Poly-Si based Passivating Contacts

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Fraunhofer Institute for
Solar Energy Systems ISE

Workshop on Passivating Contacts

Eindhoven, January 31, 2018

www.ise.fraunhofer.de

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AGENDA

- Brief history of passivating contacts
- Working principle
  - Surface passivation
  - Carrier Transport
- High-efficiency solar cells
- Steps towards industrial implementation

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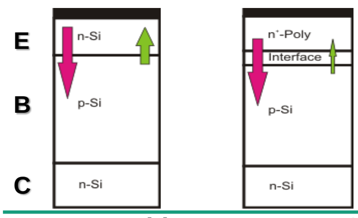
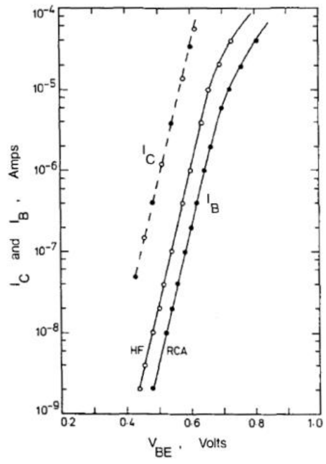
Bipolar Junction Transistors
Gain Enhancement through Polysilicon Emitter

- Hole injection into emitter limits gain
- ➔ „Minority carrier mirror“ needed
- **Polysilicon Emitter**[1]
  - Interfacial oxide is crucial for device’s performance
  - ➔ Enhanced current gain β

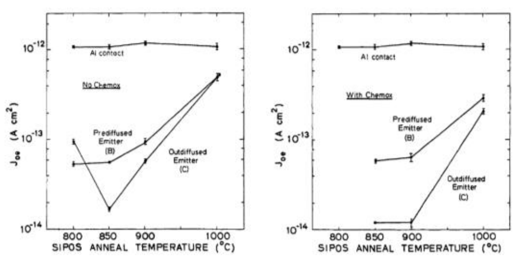




[1] I. Post, *IEEE Transactions on Electron Devices* (1992)

Passivating Contacts
1st Applications to Solar Cells

- **SIPOS Heterocontacts**[2]
  - $J_0 \approx$ 10 fA/cm² achieved

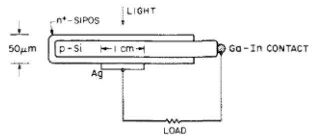


1984

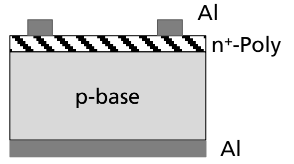
[2] Kwark et *al.*, *IEDM* (1984)

Passivating Contacts
1st Applications to Solar Cells

- **SIPOS Heterocontacts**[2, 3]
  - V_{oc} = 720 mV



- **Polysilicon Emitter Solar Cell**[4]
  - V_{oc} = 652 mV, FF = 60.5 %



1985

[2] Kwark et *al.*, *IEDM* (1984)
[3] Yablonovitch et *al.*, *IEEE Electron Device Letters* (1985)
[4] Tarr, *IEEE Electron Device Letters* (1985)

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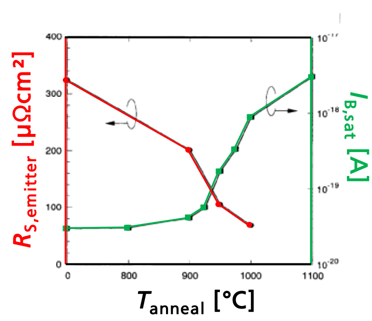
Passivating Contacts
1st Applications to Solar Cells

- Trade-off between J_0 and R_S



1985 1990

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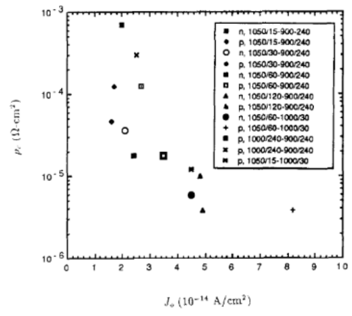
Passivating Contacts
1st Applications to Solar Cells

- Trade-off between J_0 and R_S
- **Polysilicon Emitters for IBC cells**[5]
  - Use of thicker thermally grown oxides + oxide break-up at 1050 °C
  - Low J_0 and ρ_c



1985 **1990**

[5] Gan and Swanson, *IEEE PVSC* (1990)

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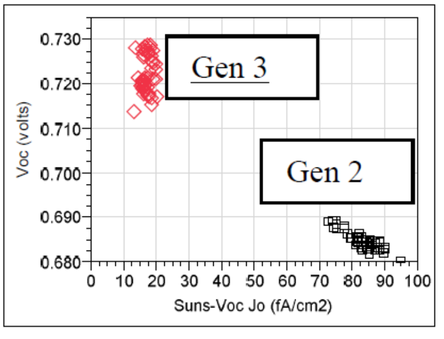
Passivating Contacts
1st High Efficiency Solar Cells

- **SunPower IBC cells**[6]
  - Type of passivating contacts not disclosed



1985 1990 **2010**

[6] Cousins et *al.*, *IEEE PVSC* (2010)

