

Electrical scanning probe microscopy approaches to investigate solar cell junctions and devices

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Jean-Paul Kleider^{1,2,3}, Raphaël Cabal⁴, Pere Roca i Cabarrocas⁶

¹Université Paris-Saclay, CentraleSupélec, CNRS, Laboratoire de Génie Electrique et Electronique de Paris (GeePs);

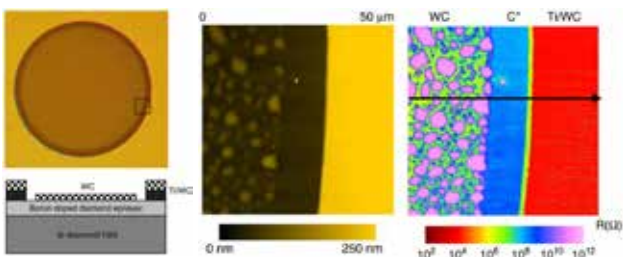
²Sorbonne Université, CNRS, GeePs; ³Institut Photovoltaïque d'Ile-de-France (IPVF); ⁴Laboratory of Homojunction

Solar Cells, Institute of Technologies for New Energies (CEA-Liten); ⁵Laboratoire de Physique de la Matière Condensée (LPMC), École Polytechnique; ⁶Laboratoire de Physique des Interfaces et des Couches Minces (LPICM),

CNRS, Ecole Polytechnique

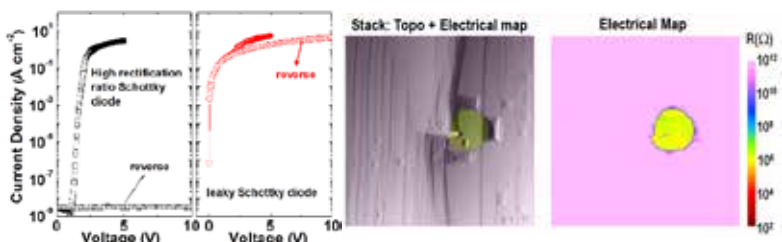
High power and high temperature devices

WC Schottky diode on homoepi. Diamond



J. Alvarez and al. *Superlattice Microst.* 40, 343-349 (2006)

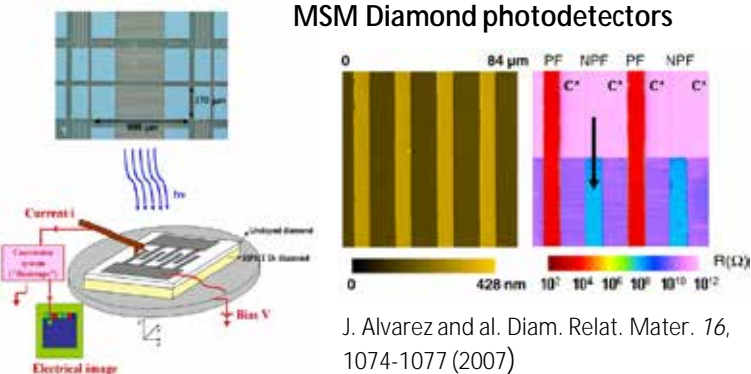
Evidencing leakage current in diamond Schottky devices



J. Alvarez et al. , *J. Phys. D : Appl. Phys.* 47, 355102 (2014)

Deep UV photodetection

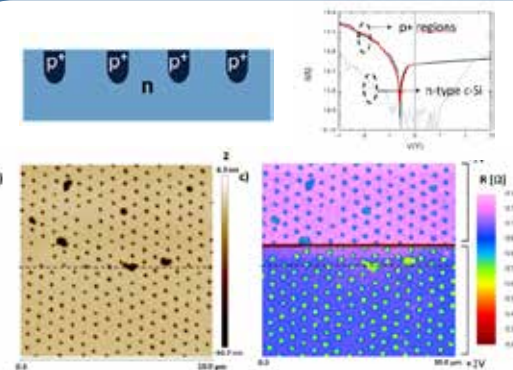
MSM Diamond photodetectors



J. Alvarez and al. *Diam. Relat. Mater.* 16, 1074-1077 (2007)

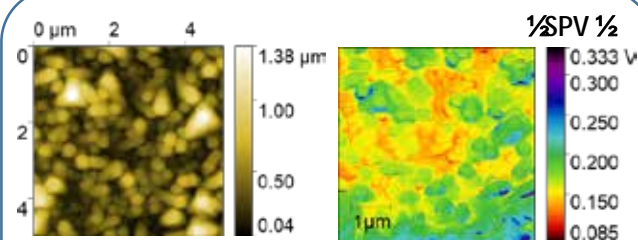
Energy harvesting

Nanodoping and evidencing PV effect



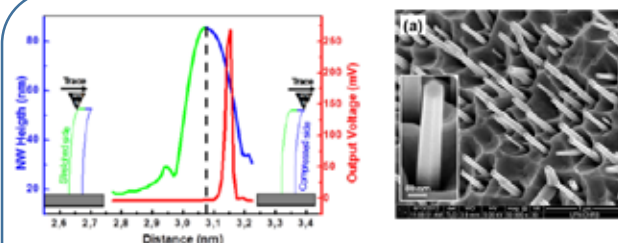
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Local V_{OC} measurements by KPFM on p-i-n SiNWs



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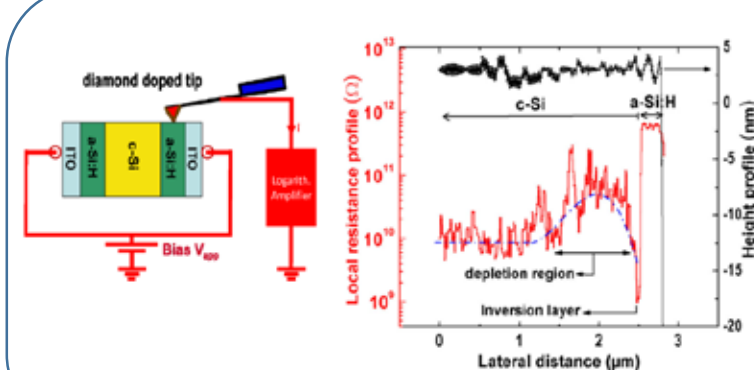
Piezoelectric Conversion of Axial InGaN/GaN NWs



N. Jegenyes et al., *MDPI.* 8, 367 (2018)

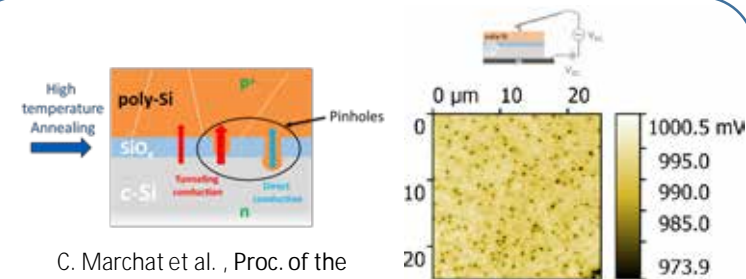
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Cross-sectional analyses of a-Si:H/c-Si heterojunction



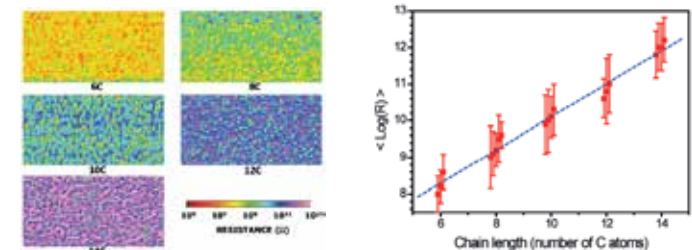
J.-P. Kleider et al. , *Phys. Status Solidi A* 216, &800877, (2019)

Polysilicon passivating contact structures



C. Marchat et al. , *Proc. of the 36th EU-PVSEC*, 22–24 (2019).

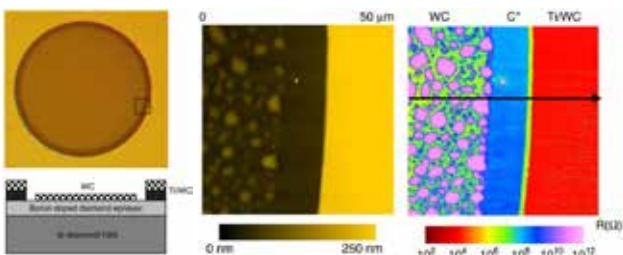
Self-assembled monolayers



A. Vecchiola et al., *APL*108, 243101 (2016)

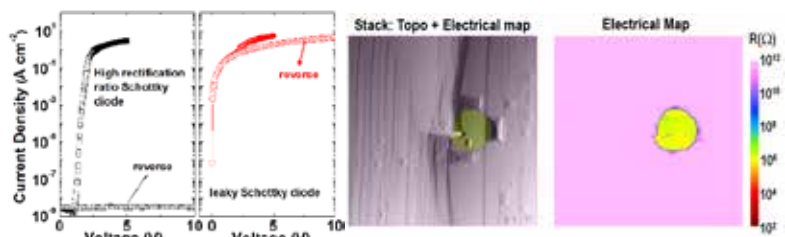
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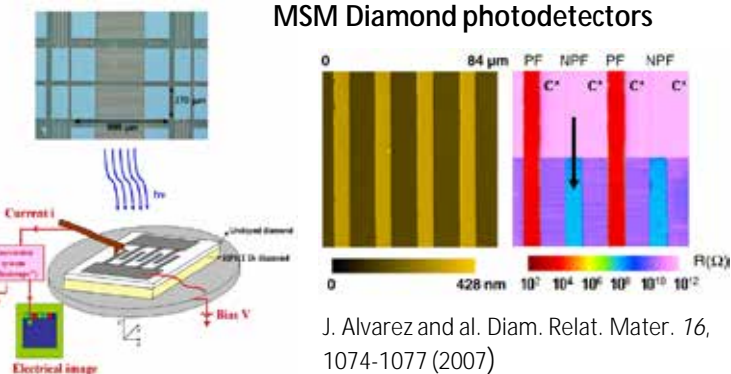
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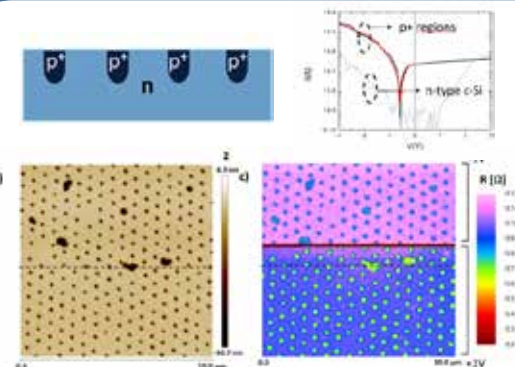
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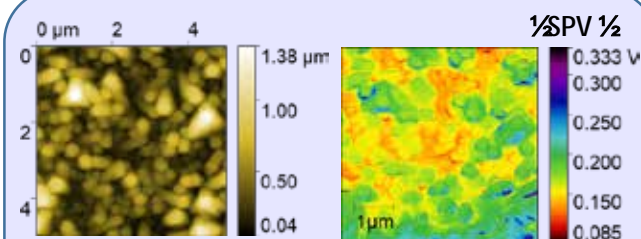
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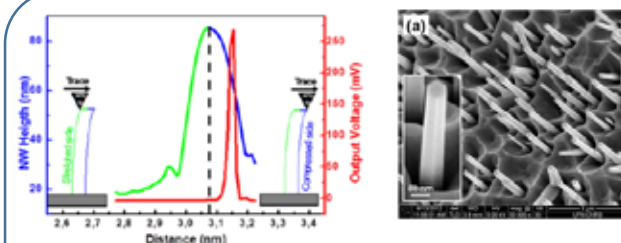
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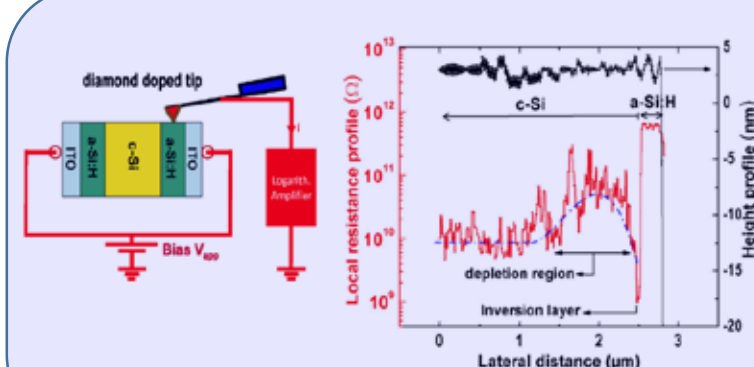
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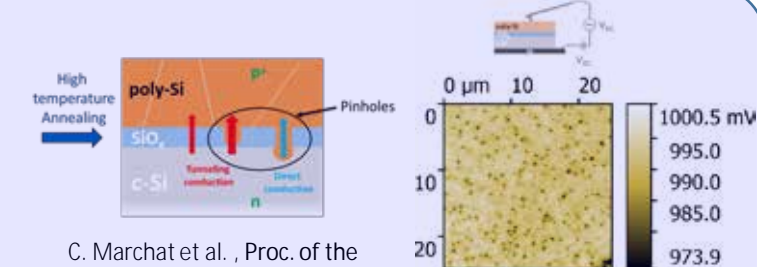
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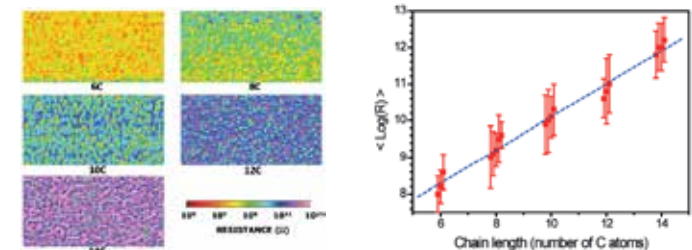
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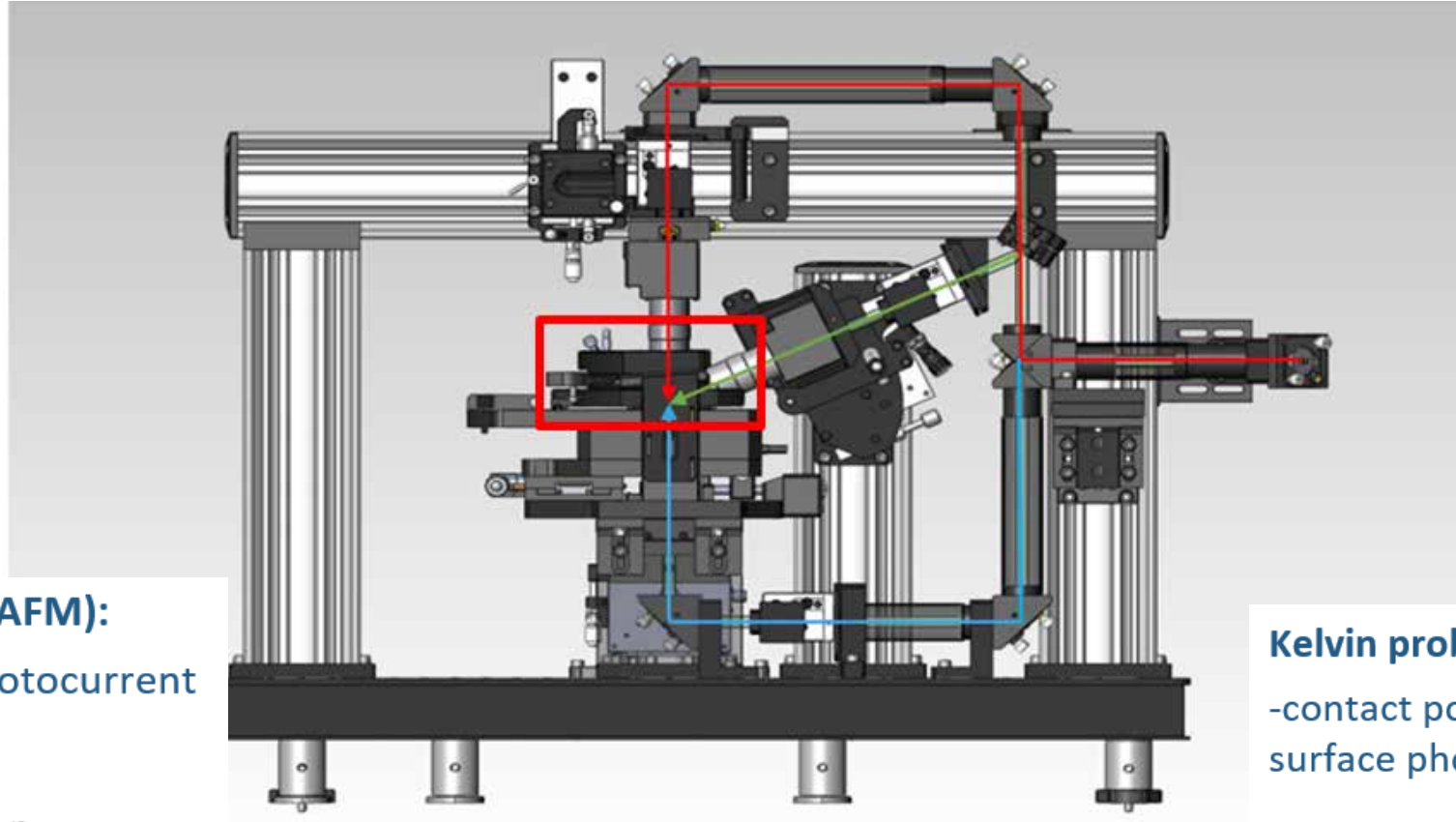
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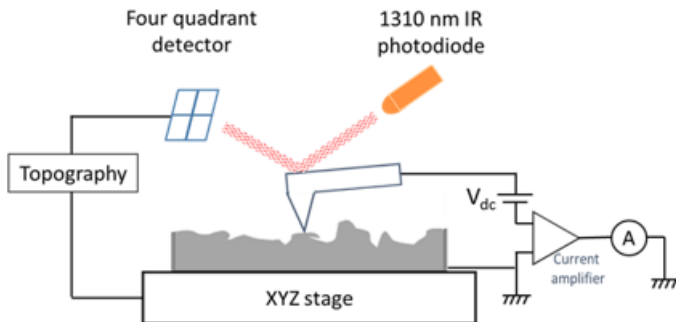


