Addressing Edge Recombination Losses in Shingle Cells by Holistic Optimization of the Process Sequence

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Cutting-Induced Edge Recombination

- Shingle solar cells: cut full host cells into sub cells
  - Cut edges: increased recombination rate[1] $R_{\mathrm{surf}} = v_{\mathrm{th}}\left(n_s\, p_s - n_{i,\mathrm{eff}}^2\right) \int_{E_V}^{E_C} \frac{D_{\mathrm{it}}(E)\, dE}{\frac{n_s + n_1(E)}{\sigma_p(E)} + \frac{p_s + p_1(E)}{\sigma_s(E)}}$
- Reduce R_{surf} by:
  - Lowering conductivity near the edge (emitter window)[2, 3]
  - Implementing a field barrier for n_s or p_s (field effect passivation, PET)[4, 5]
  - Reducing defect quantity D_{it} at the edge (chemical passivation, PET)[4, 5]

Conclusion

- Application of laser ablation of emitter windows
  - Proof of concept for edge passivation behavior
- Improvement of passivated edge technology (PET)
  - Effect on lifetime sample: +75 %
  - Recovery of cutting losses increased by 24 %
    → Up to 80 % recovery achieved

Option 1: Remove Emitter
Suppress Current Flow Towards Cut Edge

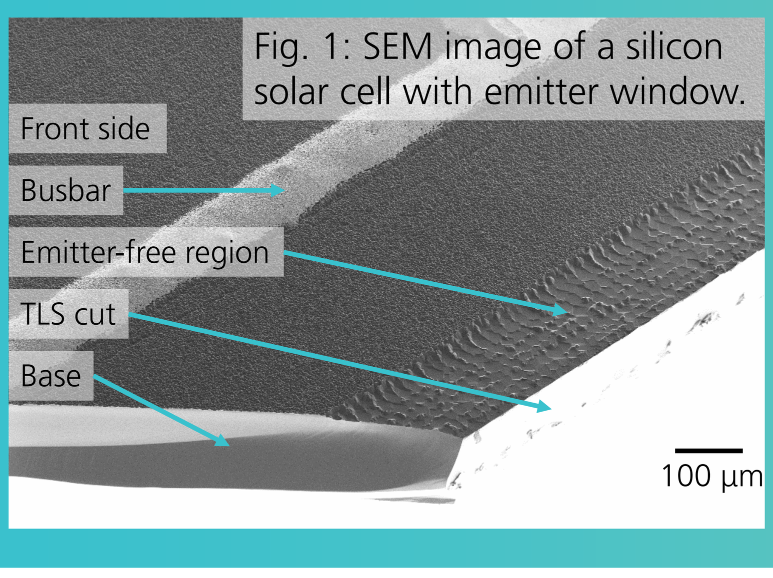
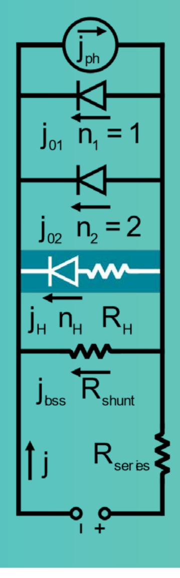


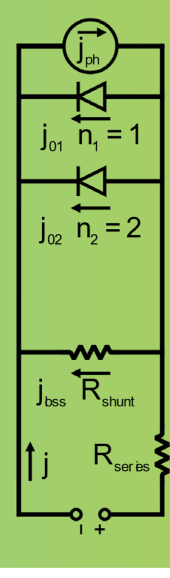
Fig. 1: SEM image of a silicon solar cell with emitter window.



Experimental Approaches

Option 1	Option 2
As-cut wafer	
Texture & diffusion	
Laser doped selective emitter (optional)	
Laser ablation	
Removal rear emitter	
Passivation and ARC	
Laser contact opening (LCO)	
Screen printing	
Contact formation	
Cell separation	
	PET: ALD + annealing

Option 2: Dielectrics
Field Effect and Chemical Passivation



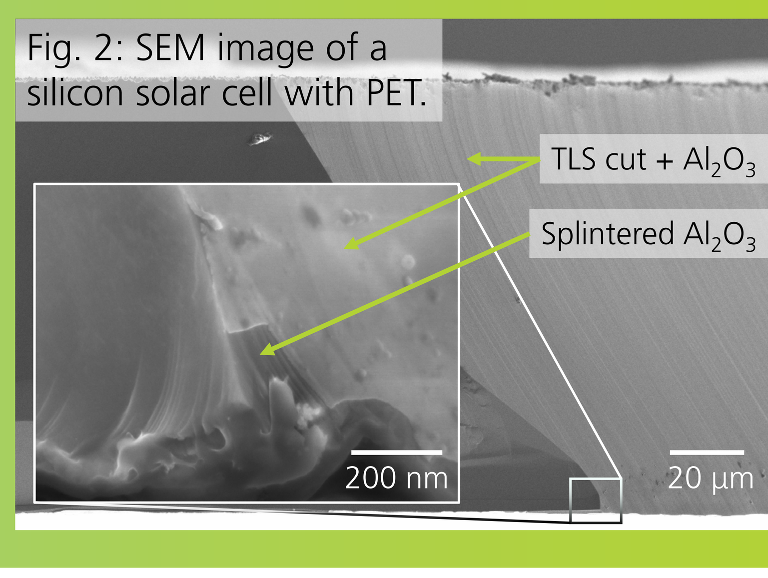


Fig. 2: SEM image of a silicon solar cell with PET.

