# The Role of Inhomogeneities for Understanding Current-Voltage Characteristics of Solar Cells

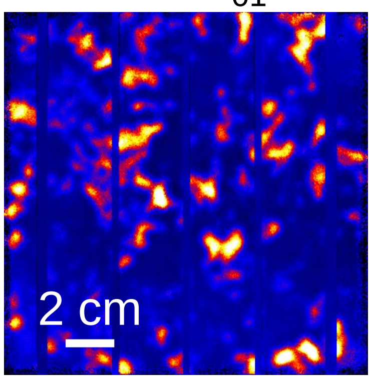
Otwin Breitenstein

Max Planck Institute for Microstructure Physics,
Halle, Germany

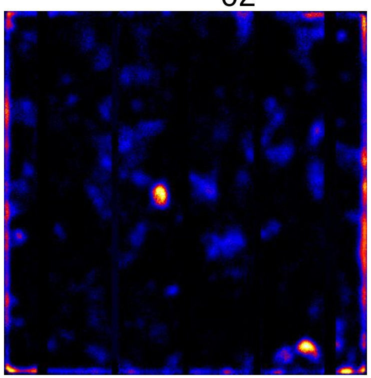
# Outline

1. Motivation and introduction
2. Used characterization techniques
3. Origin and quantitative influence of $J_{01}$, $J_{02}$, and $R_p$ inhomogeneities
4. Origin of pre-breakdown sites
5. Conclusions

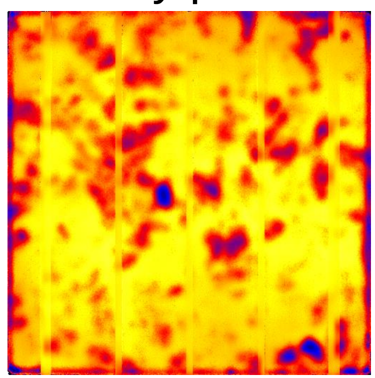
DLIT-$J_{01}$



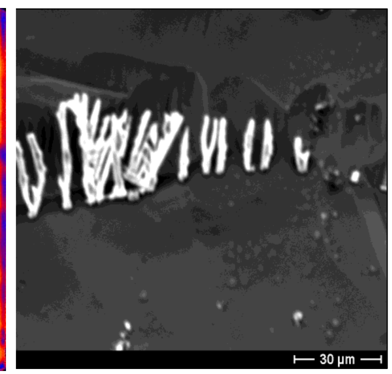

DLIT-$J_{02}$



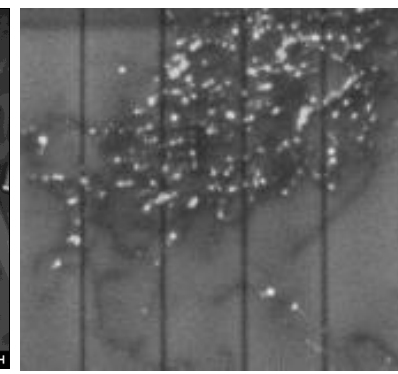
efficiency potential



SiC filaments




EL + ReBEL



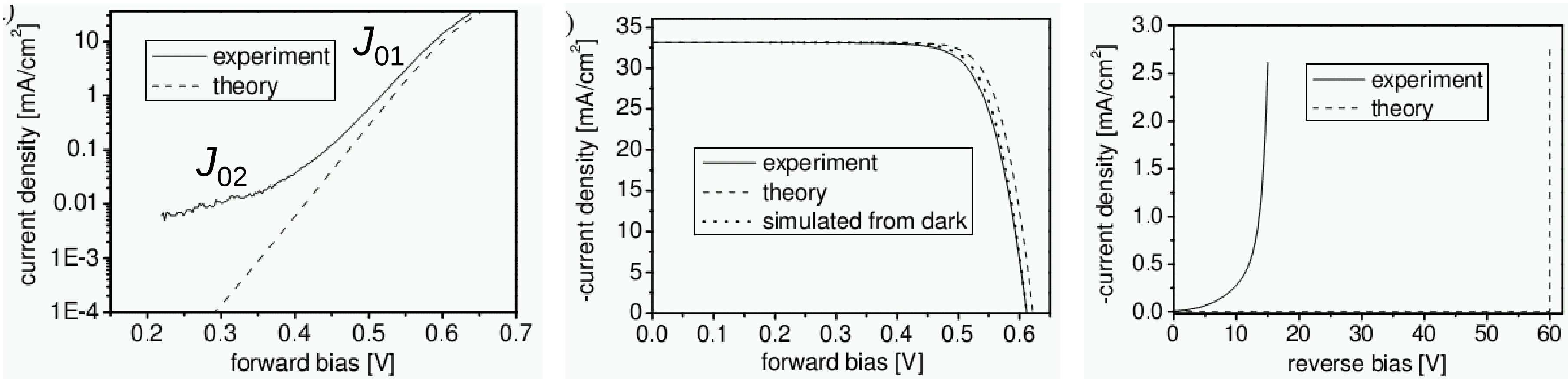
# 1. Motivation and introduction

- All solar cells are more or less inhomogeneous devices.
- In particular in multicrystalline (mc) silicon cells, the bulk lifetime varies by an order of magnitude or more due to grown-in crystal defects, leading to inhomogeneous distributions of $J_{01}$ and $J_{sc}$.
- The depletion region recombination current ($J_{02}$), ohmic shunts ($R_p$), and breakdown are always local phenomena (also in mono).
- The effective series resistance $R_s$ is position-dependent. Technological faults and cracks lead to inhomogeneous $R_s$.
- For detecting these inhomogeneities and evaluating their influence on the efficiency, solar cell imaging methods are indispensable.
- By looking for physical origins of inhomogeneous characteristics, we have unveiled in the last 20 years a number of new physical mechanisms.

# 1. Motivation and introduction

$$J(V) = J_{01}\exp\left(\frac{V}{V_T}\right) - J_{sc} \longrightarrow V_{oc} = V_T\, ln\left(\frac{J_{sc}}{J_{01}}\right)$$

Measured vs. textbook I-V characteristics of industrial mc silicon solar cells




- Global $J_{01}$ is somewhat higher, but $J_{02}$ is orders of magnitude higher than expected and shows a too large ideality factor.
- Breakdown should occur by avalanche at -60 V, but in reality significant pre-breakdown occurs, in particular for mc cells.
- Ohmic shunting is not explained by classical diode theory.

O. Breitenstein, Opto-Electronic Review **21** (2013) 259

## Dominant local solar cell imaging methods

- LBIC mapping
- Used since 1979
- Moving light spot
- Images $J_{sc}(x,y)$ (EQE / IQE)
- Spectral information yields $J_{sc}$, $L_{eff}$, bulk + surface recomb.
- Commercial system: e.g.LOANA (PV-Tools)

- Lock-in Thermography (LIT)
- Known since 1988
- Solar cell investig. since 2000
- DLIT images local dark current density
- Many variants
- Commercial system: e.g. PV-LIT (InfraTec)

- Luminescence
- Used since 2005 for EL (Fuyuki)
- PL (on cells) since 2007 (Trupke)
- images local diode voltages + $L_{eff}$
- New evaluations
- Commercial system: e.g.LIS R3 (bt imaging)

O. Breitenstein, Phys. Stat. Sol. (a) **214** (2017) 1700611

# The „Local I-V“ DLIT evaluation method (software)

- All pixels are fitted to a **two-diode model**, $R_s$ is set to fit local $V_d$ at highest bias

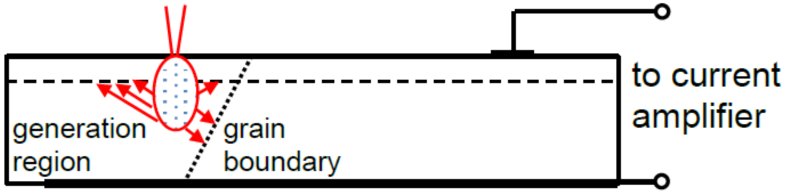
$$J = J_{01}\left(\exp\left(\frac{e(V - R_s J)}{n_1 kT}\right) - 1\right) + J_{02}\left(\exp\left(\frac{e(V - R_s J)}{n_2\, kT}\right) - 1\right) + \frac{(V - R_s J)}{R_p}$$

assumed to be homogeneous ($n_1$)

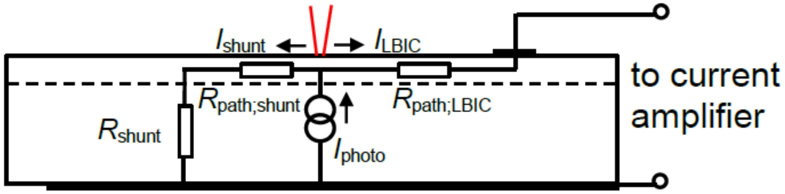
- **Results:**
  - **- Images of $J_{01}$, $J_{02}$, $n_2$, and $G_p = 1/R_p$**
  - **- $R_s$ image is calculated from evaluating $V_d$(0.6V)**
  - **- $J_{sc}$ image simulated (from $J_{01}$) or loaded**
  - **- Simulation of local and global dark and illuminated *I-V* characteristics.**
  - **- Solar cell parameters ($V_{oc}$, FF, $\eta$): global or for selected regions**