A. Vecchiola et al., *APL* 108, 243101 (2016)

Atomic Force Microscopy (AFM) setup

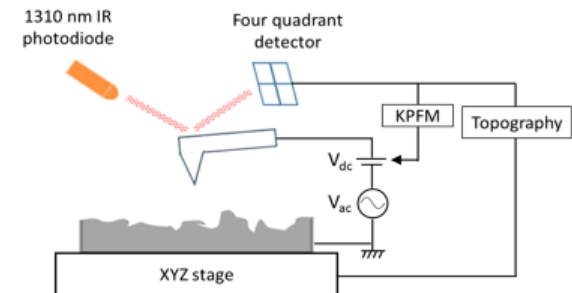


Conductive AFM (C-AFM):
-local current and photocurrent mapping



AIST-NT/HORIBA

Kelvin probe force microscopy (KPFM):
-contact potential difference (CPD) and surface photovoltage (SPV) mapping

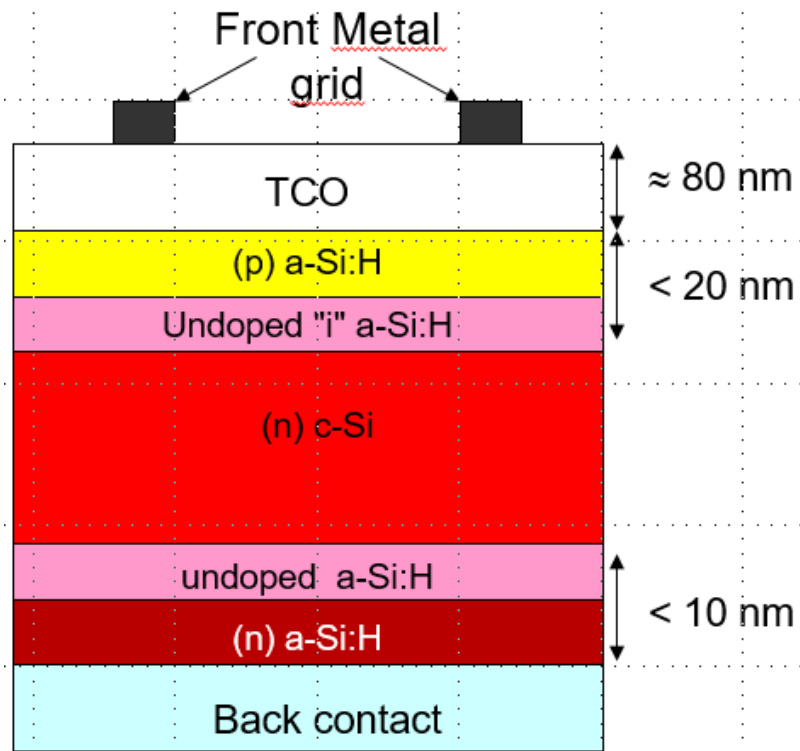


Part 1 - Hydrogenated amorphous silicon/crystalline silicon heterojunction

Part 2 - Passivating selective contacts: (p+) Poly-Si/SiO_x/c-Si

Part 3 - P-I-N radial junctions (RJ) Silicon Nanowires (SiNWs)

Hydrogenated amorphous silicon/crystalline silicon heterojunction



§ a-Si:H/c-Si Heterojunction solar cells "Si-HET" was first studied by Sanyo in the 80's [1]

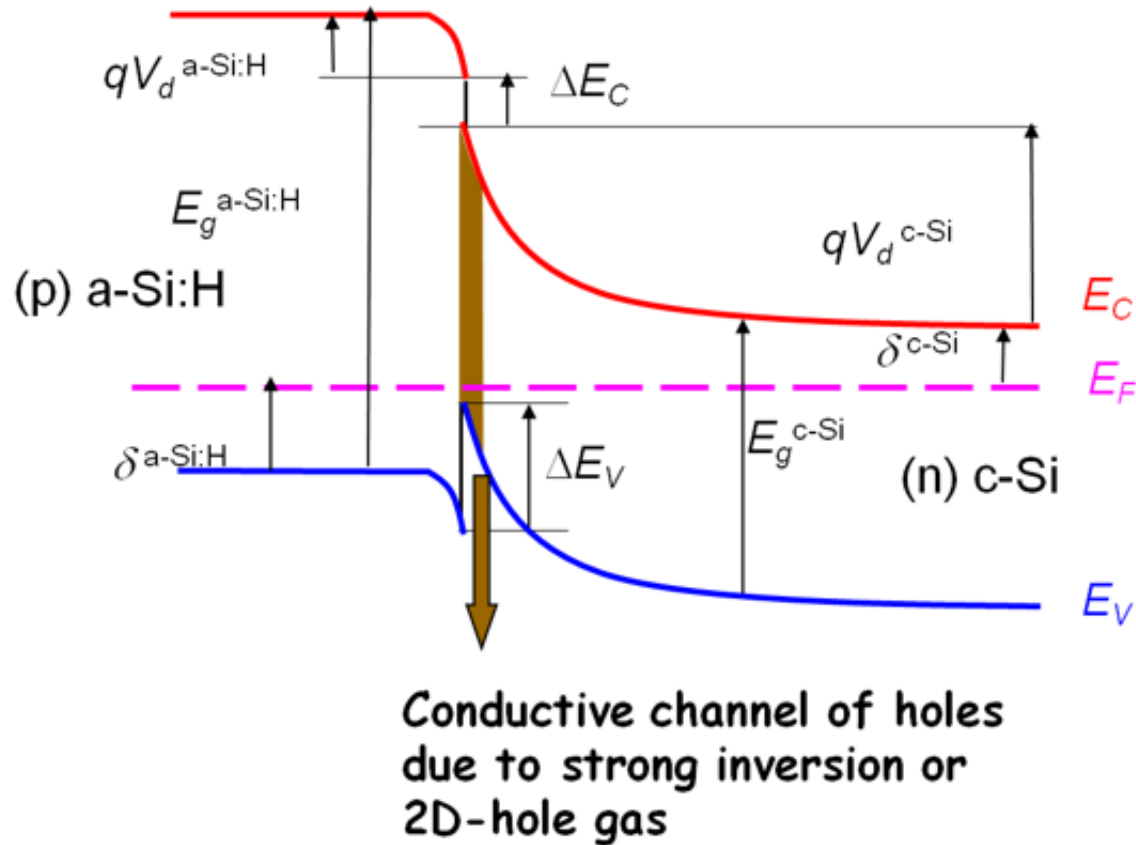
§ Reducing recombination at the interfaces Si-HET has achieved the highest efficiency for c-Si tech. : 26.3-26.7% [2,3]

[1] Hamakawa et al. , *Appl. Phys. Lett.* 43, 644 (1983)

[2] Yoshikawa et al. , *Nat. Energy* 2, 17032 (2017)

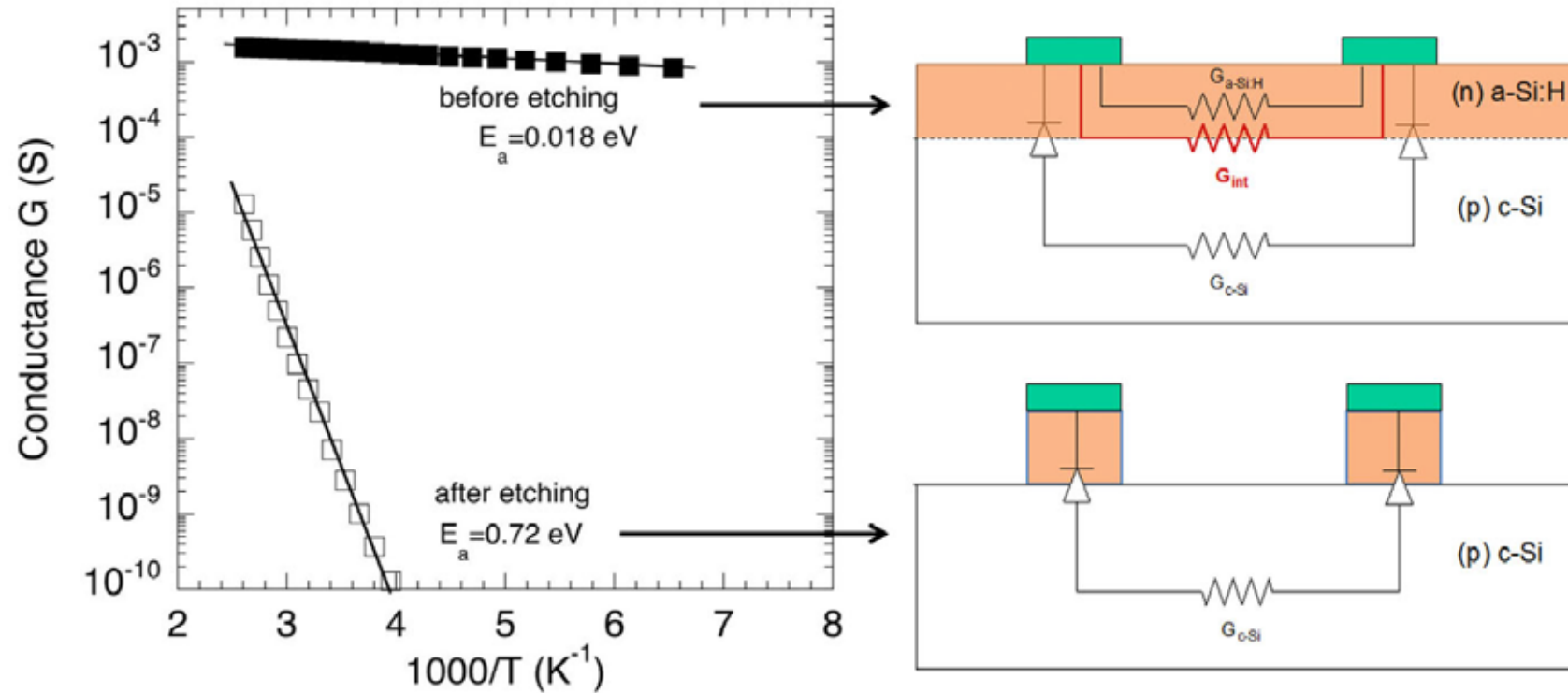
[3] Yamamoto et al. , *Japan. J. Appl. Phys.* 57, 08RB20 (2018)

1.1 Motivation : Interface Band lineup



§ a-Si:H/c-Si (N/p or P/n) studied by capacitance and planar conductance measurements suggest the presence of a strong inversion layer at the interface

