Surface roughness metrics and their relation to heat loss of solar vacuum heat collector elements (HCE)

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Motivation & study goals

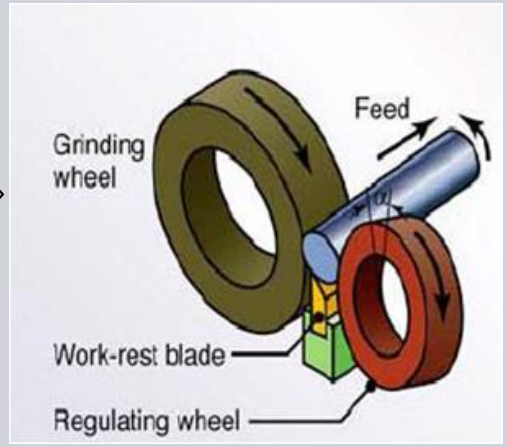
- Tube substrate roughness has a substantial impact to radiative emittance (ε) and therefore on heat loss (HL)

- HL values for HCEs with similar Ra (<0.2 μm) may vary up to 10% (between HCEs at 400 C): **~10% HL → LCOE up to 1%**
- To find the key roughness parameters that correlate the tube roughness with HL
- To control roughness in order to decrease ε, without decreasing solar absorptance (α)
- Increasing impact of HL for higher operating temperatures

HCE production flow and experimental method

Stainless steel tube

- Mechanical **grinding** of outer surface
- Optional: additional **electro polishing (EP)** process

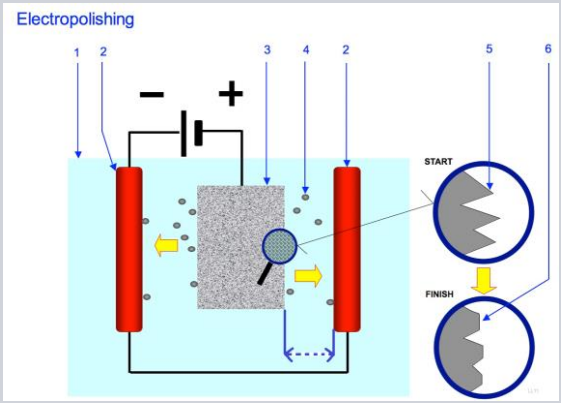


PVD (Sputtering)

- Selective coating
  - Absorptance (α) > 95%
  - Emittance (ε) ~ 10% (@400 C)

Assembly & vacuum

- Glass envelope assembly
- Vacuum process and final seal (10^{-4} mbar)

