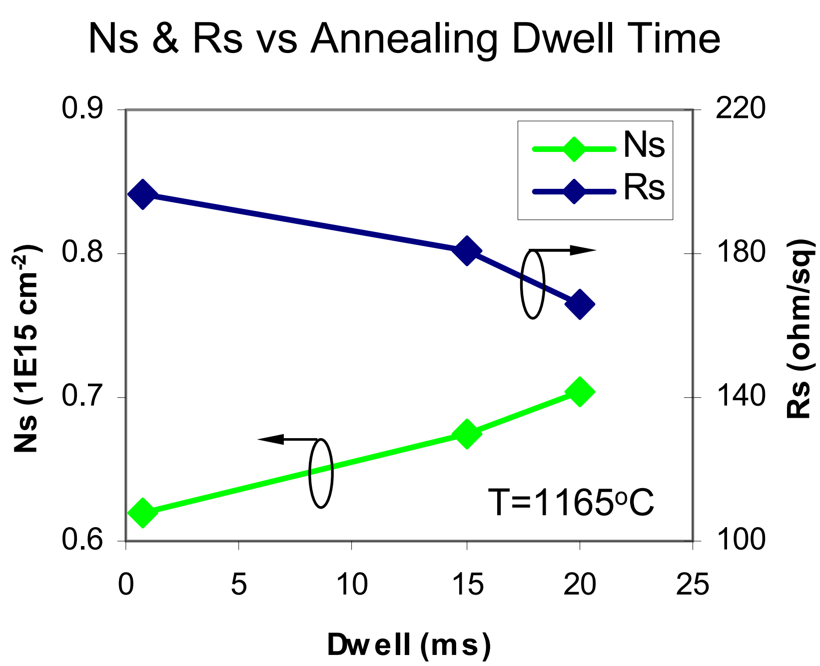
$$Ns = \int^{C_{max}} pdz$$

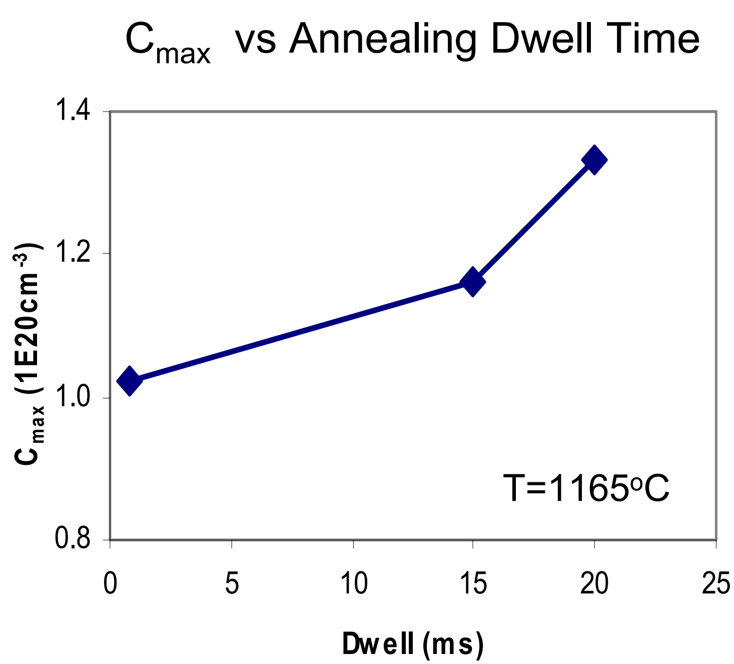
Experimental Results vs Model



- Overall good agreement between model & experimental results

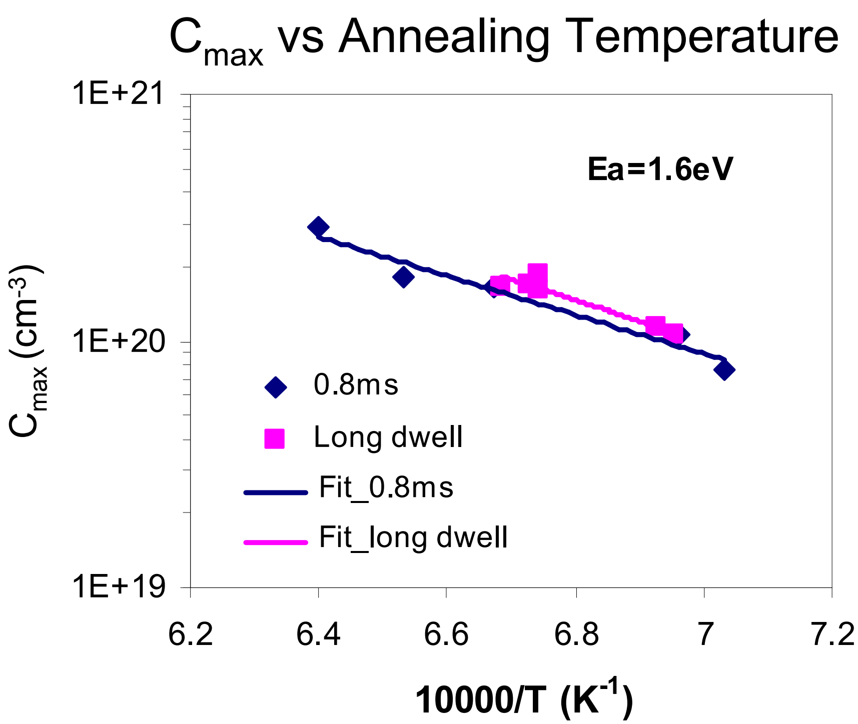
Dwell Time Effect

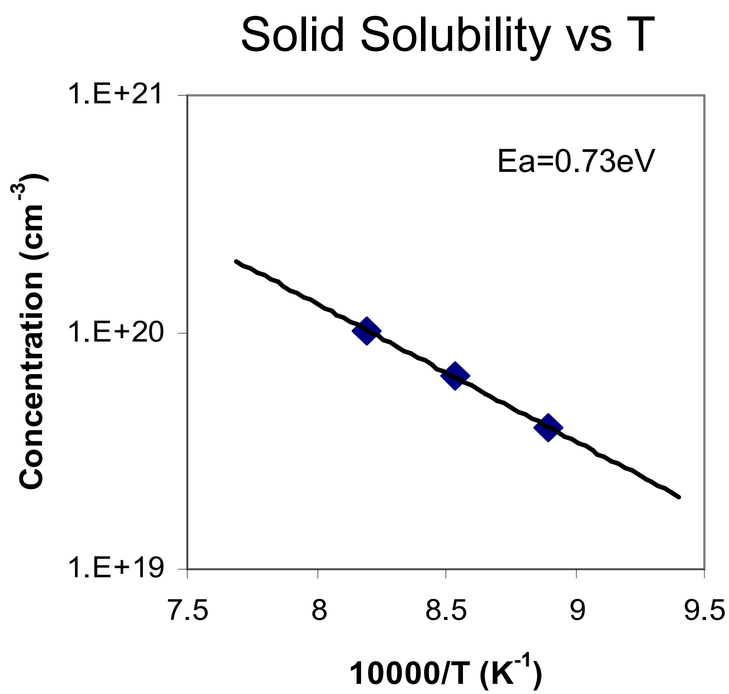




- Rs decreases w/ dwell time
- At same annealing T, long dwell time improves activation

Thermal Activation Energy Extraction





D. Nobili et. al. “Solubility of B, Al, Ga, In, Tl, P, As and Sb in c-Si,” *Property of Crystalline Silicon*, p. 620, 1999.

- Different dwell times (ms vs s) result in different *Ea*?

Conclusions

- **DB-LSA offers great process flexibility and enables a wide ranges of LSA dwell time from sub-ms to tens of millisecond**

- **Rs, Xj & leakage have been examined for various dwell time & No. of anneals**
  - Rs, leakage↓ w/i longer dwell time/multi-anneals
  - Xj slowly ↑ w/i longer dwell time/multi-anneals
  - LSA demonstrates sub-nm X_j tunability for precise junction engineering

- **Dopant activation has been evaluated with Hall Measurement**
  - Improved activation are observed w/i high LSA T or long dwell time
  - Model analysis shows good match w/i experimental results
  - Thermal activation energy of 1.6eV is extracted from experiments & model analysis

Short vs Long Dwell Process

Short dwell Process

- Better Rs-Xj performance
- Low stress relaxation
- High peak annealing T

- Insufficient lateral diffusion for MSA-only integration
- Defects and leakage existence at low T

Long dwell Process

- Low leakage
- Higher activation
- Controlled lateral diffusion

- Higher warpage
  - Limits peak T
  - Optical misalignment

DB-LSA provides extra flexibility in optimizing dopant activation, junction leakage, and wafer stress.

Acknowledgement

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