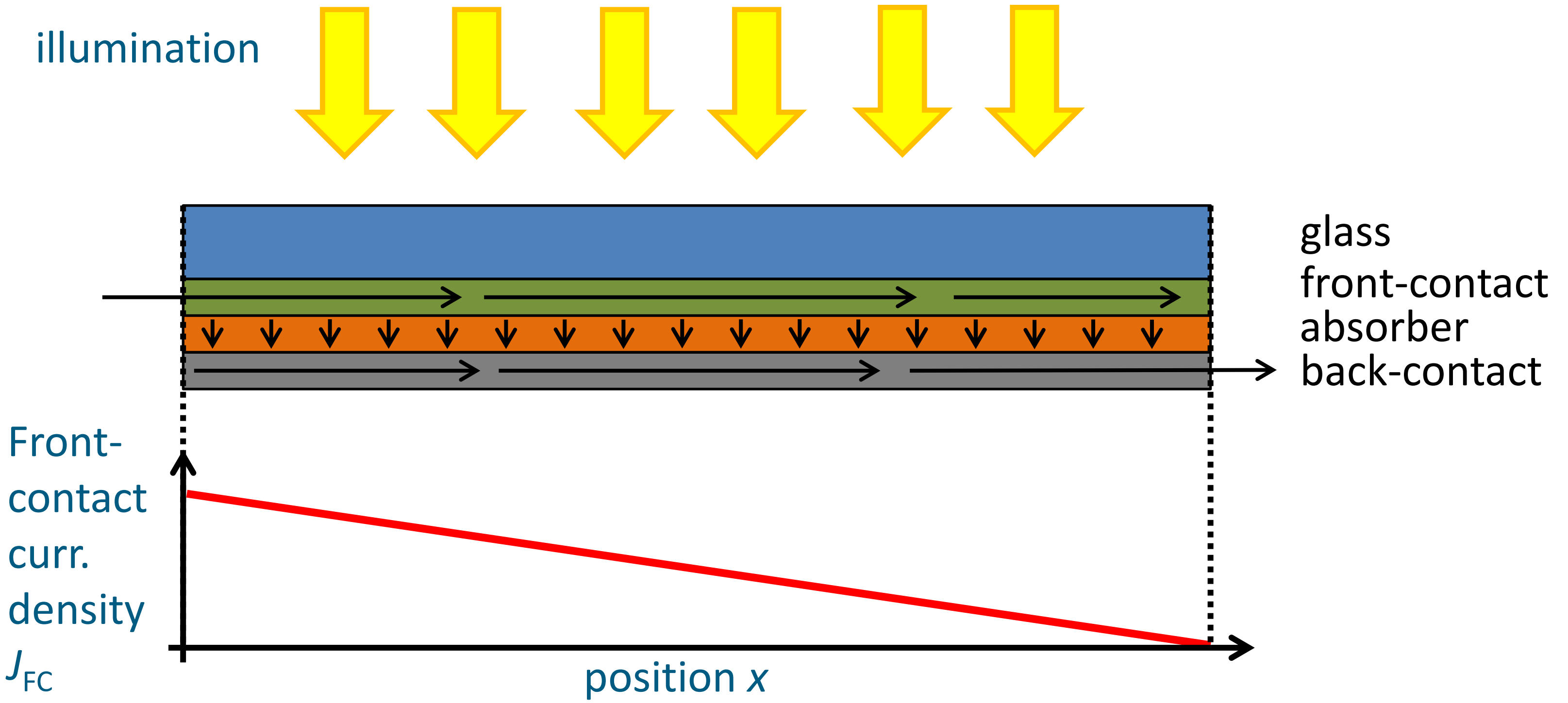
Scribe width reduction with laser-induced back-side ablation for thin-film solar modules

July 15th 2013 | Bugra Turan

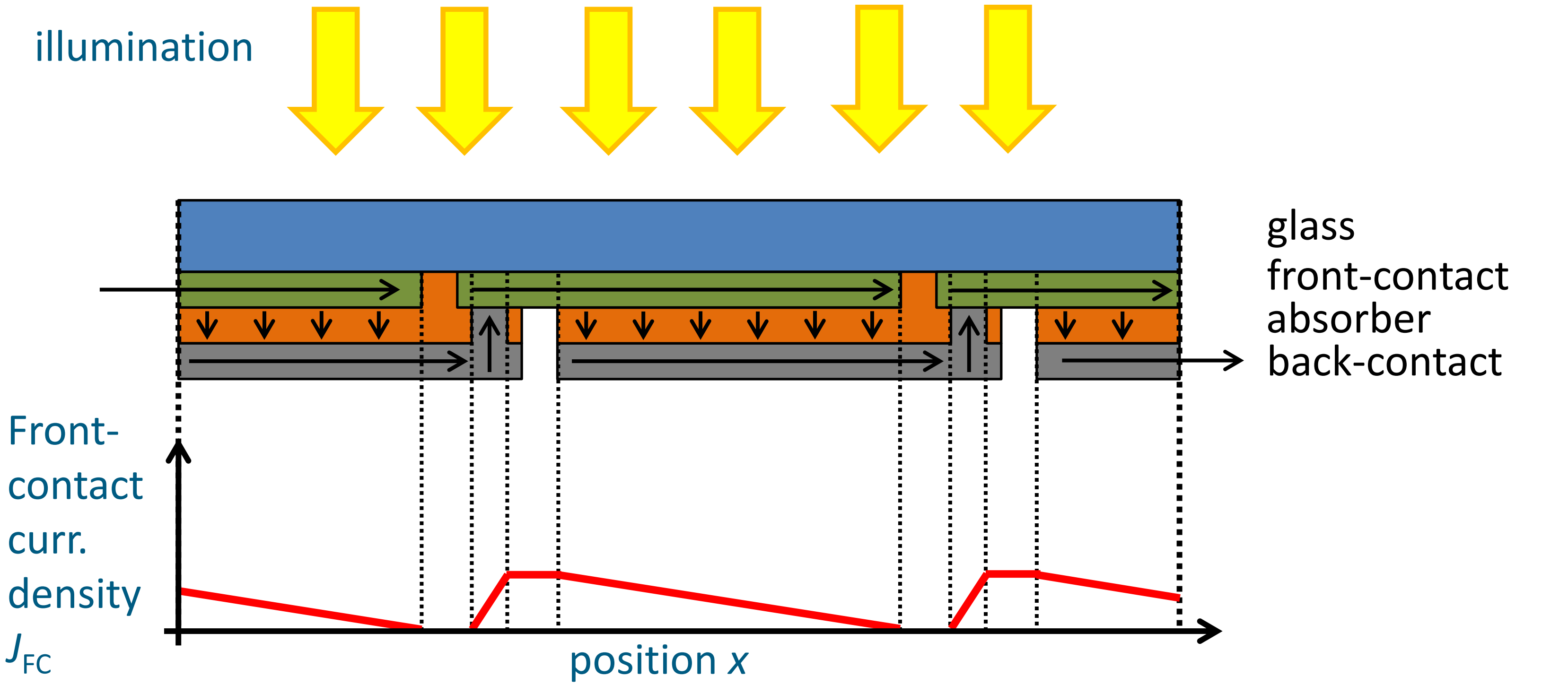
Laser Advanced Material Processing (LAMP) - 2013, Niigata, Japan

Motivation



illumination
glass
front-contact
absorber
back-contact
Front-contact curr. density J_{FC}
position x

Motivation



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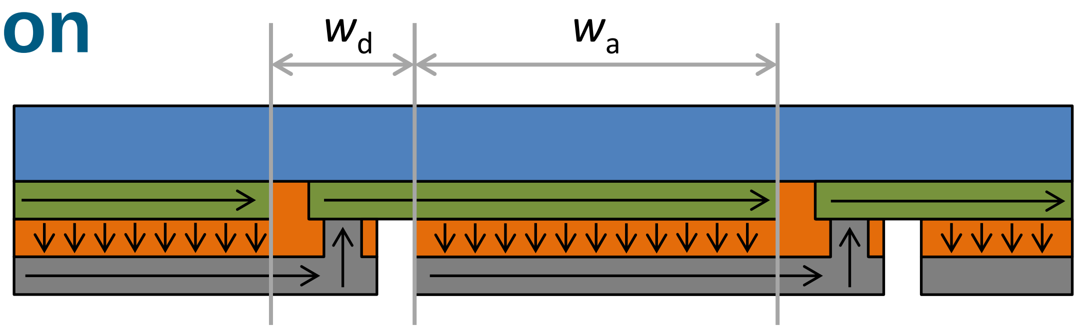
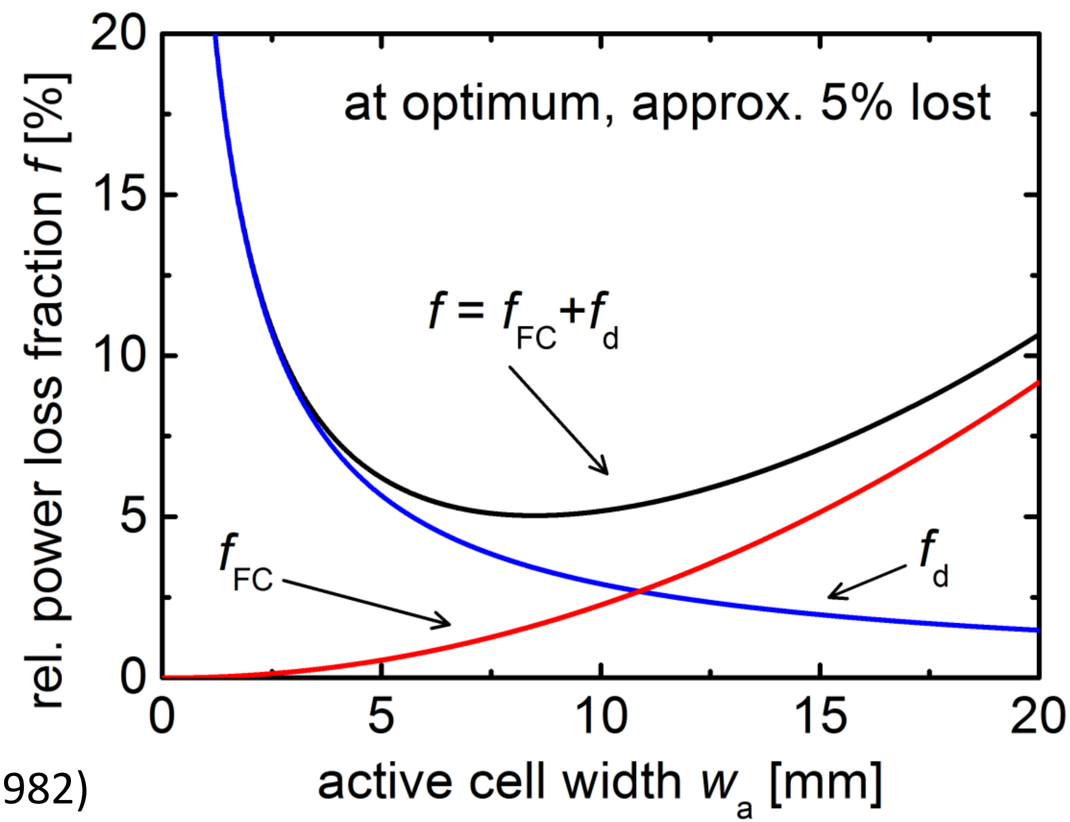