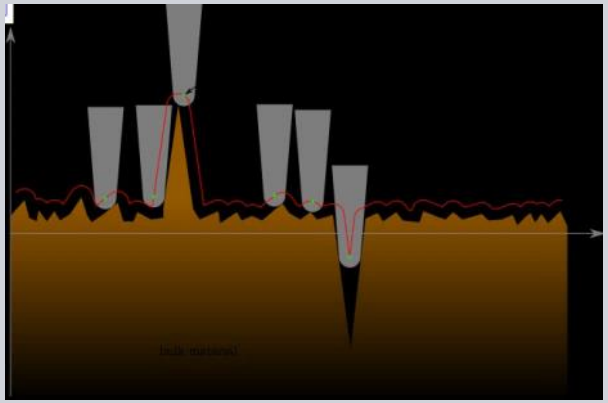


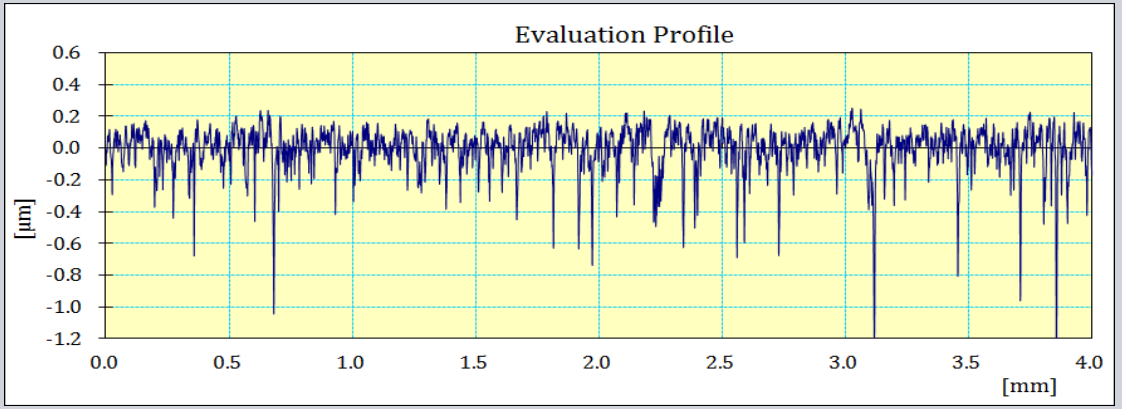
Heat loss test

→ within batch comparisons

2D surface roughness measurement

Surface roughness parameters, using a portable stylus 2D profilometer





Ra, Rc, Ry, **Rz, Rq**, Rt, Rmax, Rp, Rv, R3z, Rsk, Rku, Rc, RPc**, RSm,** Rz1max, S, HSC, RzJIS, Rppi, RΔa, **RΔq**, Rlr, Rmr, Rmr(c), Rδc, Rk, Rpk, Rvk, Mr1, Mr2, A1, A2, Vo, Rpm, tp, Htp, R, Rx

Height parameters – such as: **Ra**, **Rq** and **Rz**

Spacing Parameters – such as: **RSm**

Hybrid parameters – combination of the above: **RΔq** (RMS slope)

2D surface roughness parameters

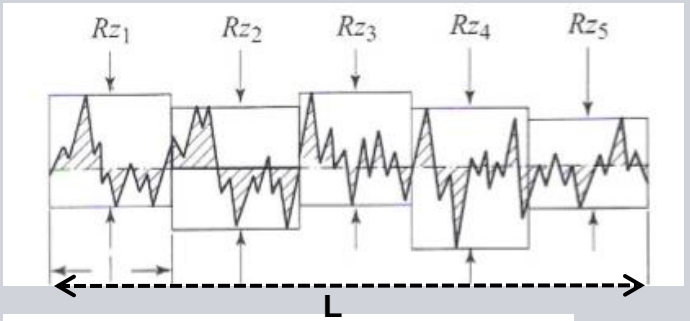
Roughness average $$Ra = \frac{1}{L}\int_0^L |Z(x)|\,dx$$

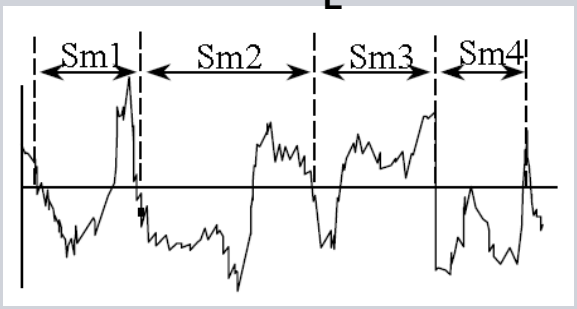
Roughness RMS $$Rq = \sqrt{\frac{1}{L}\int_0^L Z^2(x)\,dx}$$

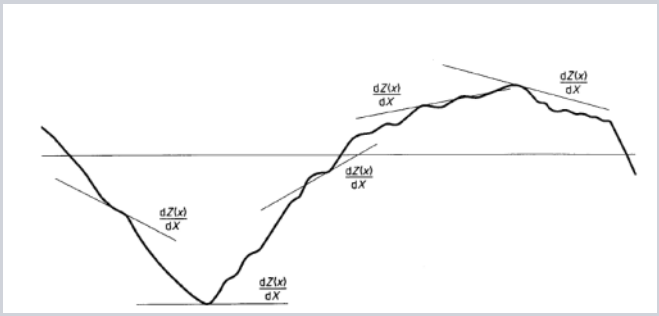
Average maximum peak to valley $$R_Z = \frac{1}{N}\sum_{i=1}^{N} R_{z_i}$$

Average spacing ("wavelength") $$RSm = \frac{1}{N}\sum_{i=1}^{N} Sm_i$$

RMS slope $$R\Delta q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dZ(x)}{dx}\right)^2 dx}$$