1.2 Lateral conductance measurements

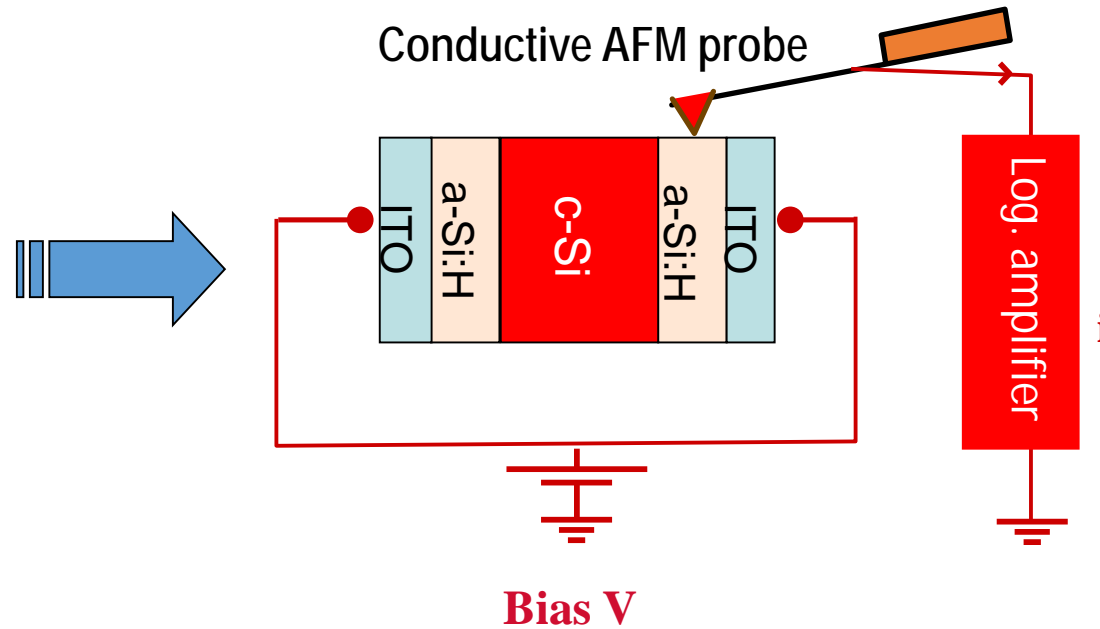
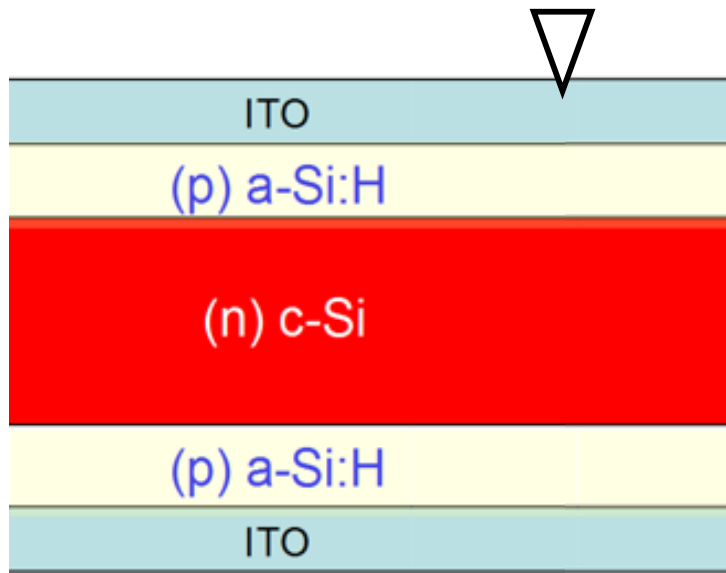


§ Considering the different current pathways only the high conductance at the a-Si:H/c-Si interface can explain the very low E_A of the Arrhenius plot.

1.3 Conductive-AFM (C-AFM) approach (1/3)

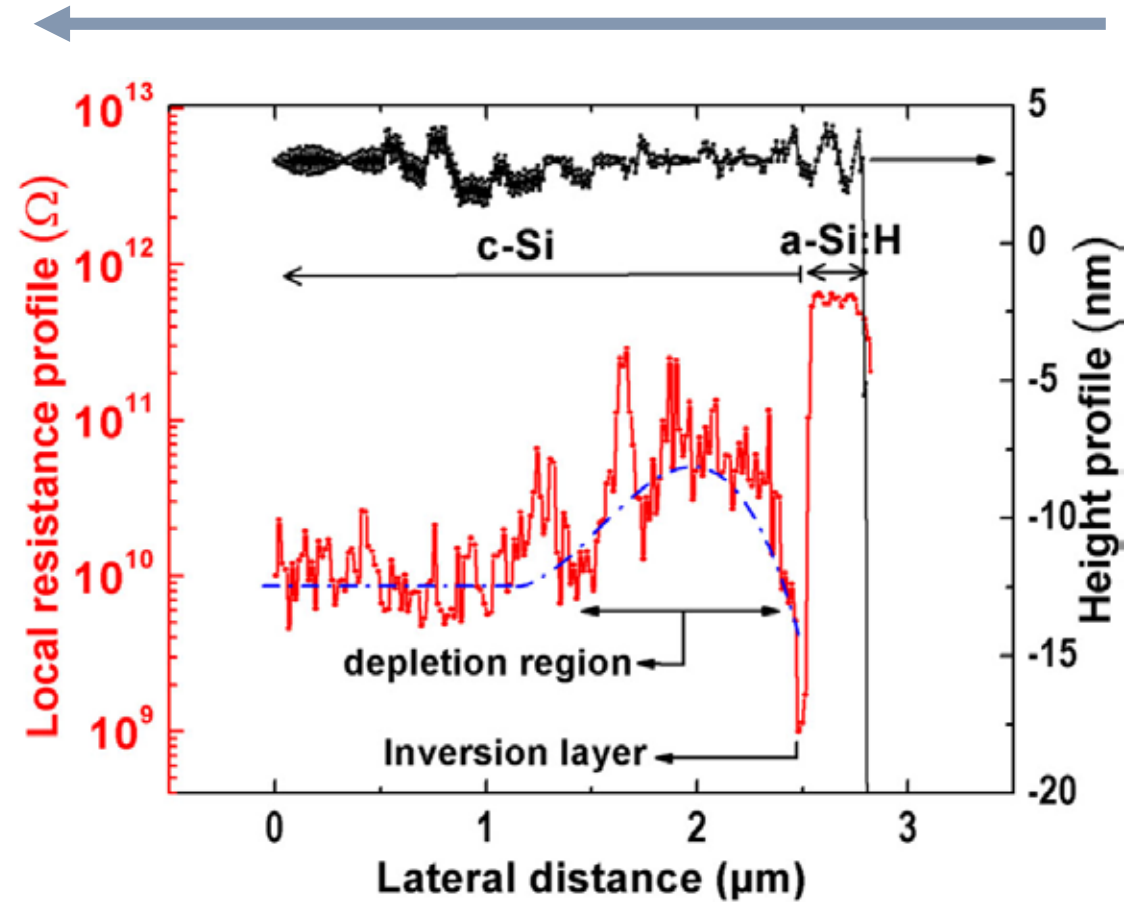
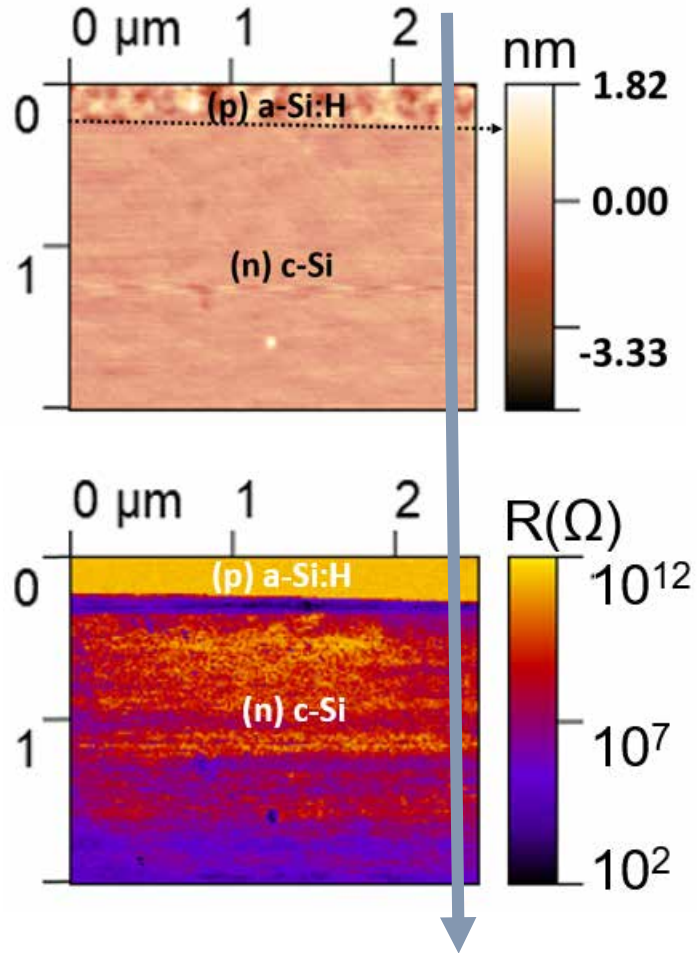
§ Sample preparation for cross-sectional investigations

- Cleavage and HF (1%) trench dipping



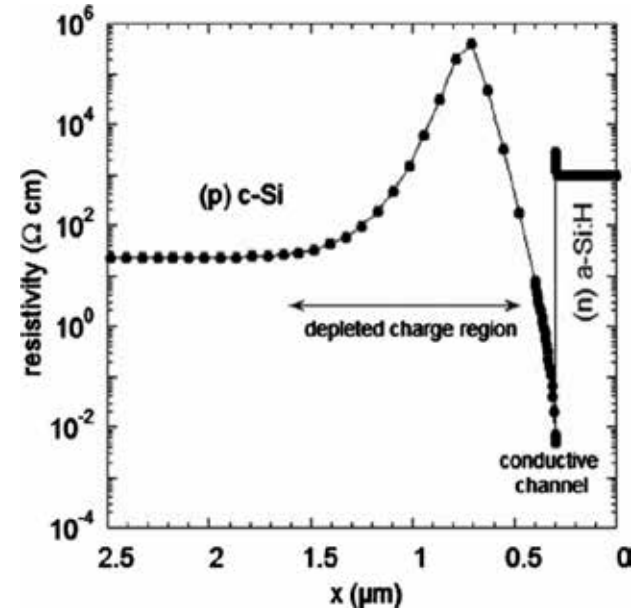
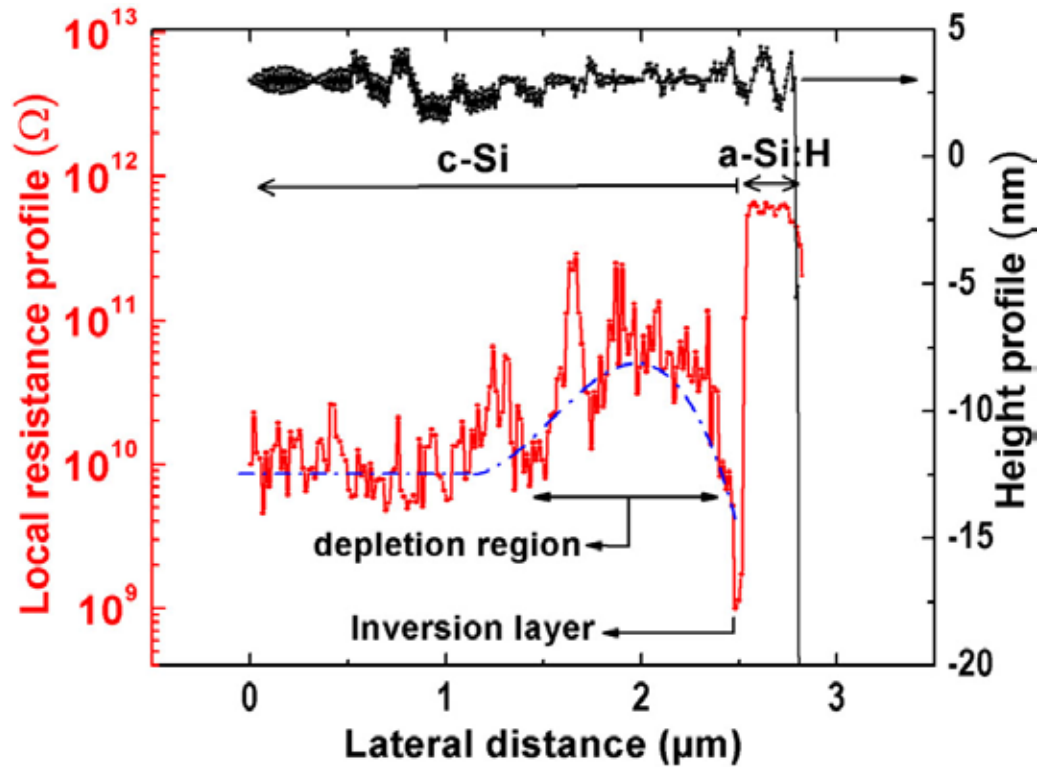
1.3 Conductive-AFM (C-AFM) approach (2/3)

§ Cross-sectional mapping



1.3 Conductive-AFM (C-AFM) approach (3/3)

§ Comparison b/w experimental C-AFM and modelling AFORS-HET



- Resistivity profile calculations confirm the qualitative C-AFM observations

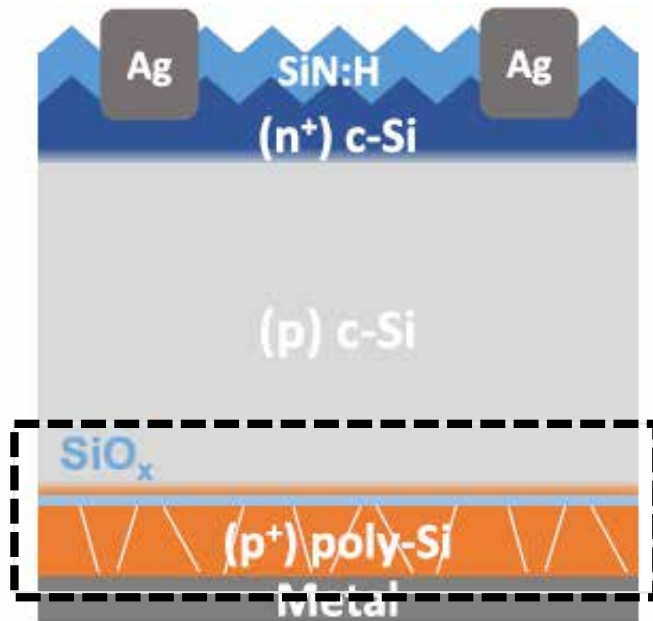
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Part 2

Passivating selective contacts: (p+) Poly-Si/SiO_x/c-Si



§ Poly-Si passivating contact studied in the 80's [1,2]

§ 2016 – present : Intensively studied by many research groups (Fraunhofer ISE, ISFH, NREL, INES-CEA...)