$$f_d = \frac{P_{loss}}{P_{max}} = \boxed{\frac{w_d}{w_a + w_d}}$$

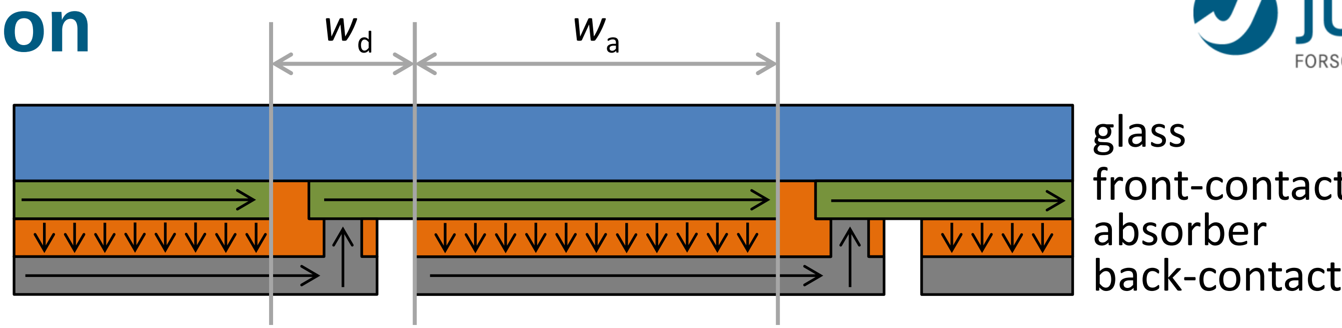
$$f_{FC} = \boxed{-\frac{J_{MPP}}{U_{MPP}} \frac{R_{\square,FC}}{3} \frac{{w_a}^3}{w_a + w_d}}$$

tandem module



[1] Gupta et al. Proc. 16th PVSC (1982)

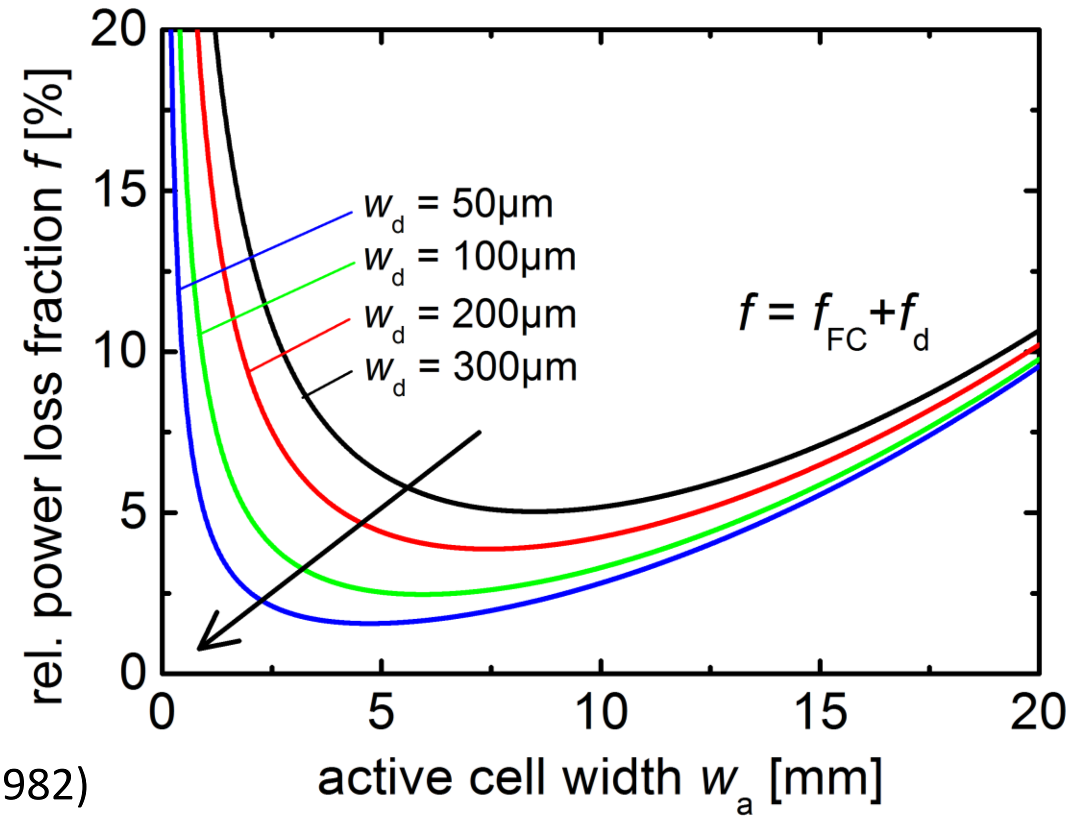
Motivation



$$f_{\mathrm{d}} = \frac{P_{\mathrm{loss}}}{P_{\mathrm{max}}} = \boxed{\frac{w_{\mathrm{d}}}{w_{\mathrm{a}} + w_{\mathrm{d}}}}$$

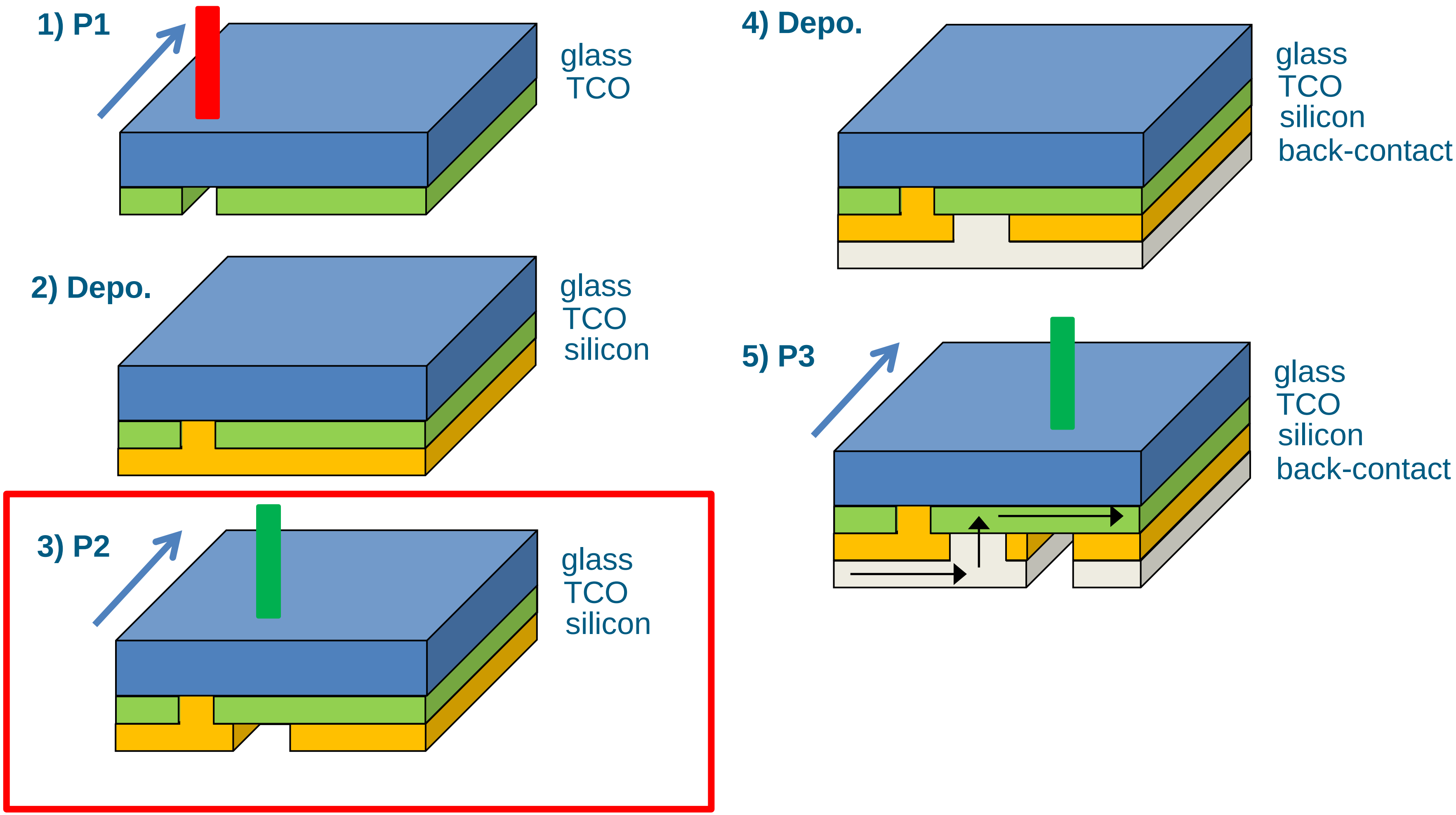
$$f_{\mathrm{FC}} = \boxed{-\frac{J_{\mathrm{MPP}}}{U_{\mathrm{MPP}}} \frac{R_{\square,\mathrm{FC}}}{3} \frac{w_{\mathrm{a}}{}^{3}}{w_{\mathrm{a}} + w_{\mathrm{d}}}}$$