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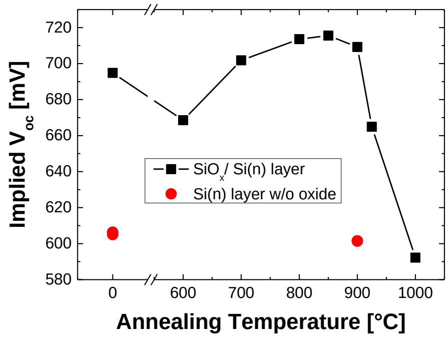
Passivating Contacts
1st High Efficiency Solar Cells

- Introduction of Tunnel Oxide Passivating Contact (TOPCon)[7,8]
- >23% efficient solar featuring passivating rear contact
- 1st time PECVD deposition



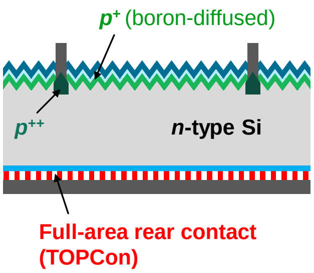
1985 1990 2010 2013

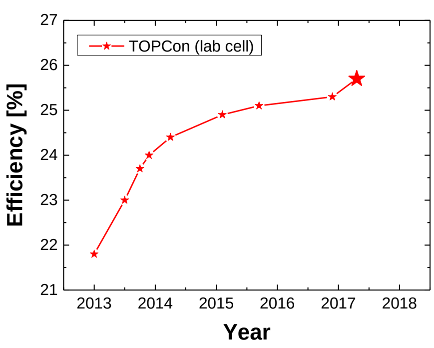
[7] F. Feldmann et *al.*, *EU-PVSEC* (2013)
[8] F. Feldmann et *al.*, *SolMat* (2014)

Passivating Contacts
Record Solar Cell[9]

- **Both-sides contacted cell** with front p+ emitter and full-area rear contact[8]

J_{sc} (mA/cm²)	V_{oc} (mV)	*FF* (%)	*η** (%)	Area** (cm²)
42.9	724	83.1	25.8	4.0 (da)

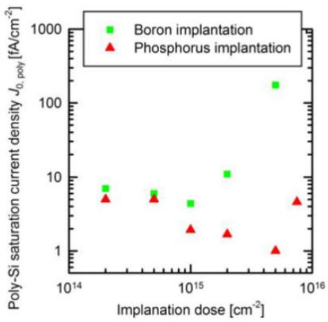




[8] F. Feldmann et *al.*, *SolMat* (2014)
[9] A. Richter et *al.*, *SolMat* (2017) / *PiP Efficiency Table* (2017)

Passivating Contacts
LPCVD Poly-Si/SiO_x

- POLO junctions[10,11]:
  - 2.4-3.6 nm thick oxide + ~200 nm poly-Si
  - Doped by ion implantation
- Low J_0 for p-type contacts achieved
- But not transferred into device



2013 2014 **2015**

11

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[10] U. Römer et *al.*, *SolMat* (2014)
[11] U. Römer et *al.*, *IEEE J-PV* (2015)

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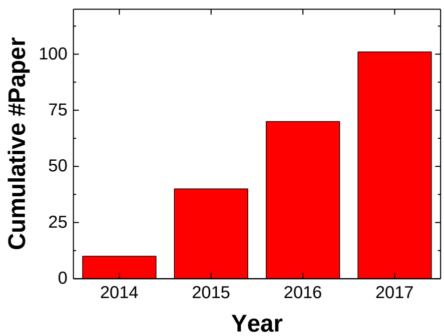
Passivating Contacts
Hot Topic in the Field of Silicon PV

- Since then plenty of papers published by
  - ANU
  - ECN
  - EPFL
  - F-ISE
  - Georgia Tech
  - ISFH
  - NREL
  - TU Delft, TU Eindhoven



2014

12

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AGENDA

- Brief history of passivating contacts
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  - Surface passivation
  - Carrier Transport
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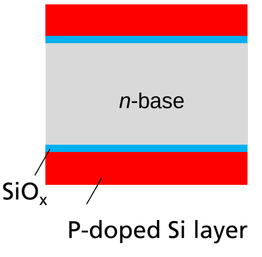
The TOPCon Approach
Process

TOPCon Process[8]

- Tunnel oxide
  (HNO_3, UV/O_3[7], O_3[7], TO)
  → Interface passivation
- PECVD deposition (single-sided)
  doped a-Si(C_x) layer
  → Carrier-selectivity

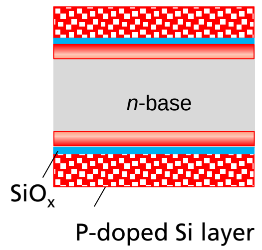


[8] F. Feldmann et *al.*, *SolMat* (2014)
[12] A. Moldovan et *al.*, *SolMat* (2015)

The TOPCon Approach
Process

TOPCon Process[8]

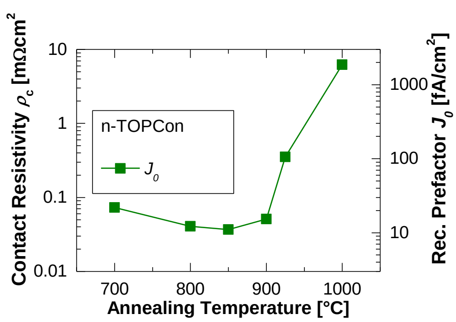
- Tunnel oxide (HNO_3, UV/O_3, O_3, TO)
  → Interface passivation
- PECVD deposition (single-sided) doped a-Si(C_x) layer
  → Carrier-selectivity
- Furnace Anneal
  → partial crystallization
  → dopant diffusion
- Hydrogenation (RPHP)
  → Defect passivation