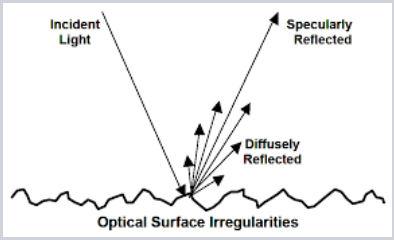




Specular region of the optical roughness: Rq/λ < 0.2

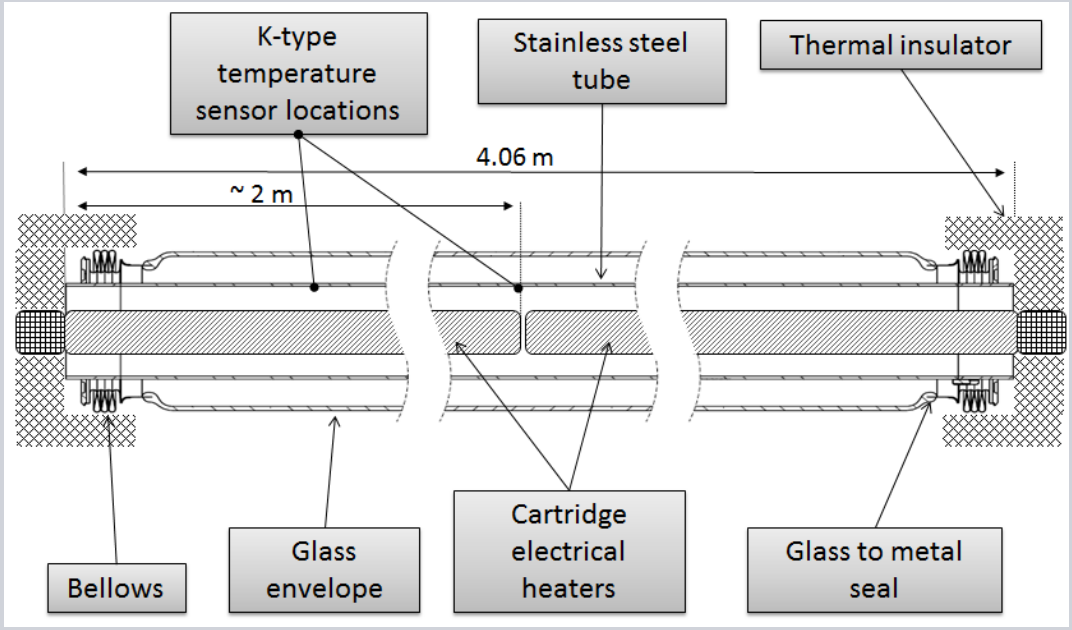
Rq < 0.25 μm, $\lambda_{BB\ 400\ C} \approx 4.3$ μm

$\epsilon = f(Rq, \lambda)$ *Wen* et. al. *(2006), Sibin* et. al. *(2015)*



Heat loss measurement

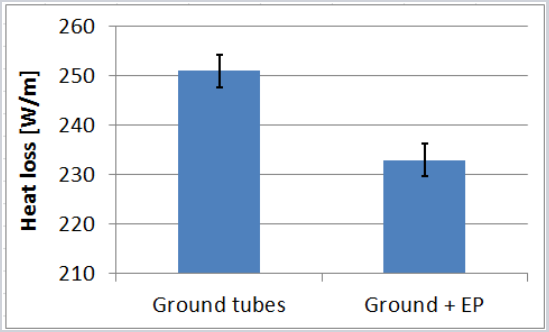
- Electrical heating of the tube to maintain ~ 400 C.
- Direct measurement of the power (electrically) = heat loss of the receiver at 400 C.
- Single test bench located at indoor laboratory, test repeatability ±1.5%.