è Reduce back contact recombination losses reaching efficiencies in the range 25-26.1% [3][4]


[1] Yablonovitch et al., *APL* 47(11), 1211–1213 (1985)

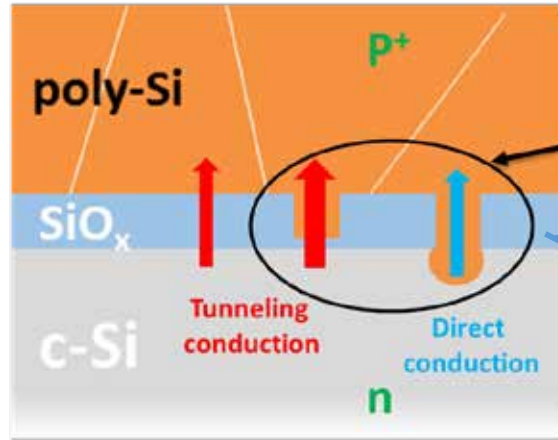
[2] Van Halen et al., *IEEE Trans. Elec. Dev.* 32(7), 1307–1313 (1985)

[3] Richter et al., *Sol. Energy Mater. Sol. Cells* 173, 96–105 (2017)

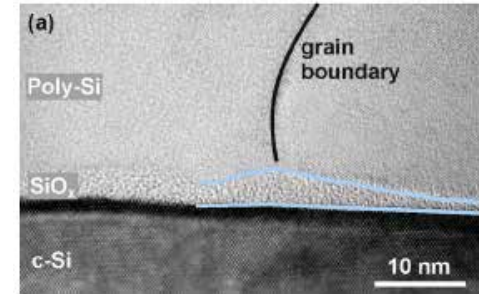
[4] Haase et al., *Sol. Energy Mater. Sol. Cells* 186, 184–193 (2018)

2.1 Motivation : conduction mechanisms across the structure?

High temperature Annealing


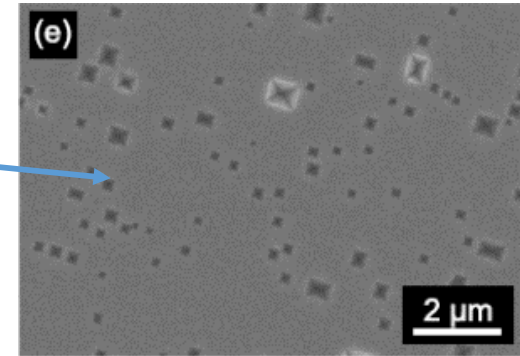


TEM : thinner oxide



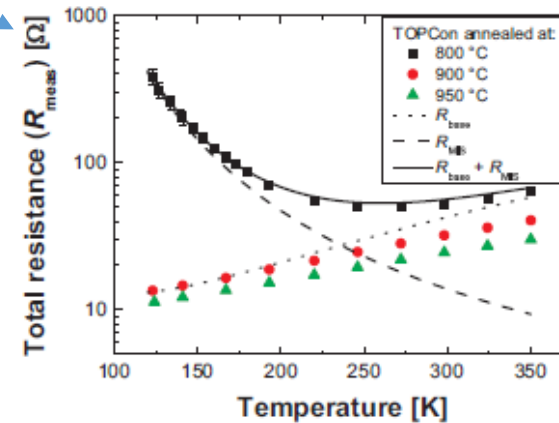
Peibst et al., *Solar energy materials and solar cells* 158, 60-67 (2016)

Chemical etching : nano-holes



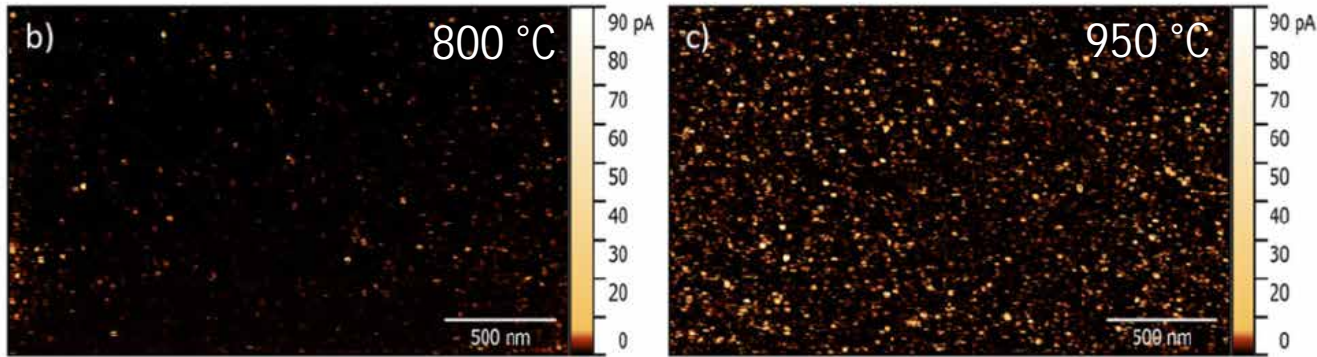
Wietler et al., *Appl. Phys. Lett.* 110, 253902 (2017)

Transport mechanism
 $R = f(T)$

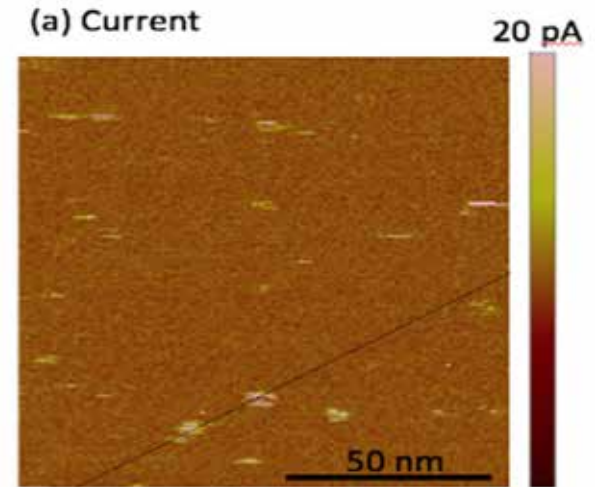


Feldmann et al., *Solar energy materials and solar cells* 178, 15-19 (2018)

2.2 Conductive –AFM (C-AFM) approach



- Lancaster et al., Energy procedia 92, 116-121 (2016)

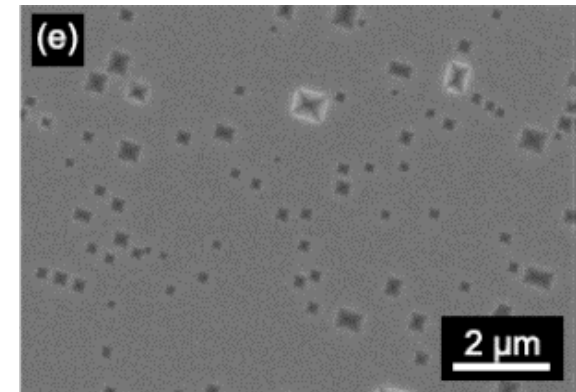


Zhang et al., Sol. Energy Mater. Sol. Cells 187, 113-122 (2018)

§ Conductive Spots = degraded oxide = pinholes $\sim 250 - 750 \mu\text{m}^{-2}$



“Inconsistent with the selective etching approach”
Pinholes density $\sim 0.1-2 \mu\text{m}^{-2}$

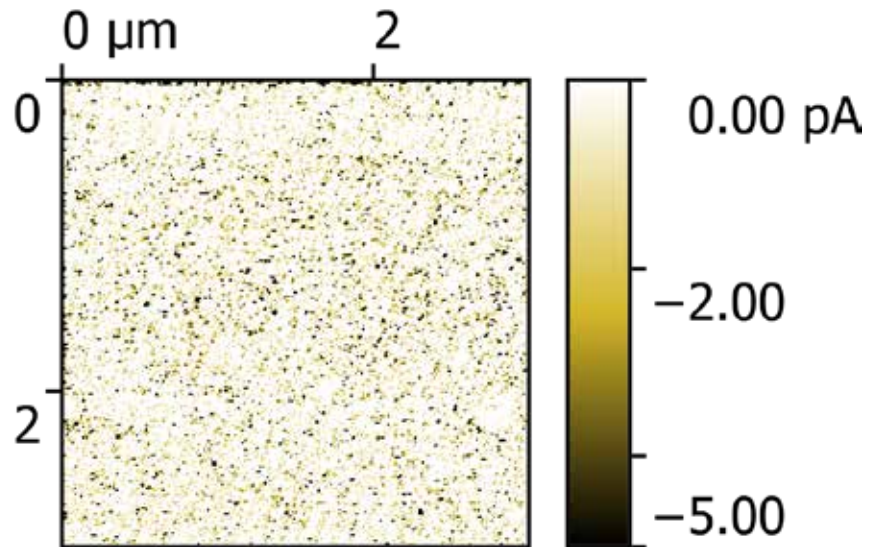


Wietler et al., Appl. Phys. Lett. 110, 253902 (2017)

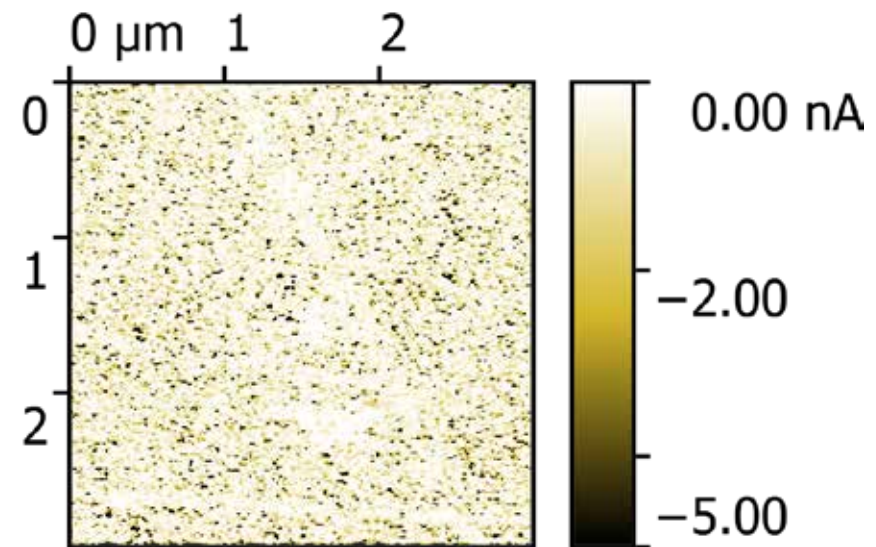
§ Lack of understanding of the C-AFM measurement !

2.3 C-AFM : new experiments on (p+) poly-Si/SiOx/c-Si (n) (1/3)

§ C-AFM versus surface preparation



“No surface preparation” :
pA current peak levels

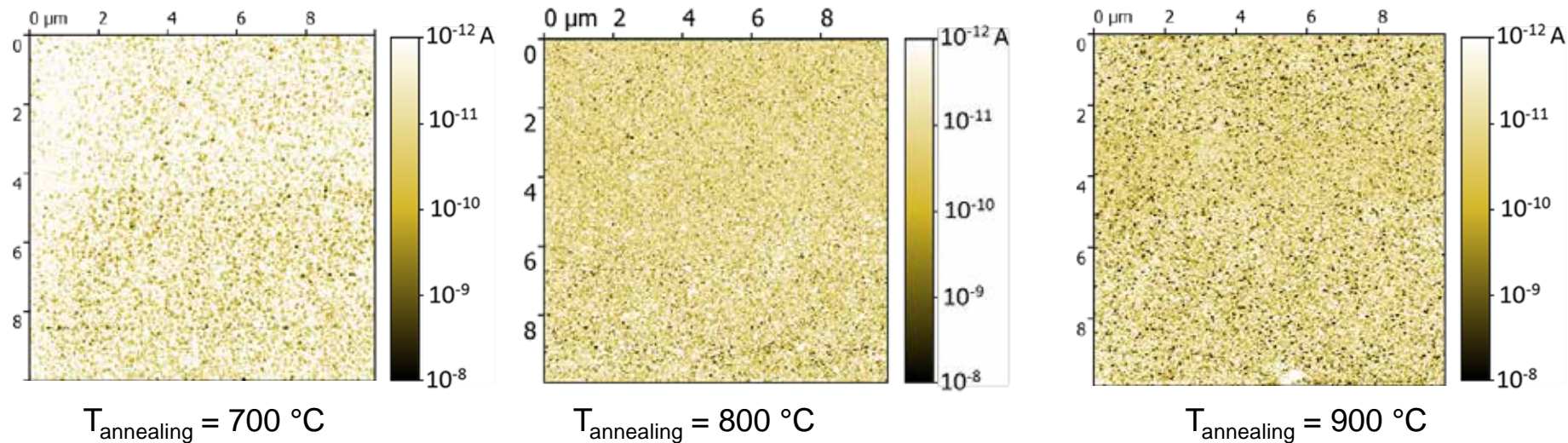


“Surface HF (1%) treated” :
nA current peak levels

- Deoxidation of the poly-Si surface is a requirement

2.3 C-AFM : new experiments on (p+) poly-Si/SiOx/c-Si (n) (2/3)

§ C-AFM versus annealing temperature



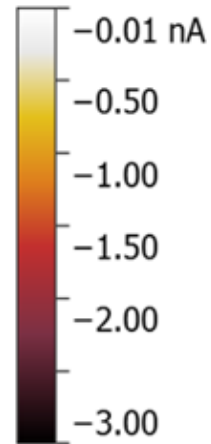
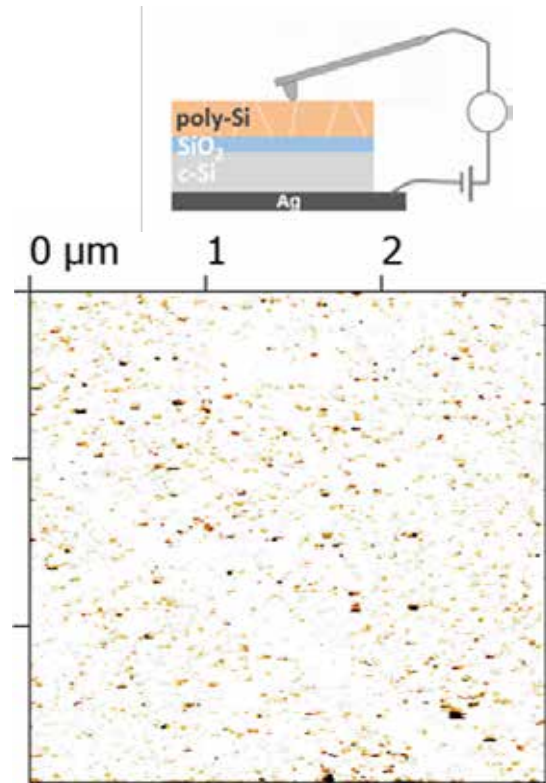
- Current peaks (CP) > 100 pA, densities ~ 10 - $100 \mu\text{m}^{-2}$

