Advanced Laser Doped Solar Cells

UNSW   22nd May 2014

Brett Hallam

Overview

- Introduction – Laser doping

- Continuous Wave Laser Doping for Deep Junction Formation

- Modelling Diffusion in Laser Doped Regions

- Laser doping from Al_2O_3

- Contacting Buried Layers in Silicon Solar Cells

- Passivation of Laser-Induced Defects

Introduction – Laser Doping

Laser Doping

- Perform diffusion in liquid phase
  - Diffusion coefficients many orders of magnitude higher than in the solid state

- First demonstrated < 1970 [Fairfield 1968]

- Variety of approaches
  - LD from ion implanted dopants or PSG layer
  - SOD layer application
  - Gas immersion laser doping
  - Laser chemical processing

Fair 1968 J. Faireld. Solid State Electronics , Vol. 11, pp. 1175 (1968).

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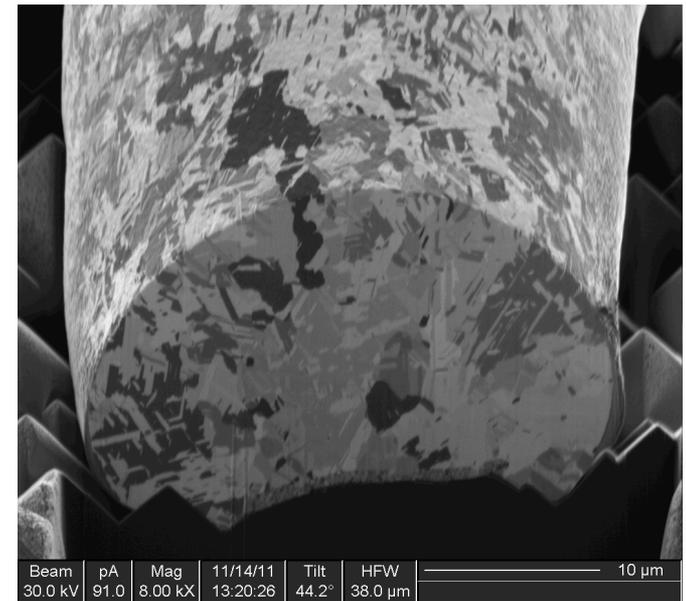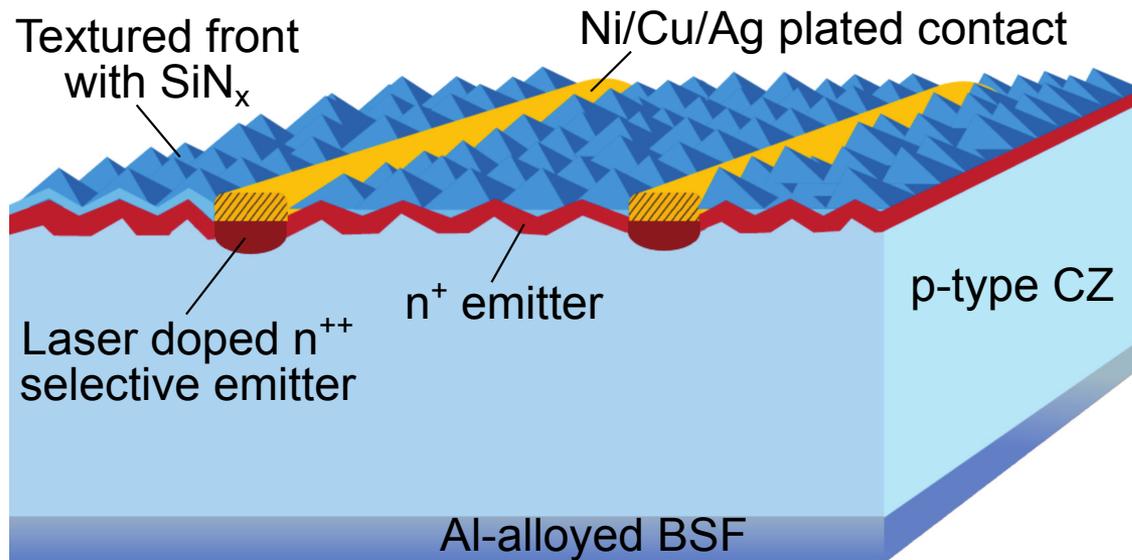THE UNIVERSITY OF NEW SOUTH WALES

Defect Generation during Laser Doping

- Laser-induced defects have hampered performance of laser doped solar cells

- Defect generation is a complex process dependent on:
  - Orientation of silicon
  - Purity of dopant sources
  - Pulse energy
  - Repetition frequency
  - Dielectric layers

- Avoiding performance degradation
  - Perform laser doping on bare silicon
 - Use an intermediate SiO_2 layer
  - Use continuous wave lasers

Self-aligned Laser Doped Selective Emitter

- Self-aligned process compatible with light-induced plated contacts [Wenham1998]
  - Simultaneous opening of dielectric / doping of silicon
  - Contacts < 30 µm

Textured front with SiNx

Ni/Cu/Ag plated contact

Laser doped n^{++} selective emitter

n$^+$ emitter

p-type CZ

Al-alloyed BSF

| Beam | pA | Mag | 11/14/11 | Tilt | HFW | 10 µm |
| 30.0 kV | 91.0 | 8.00 kX | 13:20:26 | 44.2° | 38.0 µm | |

S. R. Wenham and M. A. Green. Self Aligning Method for Forming A Selective Emitter and Metallization in a Solar Cell. US Patent No. 6429039, August 2002.

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Junction Depth Limitations

- Solidification between successive pulses greatly limits junction depths.

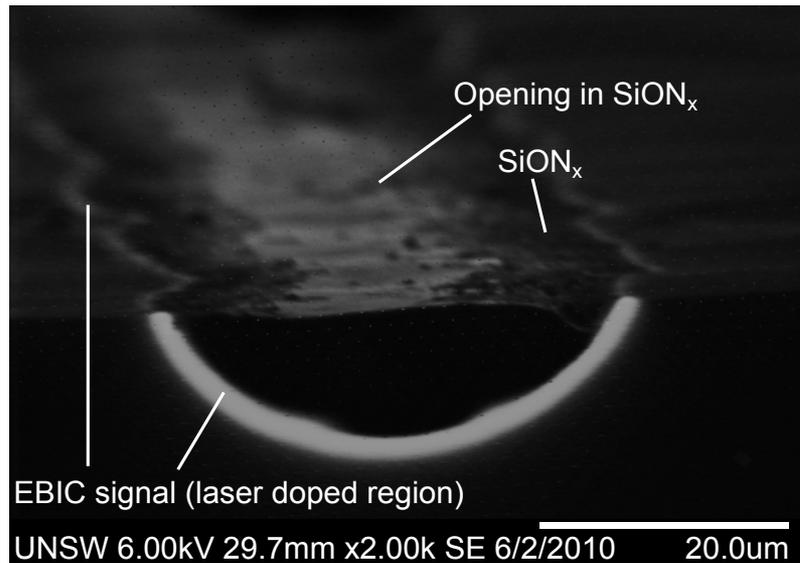- Longer pulses are required to form deep molten regions without ablation of the silicon
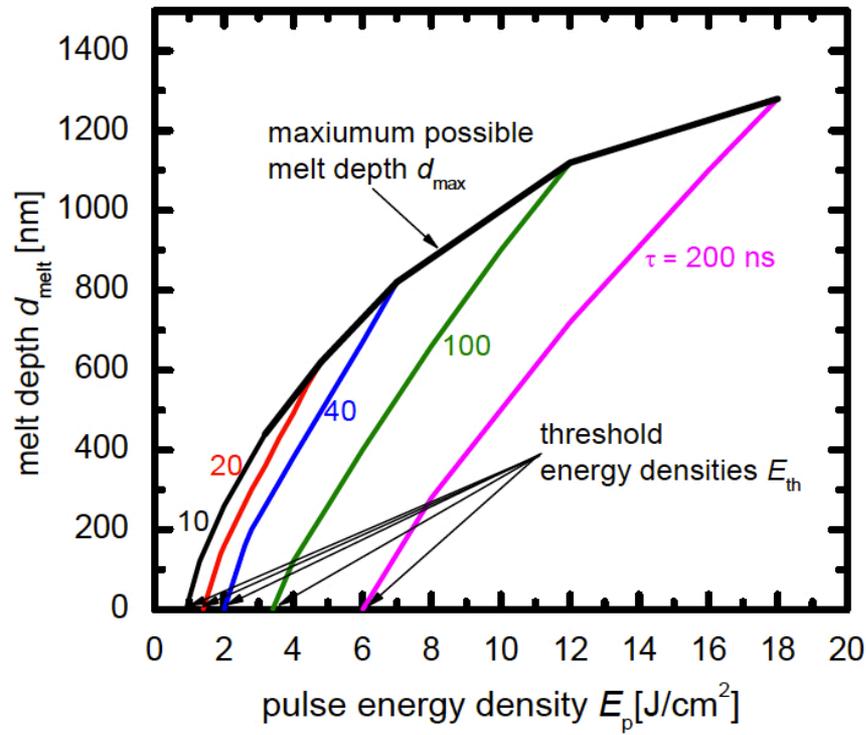
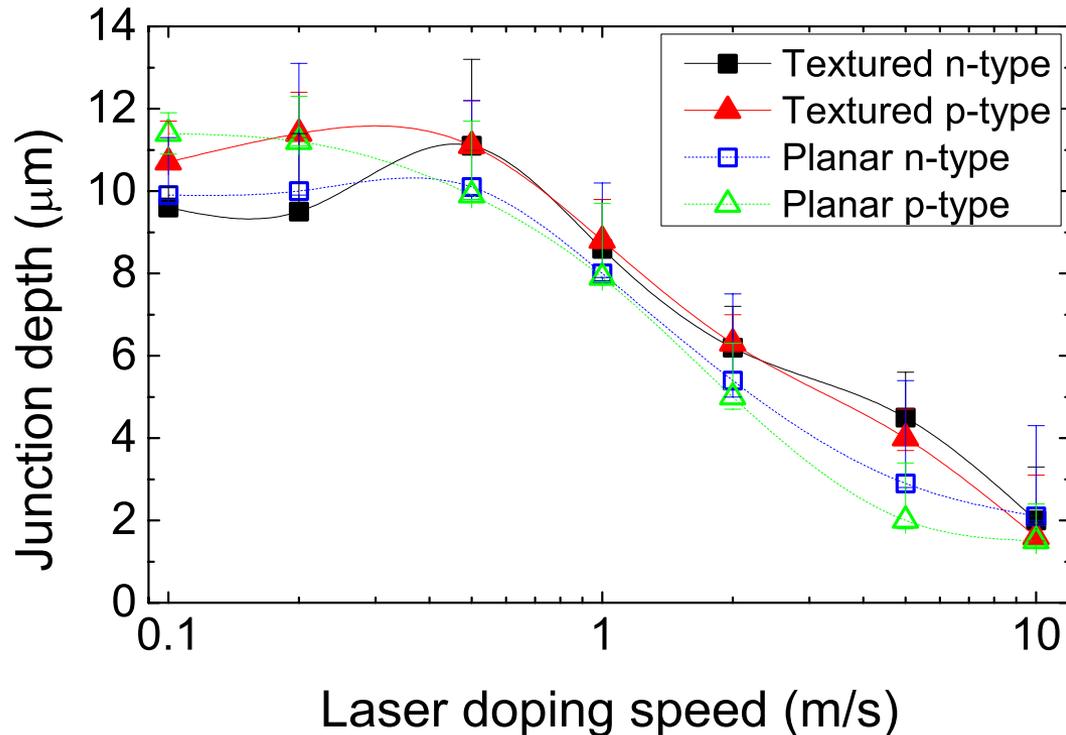# Continuous Wave Laser Doping for Deep Junction Formation

Deep Junction Formation through CW Laser Doping

- CW lasers allow for a deep molten region to form (> 10 μm)
  - Silicon remains molten throughout process
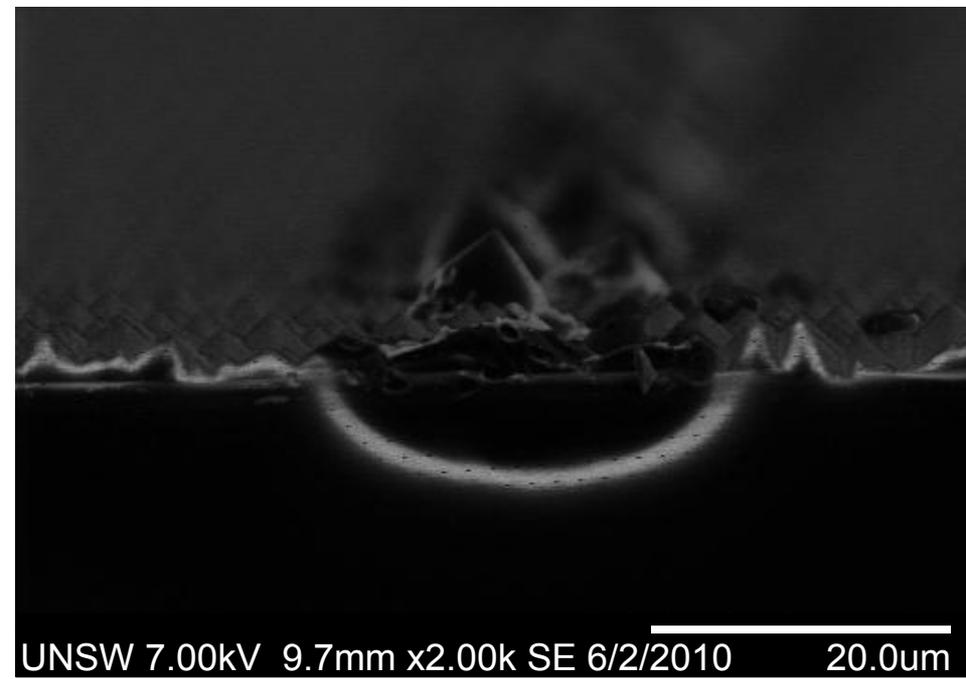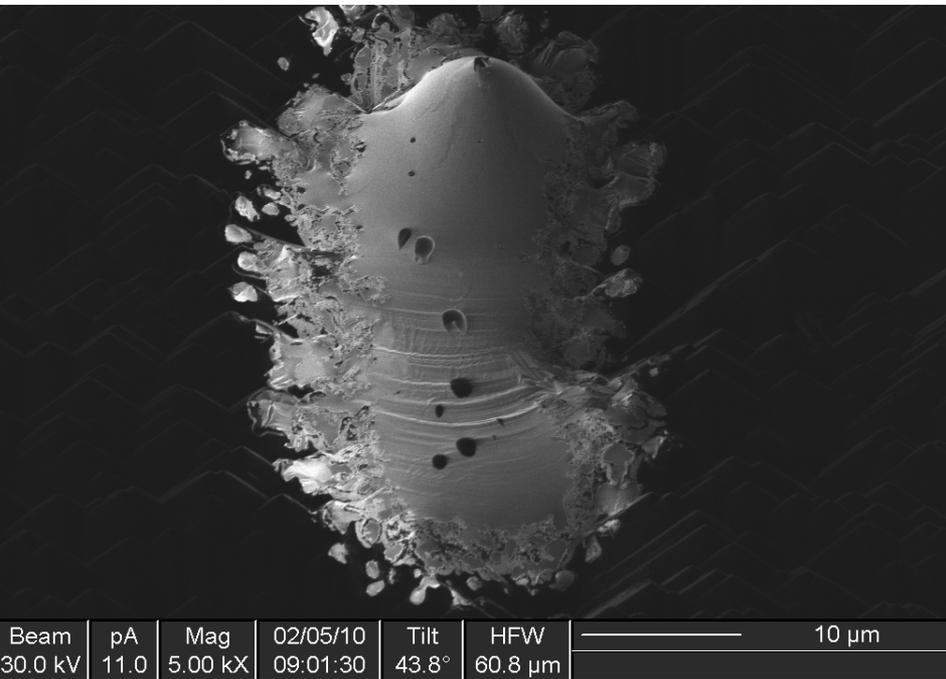- Junction depth can be controlled be processing speed

p-type LD on a planar surface (0.2 m/s)