tandem module

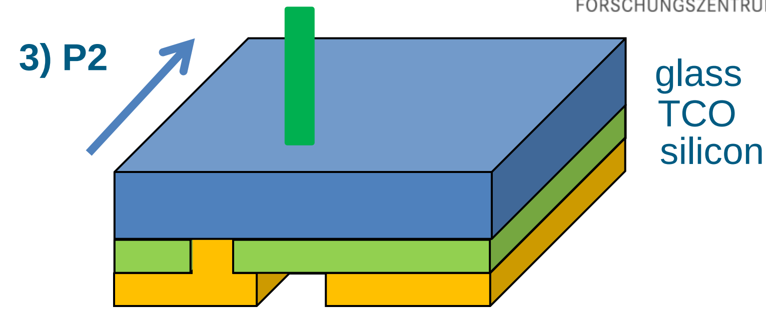


[1] Gupta et al. Proc. 16th PVSC (1982)

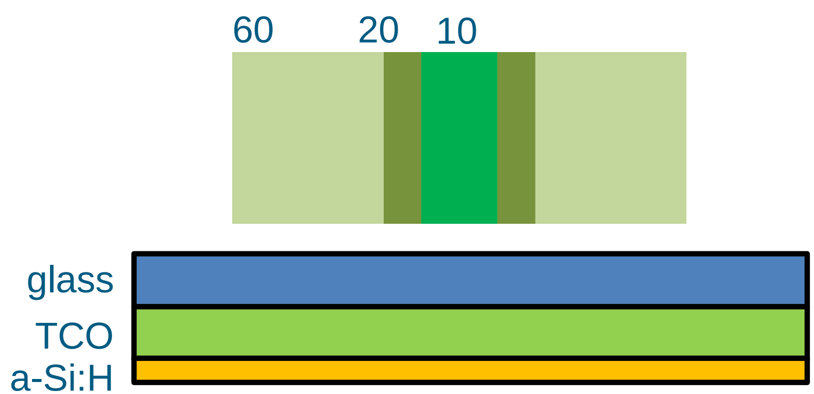
Monolithical interconnection: TF silicon

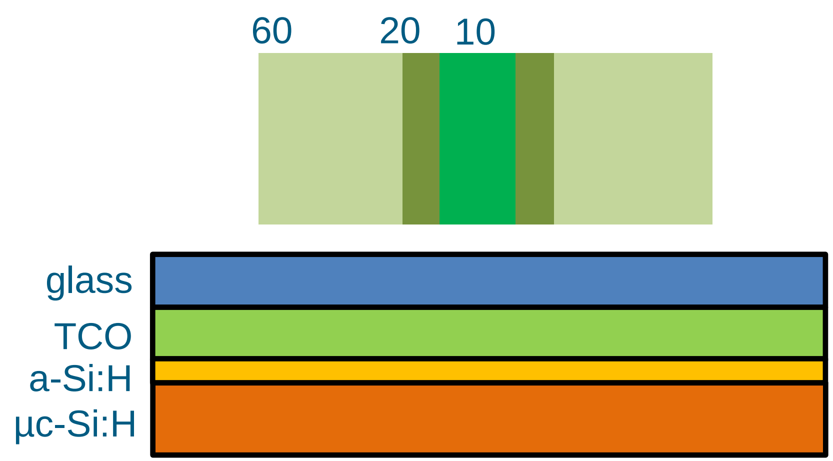


P2 processing parameter



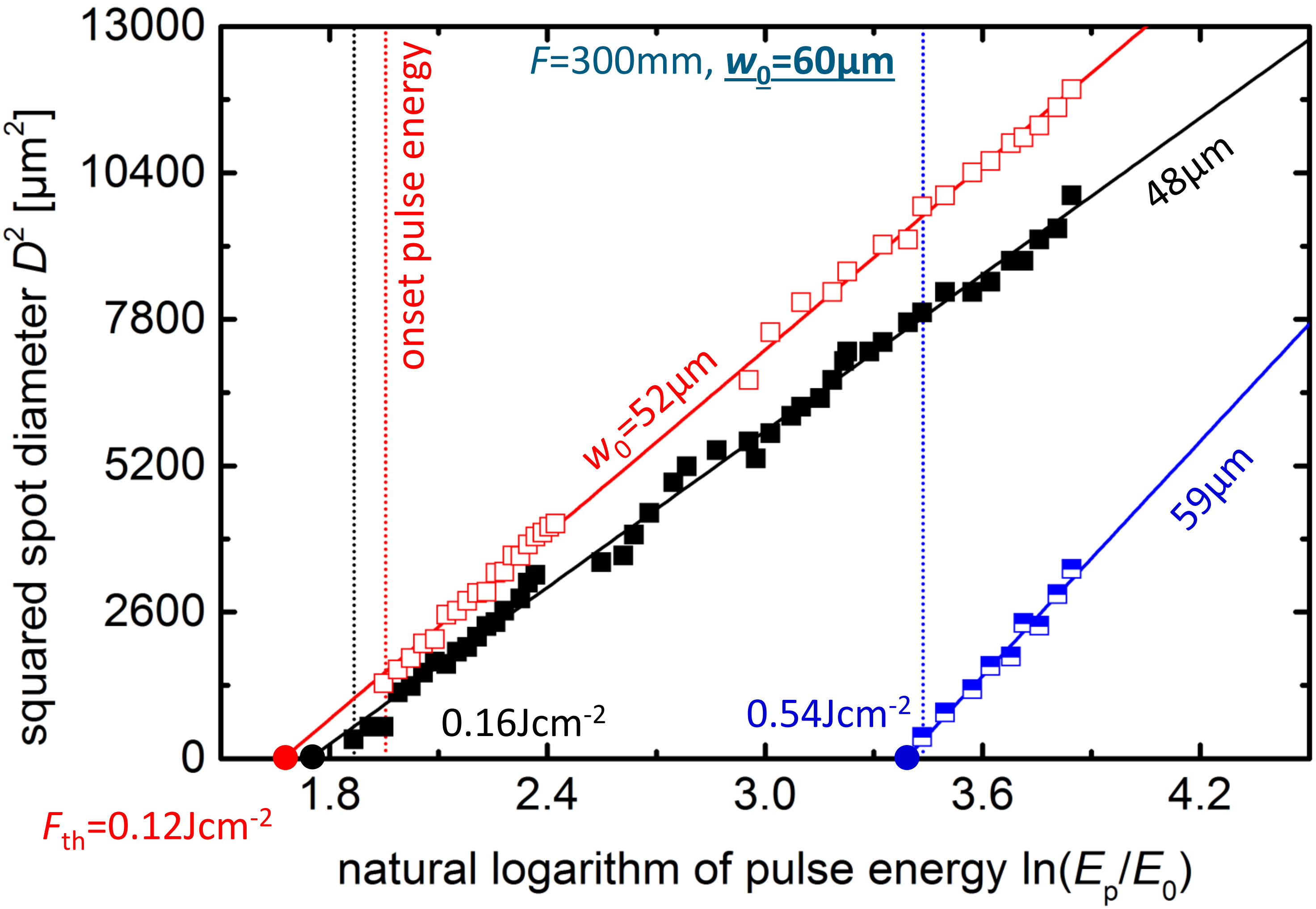
- This work: laser-induced back-side P2 processing with a Q-switched ns laser (λ=532nm)
- Processed p-i-n solar cell absorber materials on SnO_2:F TCO:
  - 300nm hydrogenated amorphous silicon (a-Si:H)
  - 1.4µm stack of a-Si:H/µc-Si:H (tandem solar cell)
- Laser beam spot radii w_0: 60µm, 20µm, 10µm





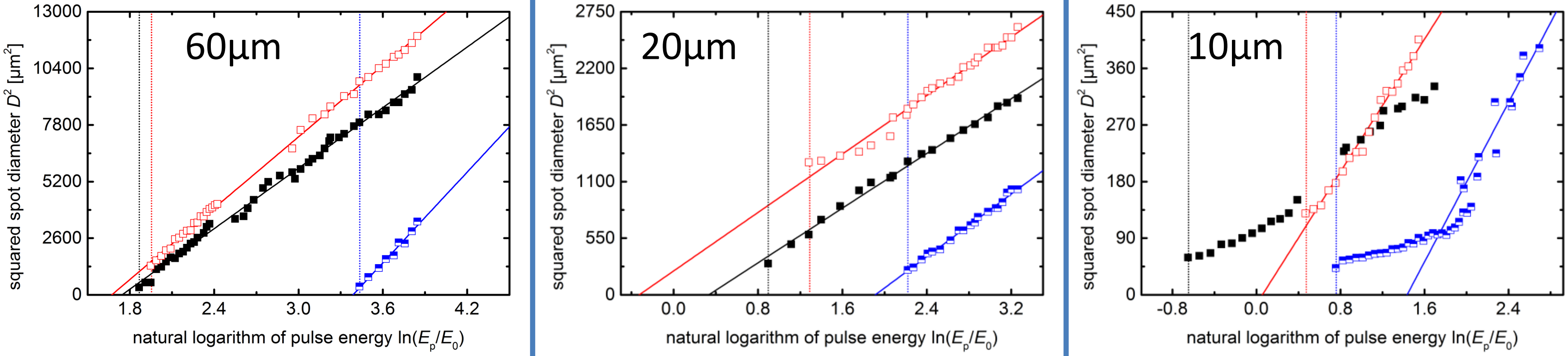
Laser ablation behavior – Liu plot

- Single spot ablation of 300nm a-Si:H and 1.4µm tandem absorber layers on SnO_2:F TCO material