è C-AFM does not allow to discriminate the conduction through the pinholes

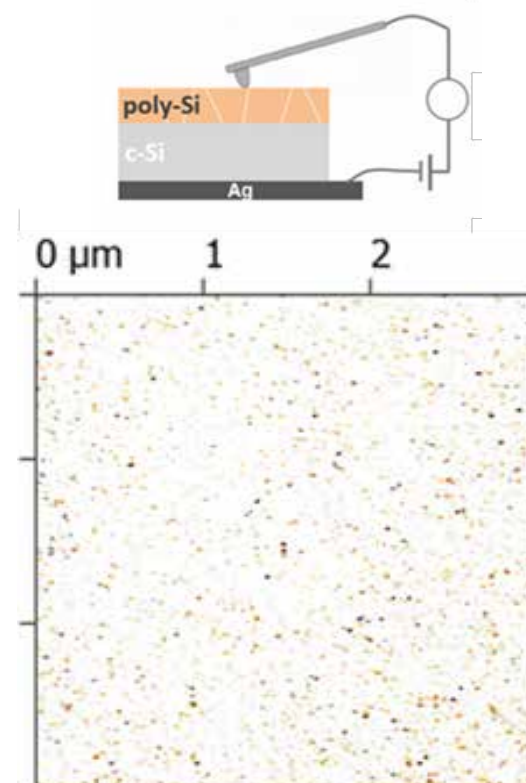
2.3 C-AFM : new experiments on (p+) poly-Si/SiOx/c-Si (n) (3/3)

§ C-AFM with and without passivating oxide

Current peak
(>100 pA) density
: $50 \mu\text{m}^{-2}$



Current peak
(>100 pA) density
: $90 \mu\text{m}^{-2}$

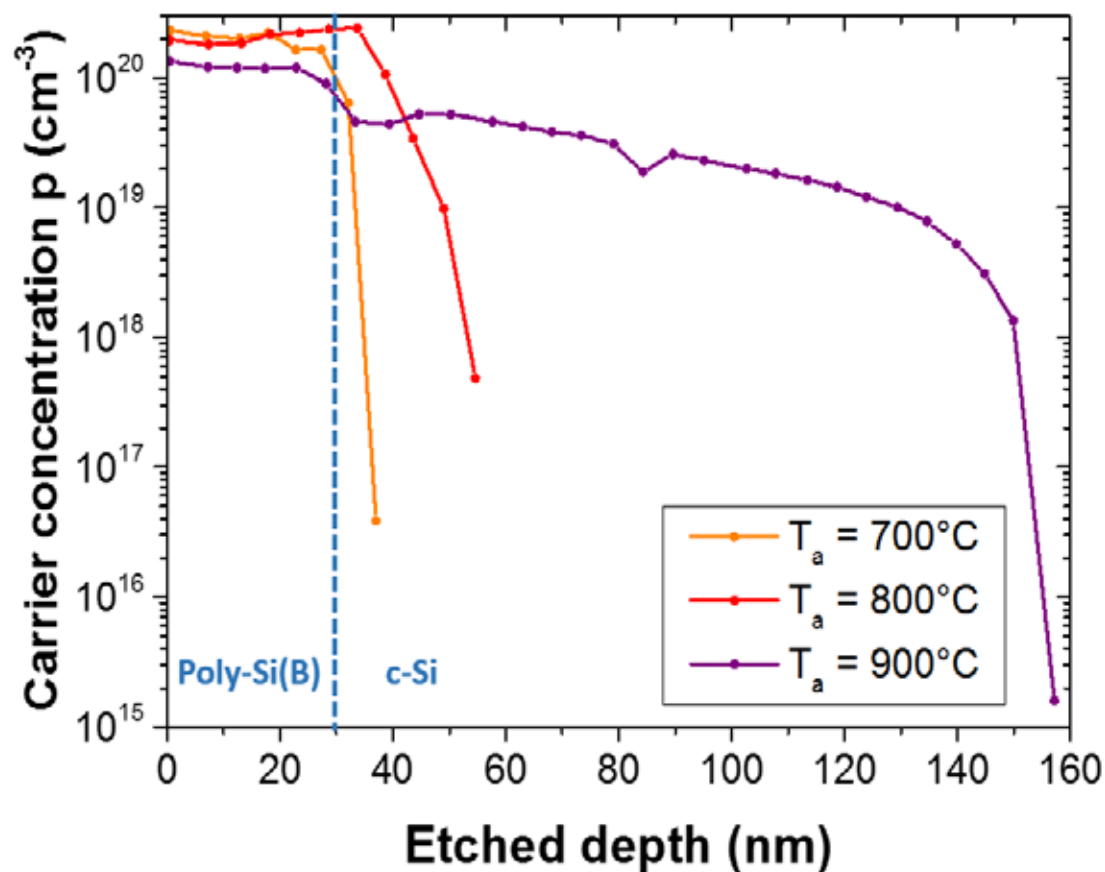


è C-AFM reflects poly-Si conduction inhomogeneities (surface morphology, doping...)

2.4 KPFM : new approach for (p+) poly-Si/SiOx/c-Si (1/3)

§ KPFM sensitive to the workfunction and the doping

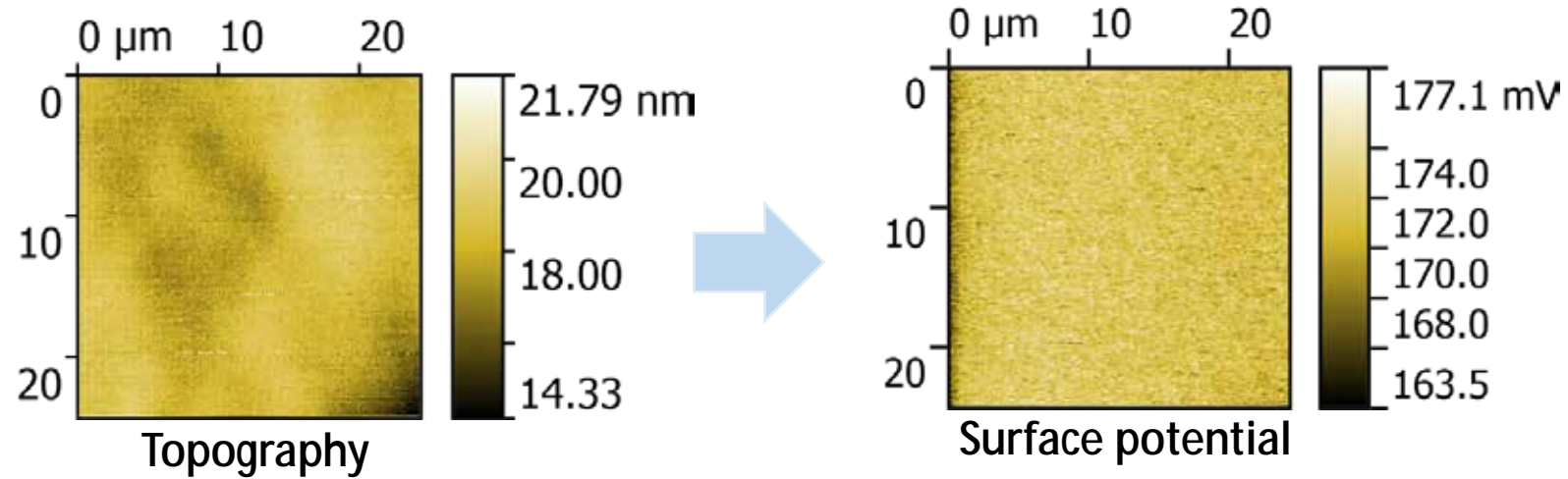
§ ECV measurements on (p+) poly-Si/SiOx/c-Si



2.4 KPFM : new approach for (p+) poly-Si/SiOx/c-Si (1/3)

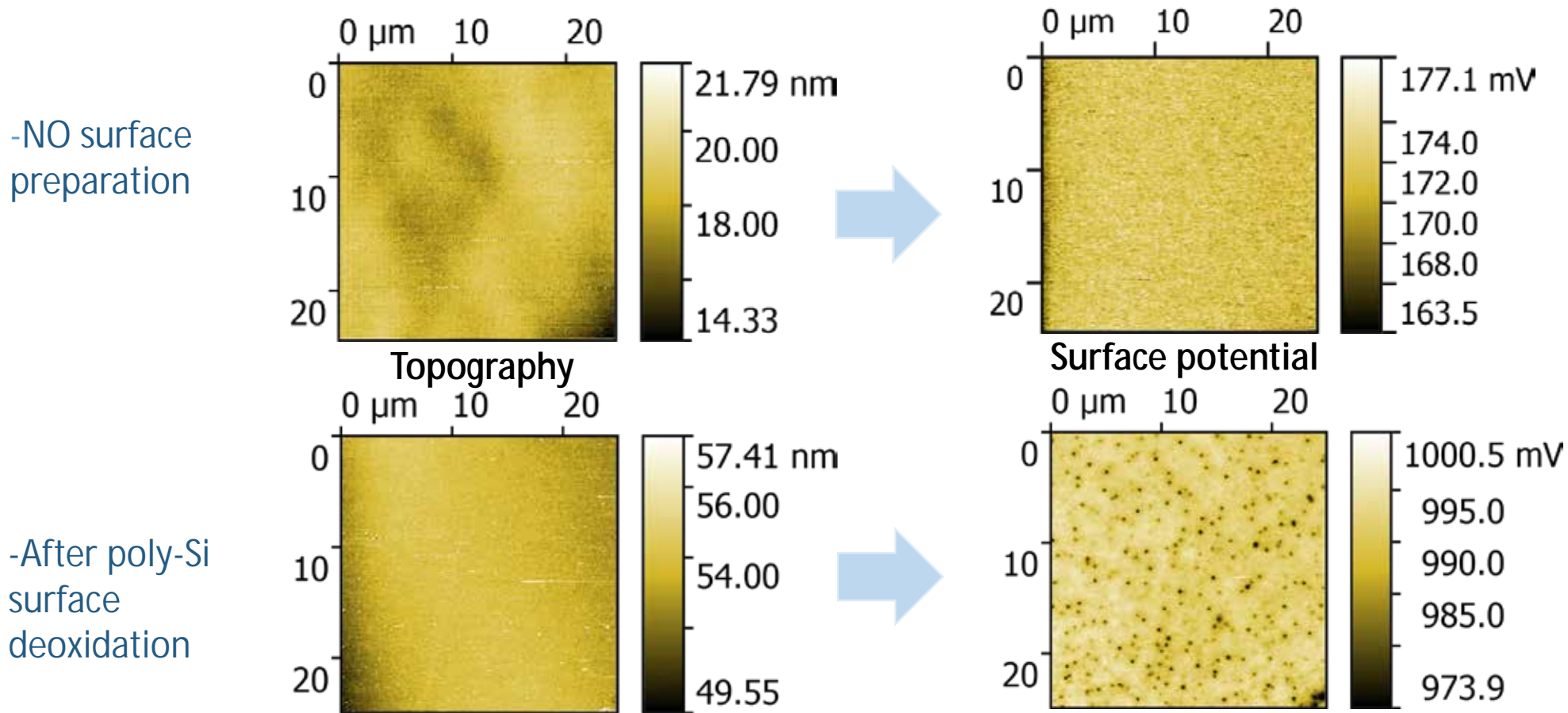
§ KPFM sensitive to the workfunction and the doping

-NO surface preparation



2.4 KPFM : new approach for (p+) poly-Si/SiO_x/c-Si (1/3)

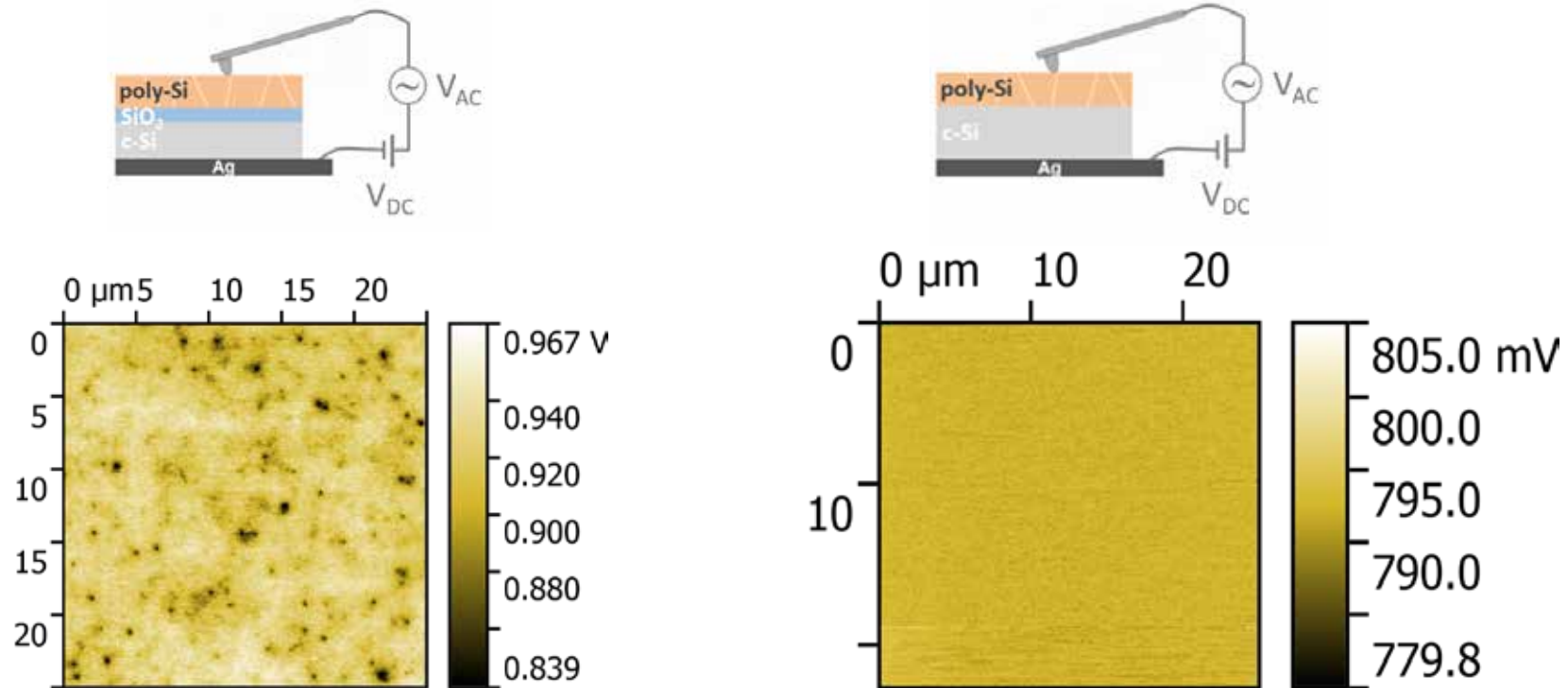
§ KPFM sensitive to the workfunction and the doping



- Deoxidation minimizes screening effects : potential drops on the poly-Si surface => Indirect pinhole observation ?