Point Contact Formation

- Point contacts formed using CW laser and physical mask
    - Junction depths over 8 µm
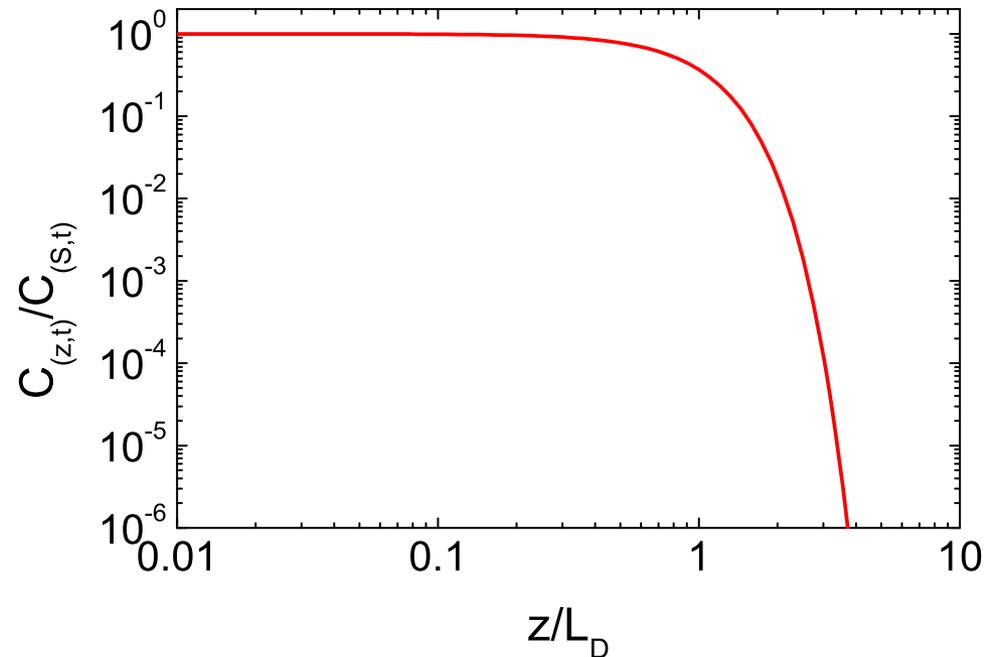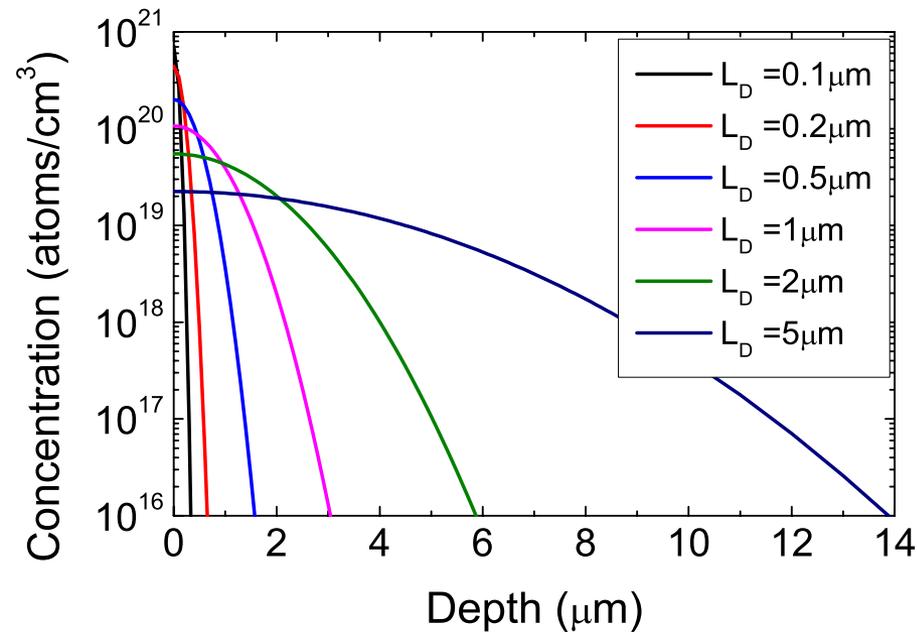   - → Small contacts with effective doping

n-type LD on a textured surface (0.5 m/s)
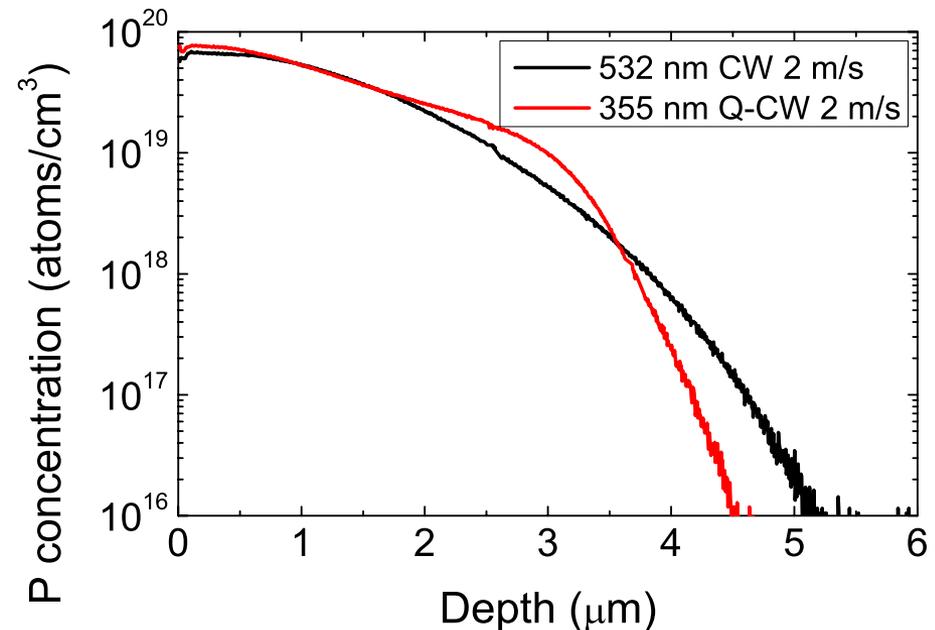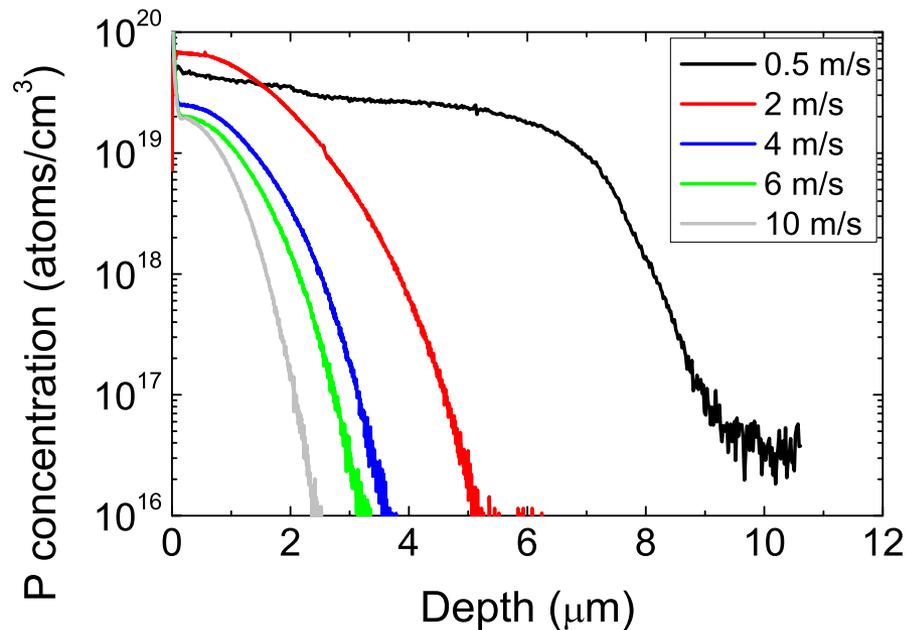
Dopant Profiles in Laser Doped Regions

- Dopant profiles in laser doped region aren't always uniform
  - Depends on z, D, t

$$C_{(z,t)} = \frac{Q}{\sqrt{\pi D t}} e^{-\frac{z^2}{4Dt}}$$

SIMS Profiles of Laser Doped Regions

- CW laser doped regions appear Gaussian for processing speeds of 2 m/s and above
- Characteristic kink for 0.5 m/s profile
- Similar kink for Q-CW laser at 2 m/s
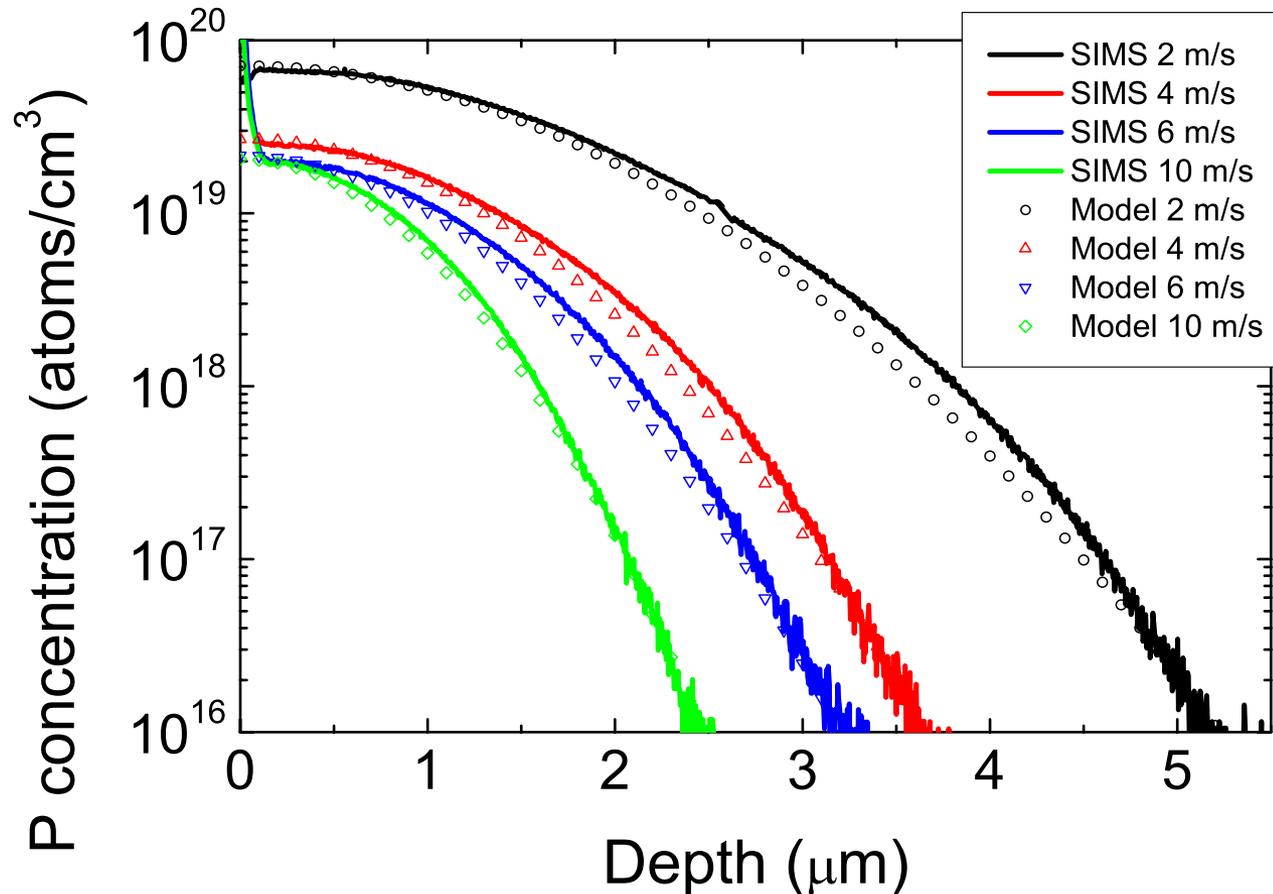- Artefacts due to multiple laser passes/pulses?