More meaningful: the onset threshold

- Punching threshold as lower limit for processing strongly depends on used beam spot radius w_0

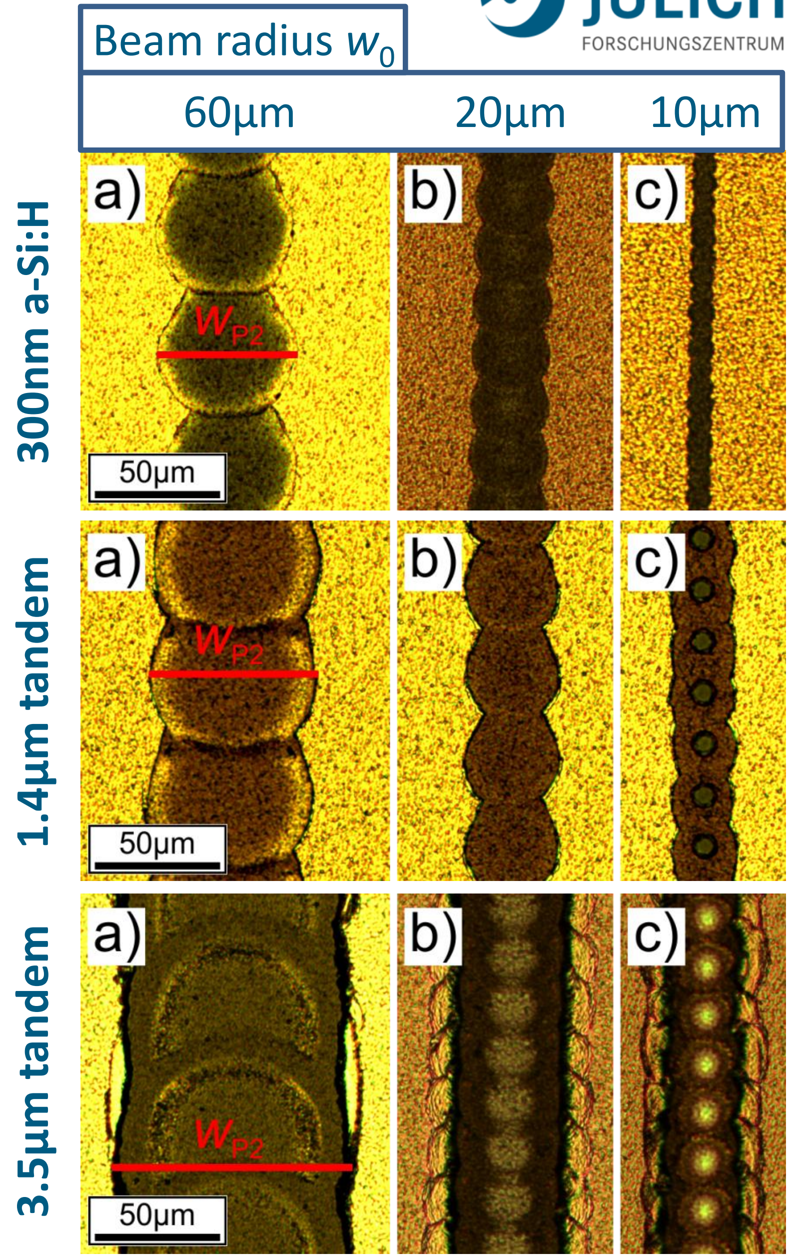


Layer type	Onset fluence $F_{p,on}$ [Jcm^{-2}] with 60µm	Onset fluence $F_{p,on}$ [Jcm^{-2}] with 20µm	Onset fluence $F_{p,on}$ [Jcm^{-2}] with 10µm
a-Si:H	0.11	0.39	0.33
Tandem	0.124	0.57	1.02
TCO	0.55	1.46	1.35

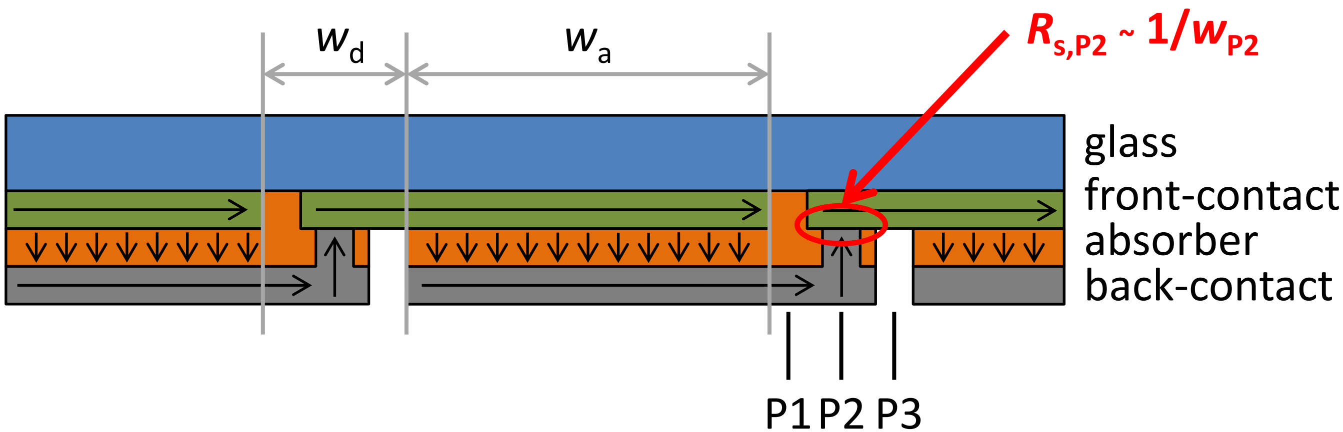
Scribe width reduction

- Good correlation between $2w_0$ and w_{P2} for processing a-Si:H
- For tandem (1.4µm) no huge width reduction from b) to c)
- Thick tandem absorber (3.5µm): limit already at b)
- Bulging at the scribe edge and TCO damage

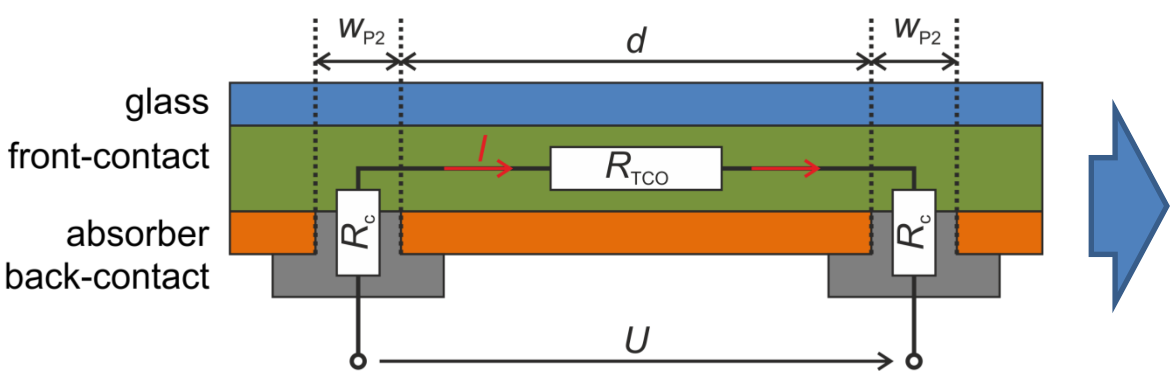
For back-side ablation: Very thin lines only achievable for thin layers!