2.4 KPFM : new approach for (p+) poly-Si/SiO_x/c-Si (2/3)

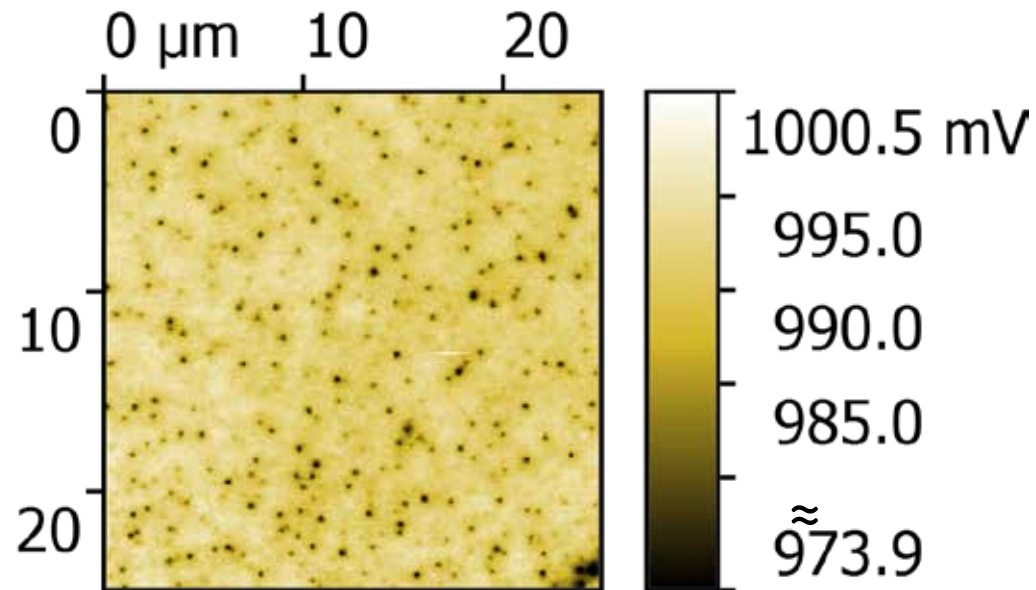
§ KPFM with and without passivating oxide



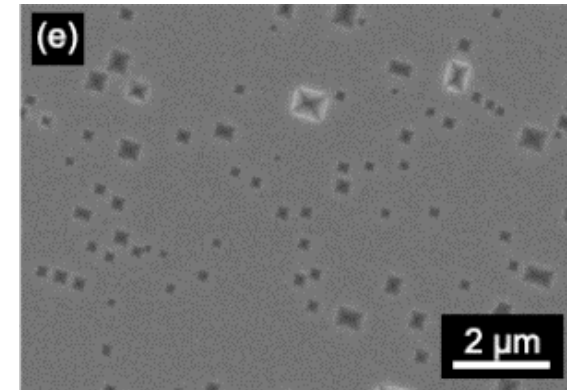
- Local potential drops observed **only with passivating oxide**

2.4 KPFM : new approach for (p+) poly-Si/SiOx/c-Si (3/3)

§ KPFM and potential drops density



Potential drops density : $0.2 - 0.5 \mu\text{m}^{-2}$



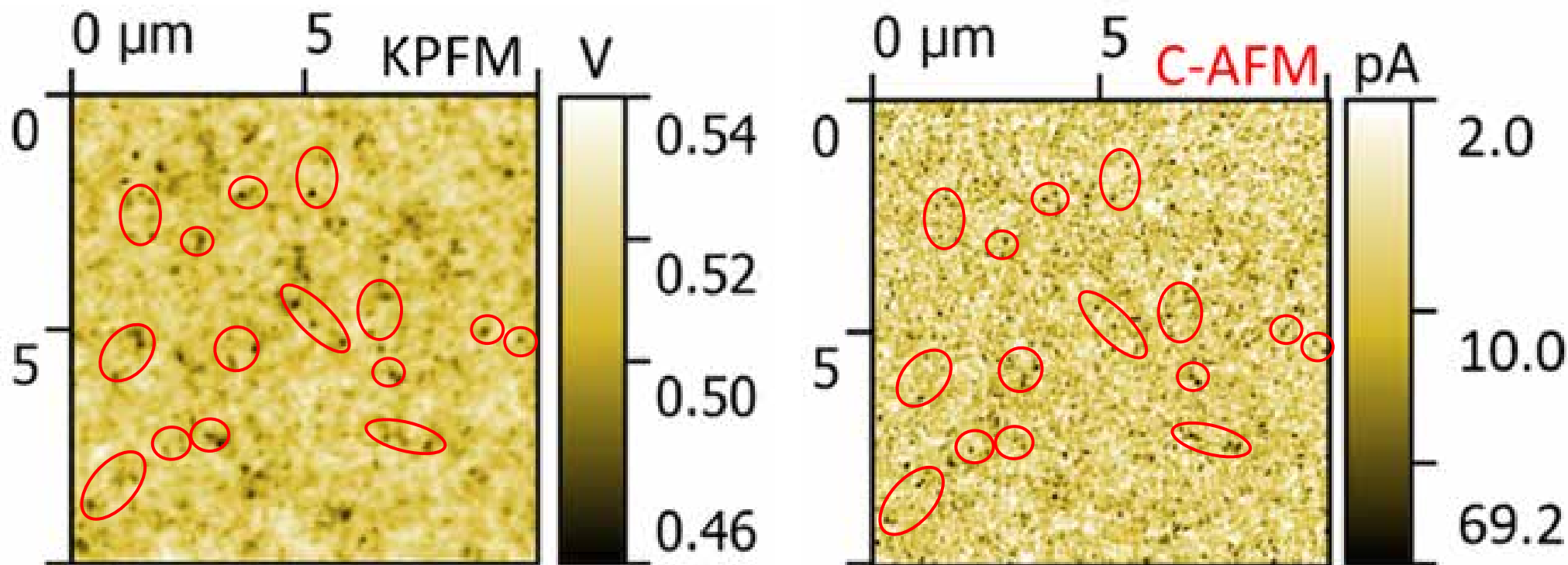
Wietler et al., Appl. Phys. Lett.
110, 253902 (2017)

Pinholes density $\sim 0.1-2 \mu\text{m}^{-2}$

-Potential drops density similar to literature pinhole density by selective chemical etching

2.5 Correlative C-AFM and KPFM on intrinsic Poly-Si/SiO_x/c-Si

§ Sample with an intrinsic top poly-Si layer



- Some local potential drops correlate well with current peaks (CPs)
- CAFM CPs reflect here conduction heterogeneities including the pinholes
- Correlations were possible due to the intrinsic layer that minimizes lateral conduction

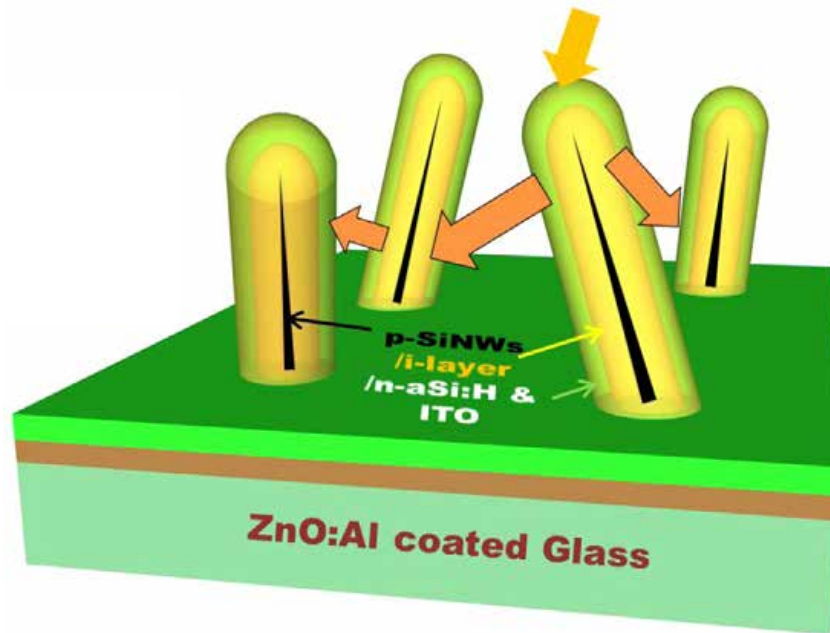
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Part 3

P-I-N radial junctions (RJ) Silicon Nanowires (SiNWs)



[1] Misra et al., IEEE JPV 5(1), 40–45 (2015).

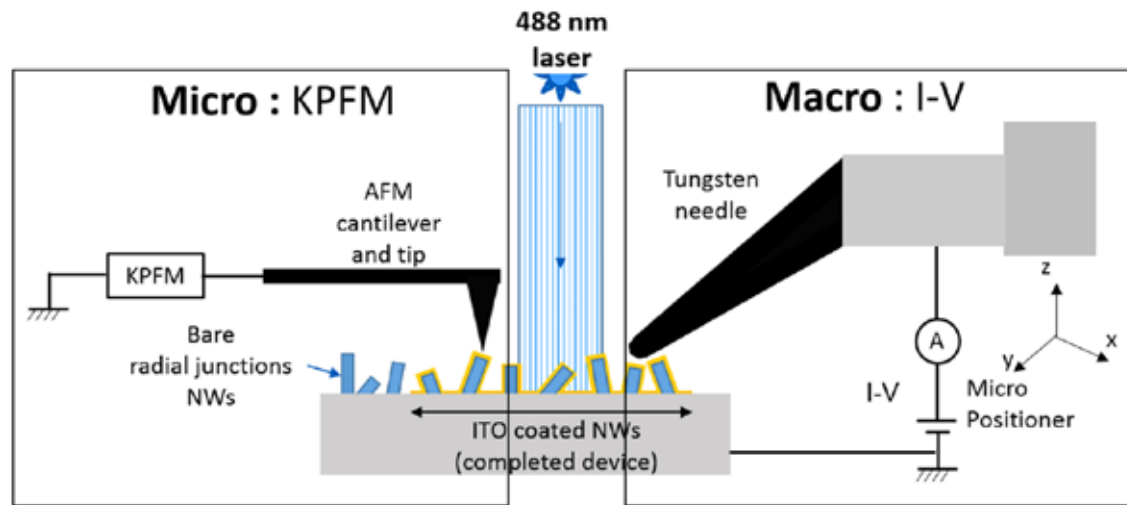
- § NWs promising route for enhancing solar performances : less material; more efficient separation/collection of photocarriers
- § RJ technology “orthogonalizes” the light absorption and the minority carrier collection
- § Highly doped SiNWs grown by VLS using Sn catalysts with conformal deposition of (i) and (n) a-Si:H, and ITO.
- § Efficiencies up to 9.6% [1] have been demonstrated
- § Improvements require a better understanding of the individual nanodevice

3.1 Evaluation of local open-circuit voltage on single RJ SiNW by KPFM

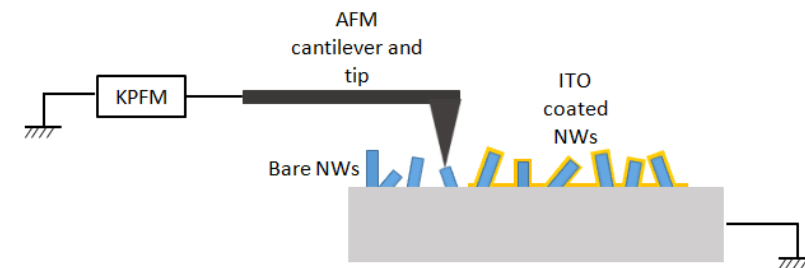
§ Surface PhotoVoltage (SPV) very effective technique to image the V_{OC} of solar cells

§ 1st approach, SPV extracted by KPFM on completed devices and comparison with V_{OC} by I-V

§ 2nd approach, SPV measurements by KPFM (only) on isolated RJs where the SiNW device



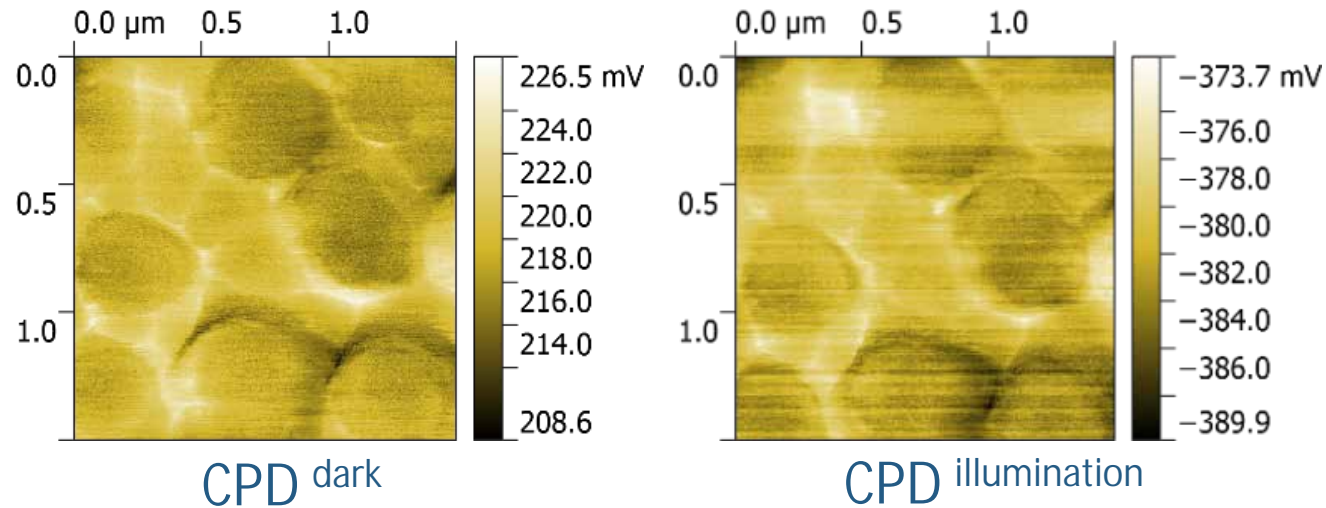
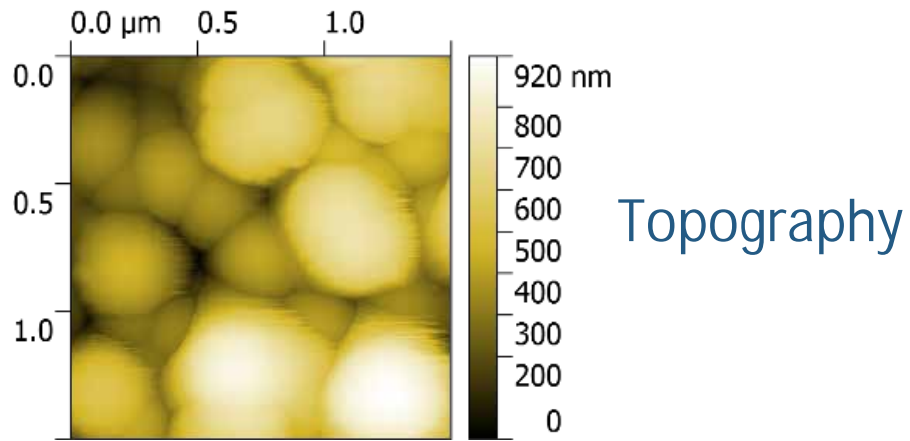
1st approach on completed devices