Modelling Diffusion Profiles

SIMS Profiles of Laser Doped Regions

- Gaussian diffusion theory closely matches profile
  - Discrepancy in intermediate depths
- Silicon remains molten for Q-CW lasers
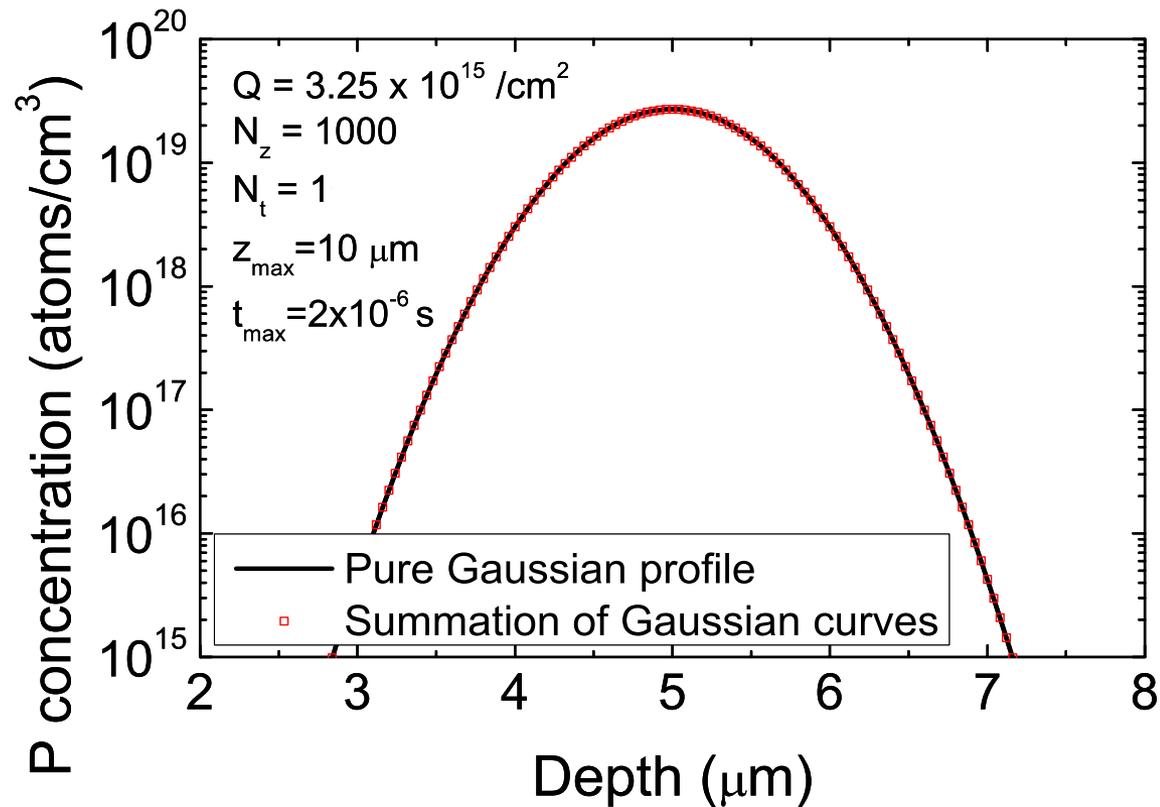
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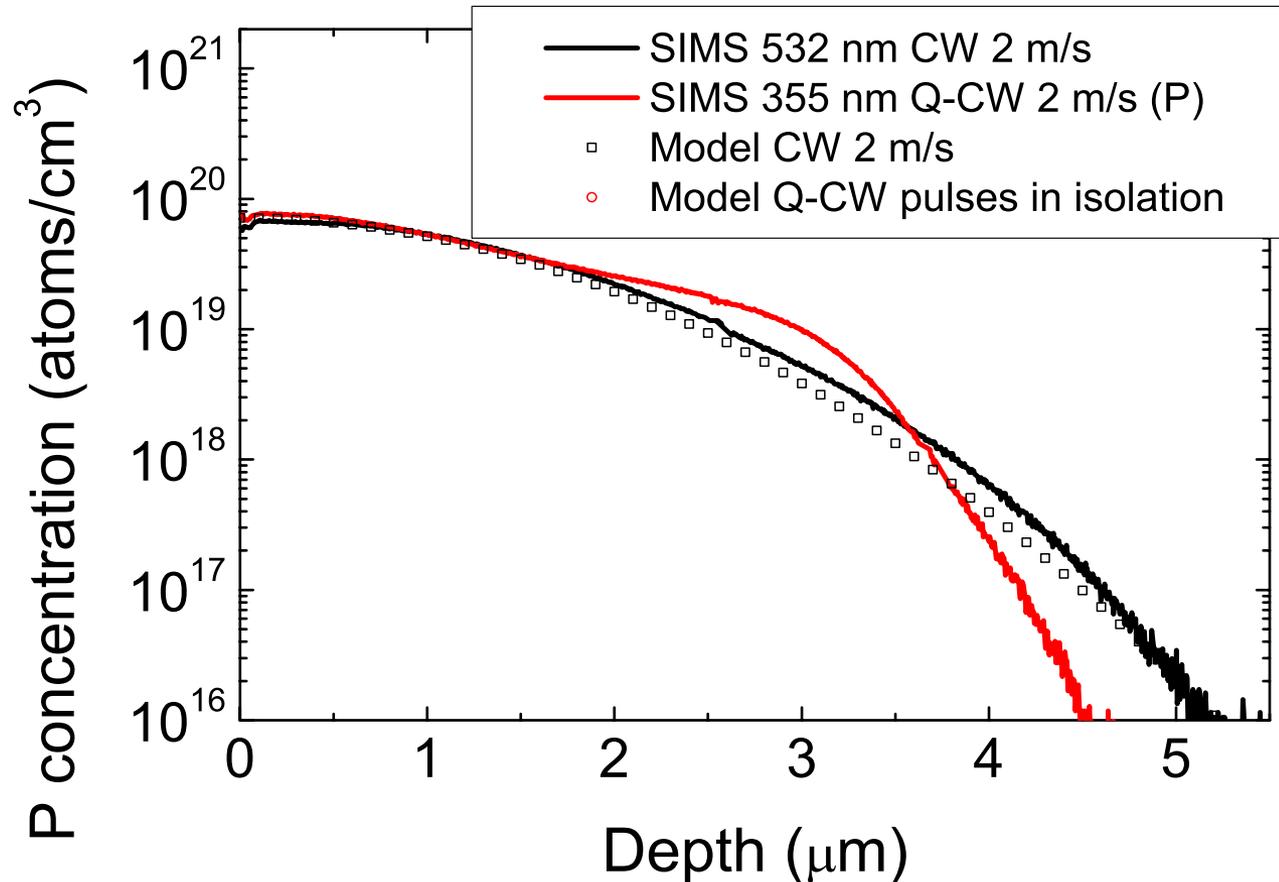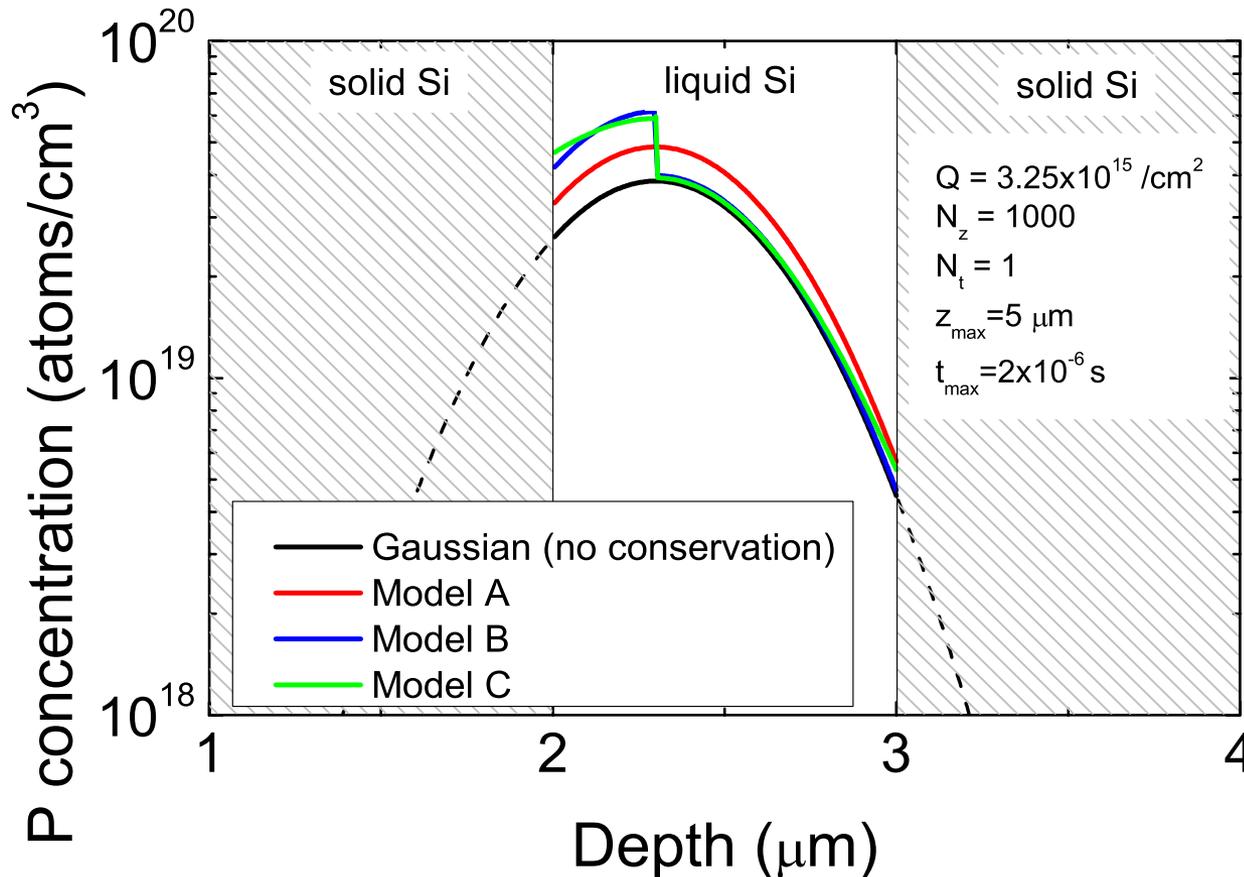
Gaussian Model in the Molten Region

- Single time-step 2 μs, single Gaussian profile seeded from z=5 μm
- 1000 time-steps, seed Gaussian profile from each depth (z_k) at each time-step (t_j)

$$\delta C_{(k,z,t_j)} = \frac{C_{(z_k,t_j)}\Delta z}{2\sqrt{\pi D \Delta t}} e^{-\frac{(z-z_k)^2}{4D\Delta t}}$$

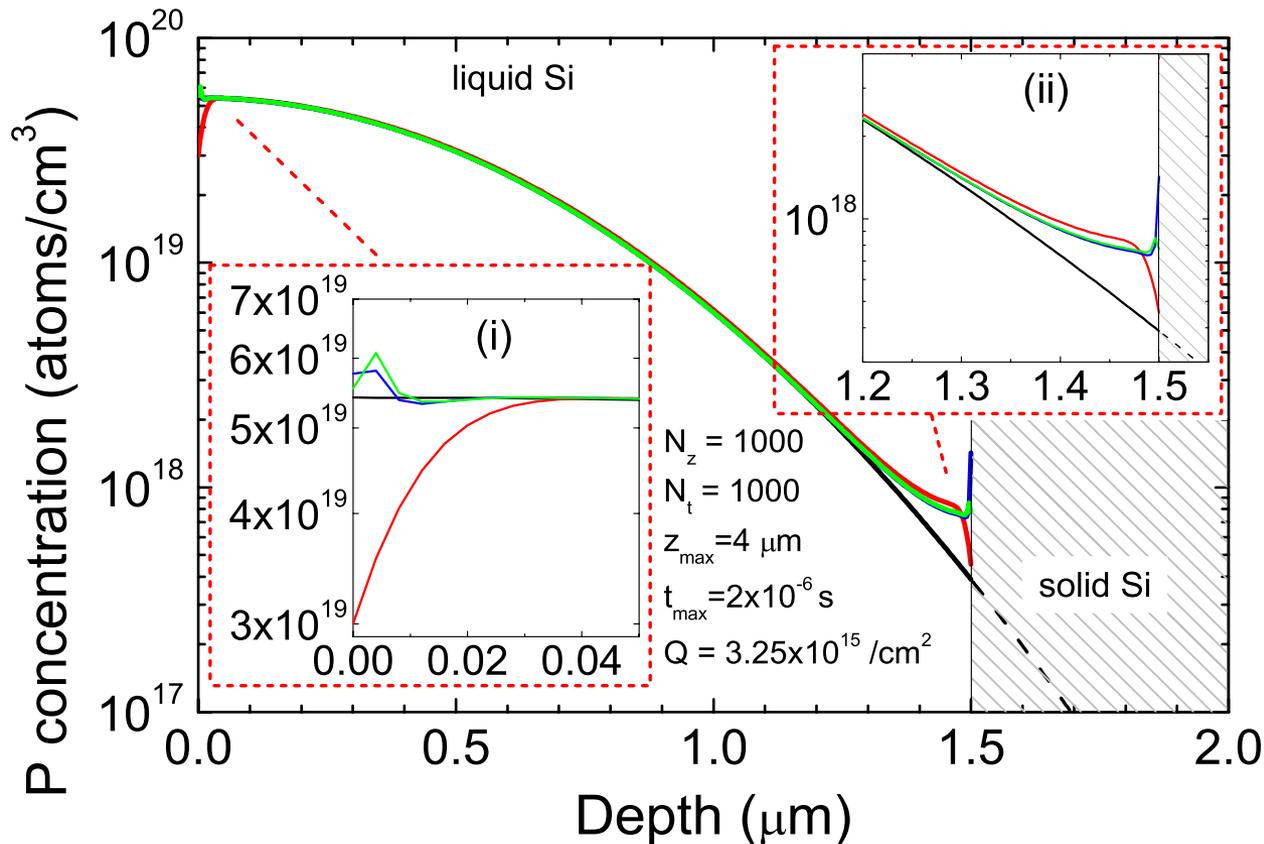$$C_{(z_i,t_{j+1})} = \sum_{k=1}^{N_z} \delta C_{(k,z_i,t_j)}$$

Plot details:
- $Q = 3.25 \times 10^{15}$ /cm^2
- $N_z = 1000$
- $N_t = 1$
- $z_{max} = 10$ μm
- $t_{max} = 2 \times 10^{-6}$ s

Y-axis: P concentration (atoms/cm^3), from 10^{15} to 10^{20}

X-axis: Depth (μm), from 2 to 8

Legend:
— Pure Gaussian profile
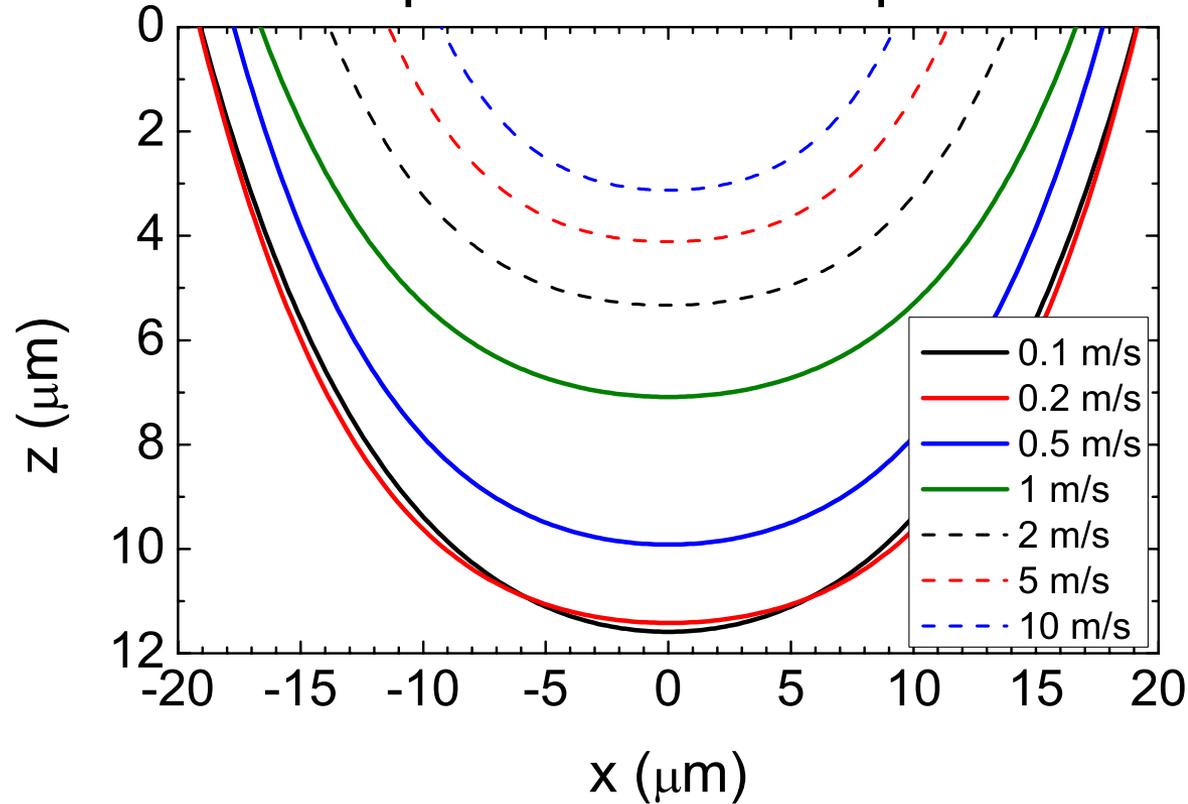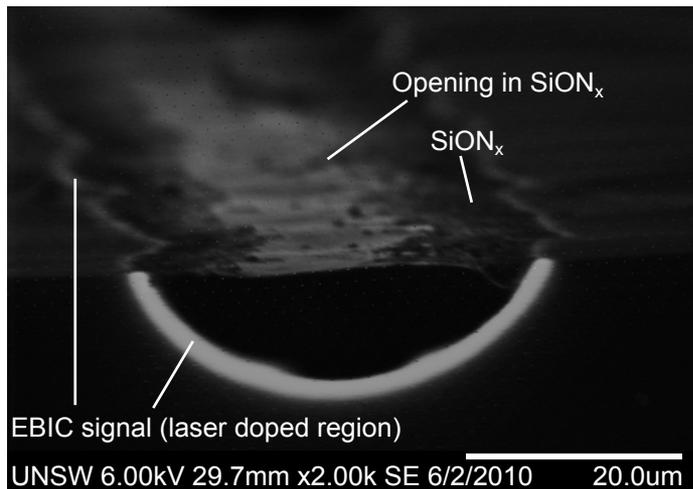□ Summation of Gaussian curves

Influence of the Solid/Liquid Interface

- Presence of a solid/liquid interface changes the dopant profile
  - → Build up of dopants at solid/liquid interface

P concentration (atoms/cm^3) vs Depth (μm)

solid Si | liquid Si | solid Si

$Q = 3.25 \times 10^{15}$ /cm^2
$N_z = 1000$
$N_t = 1$
$z_{max} = 5$ μm
$t_{max} = 2 \times 10^{-6}$ s