Emitter Window[3]

- Laser ablation process
  - Symmetric lifetime samples
  - Ablation on front, rear or both sides
  - Evaluation after passivation
- Ablated regions with increased lifetime
  - Laser process variation reveals little effect (not shown here)

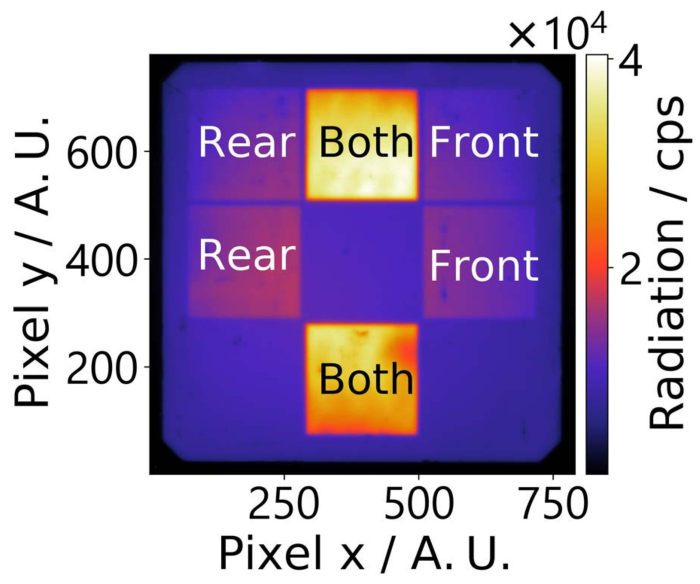


Fig. 3: The photoluminescence of the lifetime sample shows the removed emitter.

- QSSPC measurement
  - Different positions
  - Applied constant f_{abs}
- Lifetime in ablated regions increased
  - Differences due to changed optics of lasered surface
- Ablation removes emitter

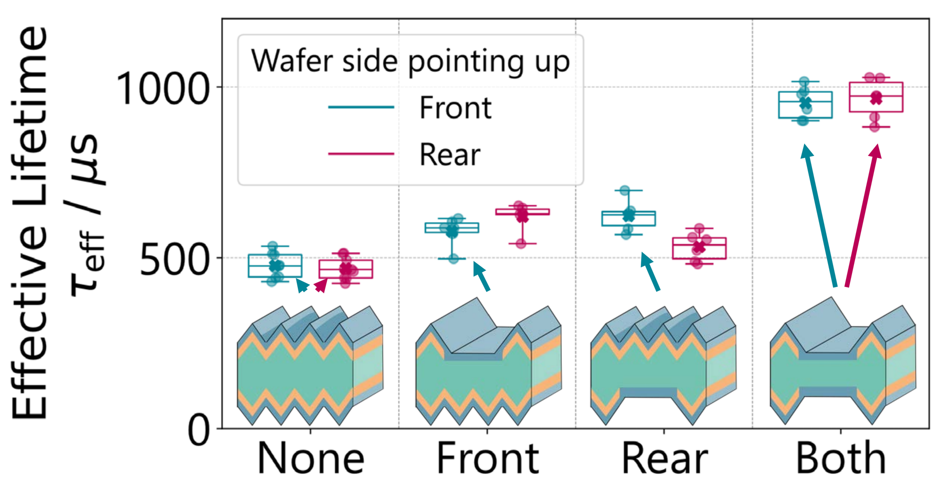


Fig. 4: The effective lifetime τ_{eff} is measured from both sides for each field from Fig. 3.

Emitter Windows on Shingle Cells

- Comparison of PERC shingle cells with and without emitter window
  - Advantage in *pFF*: $\frac{\Delta pFF(\mathrm{Host-Shingle})_{\mathrm{with\ window}}}{\Delta pFF(\mathrm{Host-Shingle})_{\mathrm{without\ window}}} = 17\ \%$
- Challenges
  - J_{sc} loss 0.24 mA/cm²: optics + less emitter area
  - Alignment: metal + cutting

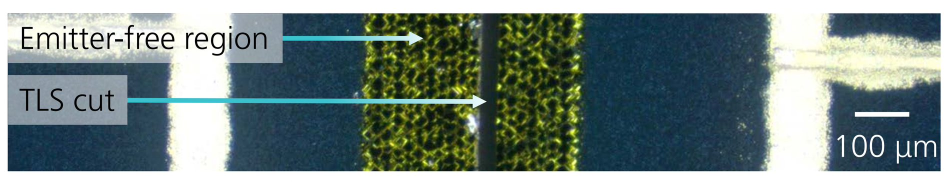


Fig. 5: Two shingle cells side by side with the emitter window after cutting using thermal laser separation (TLS).