# Further methods: SEM-EBIC

recombination contrast




current distribution contrast (due to ohmic shunts)[1]




# Transmission electron microscopy (TEM / STEM)

- Identification of crystal defects

[1] A. Kaminski et al., J. Phys.: Condensed Matter **16** (2004) S9

# 3. Origin and quantitative influence of $J_{01}$, $J_{02}$, and $R_p$ inhomogeneities

- The physical origins of $J_{01}$ and $J_{02}$ inhomogeneities and of material-induced ohmic shunts will be reviewed
- On two examples (one industrial standard technology cell and one industrial PERC cell on HP material*) the quantitative influence of such defects on the efficiency of typical multicrystalline solar cells will be analyzed

*by courtesy of Trina Solar (Changzhou, P.R. China)

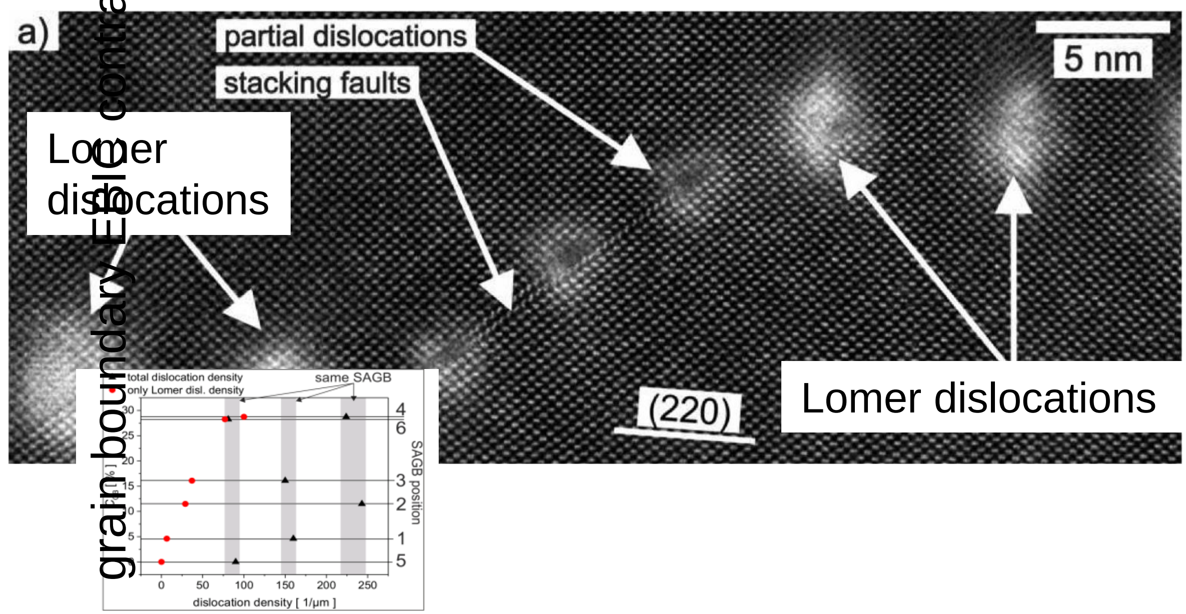
# 3.1 $J_{01}$ inhomogeneities

- The local value of $J_{01}^{bulk}$ depends on bulk lifetime $\tau_b$ and on back surface recombination velocity $S_b$
- $\tau_b$ is strongly influenced in multicrystalline material by crystal defects, like dislocations and grain boundaries (GBs)
- Luminescence and LBIC in combination with EBSD have revealed that the GBs with strongest recombination are small angle GBs (SA-GBs, rows of dislocations)
- Recent LAADF-STEM investigations[1] have shown that un-dissociated (perfect) Lomer dislocations (edge dislocations lying along [011] and having (100) slip plane; quite immobile, probably Fe-contaminated) dominate the recombination activity of SA-GBs

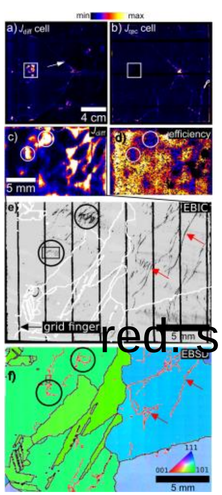
[1] J. Bauer at al., IEEE J-PV **6** (2016) 100

# 3.1 $J_{01}$ inhomogeneities

Low Angle Annular Dark Field (LAADF) STEM




white: large angle GBs

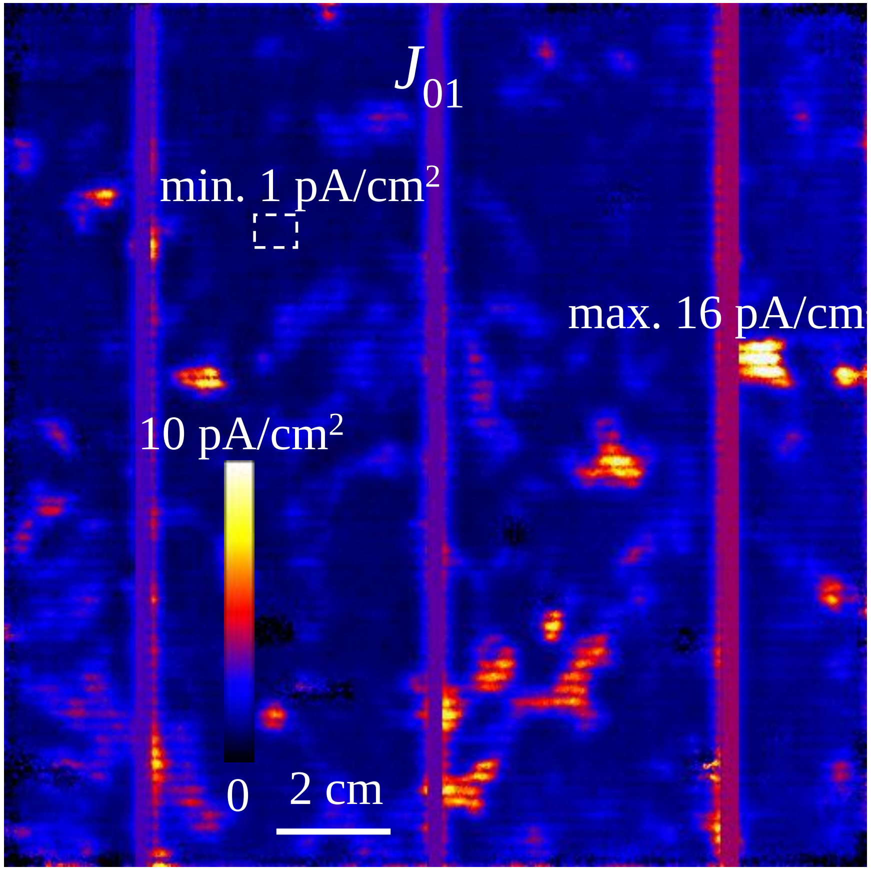



red: small angle GBs

- The recombination activity of SA-GBs clearly correlates with their density of Lomer dislocations (STEM investigations), but not with the total dislocation density

# 3.1 $J_{01}$ inhomogeneities

## Standard technology cell

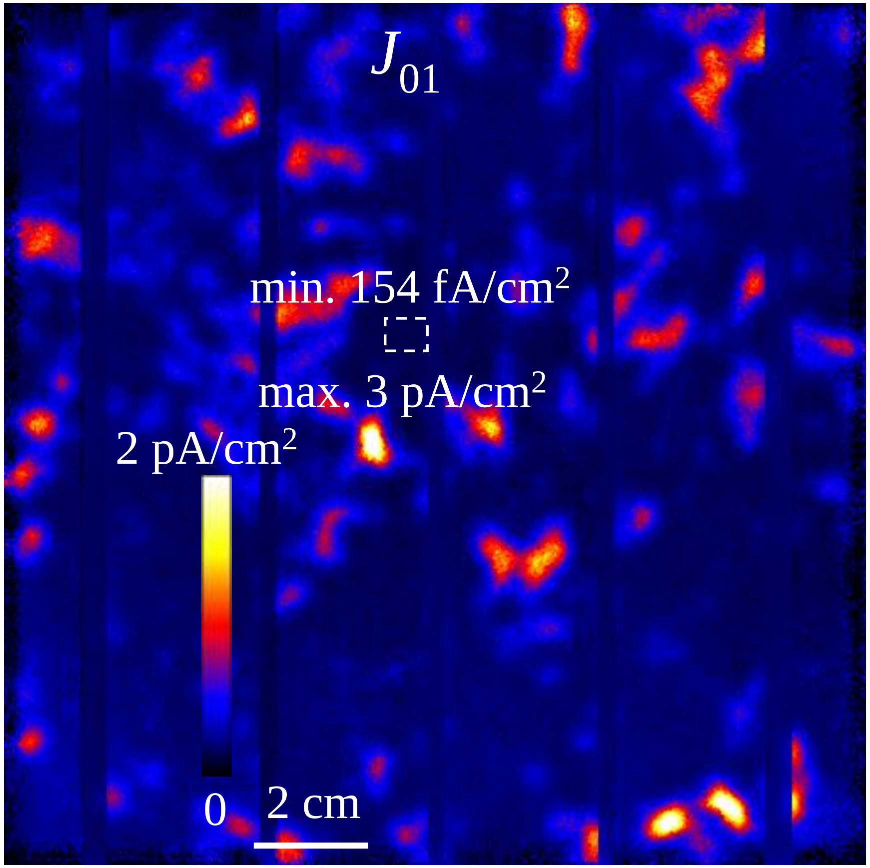




global (1 sun): $J_{01}$ = 1.7 pA/cm² $V_{oc}$ = 618 mV $\eta$ = 16.2 %

best region: $J_{01}$ = 1.0 pA/cm² $V_{oc}$ = 633 mV (+ 15 mV) $\eta$ = 17.0 % (+ 0.8 %)