[8] F. Feldmann et al., *SolMat* (2014)

TOPCon (Tunnel Oxide Passivated Contact)
J_0 and Contact Resistivity

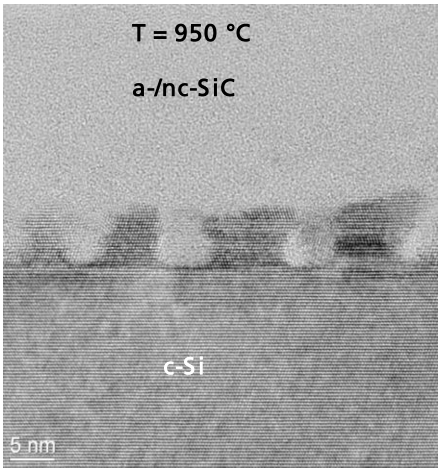
- TOPCon featuring **wet-chemical oxide**
- Good surface passivation for T_{anneal} = 800 – 900 °C
  - Typical values: J_0 ~ 4-10 fA/cm²
- T > 900 °C:
  - Degradation of passivation

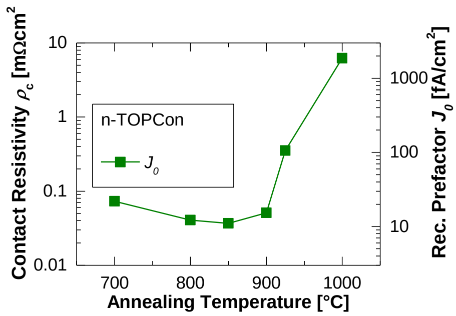


[13] F. Feldmann et *al.*, *Si Workshop* (2015)

TOPCon (Tunnel Oxide Passivated Contact)

J_0 and Contact Resistivity





17

[13] F. Feldmann et *al.*, *Si Workshop* (2015)

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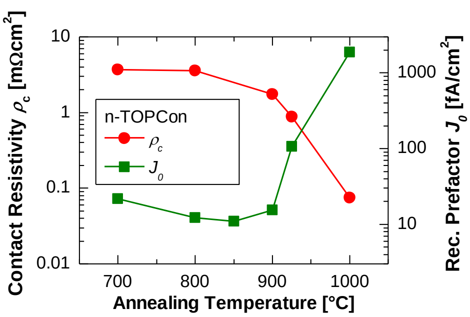
TOPCon (Tunnel Oxide Passivated Contact)

J_0 and Contact Resistivity

- TOPCon featuring **wet-chemical oxide**
- Good surface passivation for T_{anneal} = 800 – 900 °C
  - Typical values: J_0 ~ 4-10 fA/cm²
- and low contact resistivity ρ_c < 10 mΩcm²

➔ Efficient passivating and carrier-selective contact



18

[13] F. Feldmann et *al.*, *Si Workshop* (2015)

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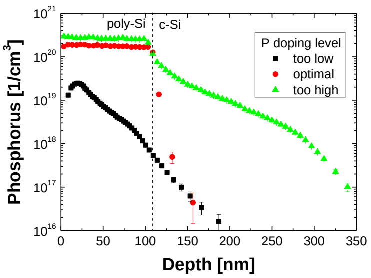
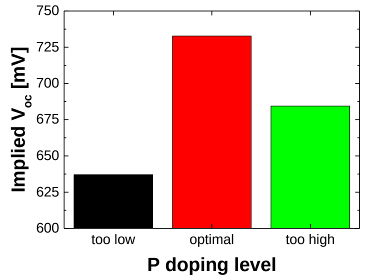
LPCVD Poly-Si/SiO_x Contacts
Influence of doping level

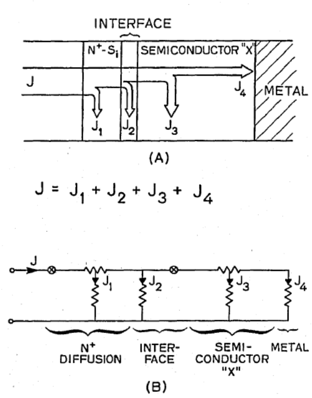
- Surface passivation quality depends on poly-Si doping and diffusion of dopants into c-Si





TOPCon
Analysis of Effective SRV

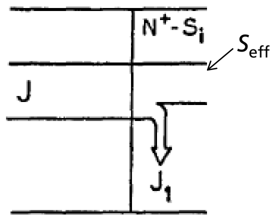
- Diffused c-Si(n⁺) region and band bending induced by poly-Si reduce minority charge carriers at interface



[14] Y. Kwark, PhD Thesis, Stanford (1988)

TOPCon
Analysis of Effective SRV

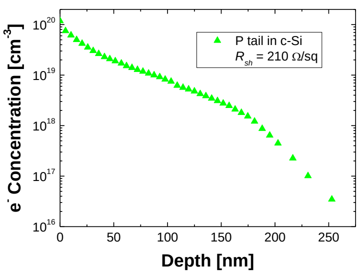
- Diffused c-Si(n+) region and band bending induced by poly-Si reduce minority charge carriers at interface
- Simplified description of J_0:
  - $J_0 = \frac{qn_{i,eff}^2}{N}\frac{D_p}{W} + qp_{int}S_{eff}$