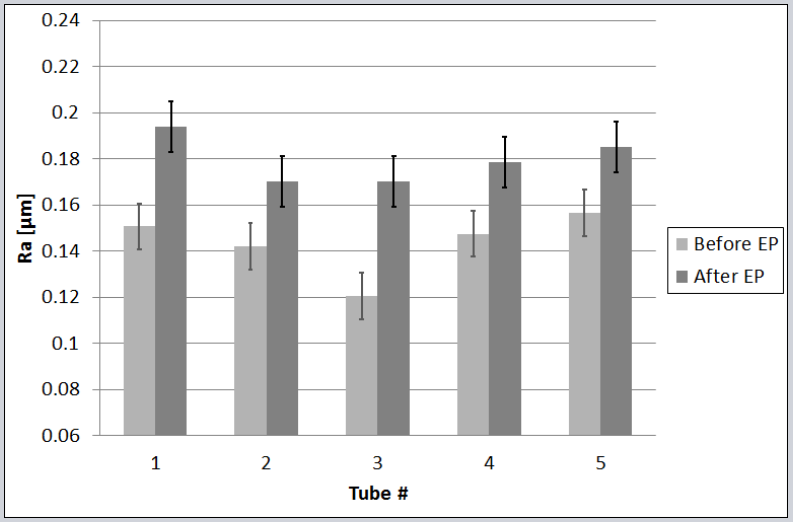
Results (1): Electro polishing impact

- EP can reduced HL by up to 10%

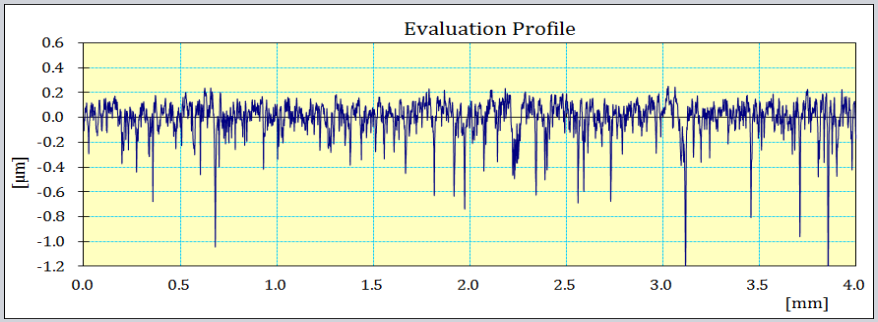
  (10 tubes: 5 ground, 5 ground + EP)



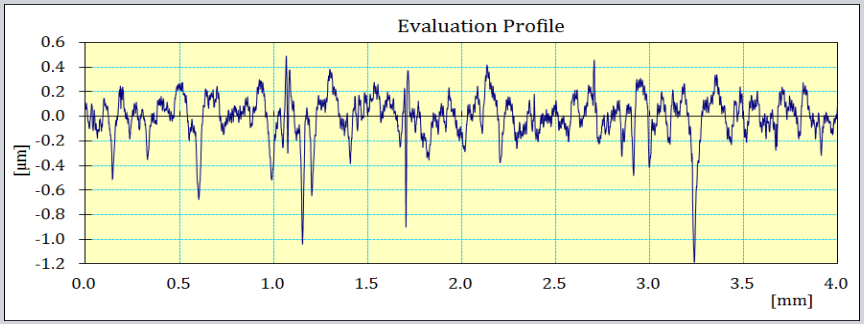
- Ra, Rq and Rz are increased after the EP process → failed to correlate roughness to HL !