— Gaussian (no conservation)
— Model A
— Model B
— Model C

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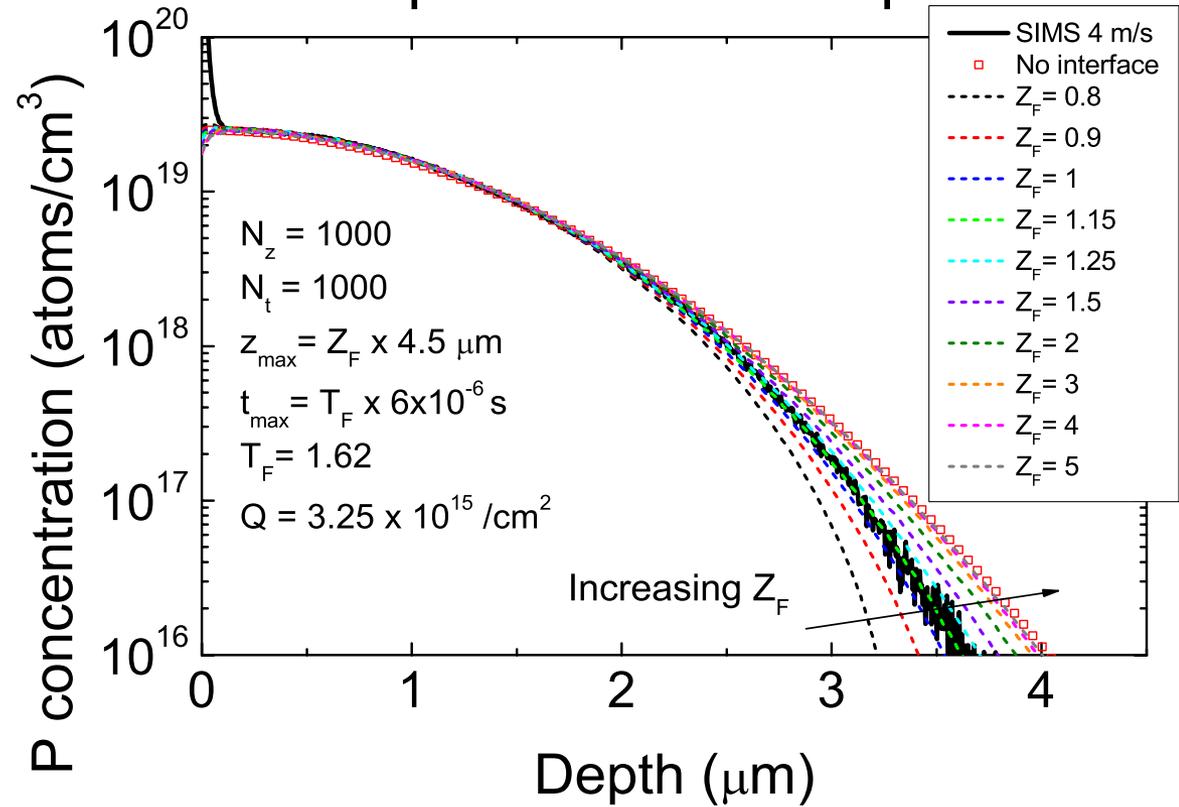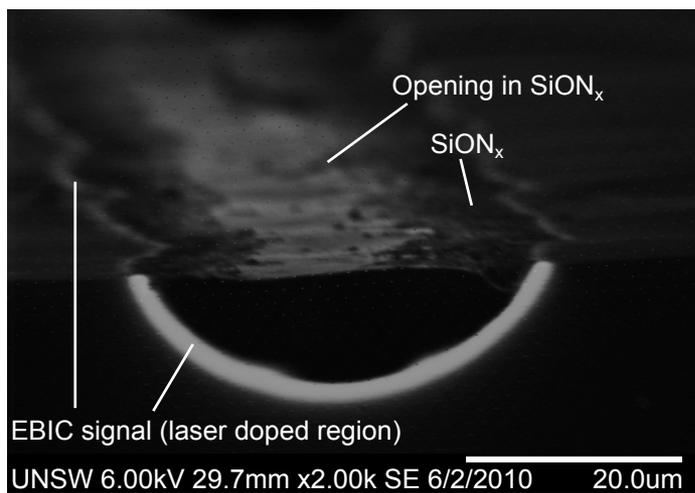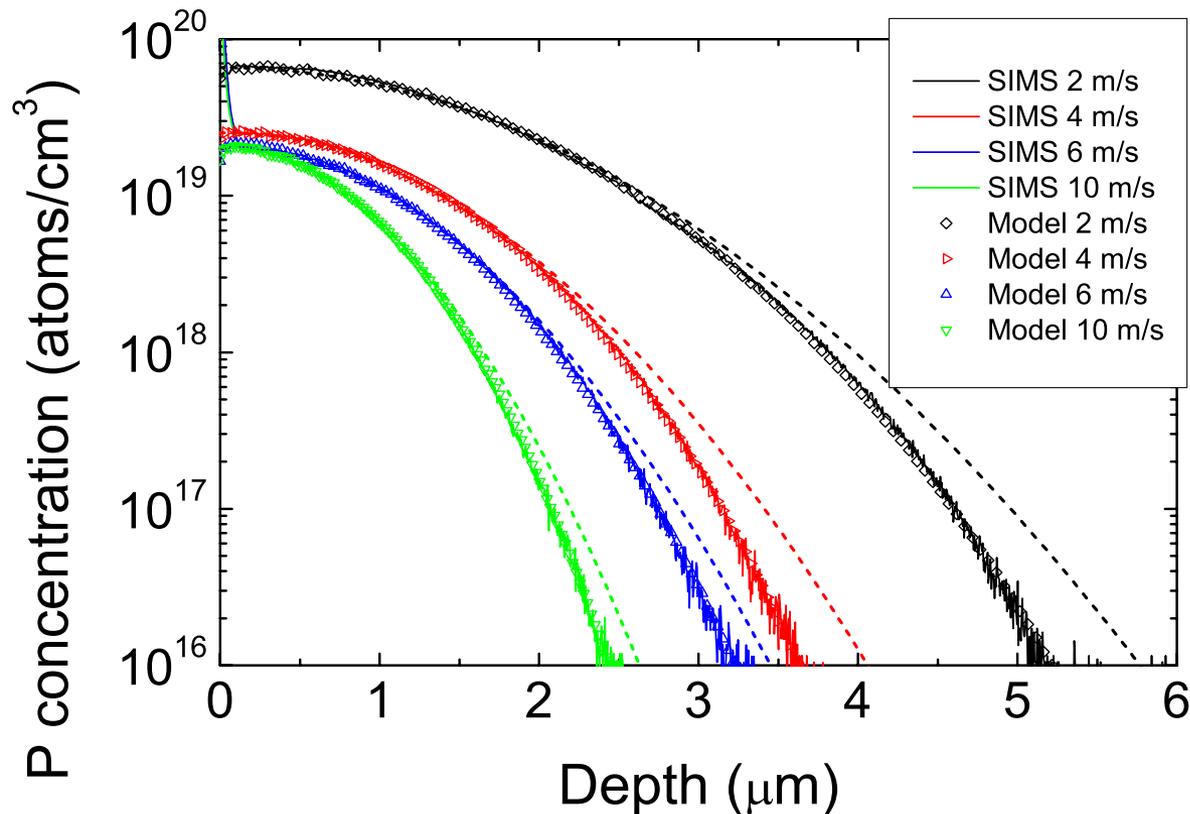 - → Build up of dopants at solid/liquid interface

A Time Dependent Solid/Liquid Interface

- $Z_M \sim f(x) \rightarrow f(t)$
- Modify cross sectional dopant profile by depth factor (Z_F) and time dilation factor (T_F) $\rightarrow$ $Z_M = Z_F f(t/T_F)$
- Clear influence of position of solid/liquid interface on profile

Opening in SiON$_x$

SiON$_x$

EBIC signal (laser doped region)

UNSW 6.00kV 29.7mm x2.00k SE 6/2/2010   20.0um

Legend:
- 0.1 m/s
- 0.2 m/s
- 0.5 m/s
- 1 m/s
- 2 m/s
- 5 m/s
- 10 m/s

z (μm)

x (μm)

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UNSW 6.00kV 29.7mm x2.00k SE 6/2/2010   20.0um

$N_z = 1000$

$N_t = 1000$

$z_{max} = Z_F \times 4.5\ \mu m$

$t_{max} = T_F \times 6 \times 10^{-6}\ s$

$T_F = 1.62$

$Q = 3.25 \times 10^{15}\ /cm^2$

Increasing Z_F

Legend:
- SIMS 4 m/s
- No interface
- $Z_F = 0.8$
- $Z_F = 0.9$
- $Z_F = 1$
- $Z_F = 1.15$
- $Z_F = 1.25$
- $Z_F = 1.5$
- $Z_F = 2$
- $Z_F = 3$
- $Z_F = 4$
- $Z_F = 5$

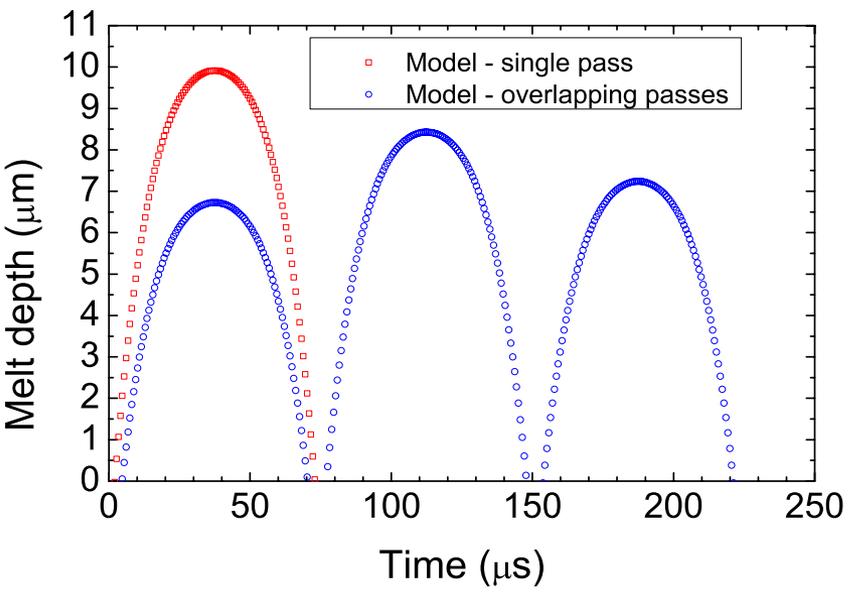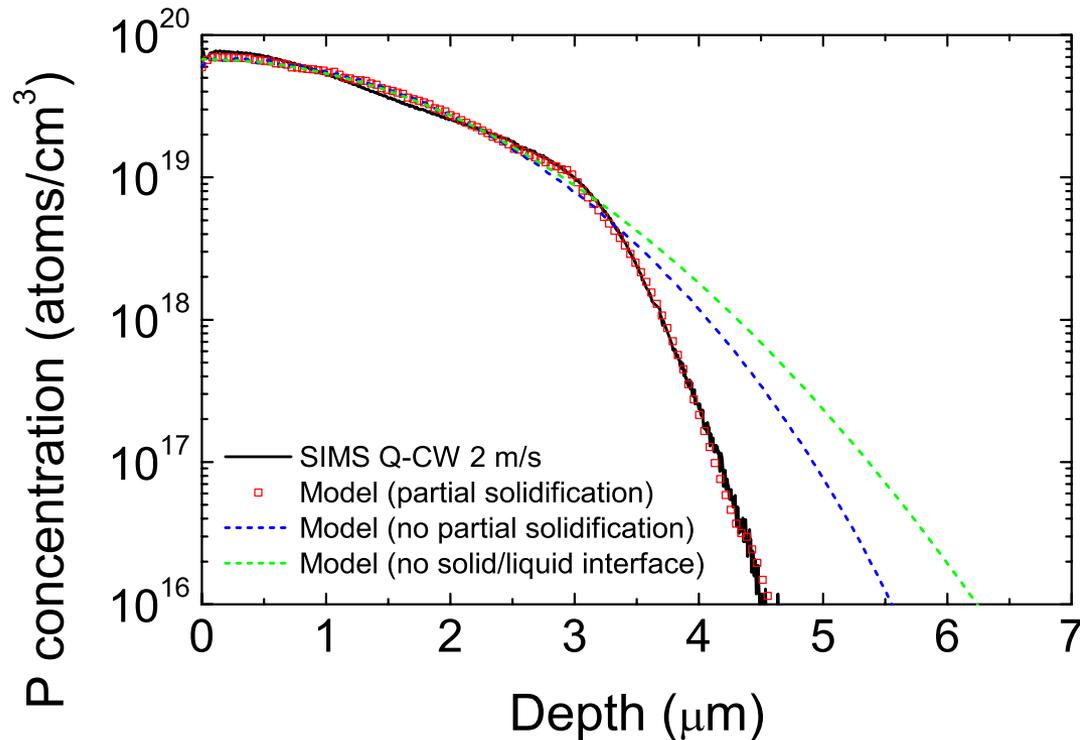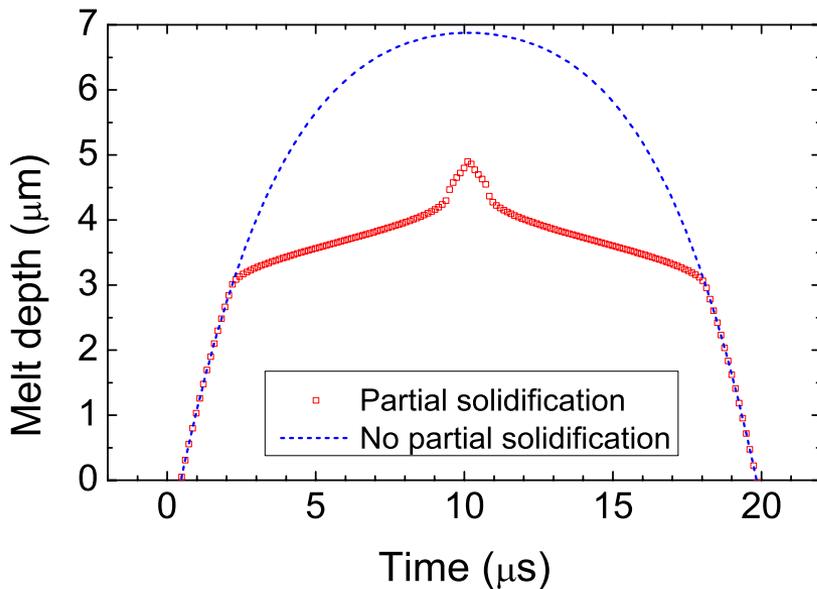P concentration (atoms/cm^3)

Depth (μm)

A Time Dependent Solid/Liquid Interface

- Influence of the solid/liquid interface can accurately describe the SIMS profiles

- Doesn't work for 0.5 m/s → multiple passes?

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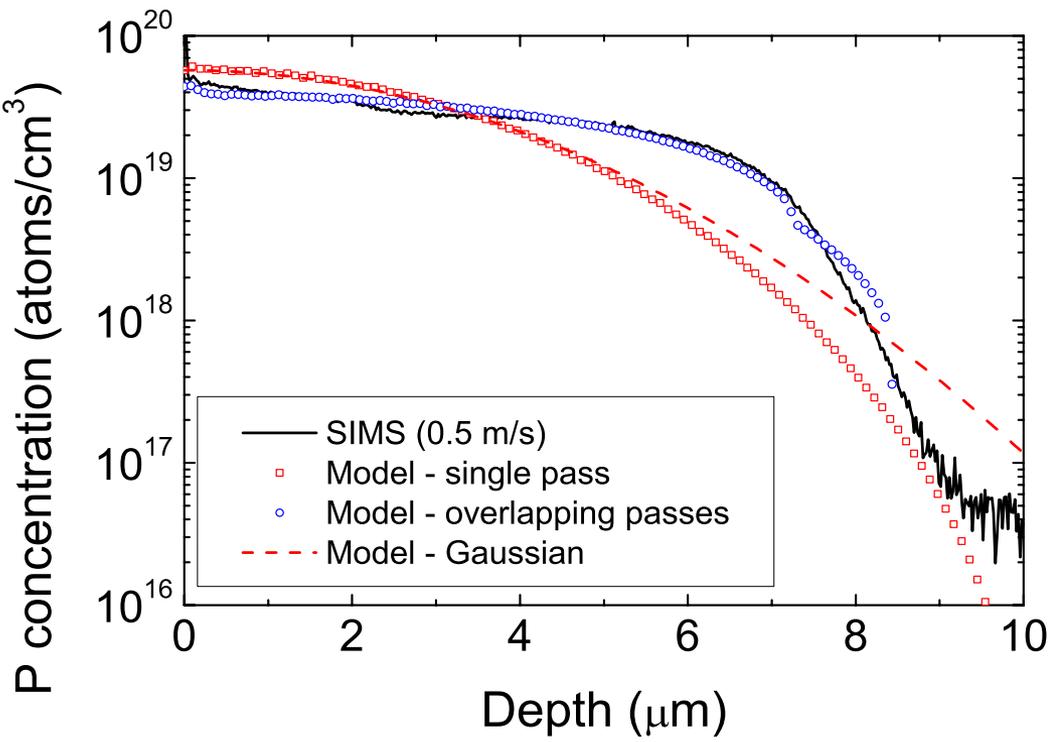
Partial Solidification for Q-CW Laser Doping