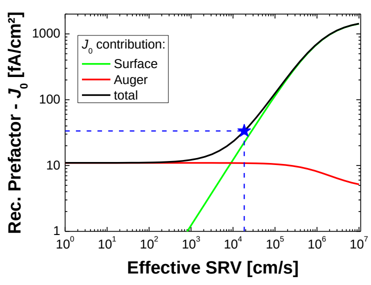


[14] Y. Kwark, PhD Thesis, Stanford (1988)

LPCVD Poly-Si/SiO$_x$ Contacts
Influence of doping level

- Profile of c-Si(n+) region into EDNA[15]
- J_0 = f(S_{eff})

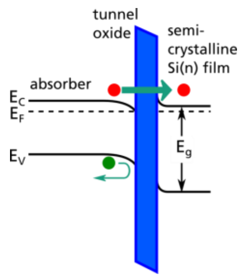


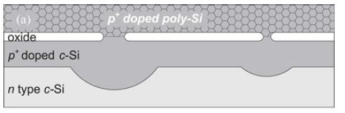


[15] K. McIntosh, *IEEE-PVSC* (2010)

Transport Mechanism
What is the Dominant Transport Mechanism?

- Tunneling through oxide barrier[16]
  - Best model for BJT
  - But controversy about barrier height
- Tunneling assisted by pinholes[6]
- Exclusively via pinholes[17]





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[6] Gan and Swanson, *IEEE PVSC* (1990)
[16] De Graaf and De Groot, *IEEE TED* (1979)
[17] R. Peibst et al., *IEEE J-PV* (2014)

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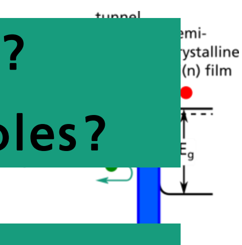
Transport Mechanism
What is the Dominant Transport Mechanism?

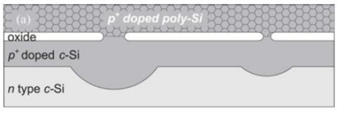
- Tu...
- Tunneling assisted by pinholes[6]
- Exclusively via pinholes[17]

Q: So what is it?

Tunneling or pinholes?

A: It depends…





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[6] Gan and Swanson, *IEEE PVSC* (1990)
[16] De Graaf and De Groot, *IEEE TED* (1979)
[17] R. Peibst et al., *IEEE J-PV* (2014)

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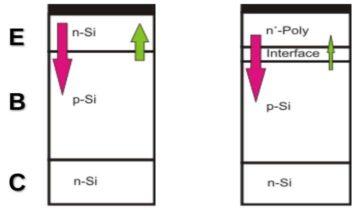
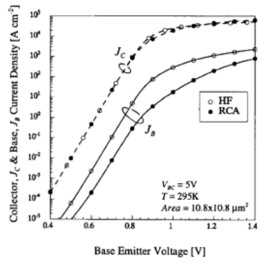
Transport Mechanism
Review on Poly-Si Transistor

- Hole injection into emitter reduced by tunnel oxide
  - $J_b \downarrow$ ➔ gain $\beta \uparrow$
- Transistor parameters:
  - $\beta = \frac{J_c}{J_b} = \frac{G_e}{G_b}$, $G_e = \int_0^{w_e} \left(\frac{n_i^2}{n_{i,e}^2}\right)^2 \frac{N_D}{D_p} dx$
  - G_e determines J_b
  - Analogy to solar cells: $J_{0,e} = \frac{q n_i^2}{G_e}$





25 [1] I. Post, *IEEE TED* (1992)

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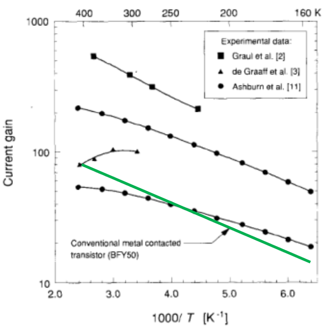
Transport Mechanism
Temperature Dependence of Current Gain

- Conventional BJT:
  - $\beta_{conv}(T) = const. \frac{1+AT^x}{\rho_{sh}(T)} \exp\left(-q \frac{\Delta E_{g,e} - \Delta E_{g,b}}{kT}\right)$
  - **T dependence of β is dominated by BGN**
- Poly-Si Transistor[18]:
  - $J_b \propto \exp\left(-2/\hbar \int_{x_1}^{x_2} \sqrt{2m^*(q\varphi_b(x) - E_x} \, dx\right)$
  - $\beta_{Poly}(T) = const. \frac{\sqrt{T}\,(1-CkT)}{\rho_{sh}(T)} \exp\left(-q \frac{\Delta E_{g,e} - \Delta E_{g,b}}{kT}\right)$
  - **Even negative slopes at high T possible**



26 [1] I. Post, *IEEE TED* (1992)
[18] Ashburn and Soerowirdjo, *IEEE TED* (1984)