# 3.1 $J_{01}$ inhomogeneities

## PERC cell on HP material


global (1 sun): $J_{01}$ = 288 fA/cm² $V_{oc}$ = 659 mV $\eta$ = 20.8 %

best region: $J_{01}$ = 154 fA/cm² $V_{oc}$ = 680 mV (+ 21 mV) $\eta$ = 21.9 % (+ 1.1 %)

# 3.1 $J_{01}$ inhomogeneities

## Conclusions to $J_{01}$ currents

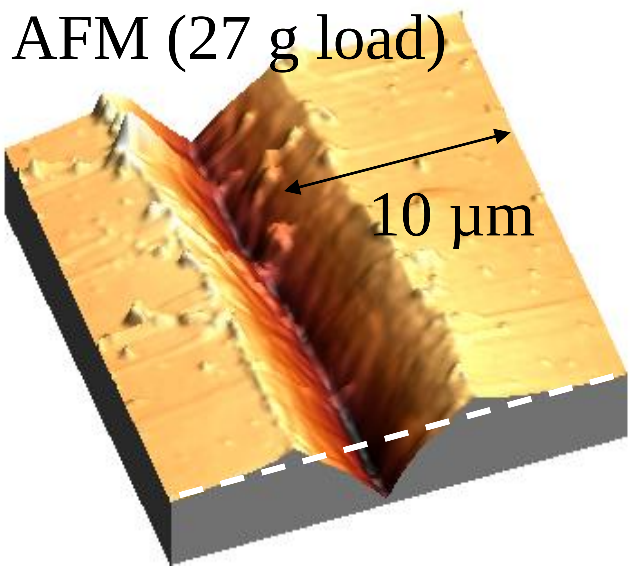
- The grown-in defects in multicrystalline Si material significantly increase $J_{01}$ of the cells.
- The dominant recombination activity in low-angle GBs is due to perfect Lomer dislocations.
- Crystal defects degrade the efficiency of typical mc solar cells by 0.8 % (absolute) for standard technology cells on standard material, and by 1.1 % (absolute) for PERC cells on HP material (under standard conditions)
- This defect-induced degradation is mainly due to an increased $J_{01}$ and occures mainly by reducing $V_{oc}$ and $J_{sc}$. It is only weakly dependent on illumination intensity.

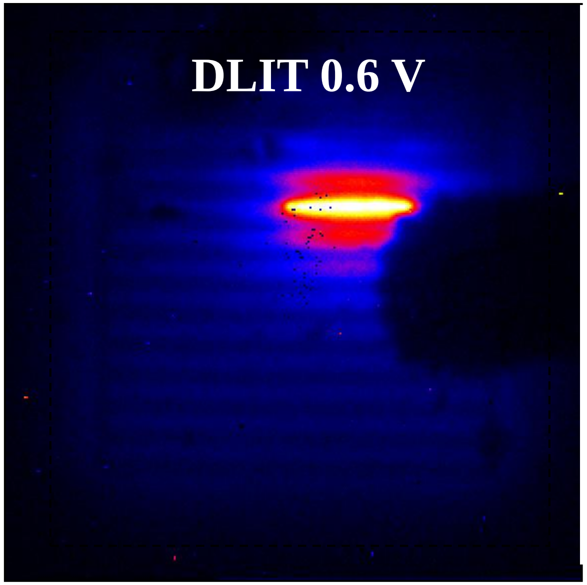
# 3.2 $J_{02}$ inhomogeneities

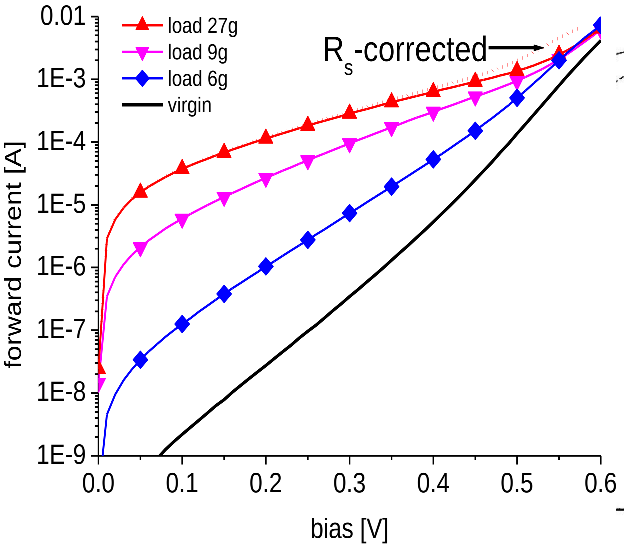
• Identifying the origin of $J_{02}$-type currents

• Mono-Si cells with passivated edge behave as ideal diodes

• Diamond scratches convert their characteristics into that of „real solar cells“ showing $n_2 > 2$ [1]




• Obviously, diamond scratches generate the type of defects which are responsible for "real characteristics" (incl. $J_{02}$ edge current)[2]

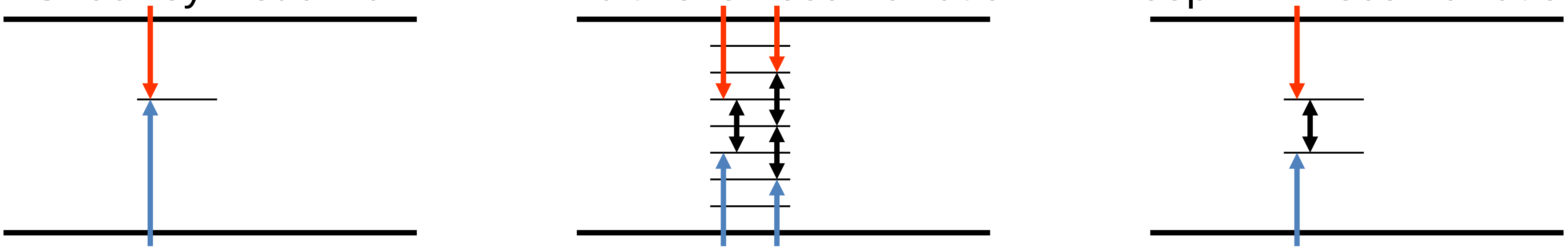
[1]O. Breitenstein et al.: Proc. GADEST 2009, [2]O. Breitenstein et al., Sol. St. Phen. 1994

# 3.2 $J_{02}$ inhomogeneities

Classic recombination: Shockley-Read-Hall

Extended defect: multi level recombination

Simplest model: "Deep DAP recombination"



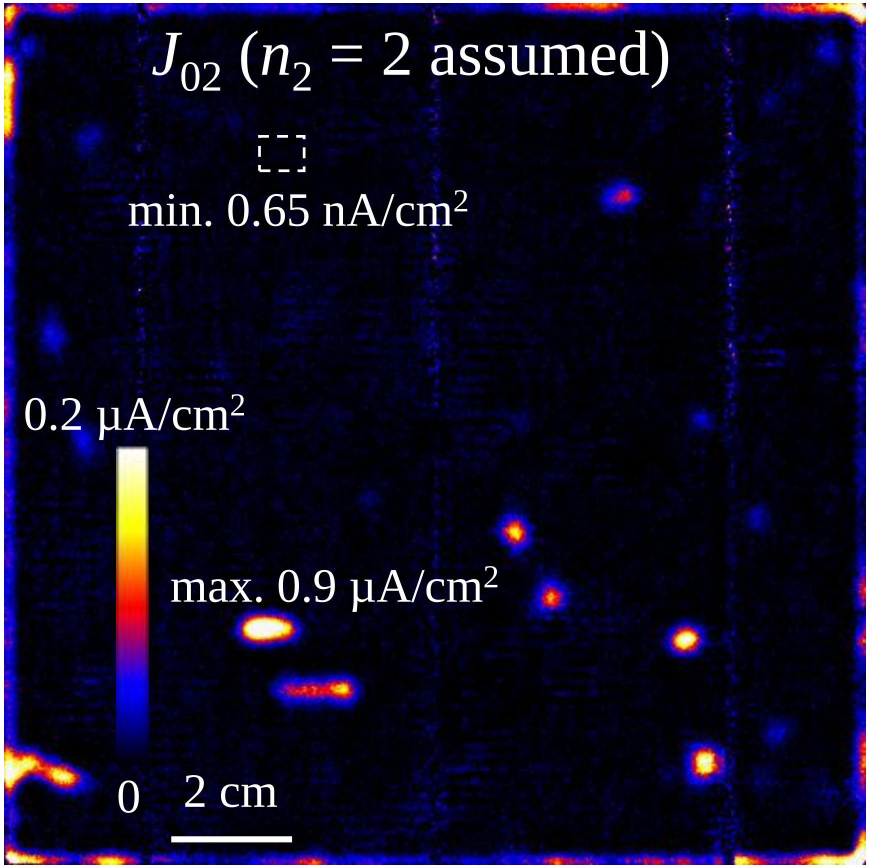
- The recombination current ($J_{02}$) in solar cells is due to **extended defects** (surface states at edges, interface states to precipitates, scratches) **crossing the p-n junction**
- **The large ideality factor is due to multi level recombination**
- First simulations have demonstrated large ideality factors[1]; realistic Sentaurus simulations allowed to fit measured characteristics[2]