- Q-CW laser doped regions can be represented by a single effective pulse with a reduced melt depth
  → Represent a partial solidification between successive pulses (80 MHz) for the larger depths
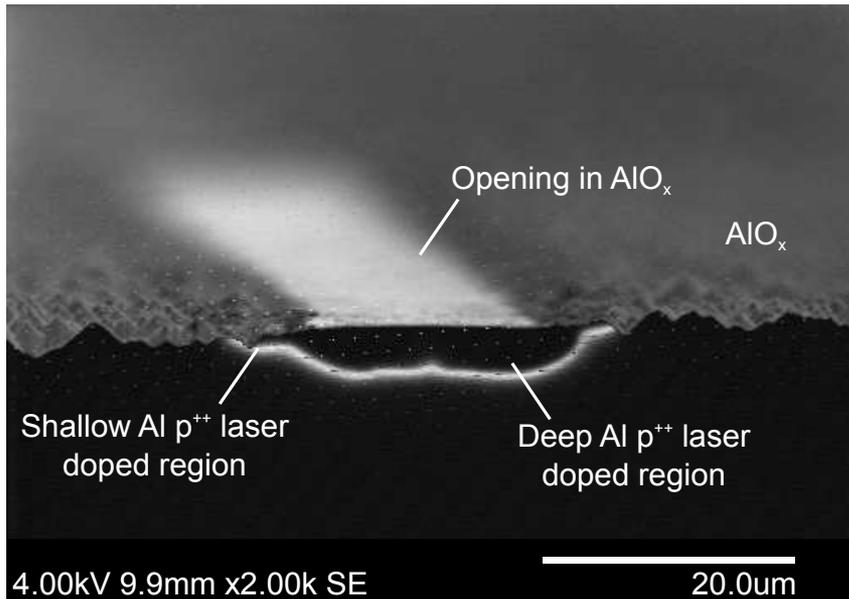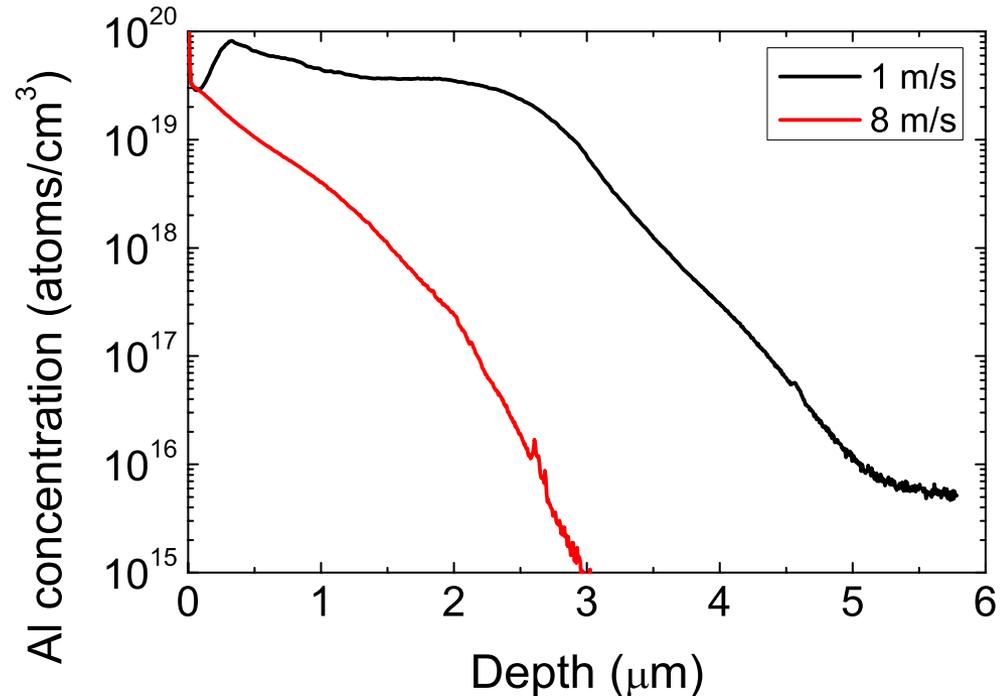
Laser Doping from Al$_2$O$_3$ Layers

Effective Doping from Al_2O_3 Layers

- Effective doping from Al_2O_3 layers
  - Solid state diffusion in peripheral regions?

- Up to 35% utilisation of Al atoms from Al_2O_3 layers (10 nm)

- Much higher doping concentrations than conventional BSF ($\sim 2 \times 10^{18}$ /cm^3)

Al$_2$O$_3$ LD on a textured surface (2 m/s)

4.00kV 9.9mm x2.00k SE   20.0um

Opening in AlO$_x$

AlO$_x$

Shallow Al p^{++} laser doped region

Deep Al p^{++} laser doped region

Al concentration (atoms/cm^3)

Depth (μm)

1 m/s
8 m/s

Contact formation by Al$_2$O$_3$ Laser Doping

- Stack of ~5 μm opening (10 m/s through 10nm Al$_2$O$_3$/ 50nm SiO$_x$)

- Increasing iV$_{OC}$ / τ$_{eff}$ with increasing speed
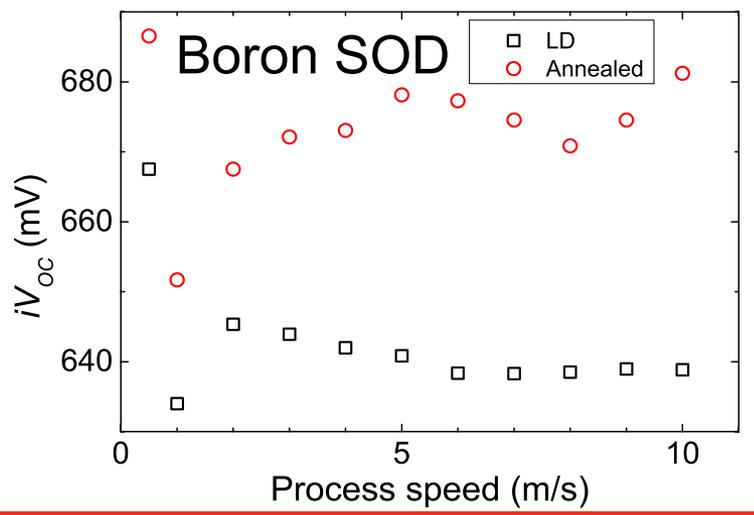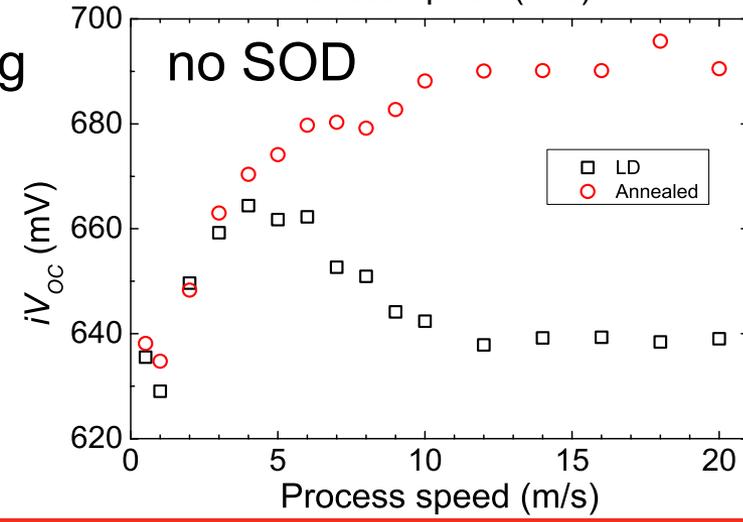
  - Avoidance of bulk defects
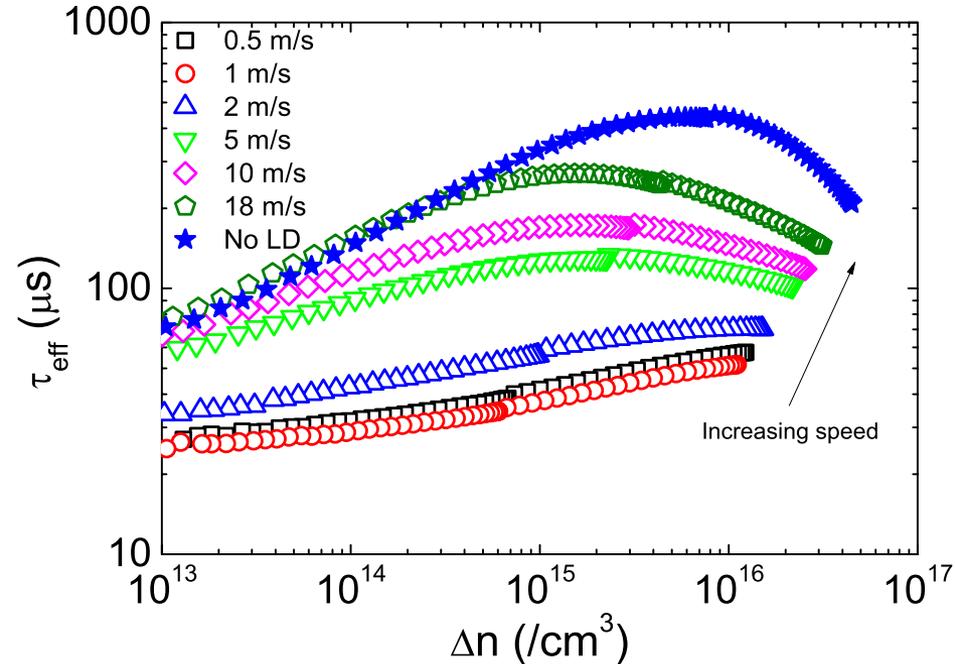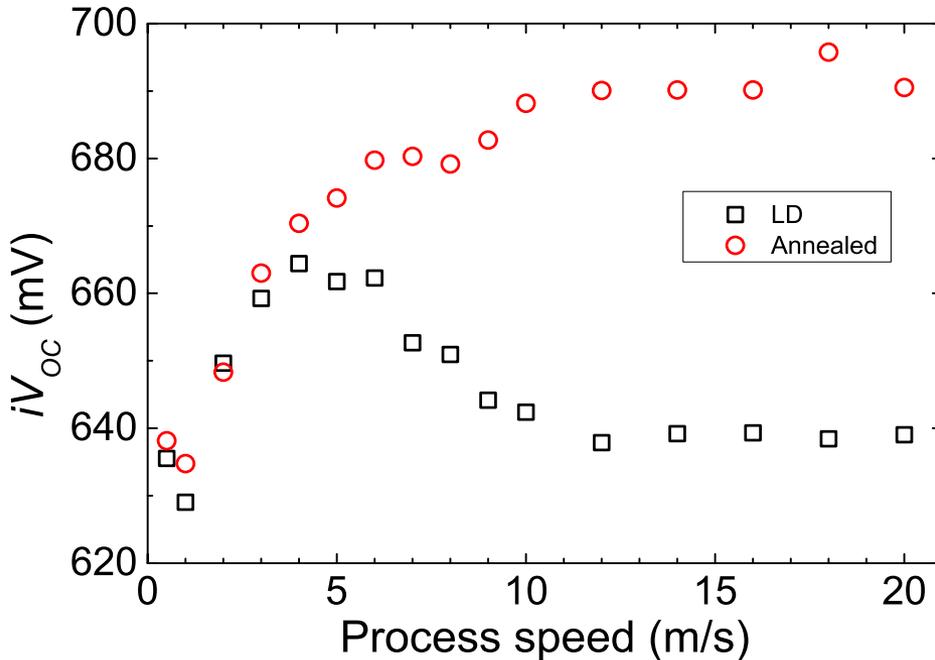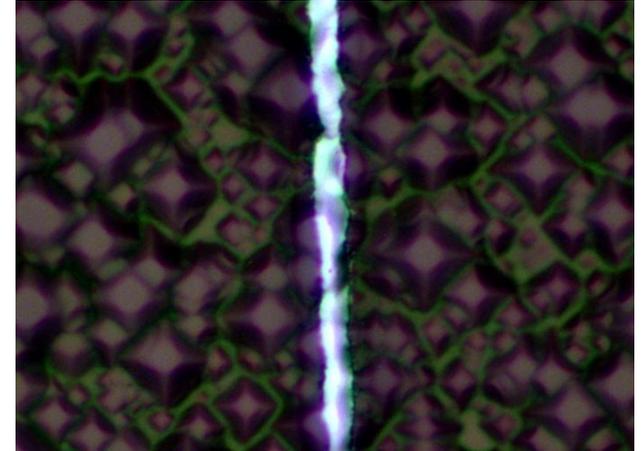
Dependence of Dielectric Layers / SOD

- Results dependent on dielectric stack / presence of additional dopants
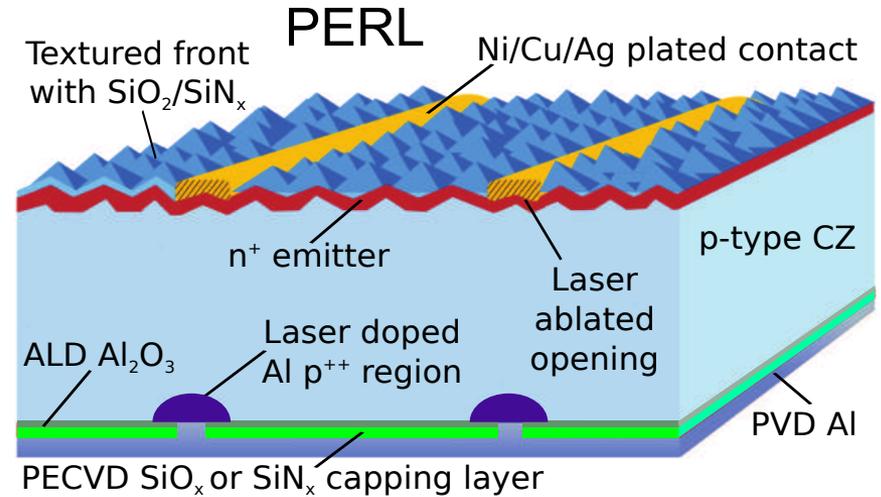
SiN$_x$ capping
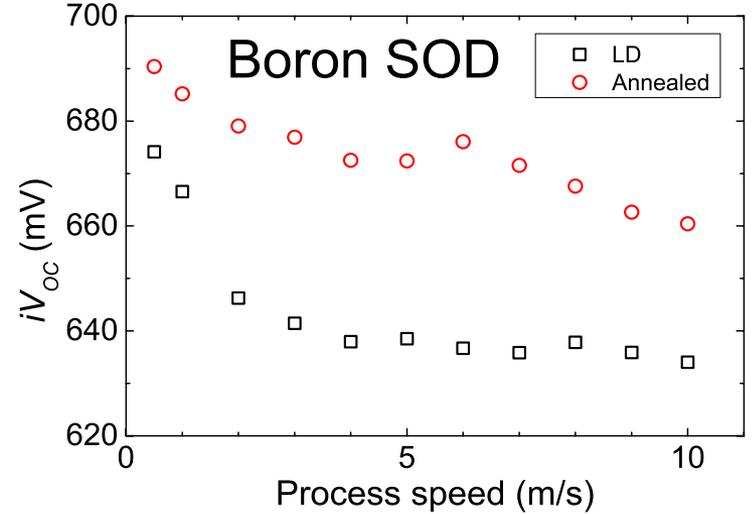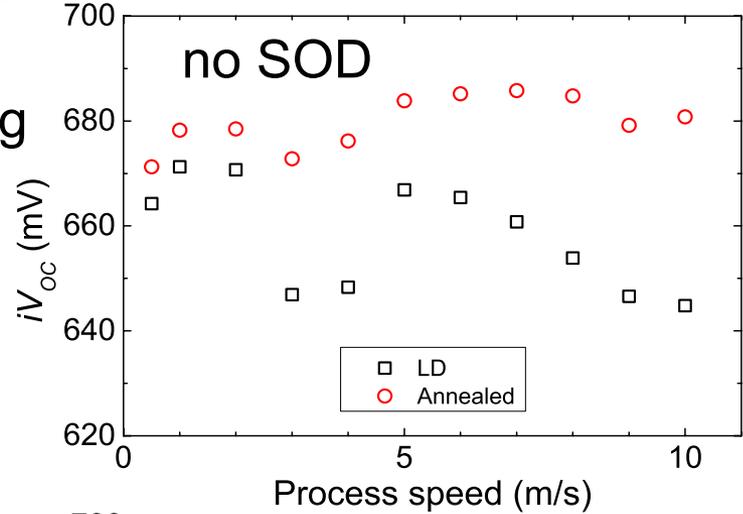
SiO$_x$ capping
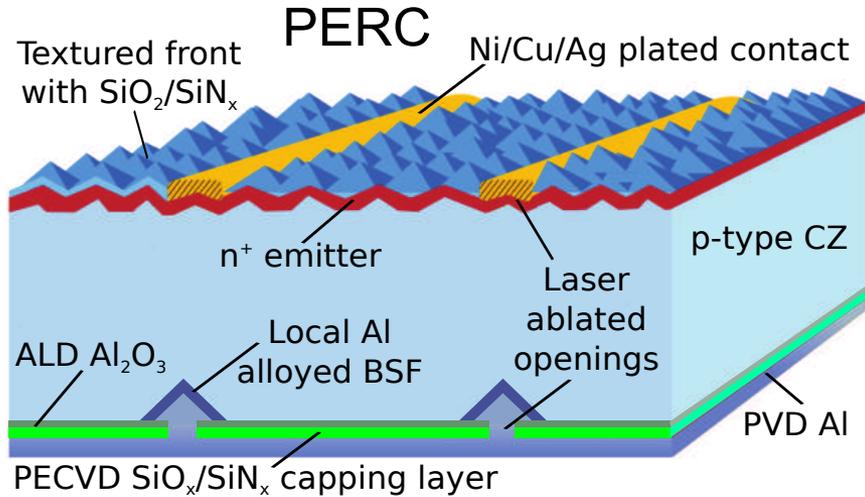
Cell Fabrication with Al_2O_3 Laser Doping