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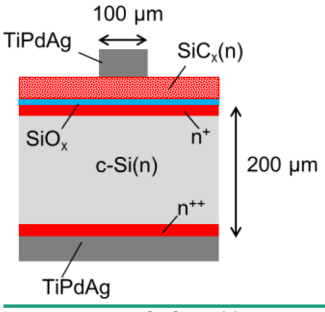
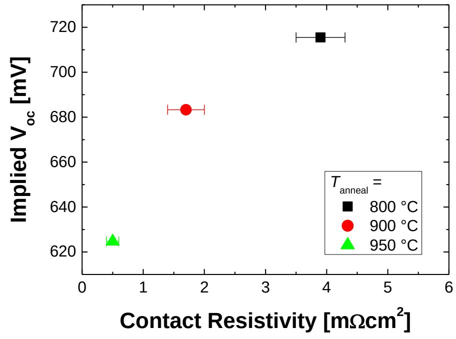
Transport Mechanism
Dark *J*-*V*(*T*) Measurements on Test Structures

- Different TOPCon structures with respect to
  - Surface passivation and
  - contact resistivity prepared

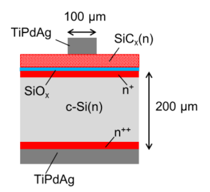


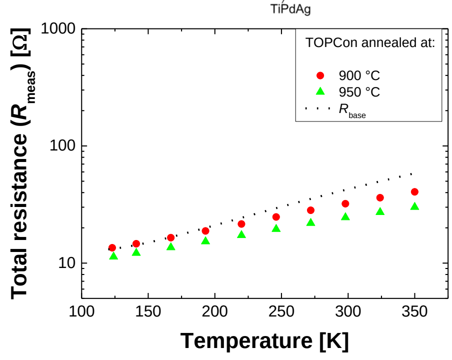


[19] F. Feldmann et *al*., *SolMat* (2017)

Transport Mechanism
Dark *J*-*V*(*T*) Measurements on Test Structures

- $T\downarrow \rightarrow R_{meas}\downarrow$
  - *T*-dependence governed by R_{base}
  - µ goes up with T
- Deviation from calculated curve due to c-Si(n$^+$)-region near surface

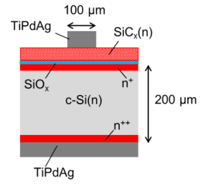


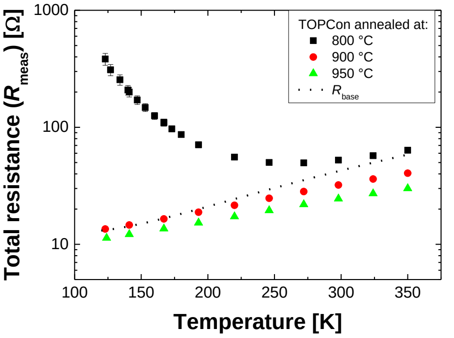


[19] F. Feldmann et *al*., *SolMat* (2017)

Transport Mechanism
Dark *J-V(T)* Measurements on Test Structures

- TOPCon with intact oxide shows exponential increase towards low T
  - Strong deviation from R_{base}





[19] F. Feldmann et *al.*, *SolMat* (2017)

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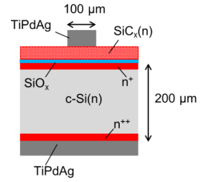
Transport Mechanism
Dark *J-V(T)* Measurements on Test Structures

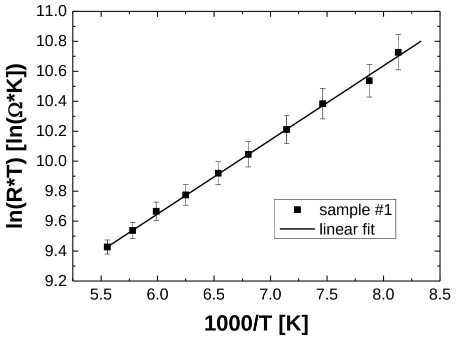
- TOPCon with intact oxide shows exponential increase towards low T
  - Strong deviation from R_{base}
- Extraction of barrier height

➔ $\phi_S = 42.6$ meV

- Thermionic emission:
  - $R_{TE} = \frac{k_B}{A^*Tq} \exp\left(\frac{q\phi_S}{k_B T}\right)$

➔ $R_{TE}(42.6\ \text{meV}) \approx 6.3\ \text{m}\Omega \ll R_{meas}$!!!





[19] F. Feldmann et *al.*, *SolMat* (2017)

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Transport Mechanism
Dark *J-V(T)* Measurements on Test Structures

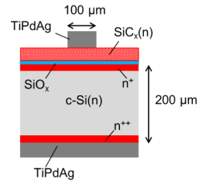
- Extraction of barrier height

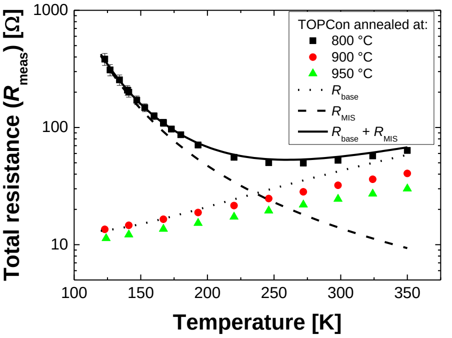
➔ $\phi_S = 42.6$ meV

- Thermionic emission:
  - $R_{TE} = \frac{k_B}{A^*Tq} \exp\left(\frac{q\phi_S}{k_B T}\right)$