[1] O. Breitenstein et al.: 21th Eur. PVSEC, Dresden 2006, GADEST 2009

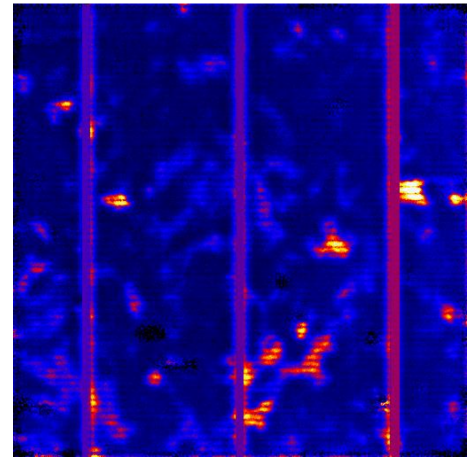
[2] S. Steingrube et al., J. Appl. Phys. **110** (2011) 014515

# 3.2 $J_{02}$ inhomogeneities

## Standard technology cell




$J_{01}$ image (0 to 10 pA/cm²)

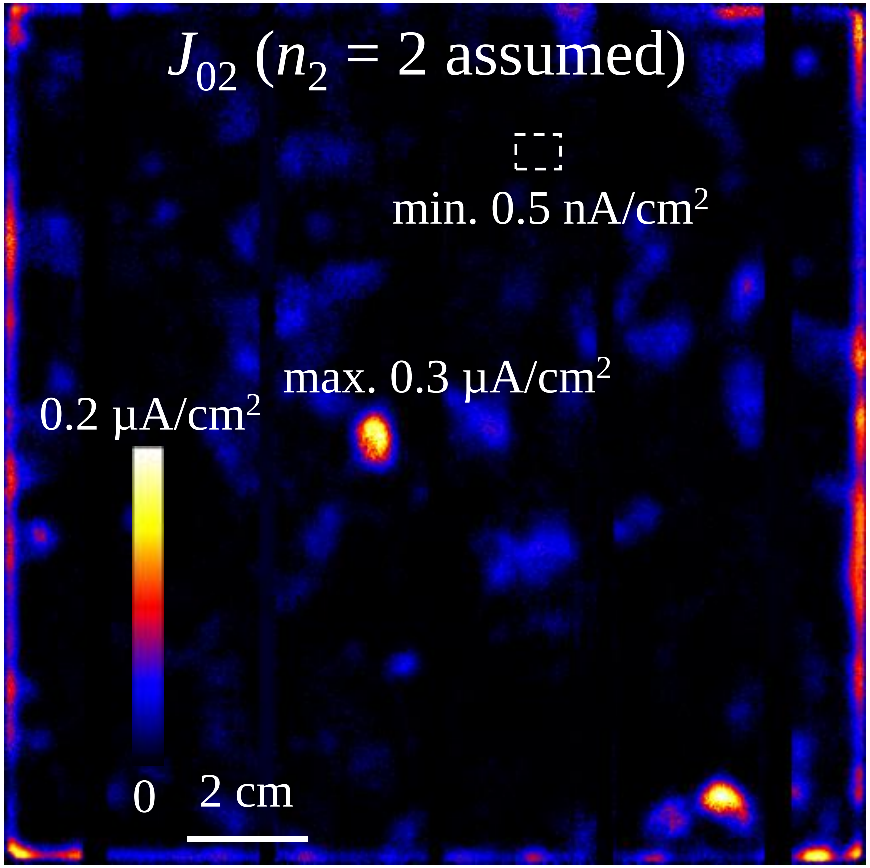


| | | |
|---|---|---|
| global, 1 sun: | FF = 78.6 % | $\eta$ = 16.2 % |
| no edge, 1 sun: | FF = 79.1 % | $\eta$ = 16.3 % |
| | + 0.5 % | + 0.1 % |
| global, 0.1 sun: | FF = 76.8 % | $\eta$ = 14.1 % |
| no edge, 0.1 sun: | FF = 78.2 % | $\eta$ = 14.4 % |
| | + 1.4 % | + 0.3 % |

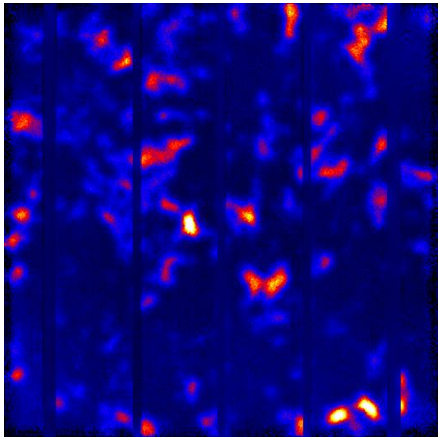
# 3.2 $J_{02}$ inhomogeneities

$\mu\Phi$

## PERC cell on HP material




$J_{01}$ image (0 to 2 pA/cm²)



| | | |
|---|---|---|
| global, 1 sun: | FF = 78.8 % | $\eta$ = 20.8 % |
| no edge, 1 sun: | FF = 79.4 % | $\eta$ = 20.9 % |
| | + 0.6 % | + 0.1 % |
| global, 0.1 sun: | FF = 77.0 % | $\eta$ = 18.0 % |
| no edge, 0.1 sun: | FF = 78.3 % | $\eta$ = 18.3 % |
| | + 1.3 % | + 0.3 % |

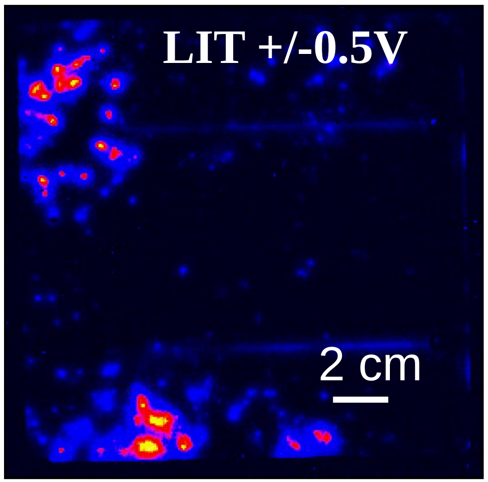
## Conclusions to $J_{02}$ currents

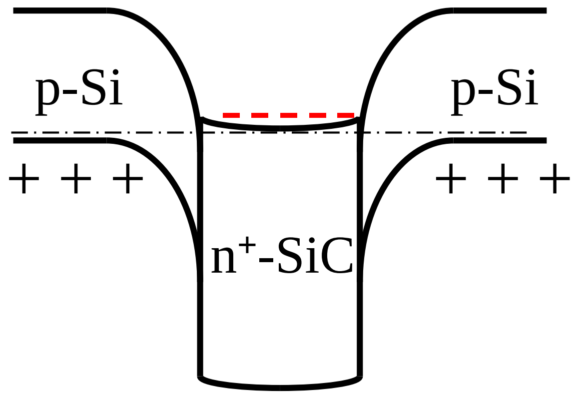
- $J_{02}$ currents are always local phenomena, the homogeneous $J_{02}$ current is negligibly small, also in mc cells.
- $J_{02}$ currents flow where extended defects (e.g. the non-passivated edge, scratches) with high local density of gap states are crossing the pn-junction.
- This high density of states may lead to an ideality factor of $n_2 > 2$ due to multilevel recombination[1,2].
- Due to the $J_{02}$ current, the edge region degrades the efficiency of typical cells (standard and PERC) at 1 sun by about 0.1 % but at 0.1 sun by 0.3 % (absolute), mainly due to a reduction of the FF.