Laser ablation debris residuals



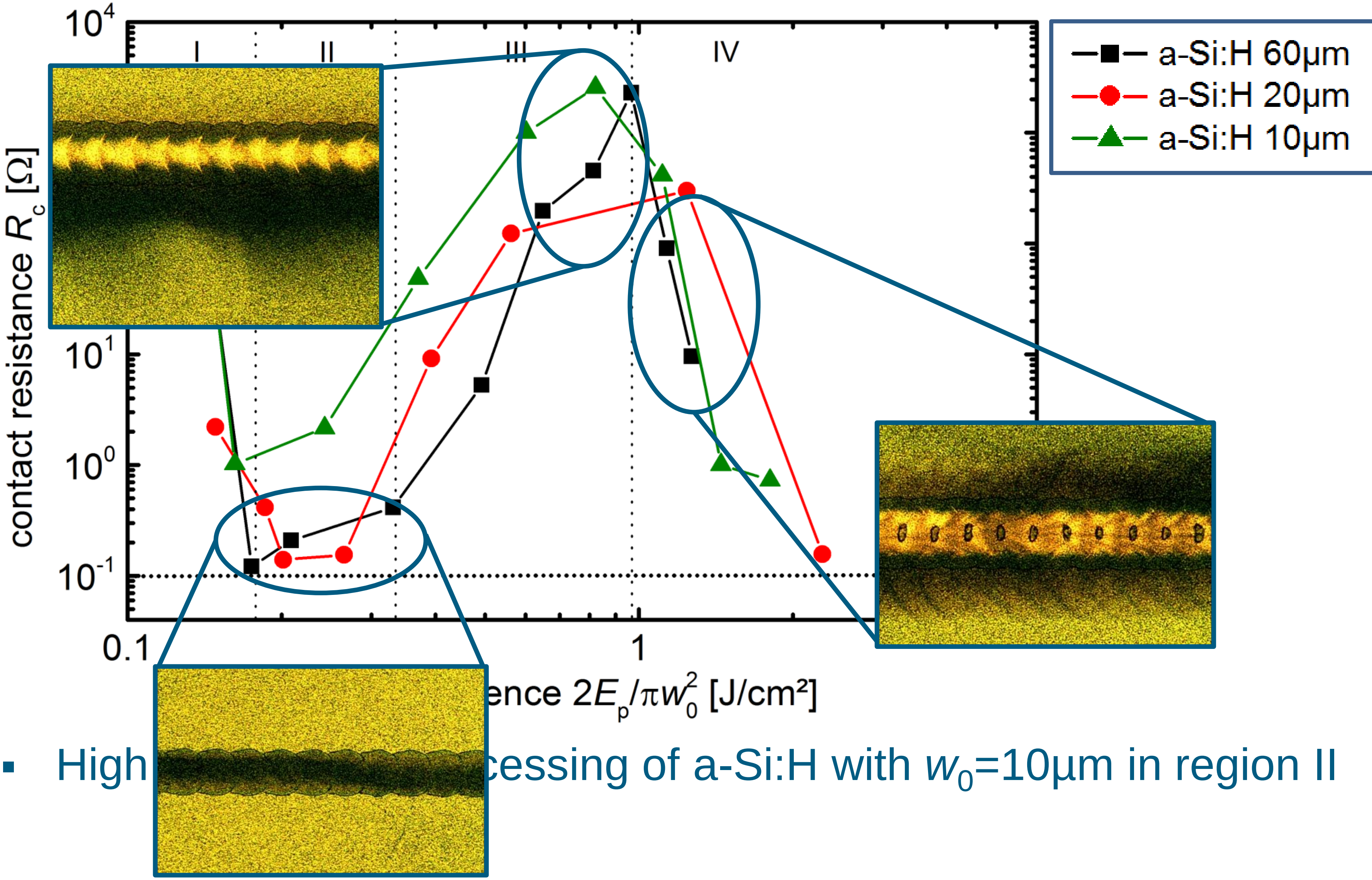
- Parasitic series resistance $R_{s,P2}$ from P2 process
- Value not directly accessible → Characterization with a transmission line method (TLM) test-structure



R=*U*/*I* for different distances *d*:

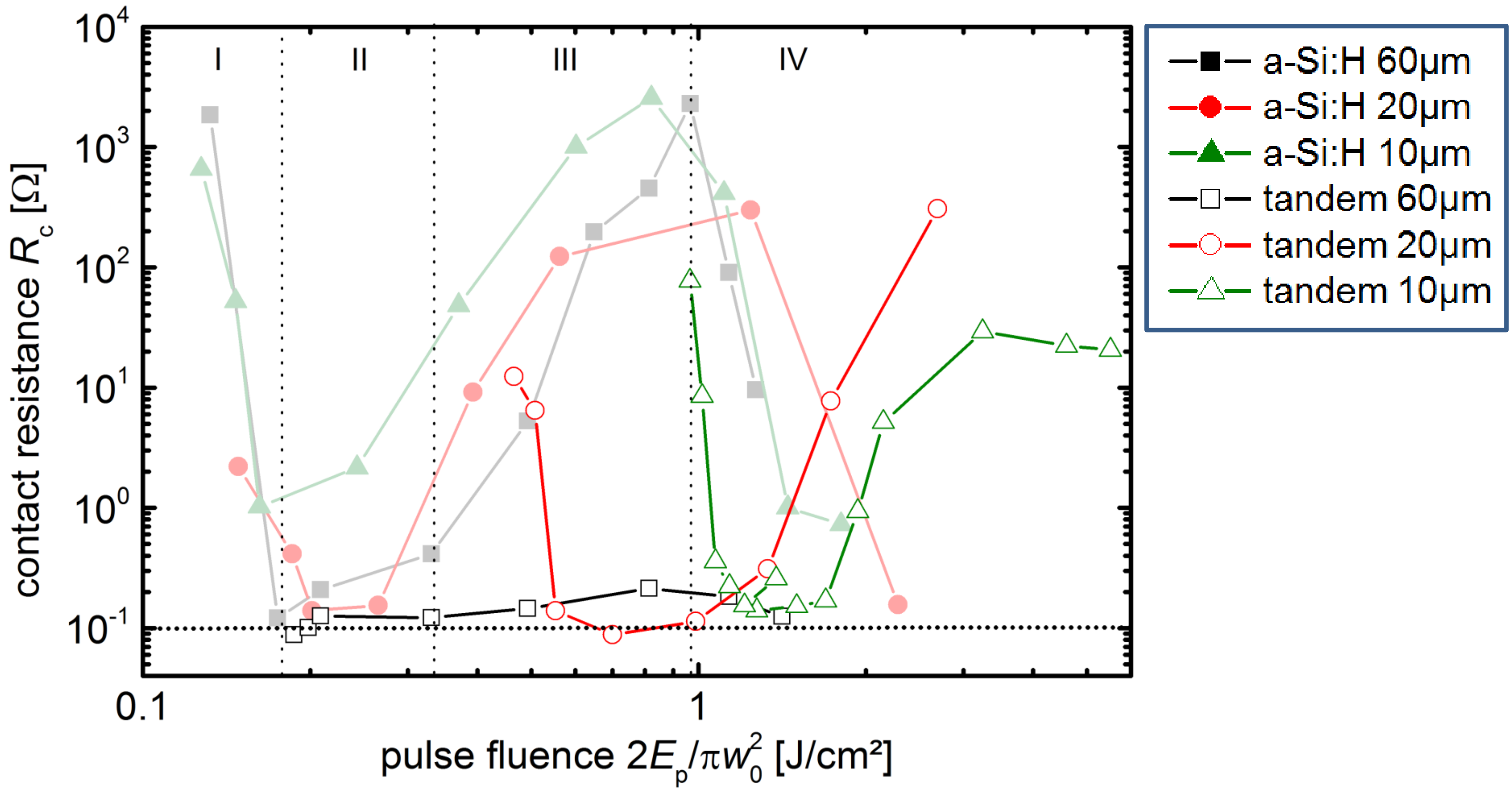
- TCO sheet resistance R_{SH} from slope
- Contact resistance $R_c = R_{s,P2}$ from intercept with y-axis

Electrical properties - TLM



- High cessing of a-Si:H with w_0=10µm in region II

Electrical properties - TLM

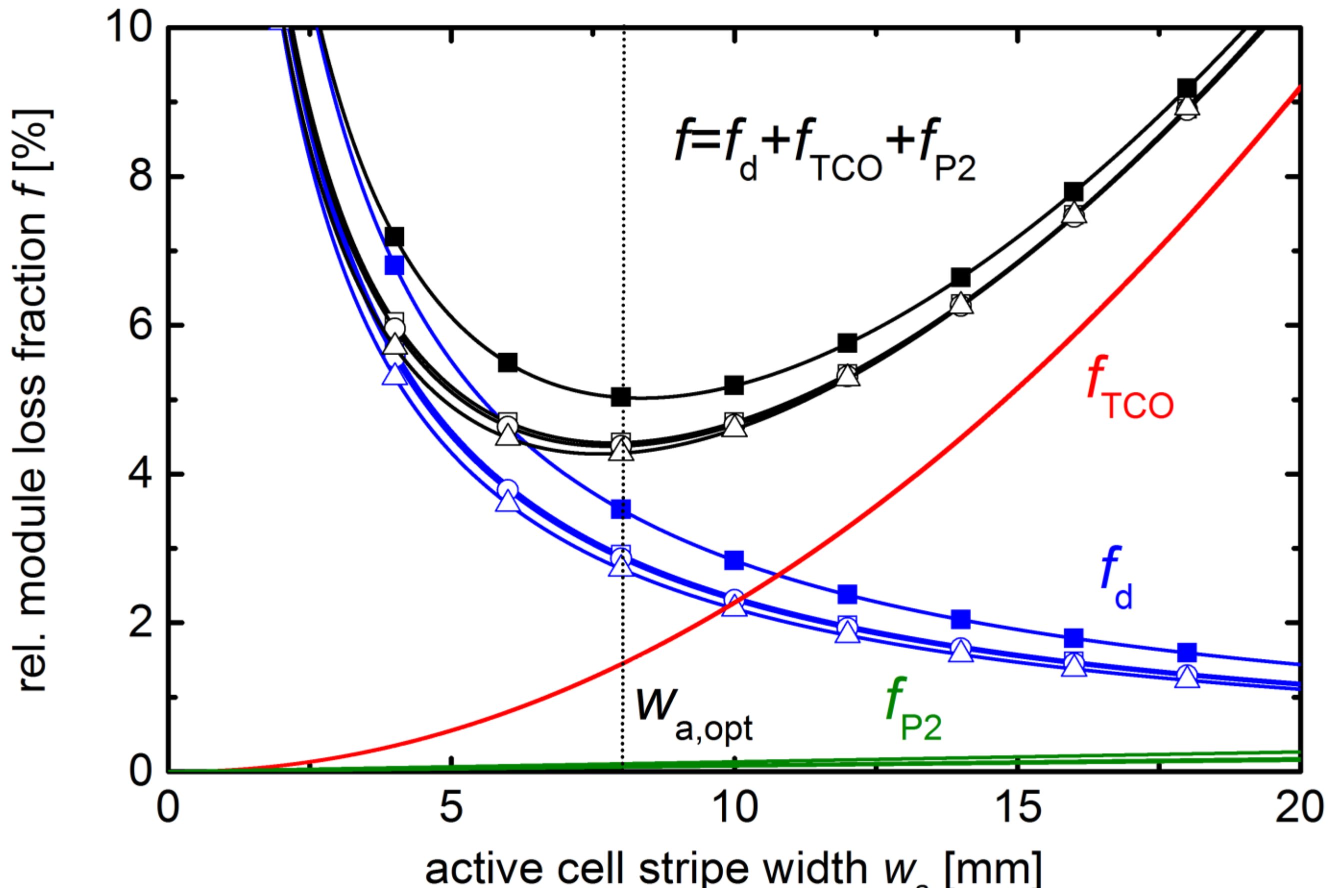


- High increase for processing of a-Si:H with w_0=10µm in region II
- Low values are achieved for scribing of tandem absorber compared to a-Si:H with same w_0