2nd approach on single RJs without ITO

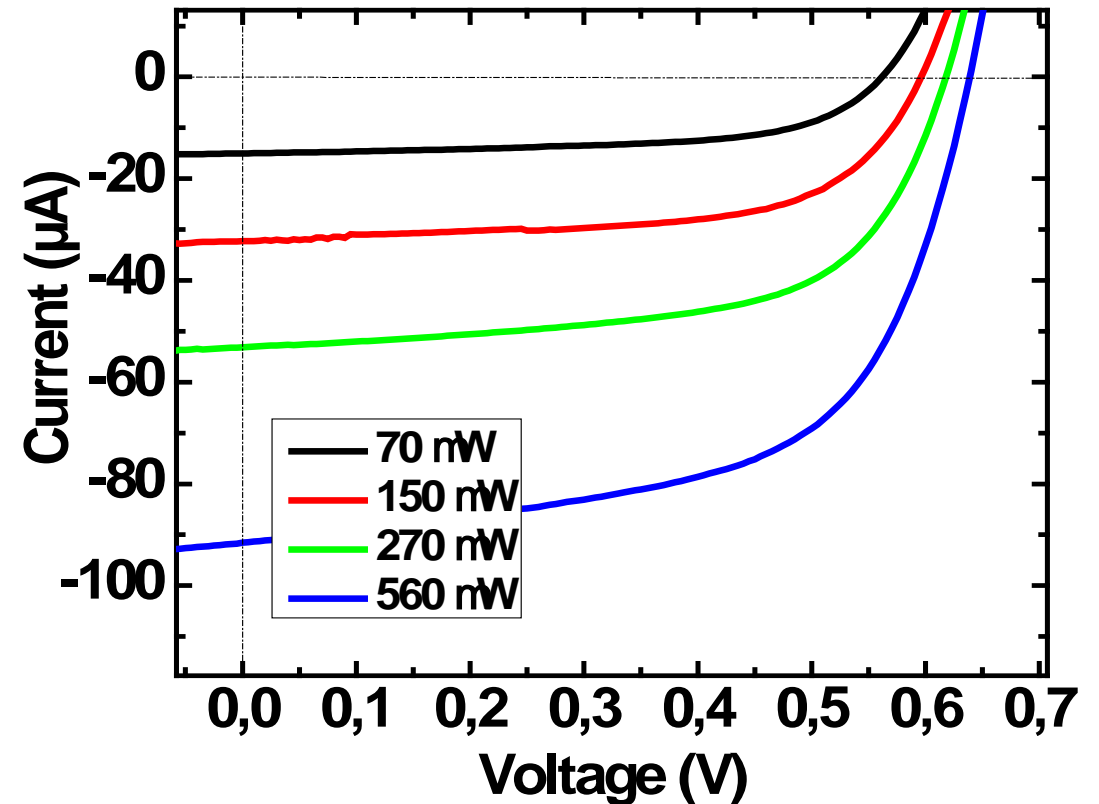
3.2 1st approach : KPFM and I-V measurement analysis (1/2)

KPFM



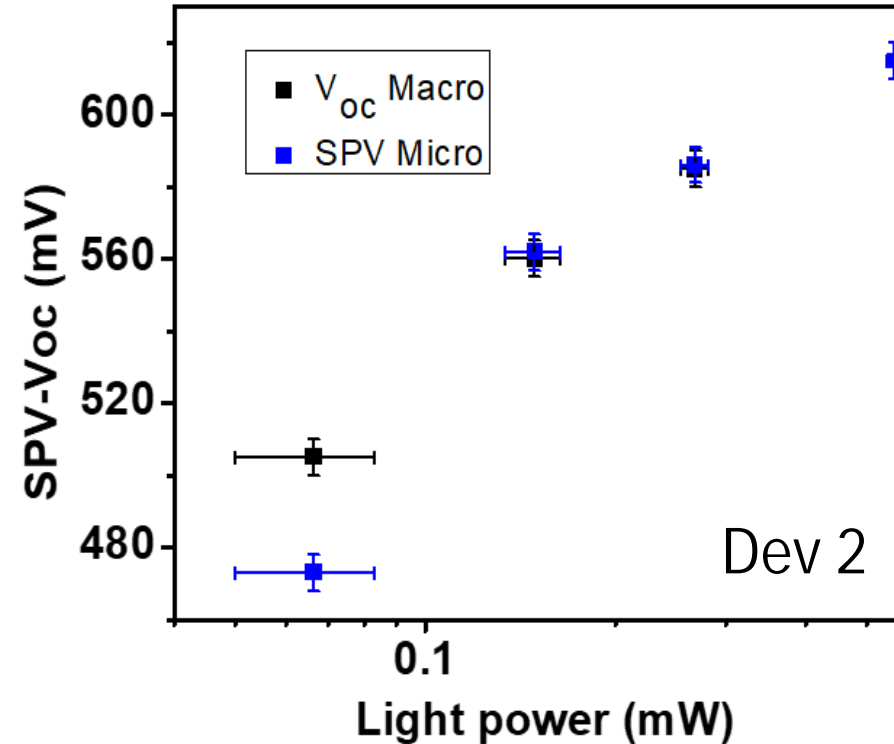
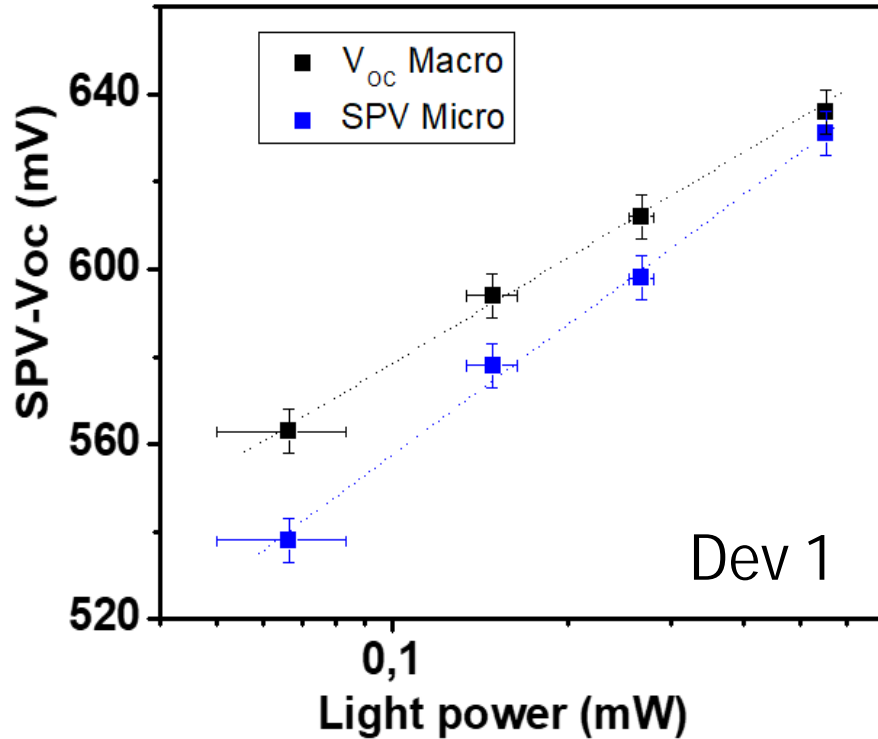
$$\frac{1}{2}SPV \frac{1}{2} = CPD^{illu} - CPD^{dark}$$

Macro I-V



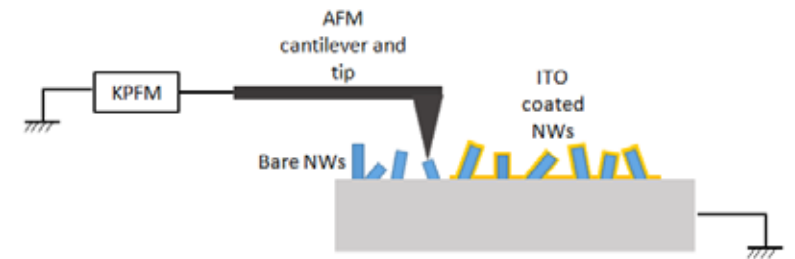
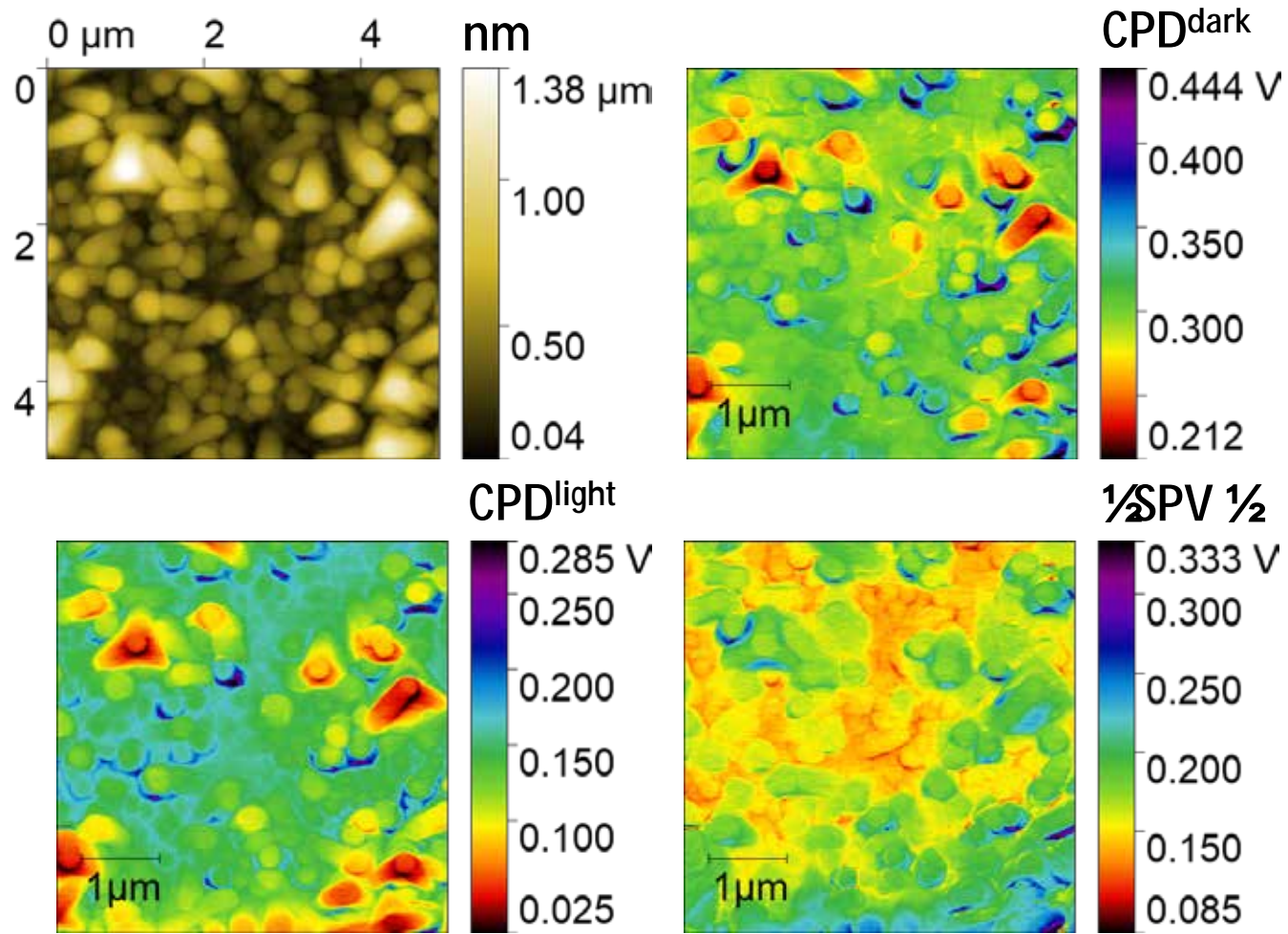
3.2 1st approach : KPFM and I-V measurement analysis (2/2)

§ V_{oc} and SPV versus light power for two different devices



- SPV and V_{oc} show linear behavior versus light power (log scale) with max. deviation b/w 2-5%.
- Ideality factor n : 1.5 ± 0.1 (dev. 1) and 1.75 ± 0.25 (dev.2) in line with a-Si:H planar devices

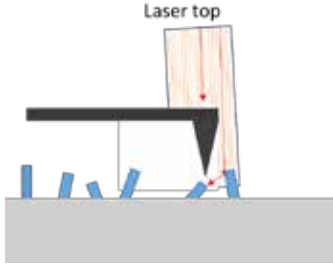
3.3 2nd approach : KPFM on single, isolated RJs (1/3)



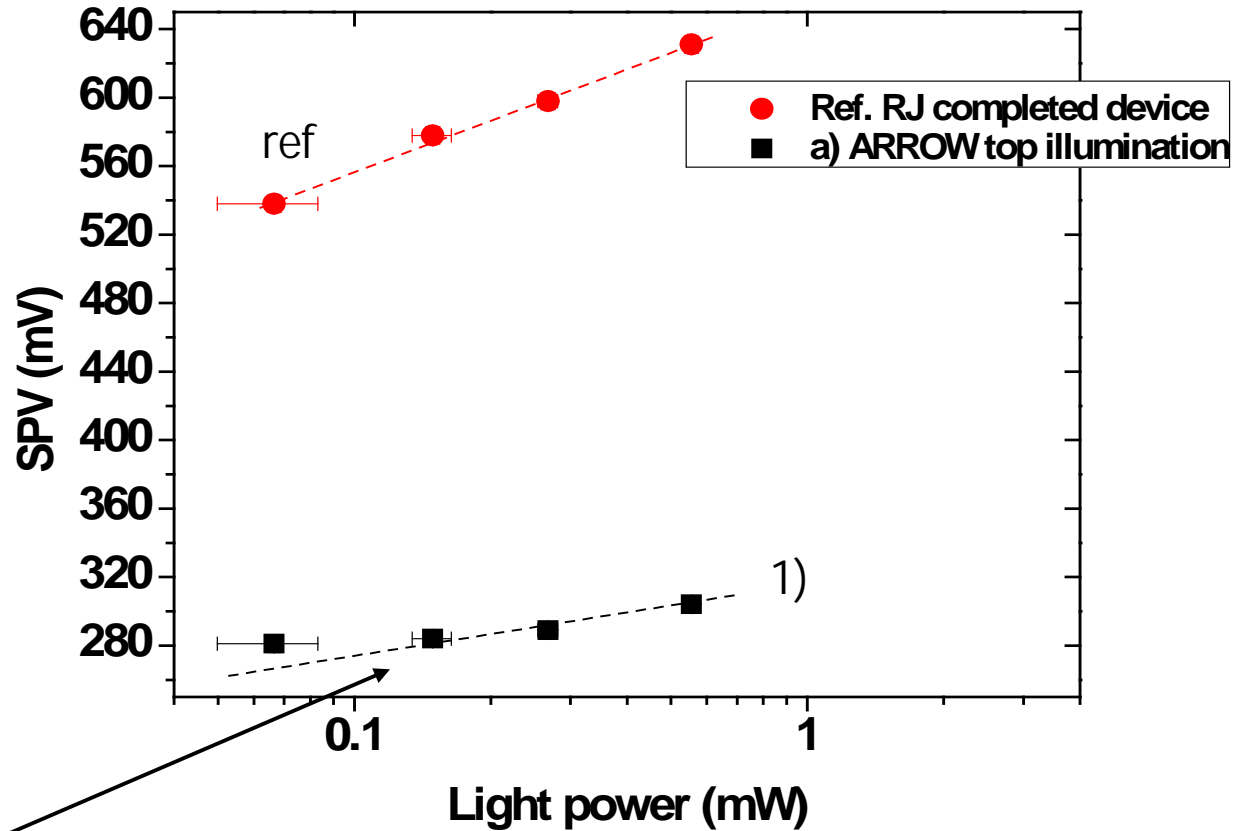
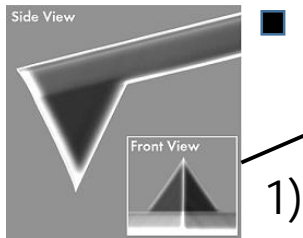
- Lowest SPV are observed in regions where the NWs appear the smallest