PERC

Textured front with SiO_2/SiN_x
Ni/Cu/Ag plated contact
n^+ emitter
p-type CZ
Laser ablated openings
ALD Al_2O_3
Local Al alloyed BSF
PVD Al
PECVD SiO_x/SiN_x capping layer

PERL

Textured front with SiO_2/SiN_x
Ni/Cu/Ag plated contact
n^+ emitter
p-type CZ
Laser ablated opening
ALD Al_2O_3
Laser doped Al p^{++} region
PVD Al
PECVD SiO_x or SiN_x capping layer

Process	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	pFF (%)	η (%)
PERC (Av)	39.4 ± 0.2	659 ± 3	79.7 ± 0.3	82.0 ± 0.2	20.4 ± 0.2
PERL (Av)	39.5 ± 0.1	653 ± 3	79.2 ± 0.4	82.4 ± 0.1	20.4 ± 0.2
PERL* (best)	39.4	657	79.9	-	20.7

- Incorporation of LDSE front → + 0.4% efficiency (21.1%)
- Incorporation of improved hydrogenation
  → increase V_{OC} > 680 mV, J_{SC} ~ 40 mA/cm^2 (21.8%)

imec
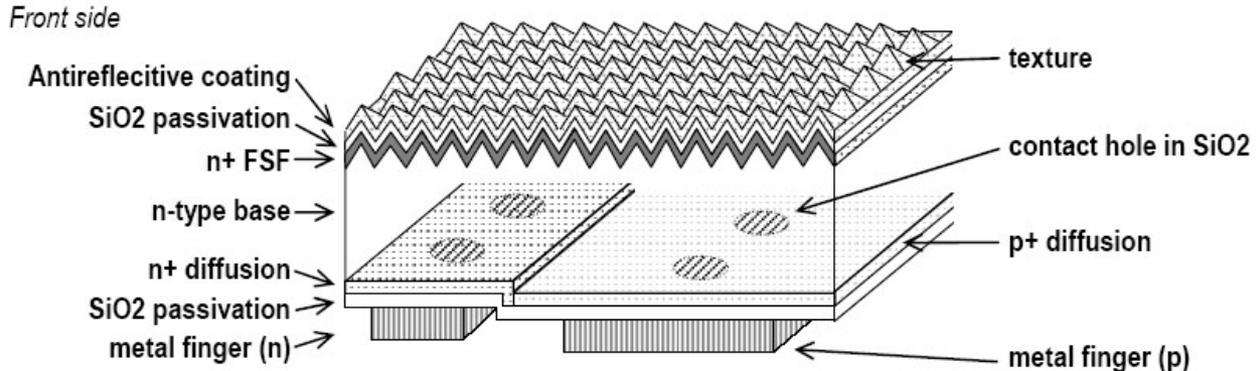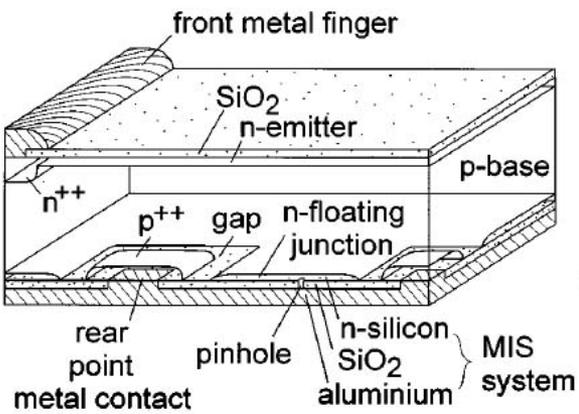
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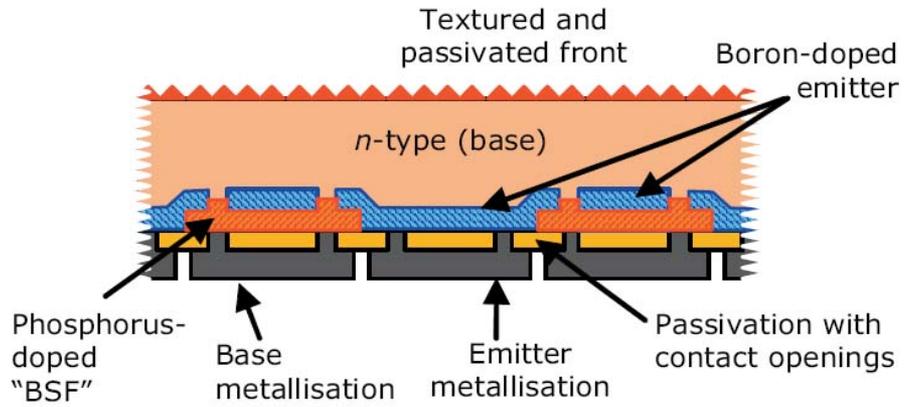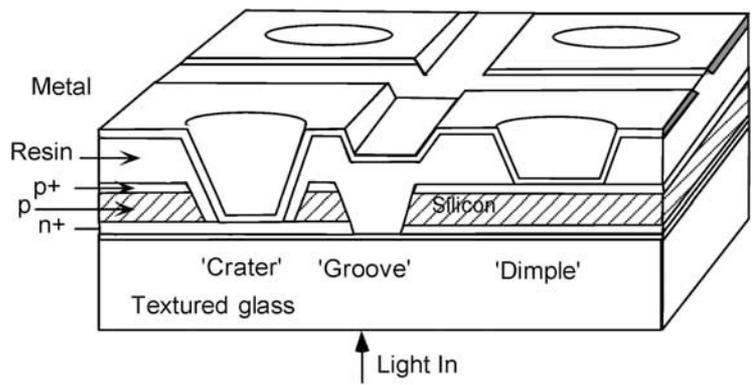# Contacting Buried Layers in Silicon Solar Cells

The Need to Contact Buried Layers

- Contacting buried layers in silicon solar cells requires complex processing
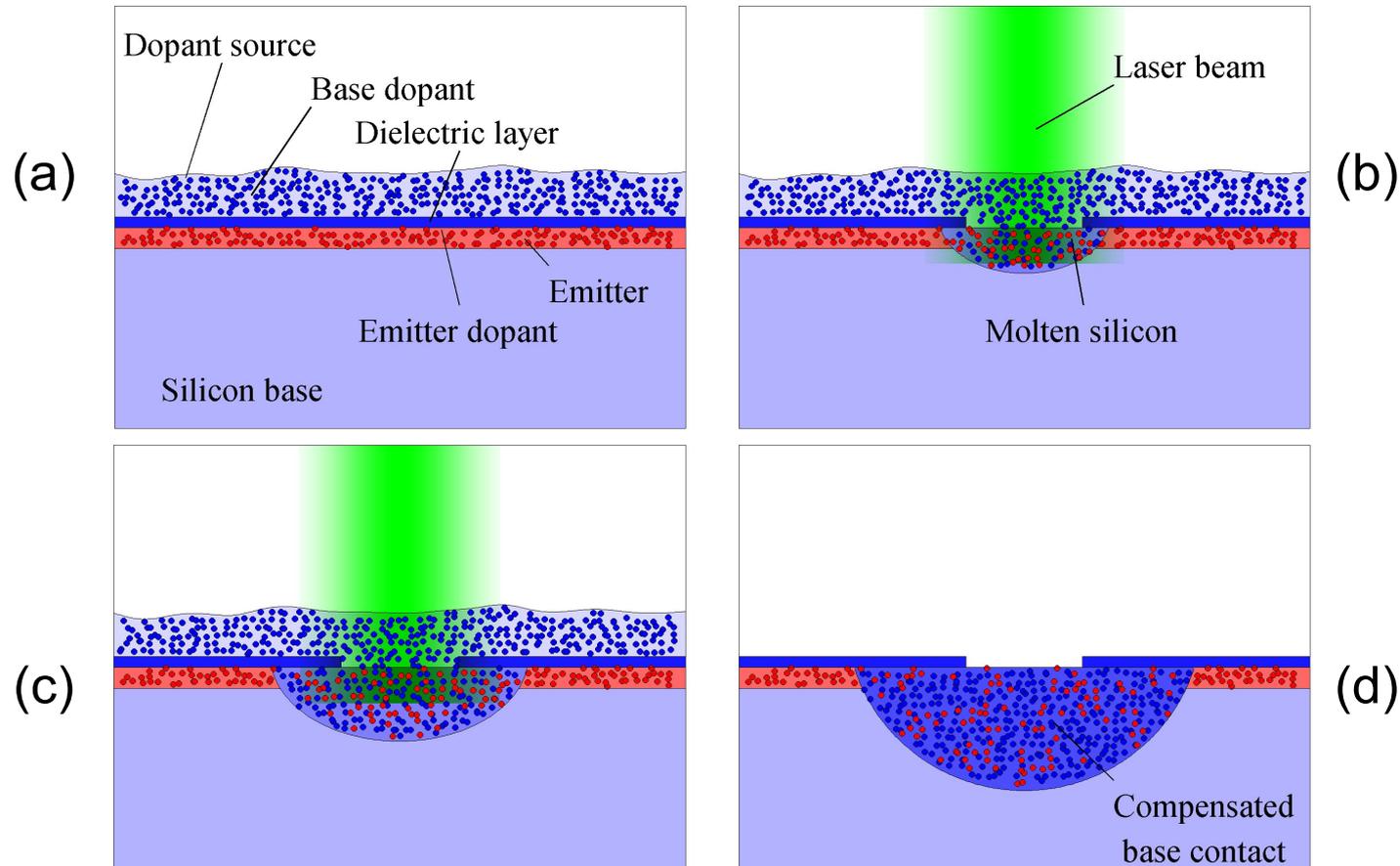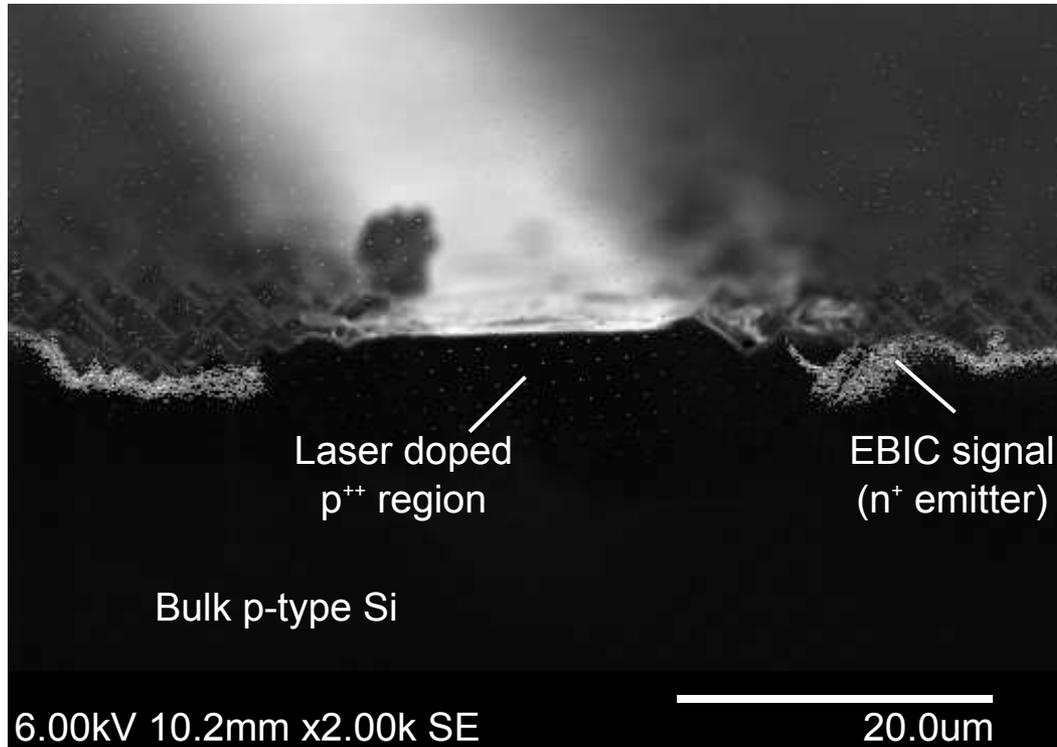 - Masking/etching
  - Multiple diffusions

Laser Doping for Contact Buried Layers

- Single self-aligned process to contact layer under the surface
  - No masking/etching
  - Single conventional thermal diffusion

(a) Dopant source, Base dopant, Dielectric layer, Emitter, Emitter dopant, Silicon base

(b) Laser beam, Molten silicon

(c)

(d) Compensated base contact

Contacting Buried Layers for IBC Cells

- Successful demonstration of penetrating through an industrial phosphorus emitter (120 Ω/sq) with boron laser doping
  - No masking/etching
  - IBC solar cells with single thermal diffusion and two alignment steps
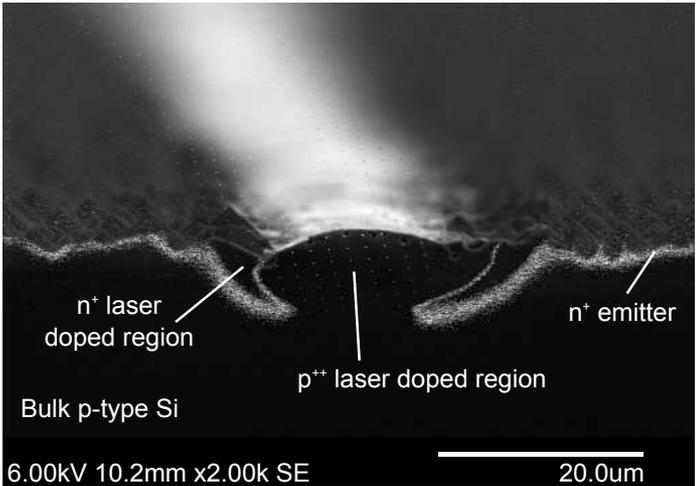 →14.5% efficiency in initial trials [Chan 2012]

Laser doped p^{++} region

EBIC signal (n$^+$ emitter)

Bulk p-type Si

6.00kV 10.2mm x2.00k SE   20.0um

p-type LD on a textured phosphorus emitter

(0.2 m/s)

C. Chan, B. Hallam and S. Wenham. Energy Procedia, Vol. 27, pp. 543 (2012).

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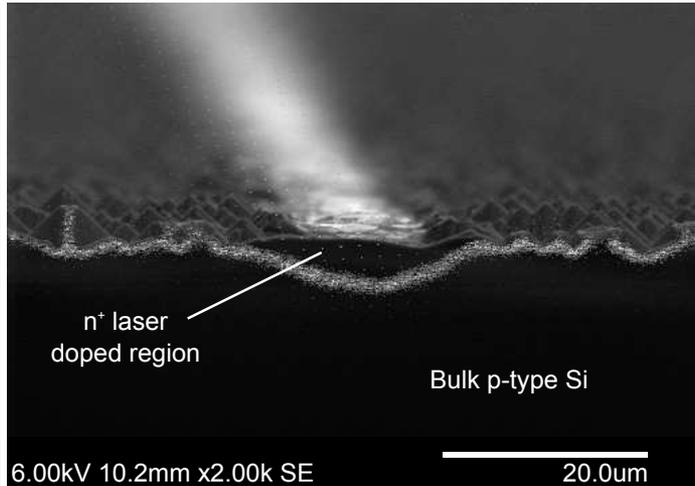THE UNIVERSITY OF NEW SOUTH WALES

Transistor formation

- Changing process conditions / emitter profile can result in transistor formation

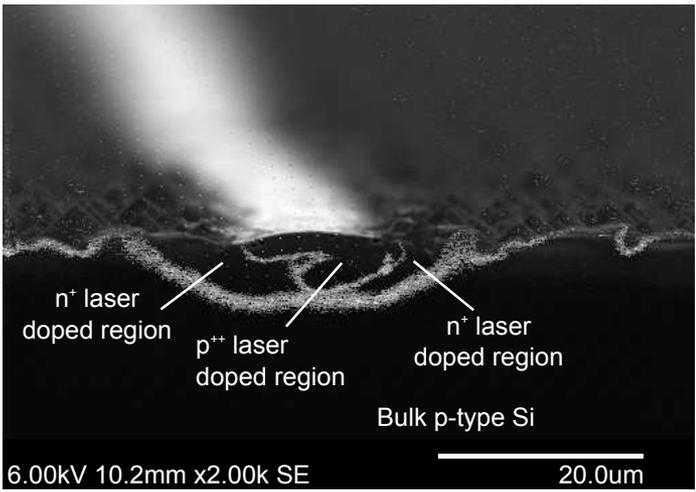1 m/s

5 m/s

2 m/s

Transistor formation

- Changing process conditions / emitter profile can result in transistor formation