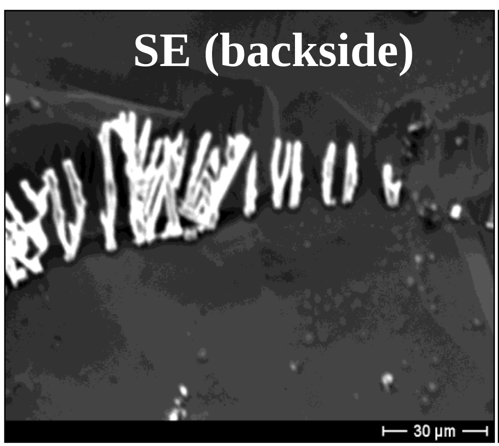
[1] O. Breitenstein et al.: 21th Eur. PVSEC, Dresden 2006, GADEST 2009

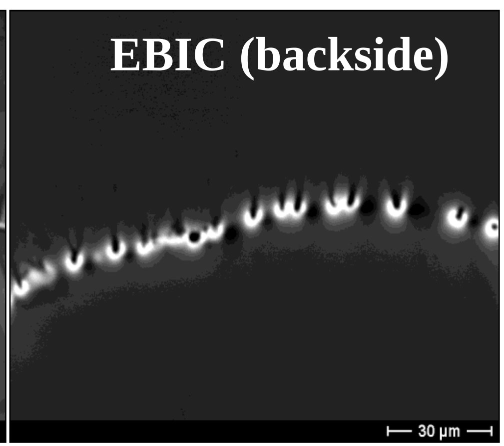
[2] S. Steingrube et al., J. Appl. Phys. **110** (2011) 014515

## Ohmic shunts in mc cells due to grown-in crystal defects



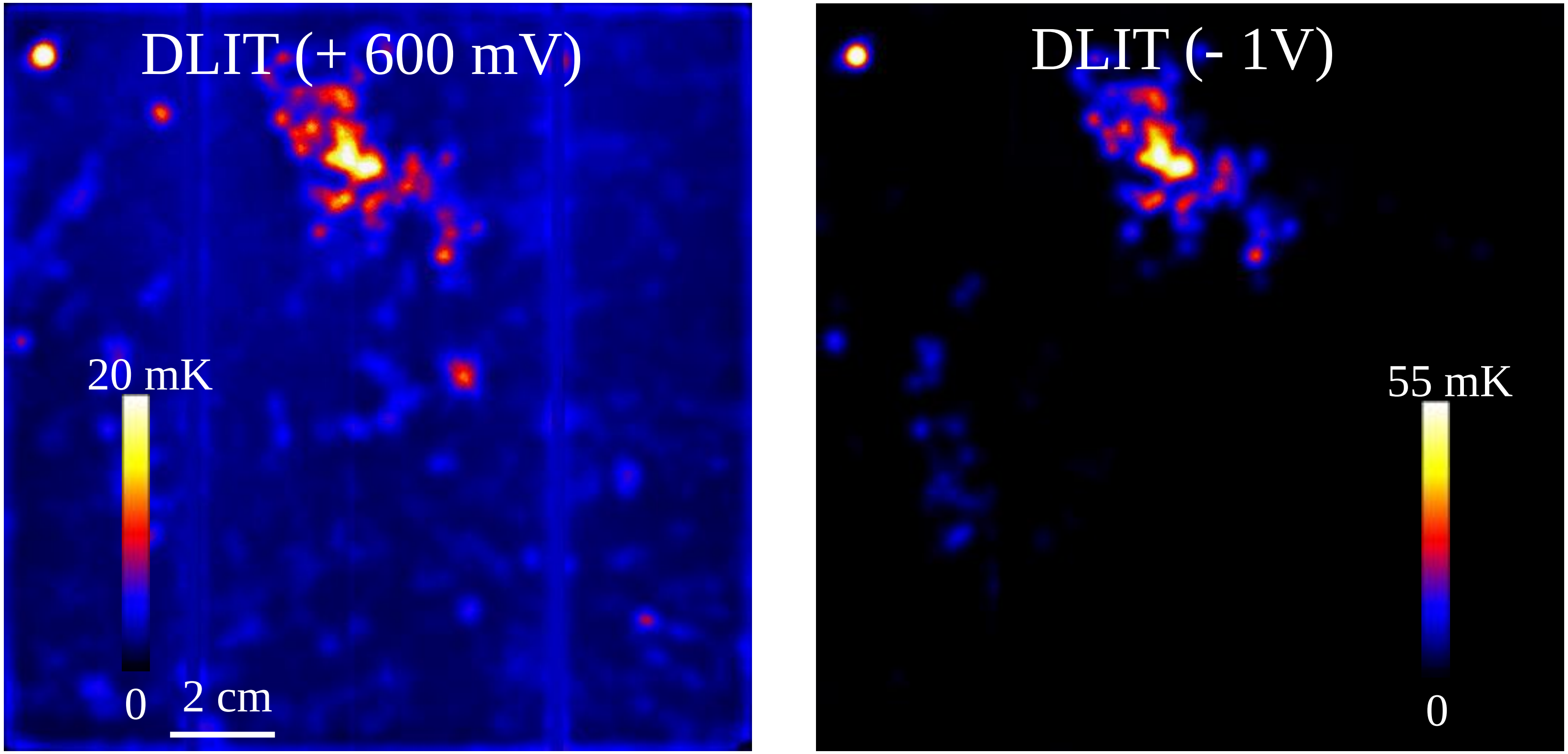

- We identified them as SiC-filaments, which are highly n-conducting (N-doped) and are crossing the whole cell, predominantly in grain boundaries[1]

[1]J. Bauer et al.: "Electronic activity of SiC precipitates in multi-crystalline solar silicon", phys. stat. sol. (a) **204**, No. 7, 2190-2195 (2007)

**Other ohmic shunts**: Al particles on emitter, metal paste in cracks, incompletely opened edge[2]

[2]Breitenstein et al., Prog. Photovolt: Res. Appl. **12** (2004) 529

## Standard technology cell with SiC filaments[1]

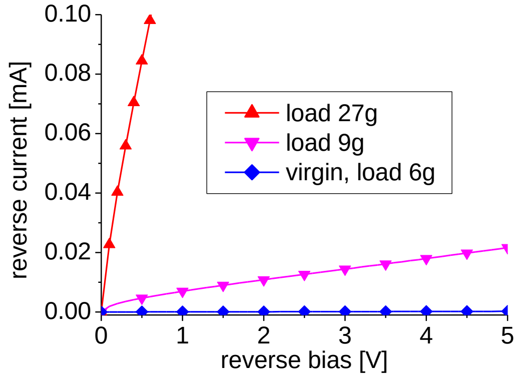



- Evaluated by using the „virtual cut shunt“ function of „Local I-V“

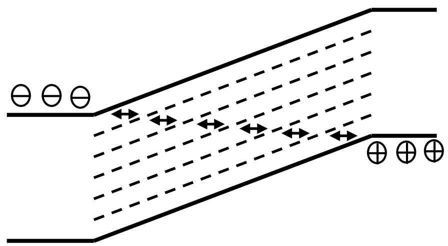
| | | | |
|---|---|---|---|
| At 1 sun, reduction of | FF by - 3.3 %, | $V_{oc}$ by -2 mV, | $\eta$ by -0.8 % |
| At 0.1 sun, reduction of | FF by -25.3 %, | $V_{oc}$ by -22 mV, | $\eta$ by -5.1 % |

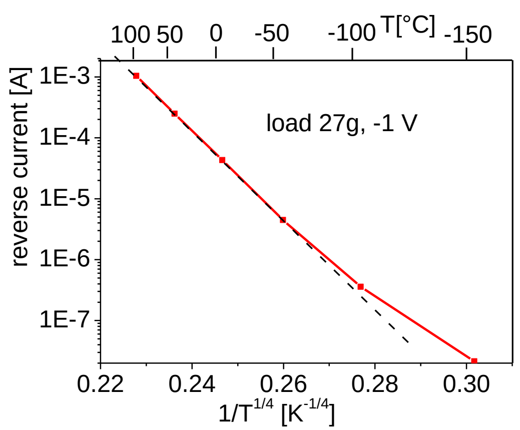
[1]Frühauf and Breitenstein, SOLMAT **169** (2017) 195

## Ohmic conductivity at extended defects



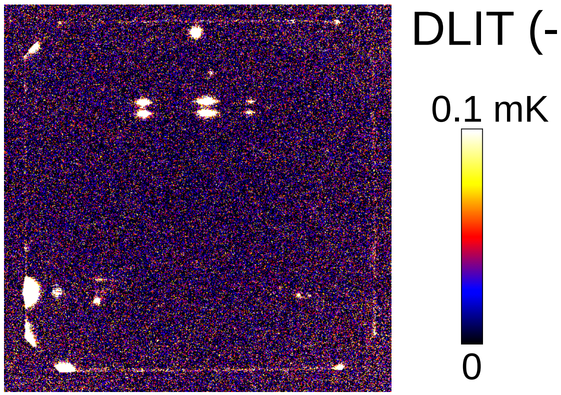

- Scratching also creates ohmic conductivity
- Exponential dependence over $1/T^{1/4}$ indicates variable range hopping conduction according to Mott's theory[1]




- Also edge currents, which predominantly show $J_{02}$ current, have a weak ohmic contribution[2]; this is the same mechanism, see also: breakdown mechanisms (below)

DLIT (-1 V)