Module losses – trade-off

- Back to the motivation: extend calc. to account for P2 → Tandem module
- Series resistance loss fraction f_{P2}

$$f_{P2} = \frac{P_{P2}}{P_{max}} = \boxed{w_a \cdot R'_{s,P2} \frac{J_{MPP}}{U_{MPP}}}$$



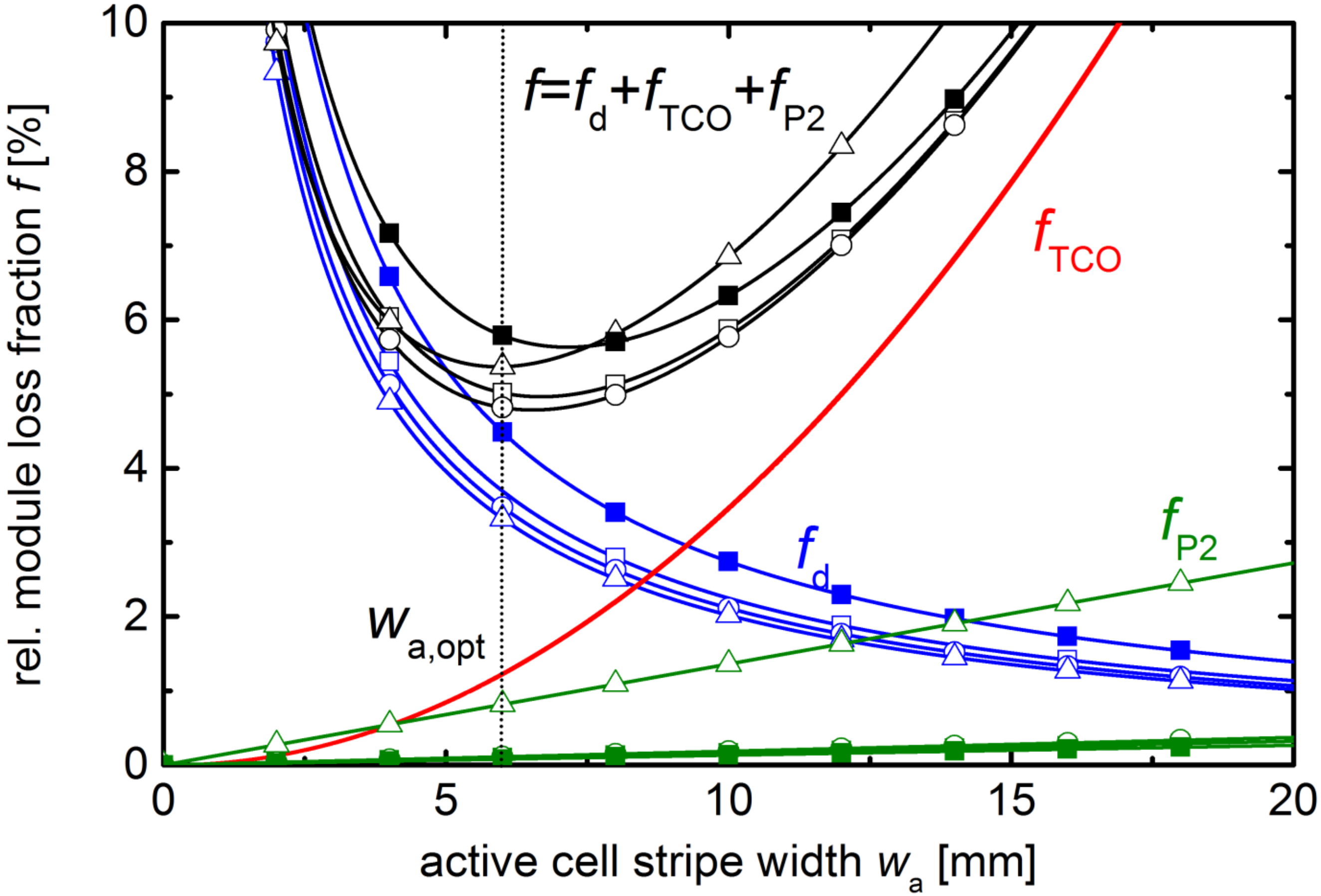
w_{P2} and $R_{s,P2}$
- ■ 90µm, 0.1Ωcm
- □ 40µm, 0.08Ωcm
- ○ 36µm, 0.09Ωcm
- Δ 24µm, 0.15Ωcm

$w_{d,rest}$ = 200µm
R_{SH} = 8Ω
J_{MPP} = 9.7mA/cm²
U_{MPP} = 1.1V

Module losses – trade-off

- Back to the motivation: extend calc. to account for P2 → a-Si:H module
- Series resistance loss fraction f_{P2}

$$f_{P2} = \frac{P_{P2}}{P_{max}} = \boxed{w_a \cdot R'_{s,P2} \frac{J_{MPP}}{U_{MPP}}}$$



w_{P2} and $R_{s,P2}$
- ■ 90µm, 0.1Ωcm
- □ 30µm, 0.12Ωcm
- ○ 16µm, 0.14Ωcm
- Δ 6µm, 1.02Ωcm

$w_{d,rest}$ = 200µm
R_{SH} = 8Ω
J_{MPP} = 10.17mA/cm²
U_{MPP} = 0.765V

Conclusion & Outlook

- Onset pulse fluences highly dependent on spot size
- Very thin lines only possible for thin layers
- Good contact resistances for tandem layers, high values for a-Si:H
- A benefit from further width reduction for tandem predicted, while improvement of ρ_c necessary for a-Si:H

- Film-side processing can help to overcome geometrical limitations by glass-side scribing
- Contact properties could be improved by reduction of debris redeposition within the P2 scribe line

Thank you for your attention!

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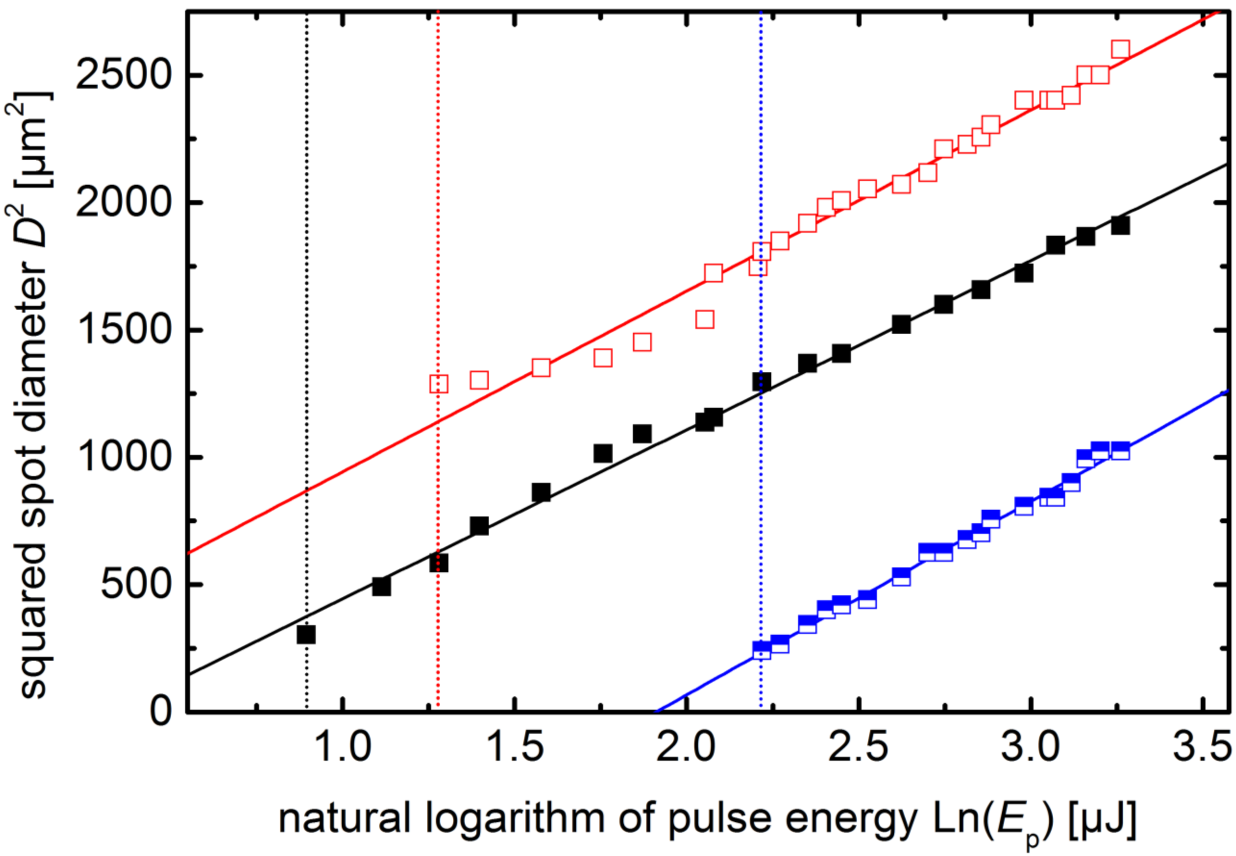
Bundesministerium
für Umwelt, Naturschutz
und Reaktorsicherheit