➔ $R_{TE}(42.6\text{ meV}) \approx 6.3\text{ m}\Omega \ll R_{meas}!$

- Apply MIS theory:
- $R_{MIS} = R_{TE} \exp\left(\frac{2}{\hbar} t_{ox} \sqrt{2qm_e^* * \phi_e}\right)$
- TOPCon/800°C well described by MIS theory





31 [19] F. Feldmann et al., *SolMat* (2017)

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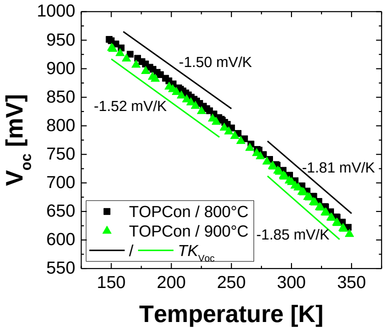
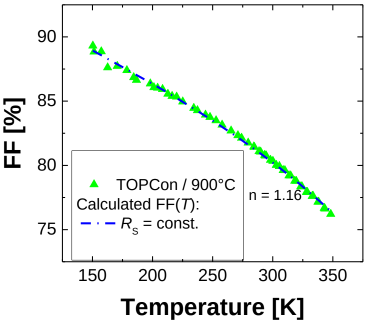
Transport Mechanism
J-V(T) Measurements on Solar Cells

- V_{oc} can be well described by Green's formula
- FF follows Green's semi-empirical expression:
  - $FF = FF_0(n, V_{oc}, T) * (1 - r_s)$





32 [19] F. Feldmann et al., *SolMat* (2017)

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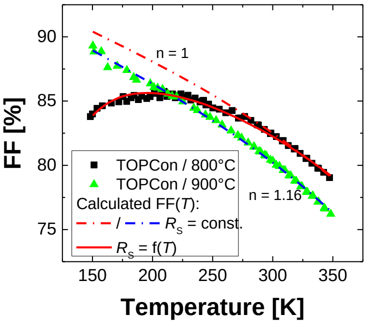
Transport Mechanism
J-V(T) Measurements on Solar Cells

- TOPCon/800°C cell shows feature of dark *J-V*(*T*) measurements
- $FF = FF_0 * \left(1 - r_{s,1} - r_{s,2}(T)\right)$
  $= FF_0 * \left(1 - r_{s,1} - r_{s,2} * \exp\left(\frac{qE_A}{kT}\right)\right)$
- TOPCon annealed at 800°C can be well explained by MIS theory



[19] F. Feldmann et al., *SolMat* (2017)

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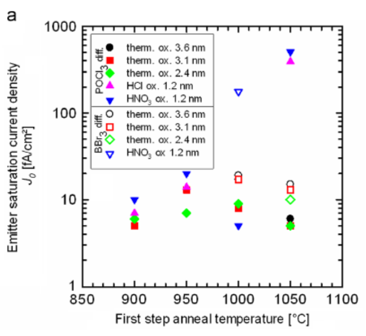
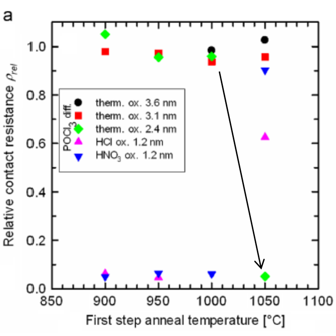
Transport Mechanism
Poly-Si/SiO$_x$ Contacts with Thicker Oxides

- $t_{ox} \approx 2.4$ nm:
  - Low ρ_c **cannot** be explained by tunneling





[10] Römer et al., *SolMat* (2014)

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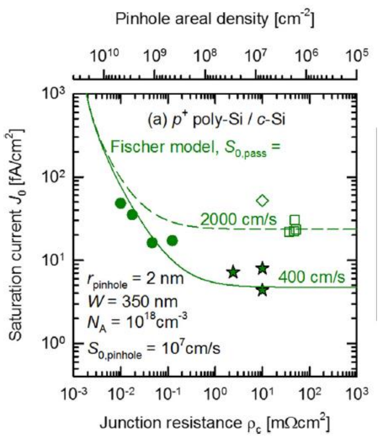
Transport Mechanism
Poly-Si/SiO_x Contacts with Thicker Oxides

- Description of passivating contact as a nano-PERC cell[20]
- Existence of pinholes verified by selective etching method[21]



[20] Peibst et *al.*, *SolMat* (2016)
[21] Tetzlaff et *al.*, *SolMat* (2017)