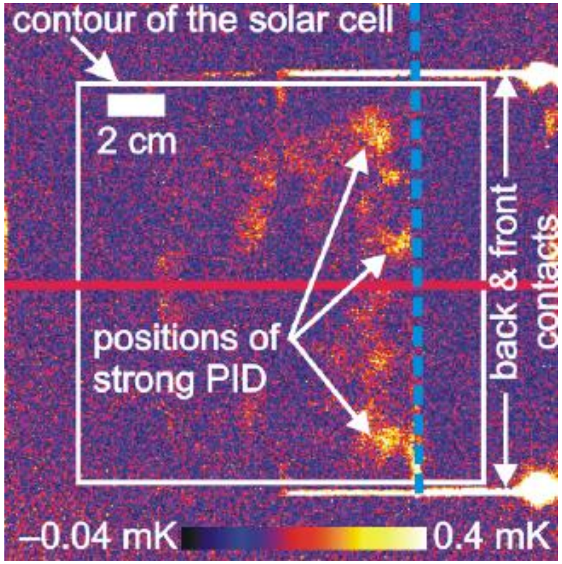



[1]O. Breitenstein et al., 21th EU-PVSEC Dresden 2006, pp. 625-628

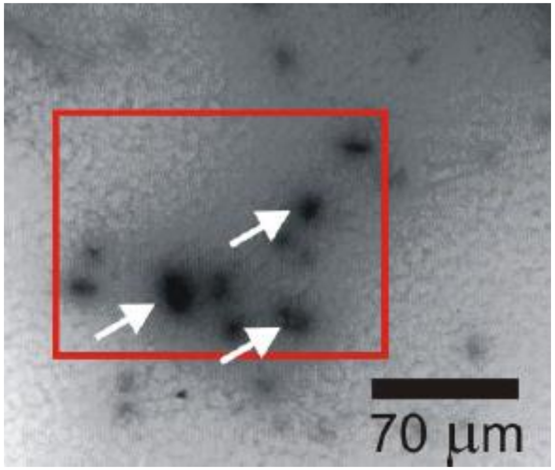
[2]O. Breitenstein, Opto-Electronics Review **21** (2013) 259-282

# Potential-induced degradation (PID) defects cause ohmic shunts and $J_{02}$ currents

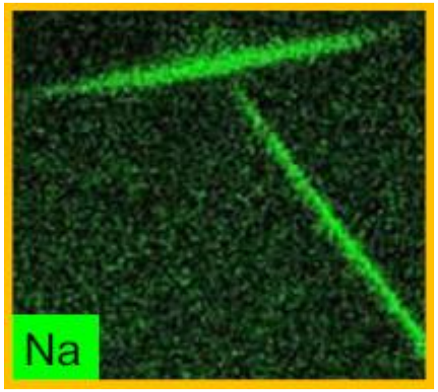
DLIT[1]



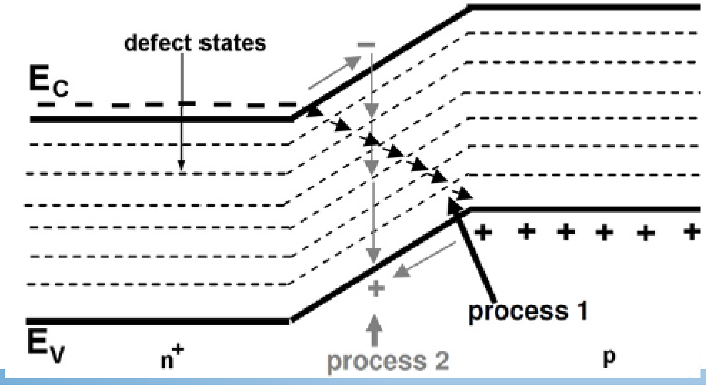

EBIC[1]




STEM: EDX[2]




physical model[2]



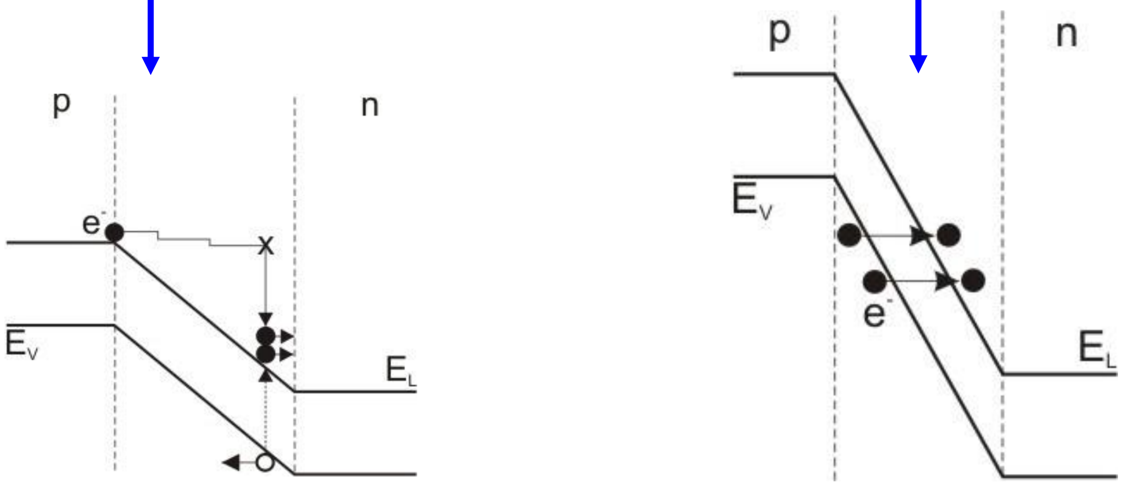

[1]J. Bauer et al., Phys. Stat. Sol. RRL **6** (2012) 331

[2]V. Naumann et al., SOLMAT **120** (2014) 383

## Conclusions to ohmic shunts

- Like $J_{02}$ currents, also ohmic shunts are always local phenomena, there is no homogeneous ohmic shunting.
- Ohmic shunts reduce mainly the FF, stronger shunts also reduce $V_{oc}$.
- The efficiency degradation due to ohmic shunts is strongly illumination intensity-dependent, their influence drastically increases with reducing illumination intensity.
- This property is due to the fact that the ohmic shunt current drops much less with reducing bias than the diode current.
- The dominant material-induced ohmic shunts in mc cells are due to SiC filaments, other ohmic shunts are due to Al particles, cracks, edge surface states, and PID defects.

- In the textbooks we find two breakdown mechanisms, which are avalanche breakdown and internal field emission (= tunneling; Zener breakdown, dominating for high doping)

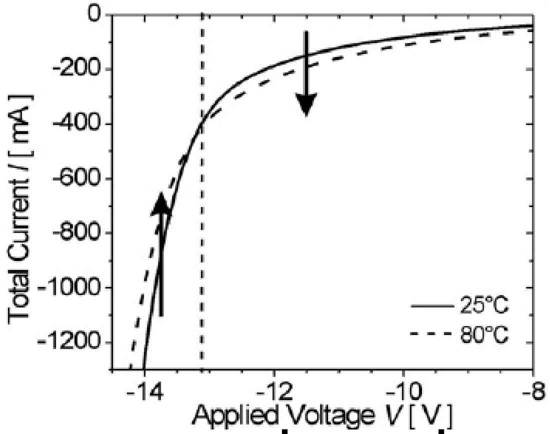



- Silicon solar cells ($p = 10^{16}$ cm$^{-3}$) should breakdown homogeneously by avalanche at -60 V[1]

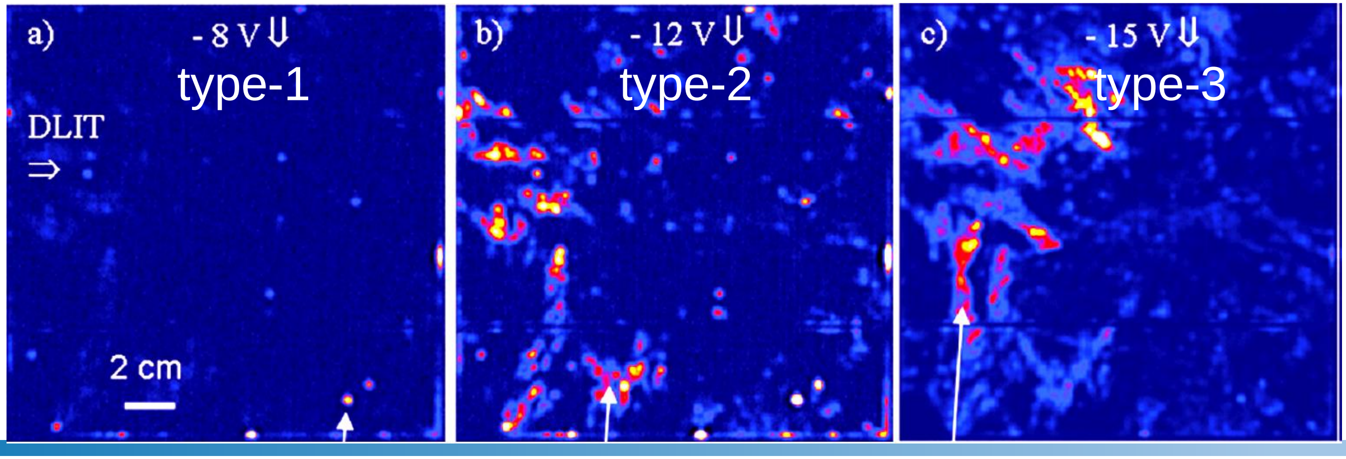
[1]Breitenstein et al., JAP **109** (2011) 071101