3.3 2nd approach : KPFM on single, isolated RJs (2/3)

Top illumination

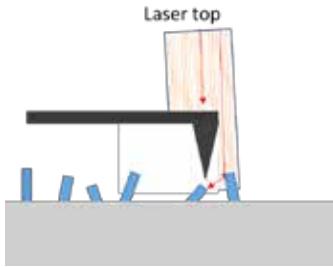


Conventional AFM tip shape

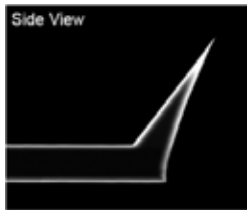


3.3 2nd approach : KPFM on single, isolated RJs (2/3)

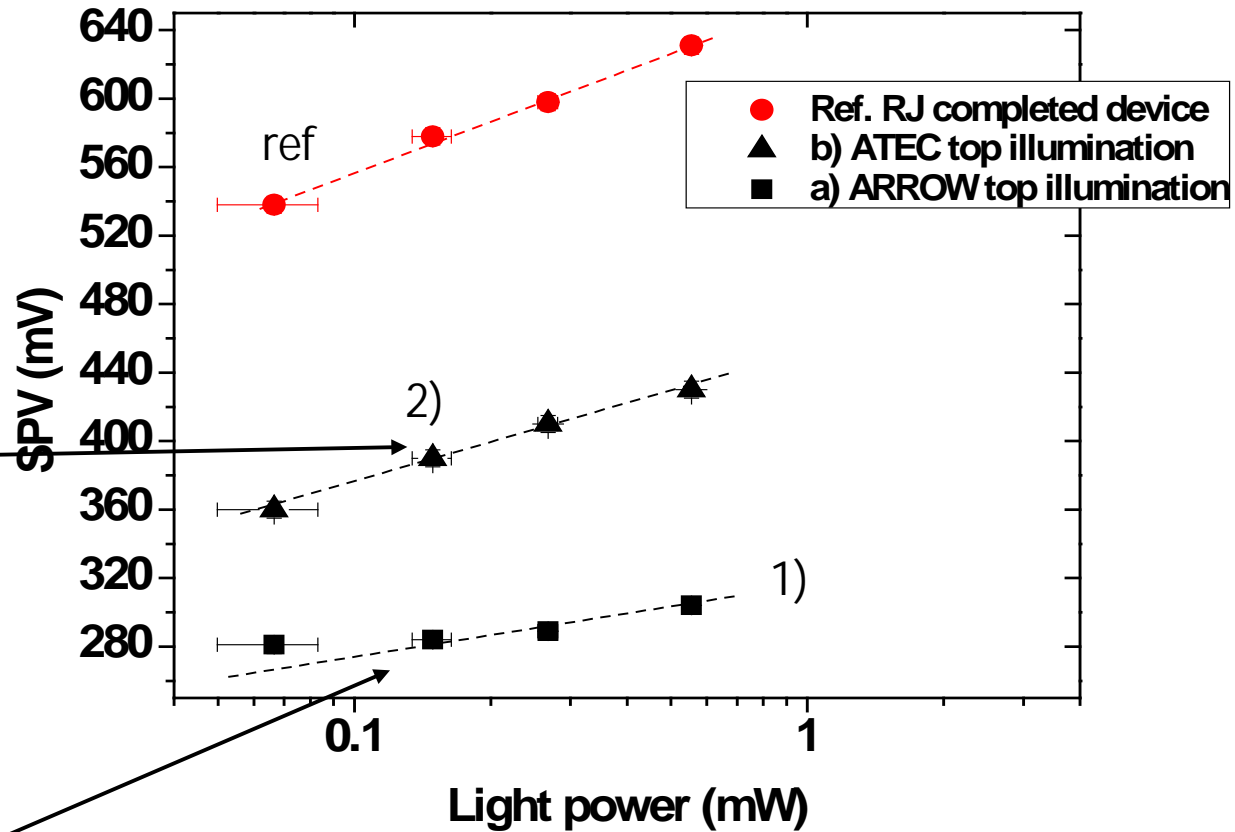
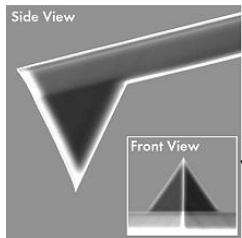
Top illumination



AFM tilted tip

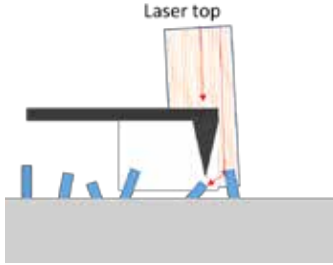


Conventional AFM tip shape

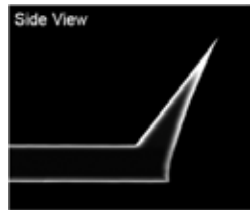


3.3 2nd approach : KPFM on single, isolated RJs (2/3)

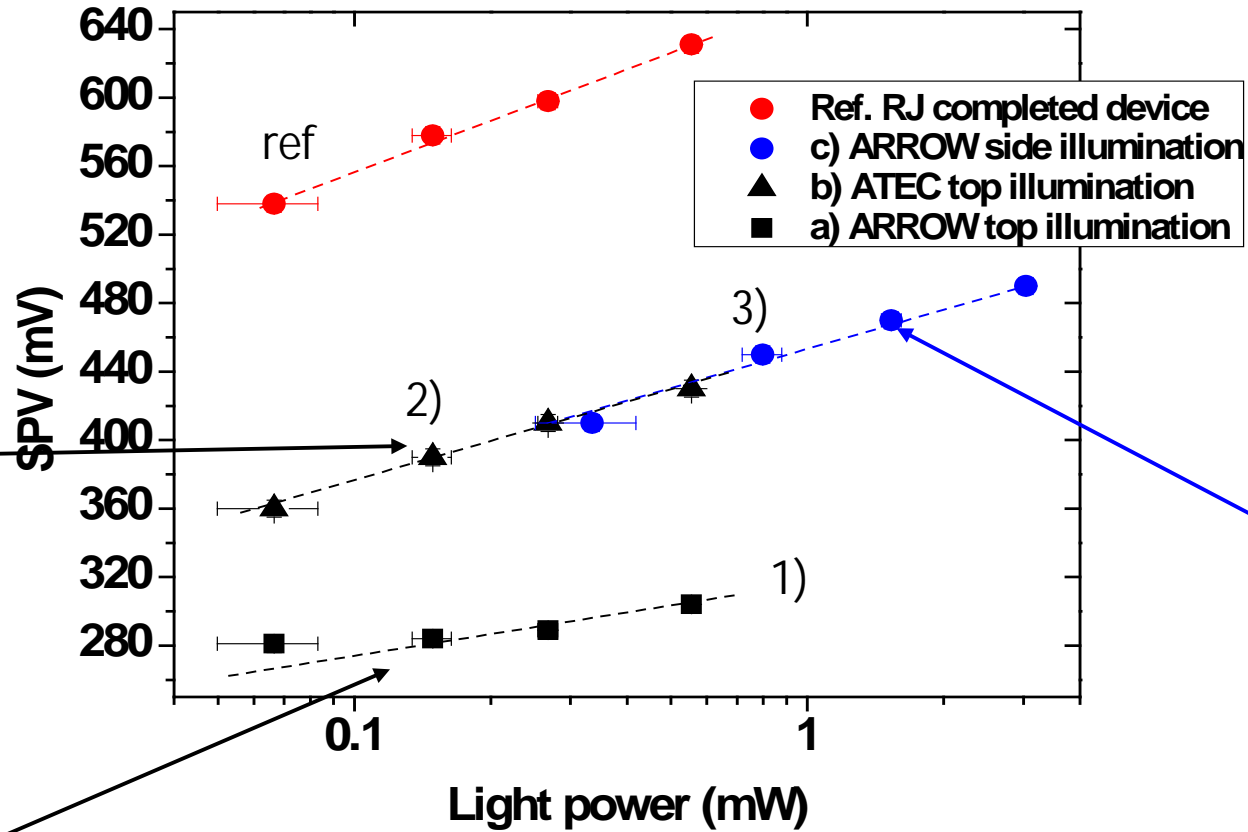
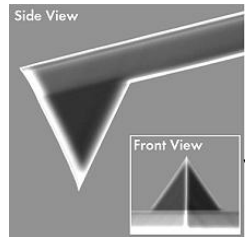
Top illumination



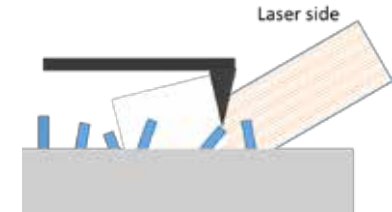
AFM tilted tip



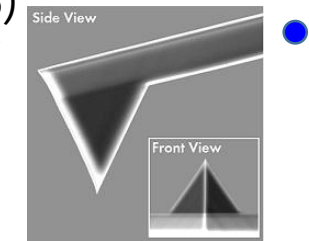
Conventional AFM tip shape



Side illumination



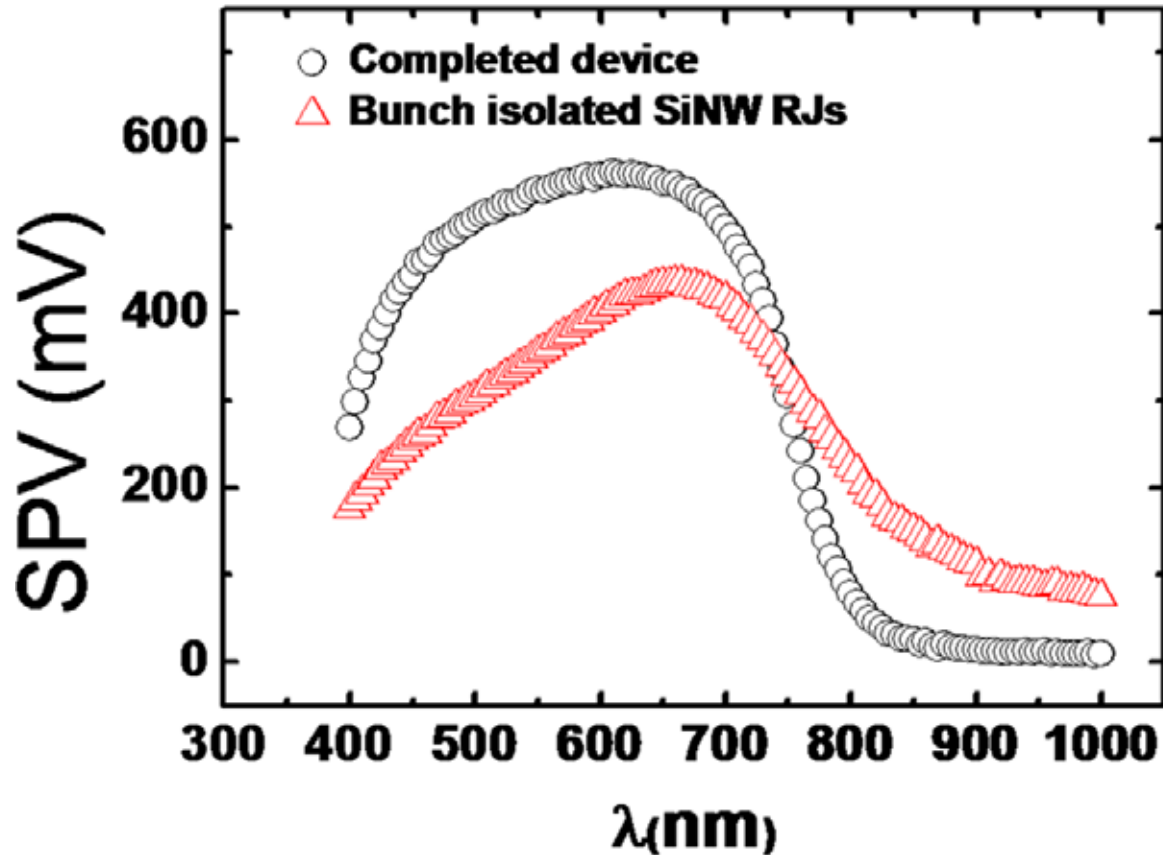
Conventional AFM tip shape



- SPV value on single Si NW RJ never reached the reference SPV

3.3 2nd approach : KPFM on single, isolated RJs (3/3)

§ Surface photovoltage Spectroscopy (SPS)



- SPS curves show large differences :

- w/o ITO "single, isolated SiNW RJ" cannot reflect the optimal V_{OC} value

- SPV is here impacted by a band-bending at the surface (no FB conditions) linked to defects or dipoles formation

Conclusion

Electrical AFM provides a unique chance to measure local properties of matter and characterize interfaces, junction and nanodevices.

§ Cross-sectional analysis applied on a-Si:H/c-Si allow to confirm the presence of the inversion layer suggested by macroscopic measurements.

§ C-AFM is not the best approach to investigate (p+) Poly-Si/SiO_x/c-Si. KPFM allows to observe local potential drops that are expected to be an indirect observation of the dopant diffusion through the existing pinholes.

§ SPV measurements by KPFM allows to get access to the V_{OC} in P-I-N RJ SiNWs only on completed devices. W/o ITO “single, isolated SiNW RJ” cannot reflect the optimal V_{OC} due that surface band bending negatively impacts SPV measurement.

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