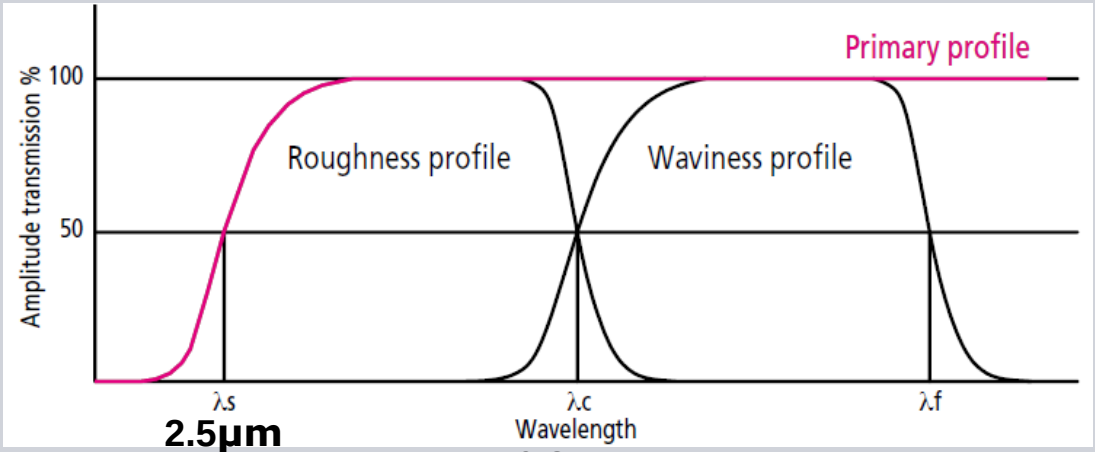
Before EP

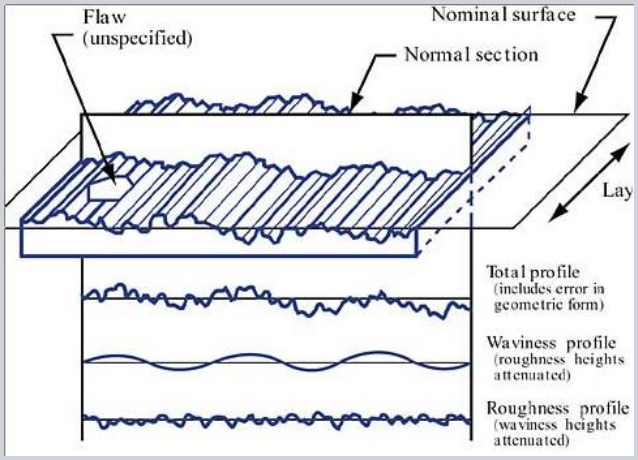


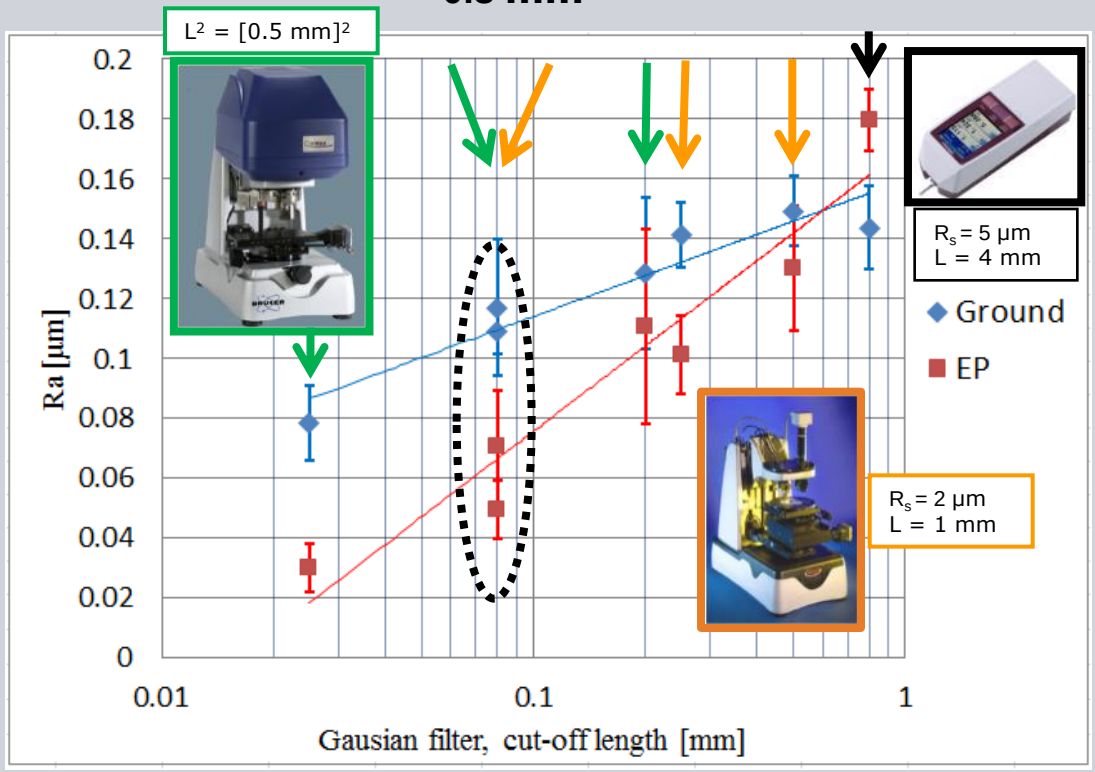
After EP

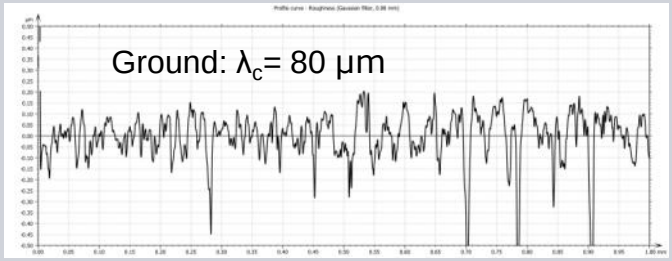


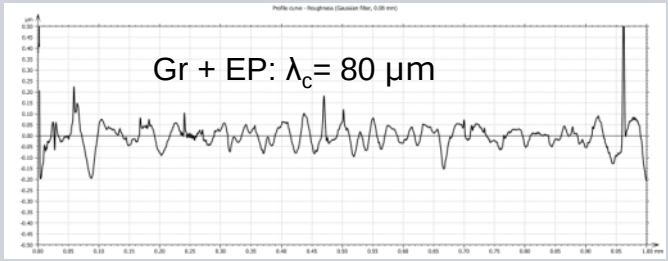
It's all about scaling…