Outline

- Monolithical interconnection process
- Ablation behavior
  - Influence of spot-size and thicknesses
  - Scribe width reduction
- Electrical properties
  - Transmission Line Method
  - Contact resistance regimes
- Module losses
- Conclusion and outlook

Laser ablation behavior

- Single spot ablation of 300nm a-Si:H (black) and 1.4µm tandem (red) absorber layers on SnO_2:F TCO material
- Damaged TCO layer ablation beneath tandem absorber (blue)



Processing geometry:
F=116mm, $\underline{\boldsymbol{w_0}\mathbf{=20\mu m}}$

Extracted parameter:

- Beam spot radius w_0
18µm, 19µm, and 19µm
- Threshold fluence F_{th}
0.27Jcm^{-2}, 0.13Jcm^{-2}, and 1.13Jcm^{-2}

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Laser ablation behavior

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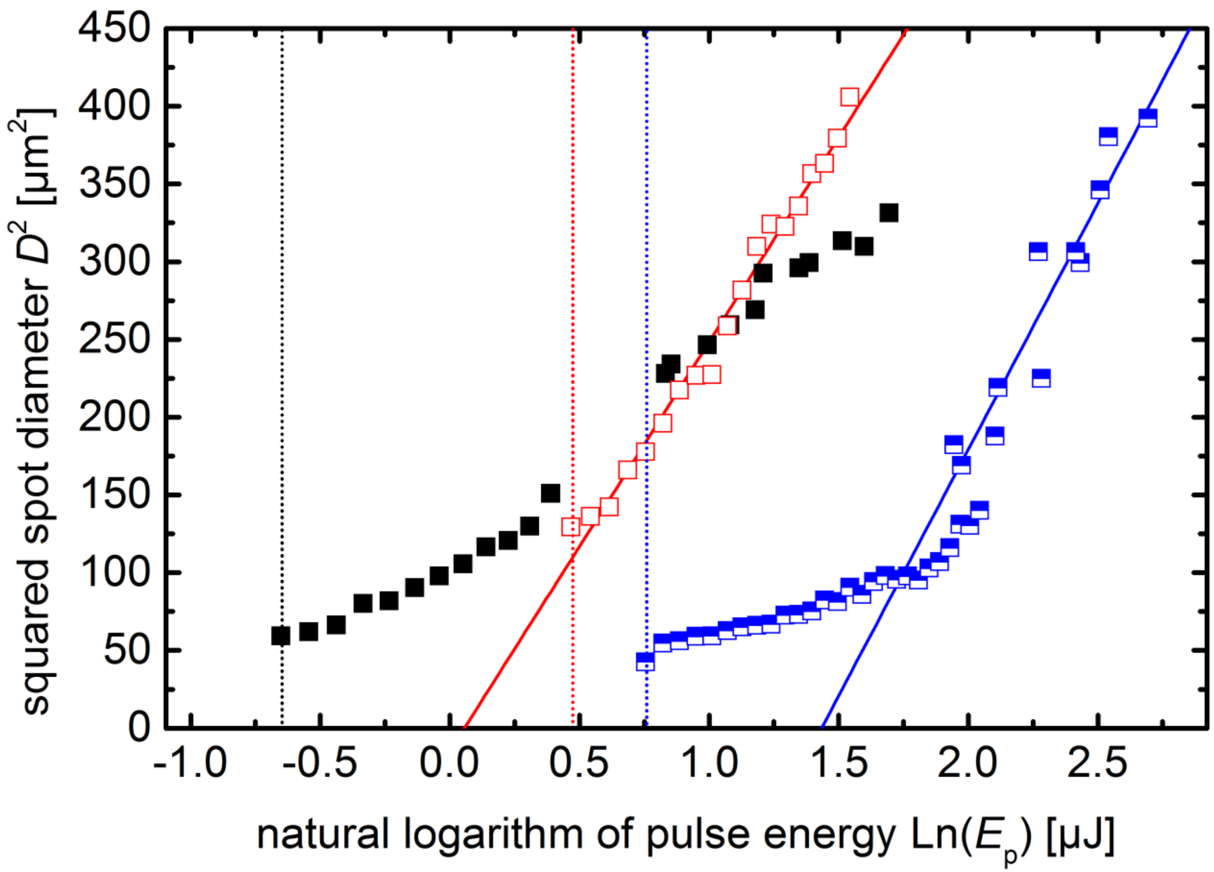


Processing geometry:
F=56mm, ***w*₀=10µm**

Extracted parameter:

- Beam spot radius w_0 ?µm, 11µm, and ?µm
- Threshold fluence F_{th} ?Jcm^{-2}, ?Jcm^{-2}, and ?Jcm^{-2}

⇨ Different ablation mechanism?

Laser ablation behavior – Liu plot

- Spatial fluence distribution of a Gaussian laser beam

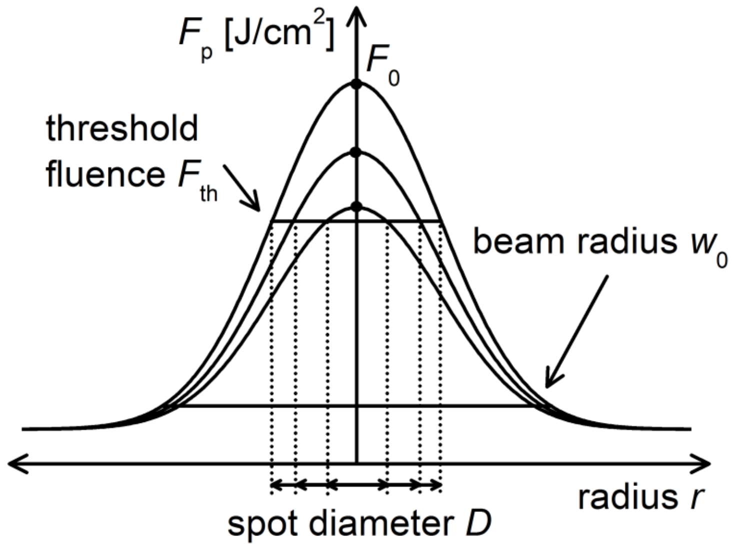
$$F_\mathrm{p}(r) = F_0 \cdot \mathrm{e}^{-\frac{2r^2}{\omega_0{}^2}} \qquad F_0 = \frac{2E_\mathrm{p}}{\pi\omega_0{}^2}$$

- Squared diameter $D^2 = 4r^2$ is related to the threshold fluence F_th

$$D^2 = 2\omega_0{}^2 \cdot \ln\left(\frac{F_0}{F_\mathrm{th}}\right)$$

- Linear fit from plot of D^2 vs. $\ln(E_\mathrm{p})$ will yield beam spot radius w_0 and threshold fluence F_th

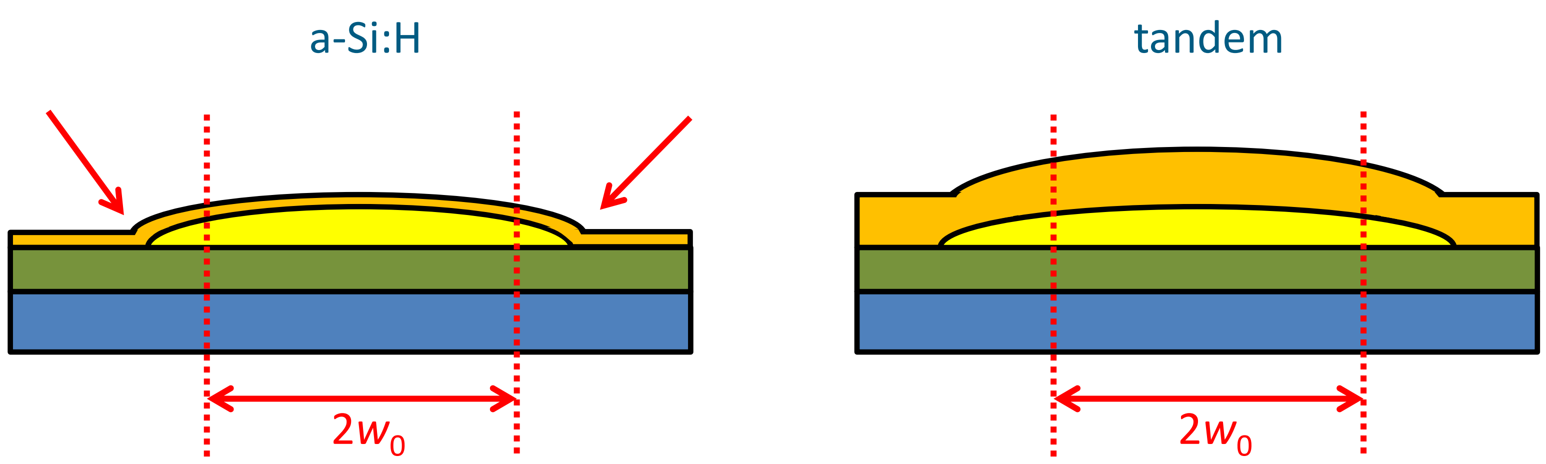
$$\boxed{\omega_0 \sim \text{slope}} \qquad \boxed{F_\mathrm{th} \sim \text{intercept}}$$



[2] Liu, J. M. Optics letters, 7(5), 196–8, 1982

Laser ablation behavior

- 1. Why is the crater diameter for tandem layer processing always higher than for a-Si:H with the same fluence
  - One explanations is the difference between $E_p \leftarrow\rightarrow E_{abs}$ for a-Si:H → Big shift on x-axis
  - More plausible, structural toughness from tandem due to hgiher thickness greater than for a-Si:H