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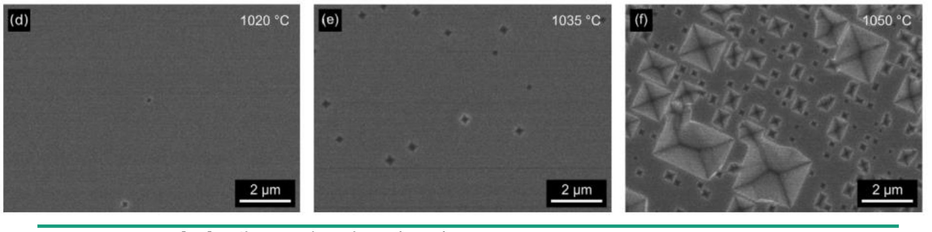
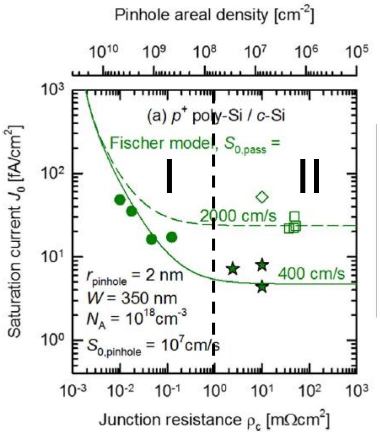


[20] Peibst et *al.*, *SolMat* (2016)
[21] Tetzlaff et *al.*, *SolMat* (2017)

Transport Mechanism
Poly-Si/SiO$_x$ Contacts with Thicker Oxides

- Description of passivating contact as a nano-PERC cell[20]
- Interestingly,
  - most passivating contacts operate in regime II
  - $J_0 = \frac{qn_{i,eff}^2}{N}\frac{D_p}{W} + qp_{int}S_{eff} \neq \boldsymbol{f(PD)}$

➔ J_0 can simply be modelled with EDNA



[20] Peibst et *al.*, *SolMat* (2016)

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Transport Mechanism
Unifying Picture

- "Thin" oxides:
  - Majority carrier transport dominated by tunneling
  - Pinholes (or thinned oxide regions) may help to stabilize ρ_c
  - T_{anneal} higher ➔ pinhole density increases ➔ J_0 increases
- "Thick" oxides:
  - Tunneling less efficient
  - Higher T_{anneal} necessary to deliberately form pinholes

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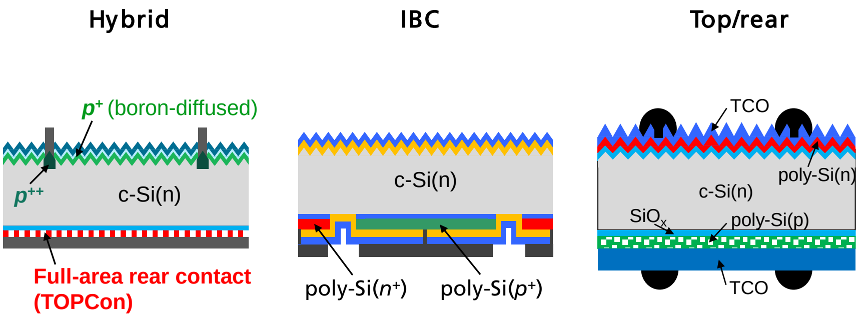
Transport Mechanism
Unifying Picture

- Transport mechanism strongly depends on
  - Surface preparation
  - Oxide thickness
  - Oxide stoichiometry, density
  - Material properties of doped Si layer
  - Annealing temperature

AGENDA

- Brief history of passivating contacts
- Working principle
  - Surface passivation
  - Carrier Transport
- High-efficiency solar cells
- Steps towards industrial implementation

High-efficiency Lab Scale Solar Cells
featuring Poly-Si Contacts



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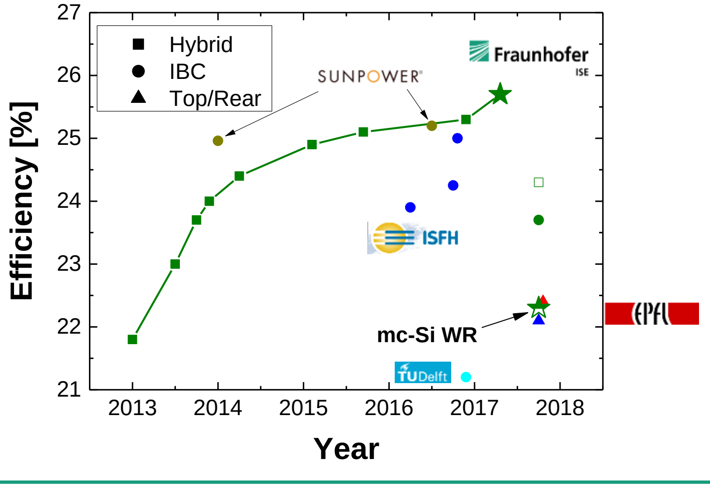
High-efficiency Lab Scale Solar Cells
featuring Poly-Si Contacts



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AGENDA

- Brief history of passivating contacts
- Working principle
  - Surface passivation
  - Carrier Transport
- High-efficiency solar cells
- Steps towards industrial implementation

Steps towards Industrial Implementation
Benefits and Challenges

Benefits:

- Almost similar J_0 but lower ρ_c values compared to HJT possible
- Higher processing temperatures possible

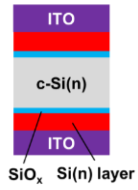
➔ Higher compatibility with mainstream technology?