# 4. Origin of Pre-Breakdown Sites

- Temperature-dependent breakdown measurements on mc cells have revealed regions of positive and negative TC of the reverse current[1]




- Three different breakdown types have been found[1]

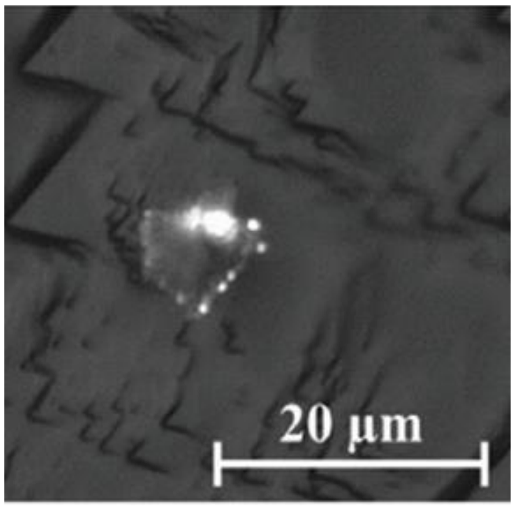



[1]Breitenstein et al., JAP **109** (2011) 071101

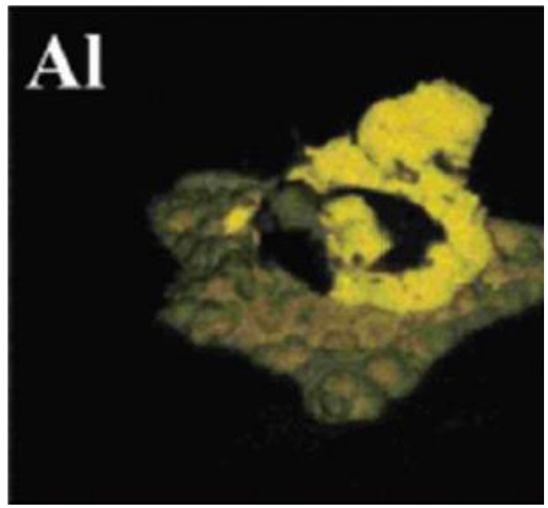
# 4. Origin of Pre-Breakdown Sites

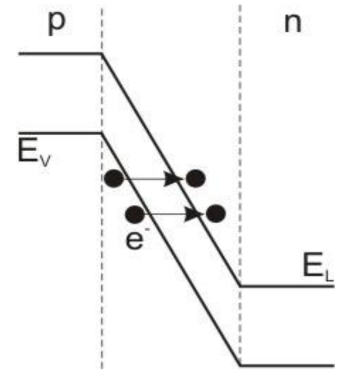
- „Early breakdown“ (type-1) is due to Al particles at the surface (Zener breakdown, close to ohmic shunting)[1]

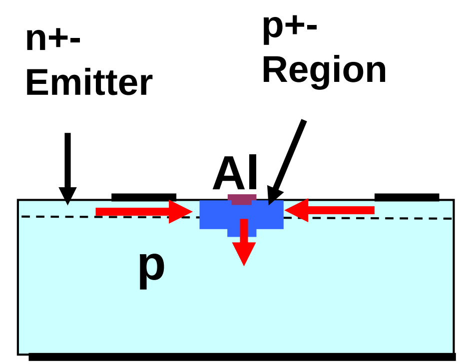
light microscopy




EDX mapping



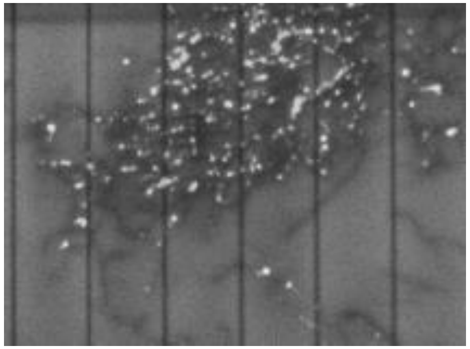

- During contact firing, Al diffuses in the P emitter ($p^+$ around) and compensates it locally, leading to an $n^+$-$p^+$ junction

[1]Lausch et al., APL **97** (2010) 073506

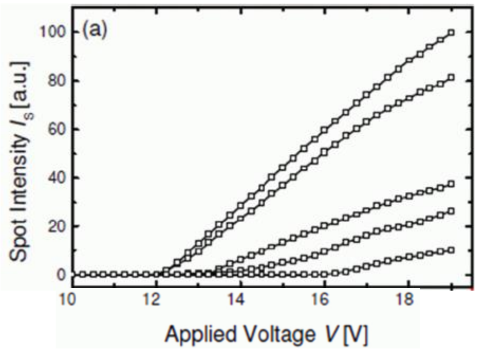
# 4. Origin of Pre-Breakdown Sites

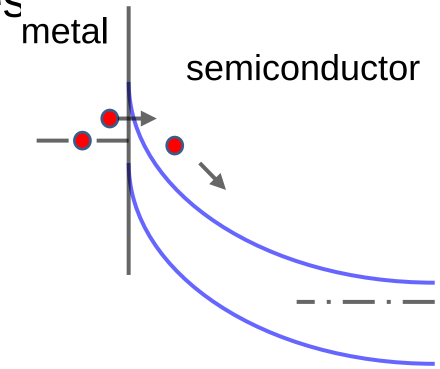
- „Defect-induced breakdown“ (type-2) is due to $FeSi_2$ needles[1] in grain boundaries crossing the pn-junction
- Mechanism: Schottky breakdown (thermionic field emission), influenced by tip effect

EL + ReBEL[2]

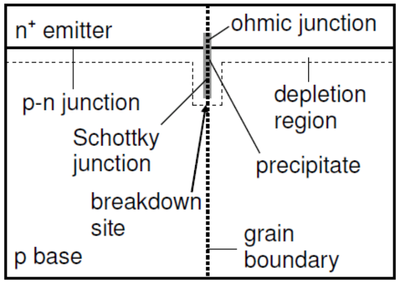


light emission, single sites




model[2]



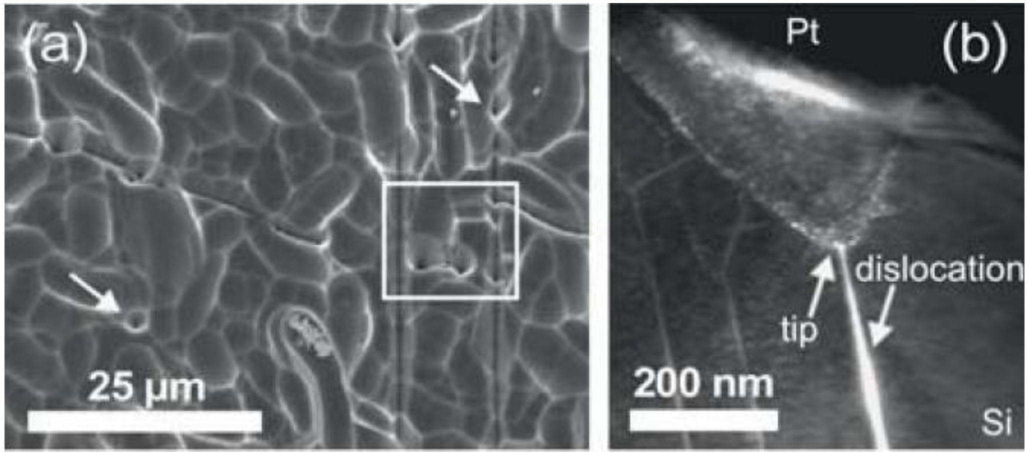

- Depending on geometry, breakdown voltages vary from site to site. All local breakdown sites are $R_s$-limited[3]

[1]Haehnel et al., JAP **113** (2013) 044505
[2]Breitenstein et al., JAP **109** (2011) 071101
[3]Schneemann et al., Phys. Stat. Sol. A **207** (2010) 2597

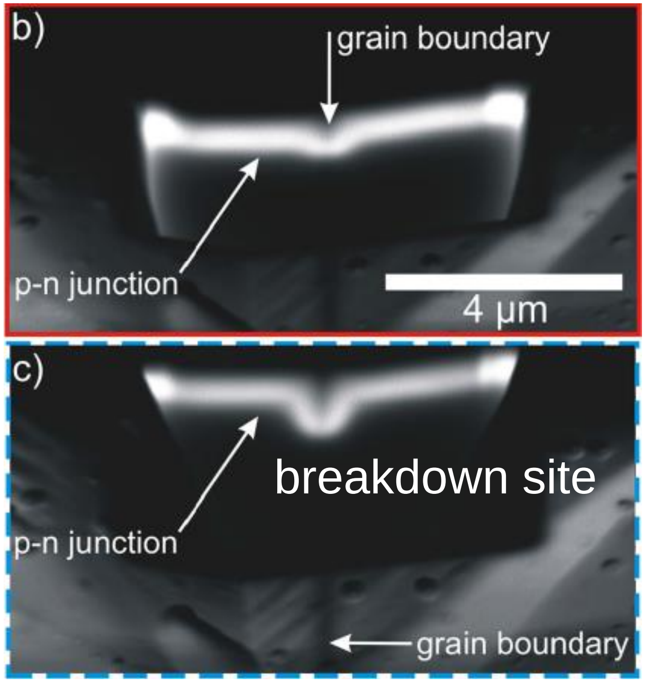
# 4. Nature and Origin of Pre-Breakdown Sites