1 m/s

5 m/s

2 m/s

1000 Ω/sq 5 m/s
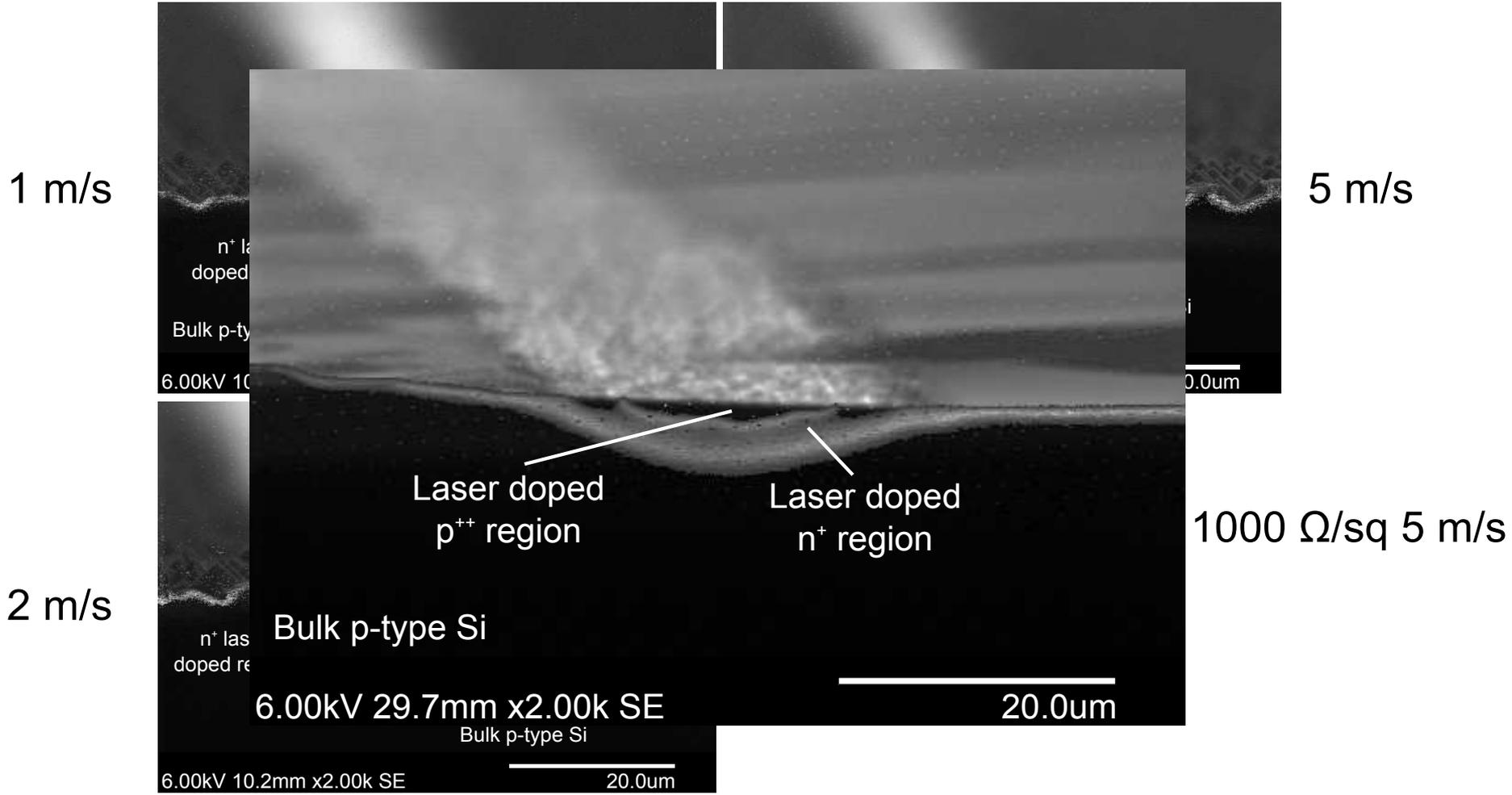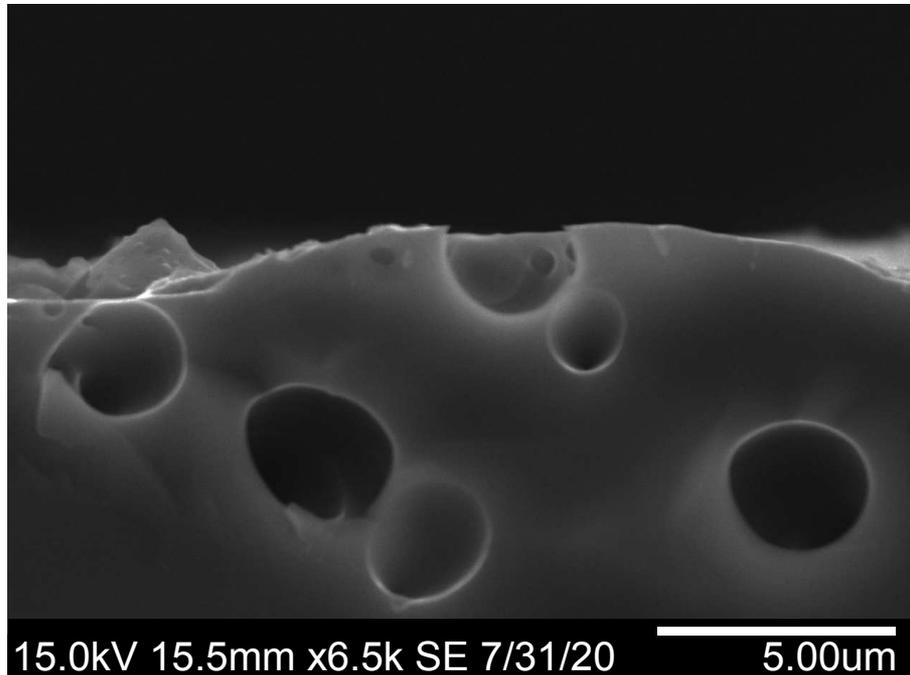

Laser doped p++ region

Laser doped n+ region

Bulk p-type Si

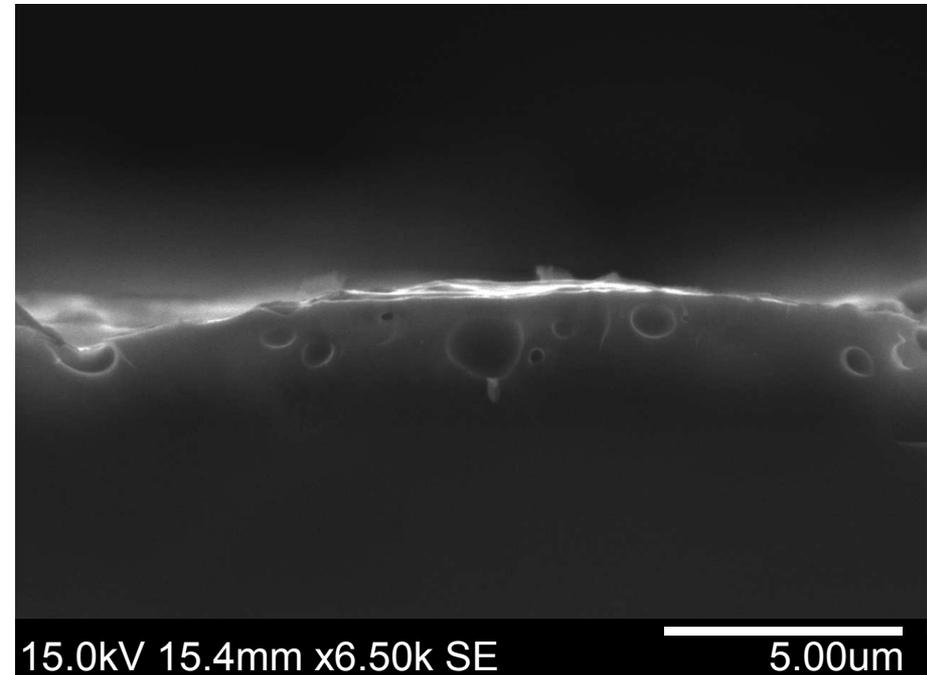6.00kV 29.7mm x2.00k SE   20.0um

Passivation of Laser-Induced Defects

Void Formation during CW Laser Doping

- Voids can form with diameters > 4 um
- Dependent on speed / SOD / dielectric layer
  - Most prevalent at 0.5 m/s

15.0kV 15.5mm x6.5k SE 7/31/20   5.00um
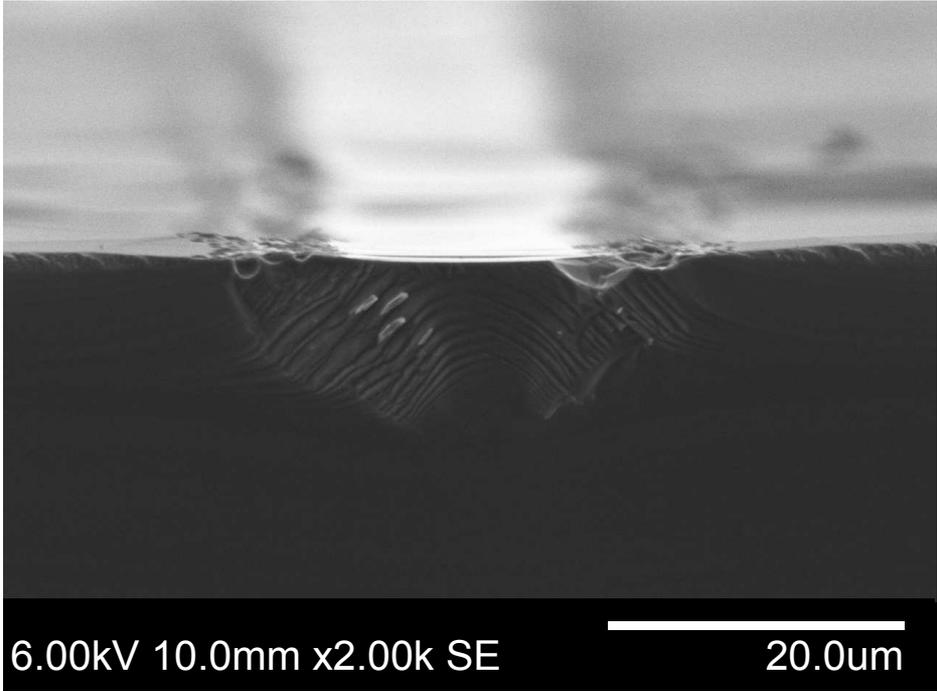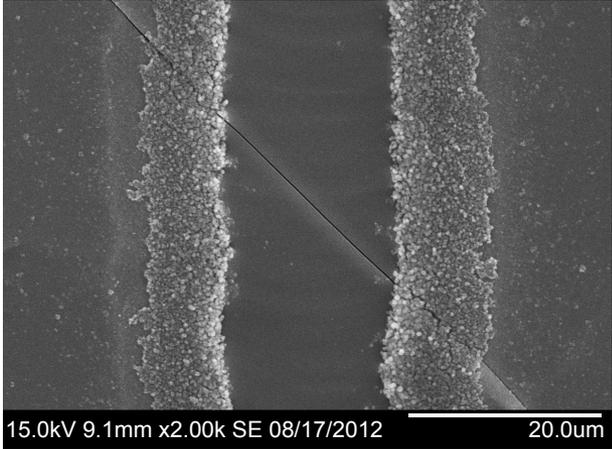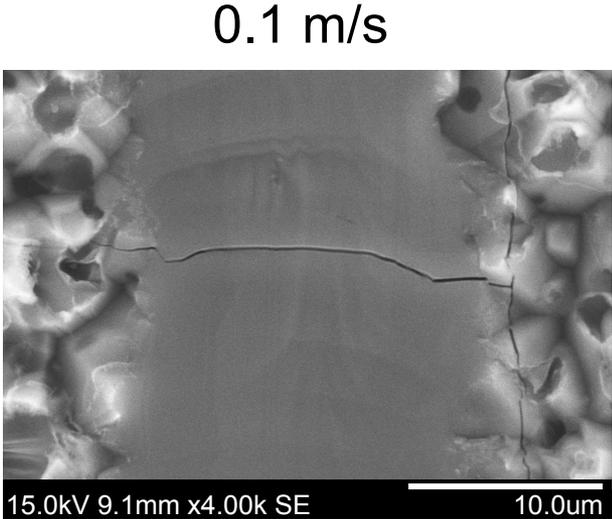
0.5 m/s

15.0kV 15.4mm x6.50k SE   5.00um

1 m/s

Crystallographic Defect Formation

- Crystallographic defects are evident for processing speeds < 0.5 m/s

0.1 m/s

6.00kV 10.0mm x2.00k SE   20.0um

0.1 m/s

15.0kV 9.1mm x4.00k SE   10.0um
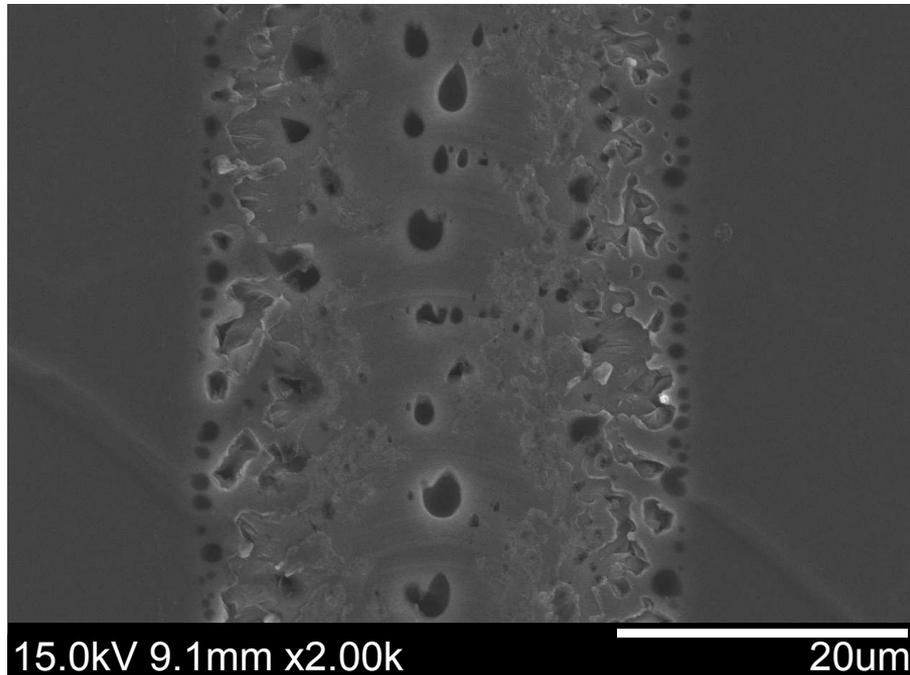

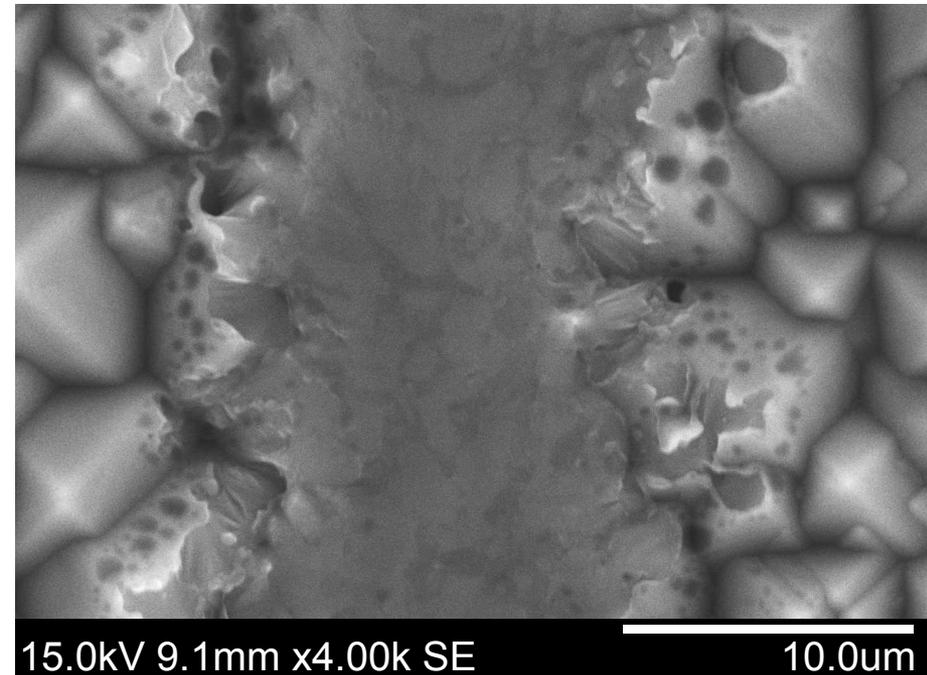15.0kV 9.1mm x2.00k SE 08/17/2012   20.0um