Passivated Edge Technology (PET)[4]

- FZ-Si lifetime samples and cut shingle cells
- Coating Al_2O_3: plasma enhanced atomic layer deposition (PE-ALD)[6]
- Annealing: batch oven
- Characterization
  - τ_{eff} by QSSPC
  - *I-V* by cell tester

Fig. 6: FZ-Si wafer

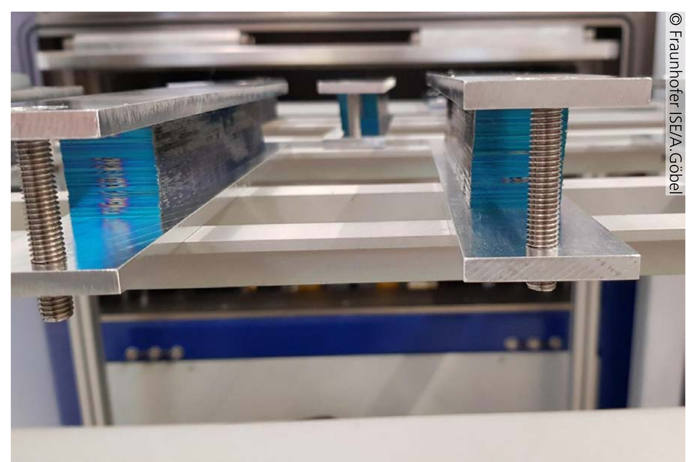


Fig. 7: Stacked shingle cells before running the high throughput ALD reactor.

- Variation of ALD process
  - PE-ALD layers require anneal for high lifetimes
- Reference process[4]: τ_{eff} = 2.1 ms
- Adjusted process (same cycle time): τ_{eff} = 3.8 ms (+ 75 %)

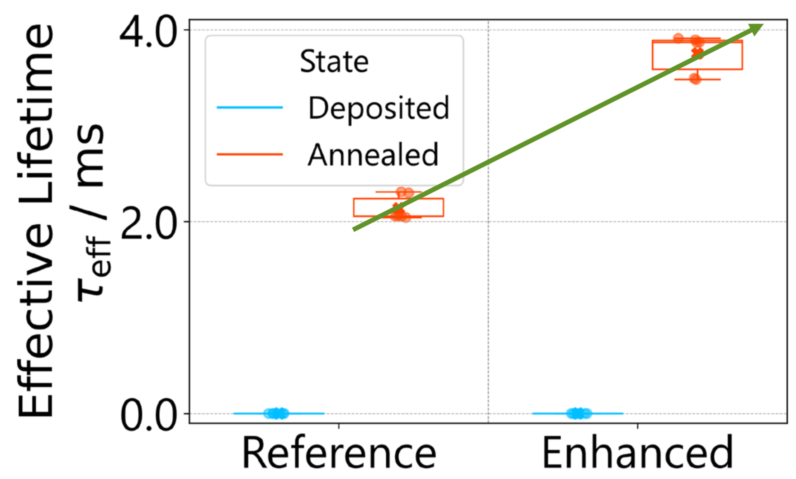


Fig. 8: The effective lifetime τ_{eff} is strongly increased with an enhanced ALD process.

Effect of Improved ALD Process on Cells

- Cells cut by thermal laser separation (TLS)
- Gain of PET improved by 24 %
- Relative improvement less than on lifetime samples
- PET achieves recovery of up to 80 %

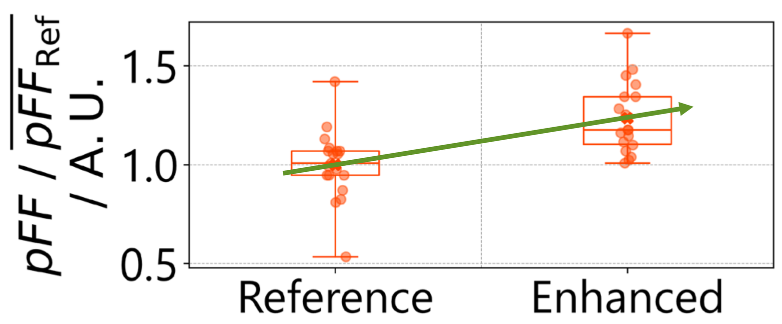


Fig. 9: The enhanced ALD process increases the *pFF* recovery on cut silicon solar cells.

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