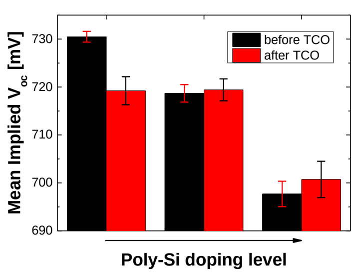
Challenges:

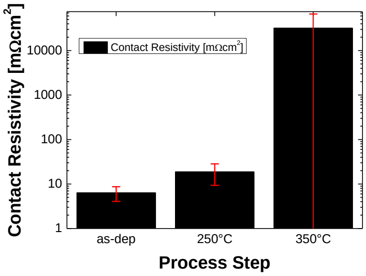
- Metallization and module integration
  - TCO
  - Screen-print and firing

Steps towards Industrial Implementation
TCOs for TOPCon

- Soft TCO deposition process and/or curing at T_{anneal} » 200°C
- But: contact resistivity increases at higher T_{anneal}
- → More details will be presented by L. Tutsch at SiliconPV (2018)

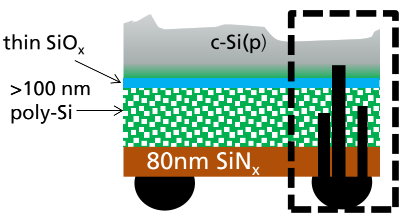


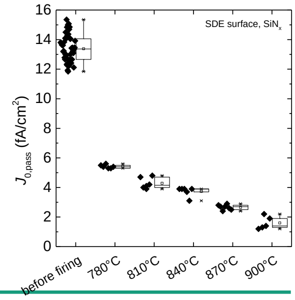




Steps towards Industrial Implementation
Firing of Ag Screen Printing Pastes

- Simple process sequence
- Effective hydrogenation
  - Low $J_{0,pass}$





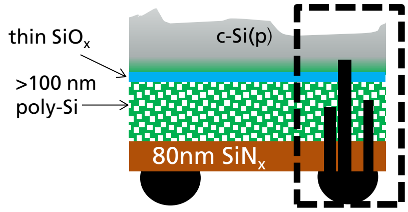
[22] S. Mack et *al.*, *Solar RRL* (2017)

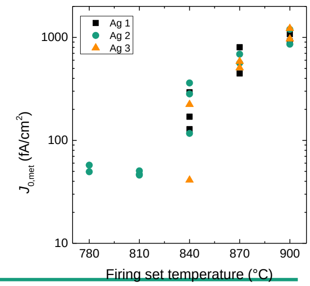
Steps towards Industrial Implementation
Firing of Ag Screen Printing Pastes

- Simple process sequence
- Effective hydrogenation
  - Low $J_{0,pass}$

But:

- $J_{0,met}$ increases with T_{firing}
  - $J_{0,met} >> J_{0,pass}$
  -
- Best efficiencies:
  - 21.5% (ECN) and 21.2% (ISFH)





[22] S. Mack et *al.*, *Solar RRL* (2017)
[23] H.E. Ciftpinar et *al.*, *Energy Procedia* (2017)

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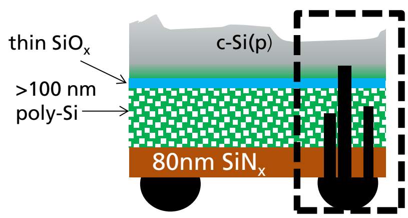
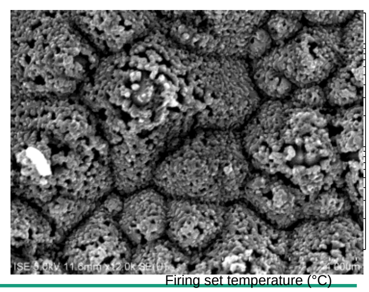
Steps towards Industrial Implementation
Firing of Ag Screen Printing Pastes

- Simple process sequence
- Effective hydrogenation
  - Low $J_{0,pass}$

But:

- $J_{0,met}$ increases with T_{firing}
  - $J_{0,met} >> J_{0,pass}$
  - Local penetration / damage of poly-Si[22,23]
  - FCA in thick, heavily-doped poly-Si
- Best efficiencies:
  - 21.5% (ECN) and 21.2% (ISFH)





[22] S. Mack et *al.*, *Solar RRL* (2017)
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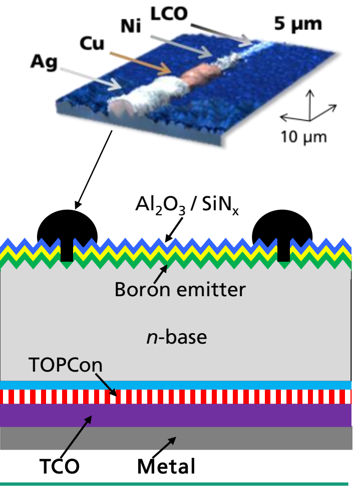
Steps towards Industrial Implementation
Large Area Solar Cells at F-ISE

Non-firing approach:
- LCO and NiCuAg plated contacts
- Rear: TCO/metal stacks
- Best result so far with evap. Ag



Area [cm²]	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	pFF [%]	η [%]
100	697	41.4	81.1	84.5	23.4

* Calibrated by F-ISE CalLab, (ap)

Summary

- Different views on transport mechanism reconciled
  - Depends strongly on used processes
- Excellent J_0 values and ρ_c values achieved by many groups
- Very high efficiencies of up to 25.8% achieved in the lab
- Poly-Si based passivating contacts still hold the promise of a facilitated back-end processing
  - But there are some hurdles to overcome

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Thank You Very Much for Your Attention!

13

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