0.01 m/s

Pinhole Formation in Dielectrics

- Pinhole formation in dielectrics beyond opened region
  - Require doping to protect against recombination

15.0kV 9.1mm x2.00k   20um

15.0kV 9.1mm x4.00k SE   10.0um

0.5 m/s   5 m/s

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Passivation of Laser-Induced Defects

- Laser processing can introduce bulk/surface defects
- H a key to passivating laser-induced defects
  → Annealing 1-2 min @ 400°C utilising H in the the wafer
- Ni sinter can also be used for H passivation

Process	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	pFF (%)	η (%)
No anneal (Av)	37.78	627.4	77.42	83.2	18.35
Anneal (Av)	37.69	636.7	77.97	83.6	18.71

+10 mV +0.4% +0.35%

Al-BSF   LD   Anneal

Implied V_{OC} (mV)
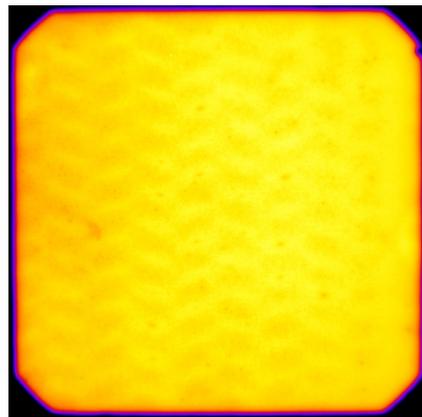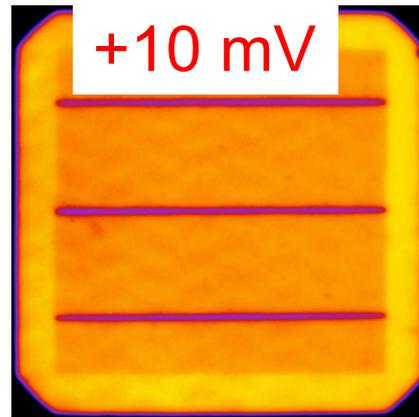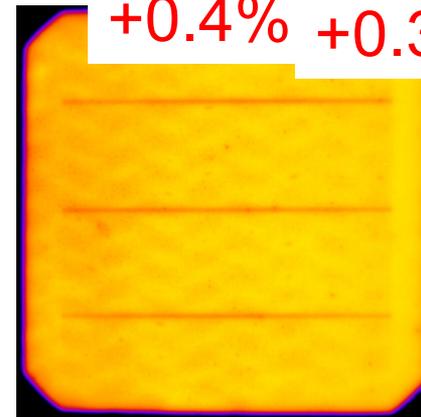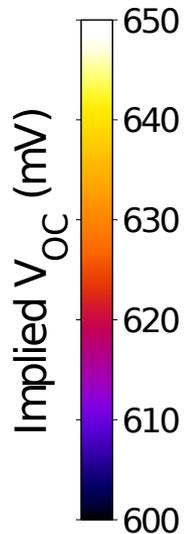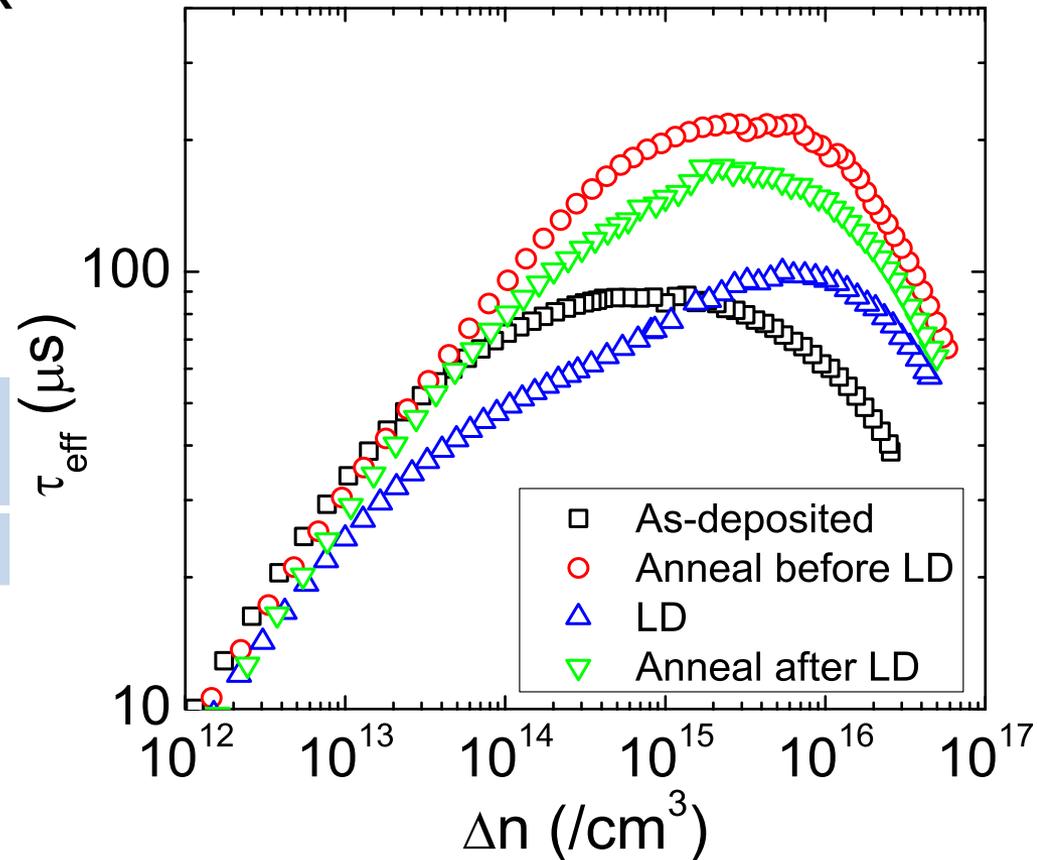
Bulk and Surface Damage from LD

- Test structure $n^+/p/n^+$ passivated by SiON:H
- H passivation (400 °C in N_2) reduces J_{0d} and increases τ_{bulk}
- Laser doping damages bulk
- Subsequent anneal passivates laser-induced defects

Process	iV_{OC} (mV)	J_{0d} (fA/cm^2)	τ_{bulk} (µs)
As-dep	648	140	129

High Voltage Test Structures

- Modification of PECVD process to enhance hydrogen passivation (only little extra improvement from P2)
  - Enhanced H-radical incorporation into SiN and Si
- Laser processing generates defects
- H passivation important for laser induced defects
  - Up to 1% absolute increase in efficiency observed so far
  - Can recover ~40 mV iV_{OC}, substantial increases in J_{SC} and pFF
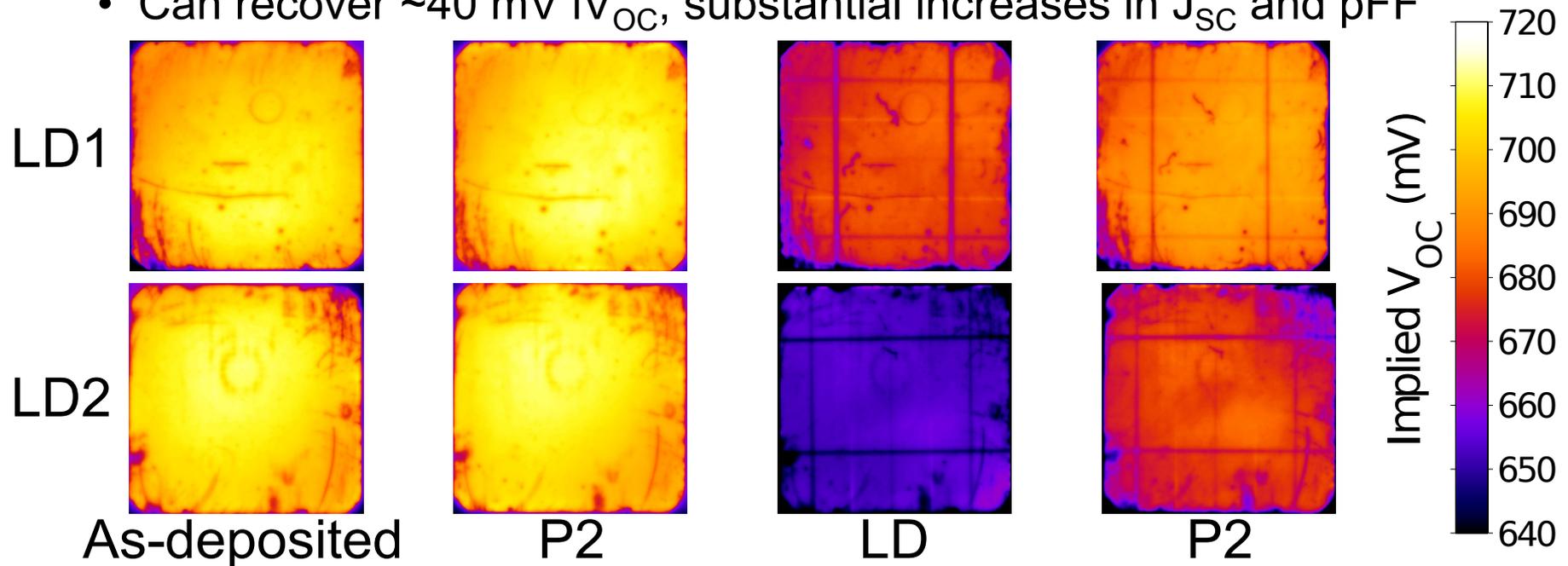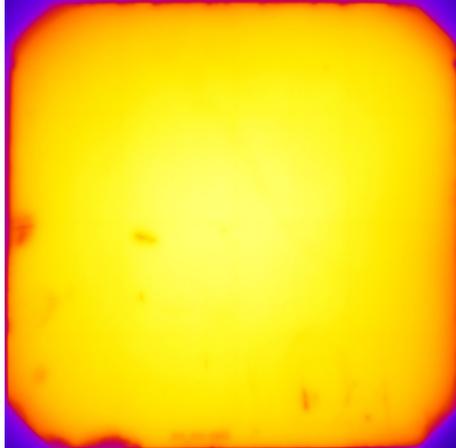
Passivation of Laser-Induced Defects for n-PERT

- Similar effect for passivation of laser-induced defects on n-PERT solar cells

- 15 mV improvement through passivation of laser-induced defects

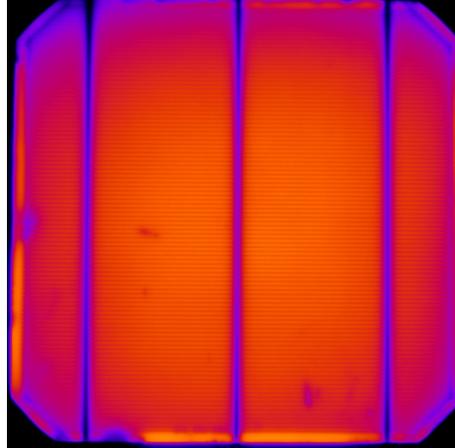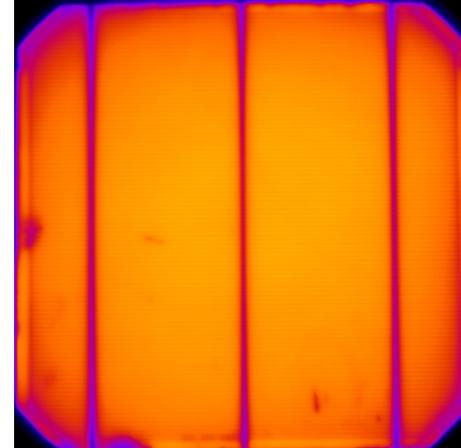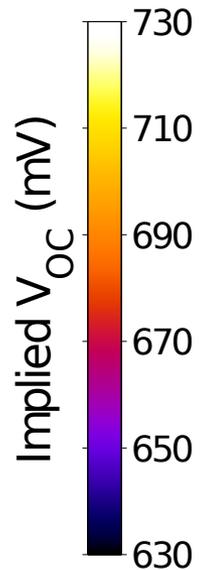- iV_{OC} still limited by busbar region (20 mV lower)

710 mV   670 mV   685 mV

Alneal   LD   Anneal

Implied V_{OC} (mV)

730
710
690
670
650
630

Improvement in passivation for n-PERT

- Standard IMEC Ni sintering process (SS) reasonably ineffective for hydrogen passivation of laser-induced defects

- Performing an extra sinter at elevated temperature (ES) more effective for passivation

- Annealing at 450 °C for 3 mins in O_2 ambient (A) prior to plating substantially improves V_{OC}

- Passivation stable during subsequent SS process

+15 – 20 mV

1 mm finger pitch
1.5 mm finger pitch

+4 mV

+4 mV

V_{OC} (mV)

NA   NA + SS   NA + SS + ES   A   A + SS
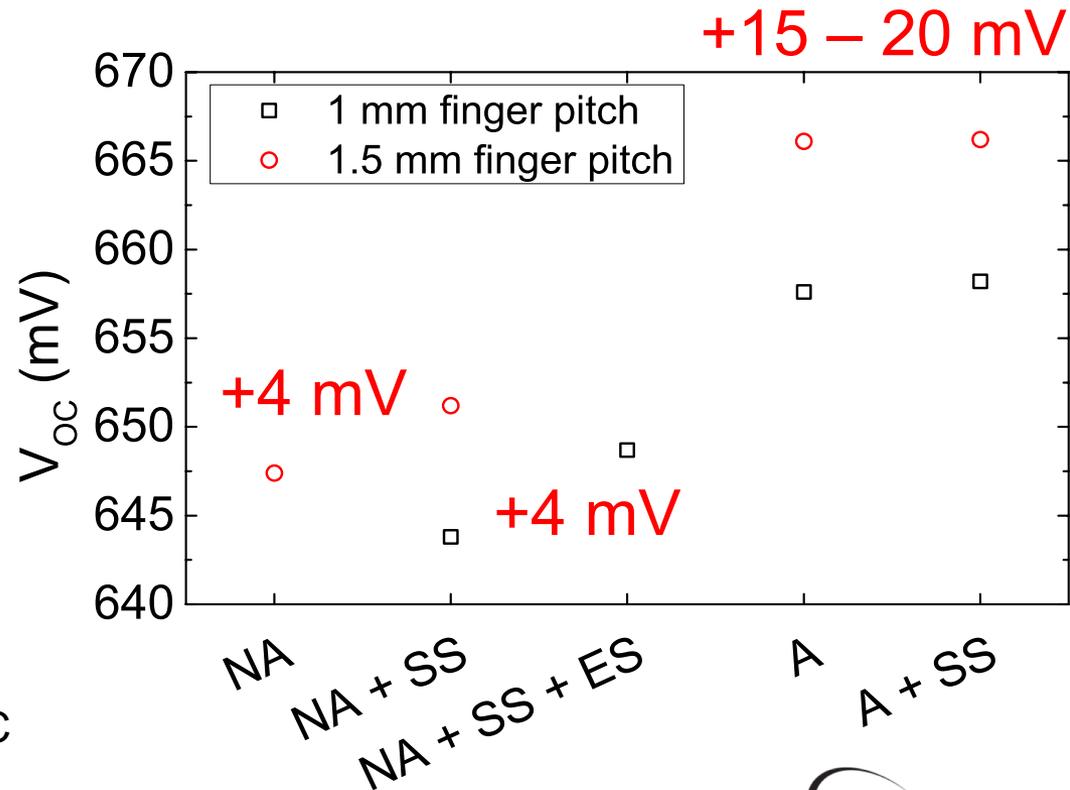
Efficiency enhancement for n-PERT through passivation of laser-induced defects

- 0.7% efficiency increase through hydrogen passivation of laser-induced defects

- Further efficiency increases through improved hydrogen passivation of other defects in the device

+0.3 mA/cm^2 +15 mV   +0.2%
                                                        +0.7%

Process	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	pFF (%)	η (%)
No anneal 1.5 mm (Av)	39.19	648.4	77.97	82.18	19.81
Anneal 1.5 mm (Av)	39.48	664.1	78.34	82.42	20.54
No anneal 1.0 mm (Av)	38.23	643.2	79.56	82.13	19.56
Anneal 1.0 mm (Av)	38.75	657.1	79.53	82.26	20.25

Thank you for your attention

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