- „Avalanche breakdown“ (type-3) is due to field enhancement at etch pits[1] (acidic etch) and at preferred P-diffusion sites at „grain boundary dislocations“ (alkaline etch)[2]

Etch pit with dislocation (SEM, TEM)[1]




Alkaline etched, EBIC, FIB cross section, bottom: at “GB dislocation” (GB-kink)[2]



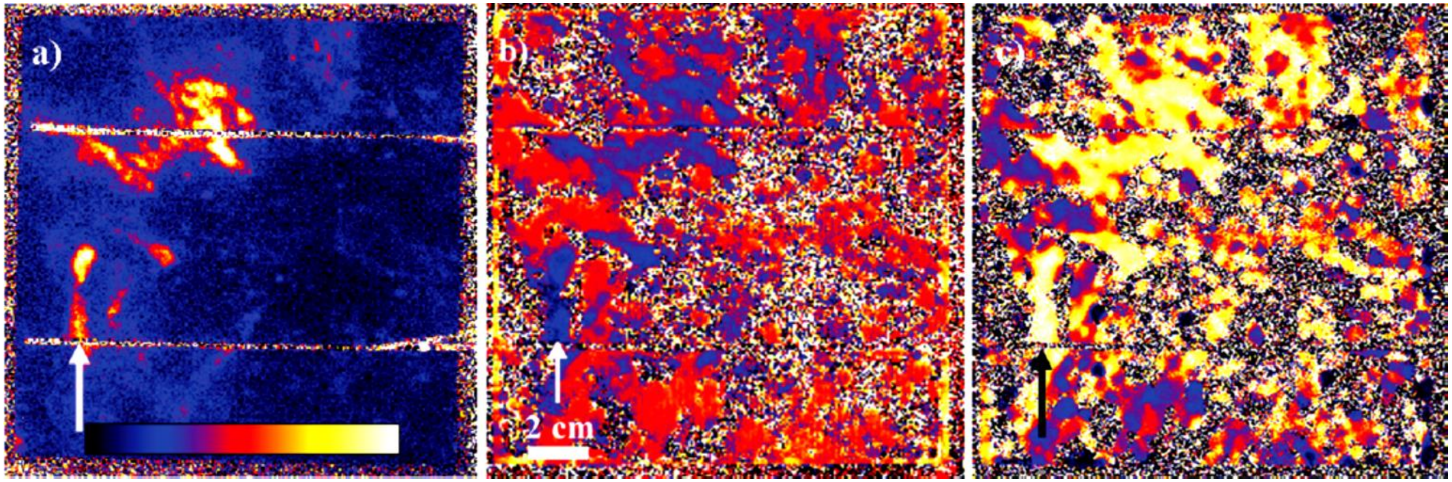

- For spherically bent pn-junction the breakdown voltage reduces from -60 V to -13 ... -20 V[1]

[1]Bauer et al., Phys. Stat. Sol. RRL **3** (2009) 40
[2]Bauer et al., Prog. Photovolt. **21** (2013) 1444

# 4. Nature and Origin of Pre-Breakdown Sites

- Nature of defect-induced and avalanche breakdown regions has been confirmed by LIT-based imaging of the avalanche multiplication factor (MF), TC, and slope of the characteristics[1]

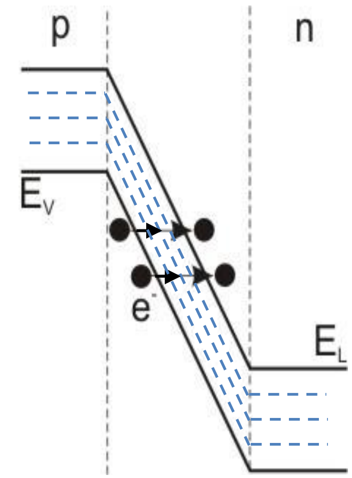
MF (1 ... 3) TC (-3 ... 3 %/°C) slope (0 ... 200 %/V)



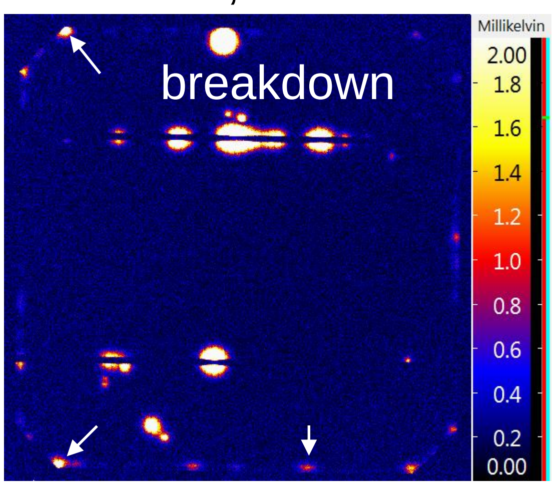

- The higher slope of the avalanche breakdown characteristics is due to the fact that all avalanche sites show the same breakdown voltage

[1]Breitenstein et al., JAP **109** (2011) 071101

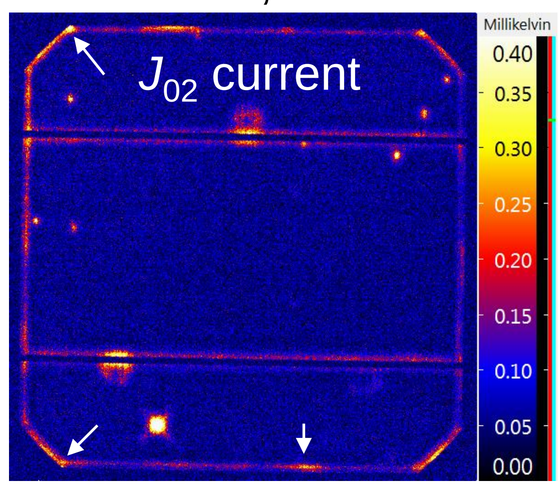
- The dominant breakdown mechanism in monocrystalline Si cells is trap-assisted tunneling in edge regions, where the pn junction crosses the surface
- This is physically related to ohmic and $J_{02}$ currents at the edge (see slides 14,15,21)



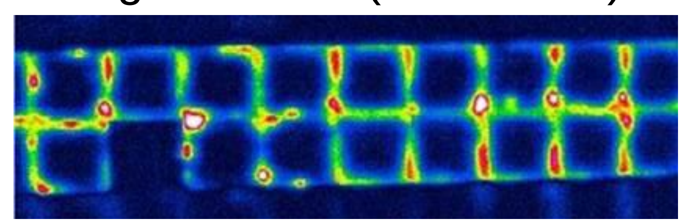

-15 V, -9 mA




+ 0.5 V, 100 mA




DLIT monocrystalline module string at -300 V (≈-15 V/cell)



by courtesy of E. Gerritsen, CEA-INES

## Conclusions to pre-breakdown sites

- Theoretically, silicon solar cells should break down at -60 V.
- In reality, in particular mc cells show significant pre-breakdown and also ohmic conductivity at reverse bias
- For mc cells, the dominant pre-breakdown mechanisms are:
  - early breakdown (close to ohmic): Al particles at emitter
  - defect-induced breakdown: $FeSi_2$ needles in GBs
  - early avalanche breakdown: etch pits, preferred P diffusion
  - trap-assisted tunneling in edge regions, where extended defects (e.g. surface states) cross the pn-junction, „type-4“, dominant for mono.

# 5. Final Conclusions

- The „Local I-V“ DLIT evaluation method enables a quantitative local efficiency analysis, though its spatial resolution is limited.
- This is the only method that may reliably separate $J_{01}$, $J_{02}$, and ohmic current contributions from each other and may quantify breakdown currents.
- By simulating dark and illuminated I-V characteristics of the whole cell and of selected regions, „Local I-V“ allows to check the influence of certain defect regions on cell parameters.
- The „virtual cut shunt“ option allows to exclude local defect regions from the analysis by setting their diode parameters to that of their environment (e.g. for evaluating ohmic shunts).
- „Local I-V“ software is available[1] and is a very useful tool for understanding local reasons for a poor cell efficiency ($V_{oc}$ and FF).

[1]www.maxplanckinnovation.de

# 5. Final Conclusions

- Understanding the dark current of solar cells is the key for maximizing their efficiency, in particular $V_{oc}$ and FF.
- By detecting inhomogeneities of the cell current by DLIT and physically investigating the root causes of local currents, in the last 15 years we have identified the nature of many previously unknown conduction mechanisms.
- We have identified the dominant recombination mechanism for grown-in defects in mc-Si cells, the nature of $J_{02}$ currents, the nature of ohmic currents, and of most of the pre-breakdown mechanisms.
- Now we understand much better than before the limitations of silicon solar cells, in particular for $V_{oc}$ and FF of multicrystalline cells.

# Acknowledgements

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