Laser ablation behavior #2

- 2. Spot size dependence of the onset fluence can be described by crack formation and propagation:
  - From linear elastic fracture mechanics – simple approach
  - Griffith criterion for edge cracks:

$$\sigma_{\mathrm{crit}} = \sqrt{\frac{2E\gamma}{\pi a}}$$

  - With *E* as Young´s modulus, $\boldsymbol{\gamma}$ as surface energy per unit area of the crack and ***a*** as the crack length
  - No matter if thermal stress or vapor induced stress, in both cases does $\boldsymbol{\sigma_{\mathrm{crit}}}$ increase with decreasing $\boldsymbol{a \sim w_0}$

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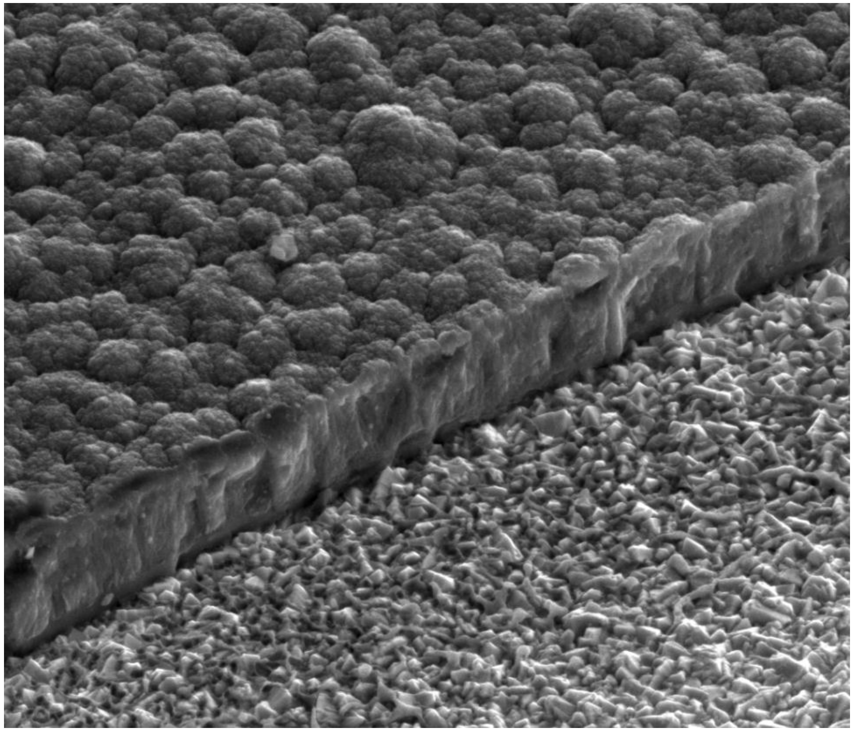
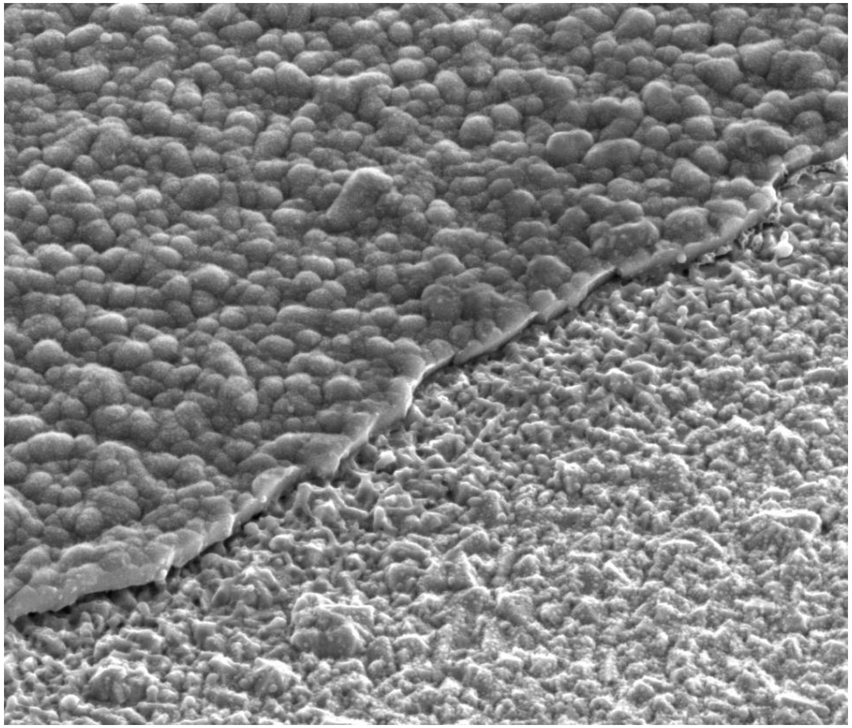
Electrical properties – a-Si:H vs. tandem

- Differences between a-Si:H and tandem can be described by the different dominating ablation behavior



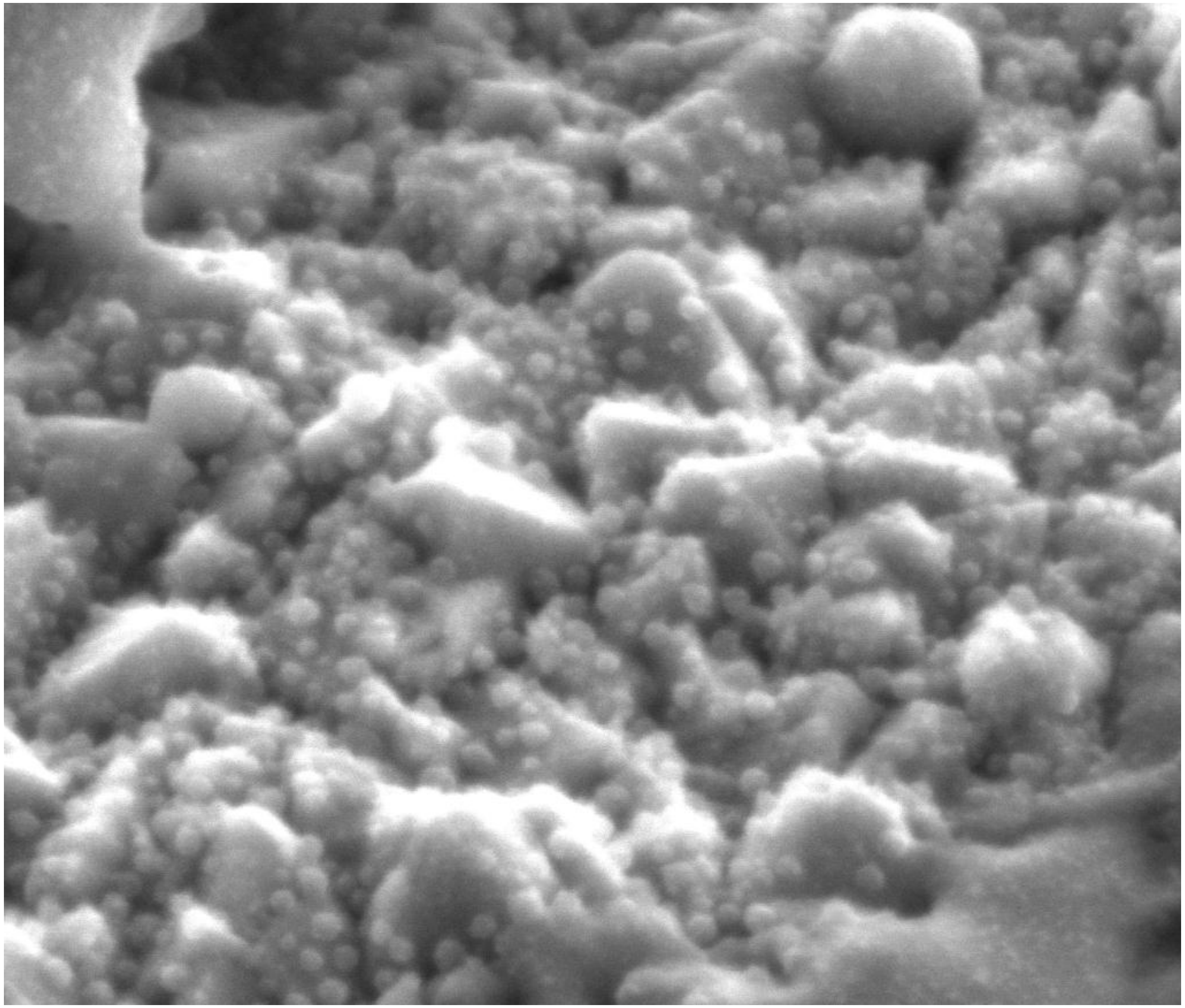
60µm - Tandem region IV



60µm - a-Si:H region IV

- Much less residuals on the surface for tandem processing

Electrical properties – a-Si:H vs. tandem



a-Si:H region IV

Electrical properties – specific contact

- Increase for processing of a-Si:H could not be explained by reduction of w_{P2}
- Evaluation of the specific contact resistance ρ_c for minimal values $R_{c,min}$ from:

$$R_{c,min} = \frac{\sqrt{\rho_c \cdot R_{SH}}}{W} \cdot \coth\left(\frac{w_{P2}}{\sqrt{\frac{\rho_c}{R_{SH}}}}\right)$$

Absorber type/spot radius	Sheet resistance R_{SH} [Ω/□]	Contact resistance $R_{c,min}$ [mΩ]	Specific contact resistance ρ_c [Ωmm²]
a-Si:H/60µm	7.68 ± 0.017	121 ± 2	0.034
a-Si:H/20µm	7.6 ± 0.02	140 ± 21	0.021
a-Si:H/10µm	7.57 ± 0.01	1024 ± 6	0.061
Tandem/60µm	8.57 ± 0.01	88 ± 5	0.031
Tandem/20µm	8.67 ± 0.01	90 ± 4	0.028
Tandem/10µm	8.57 ± 0.01	152 ± 3	0.034