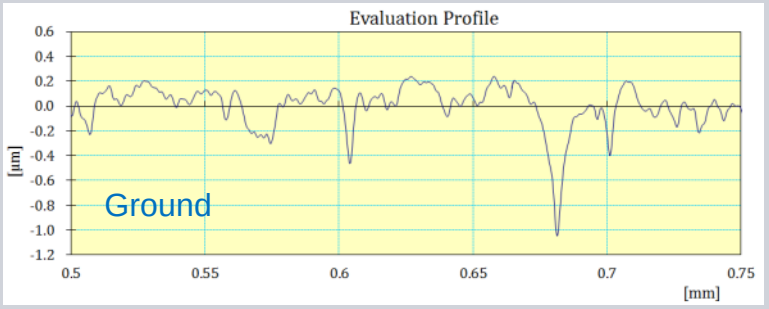


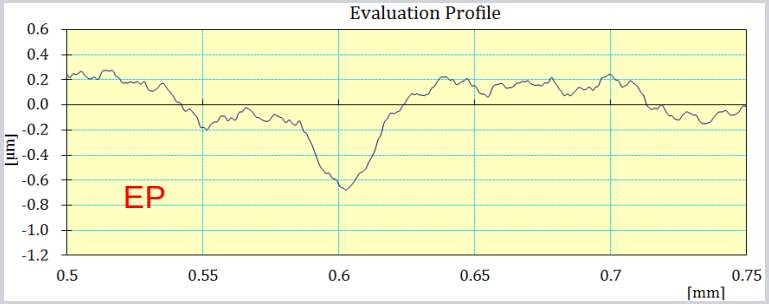


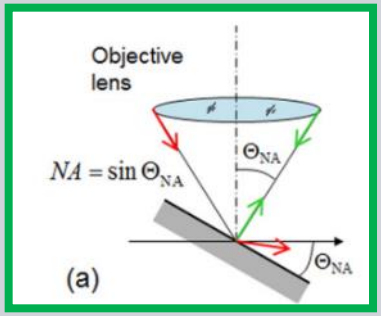


Similar effect for Rq, Rz etc

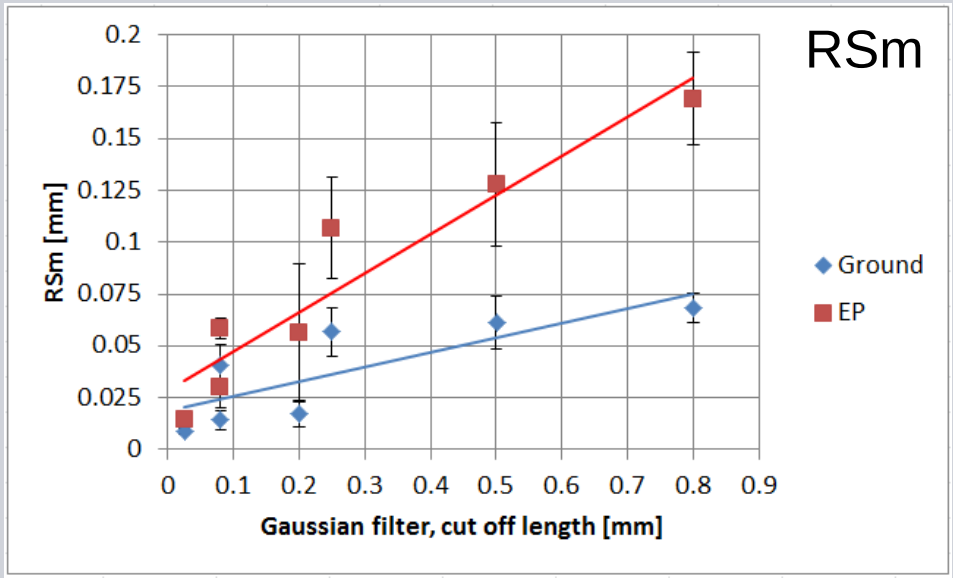
Cut-off length effect on spacing (RSm) and slope (RΔq)

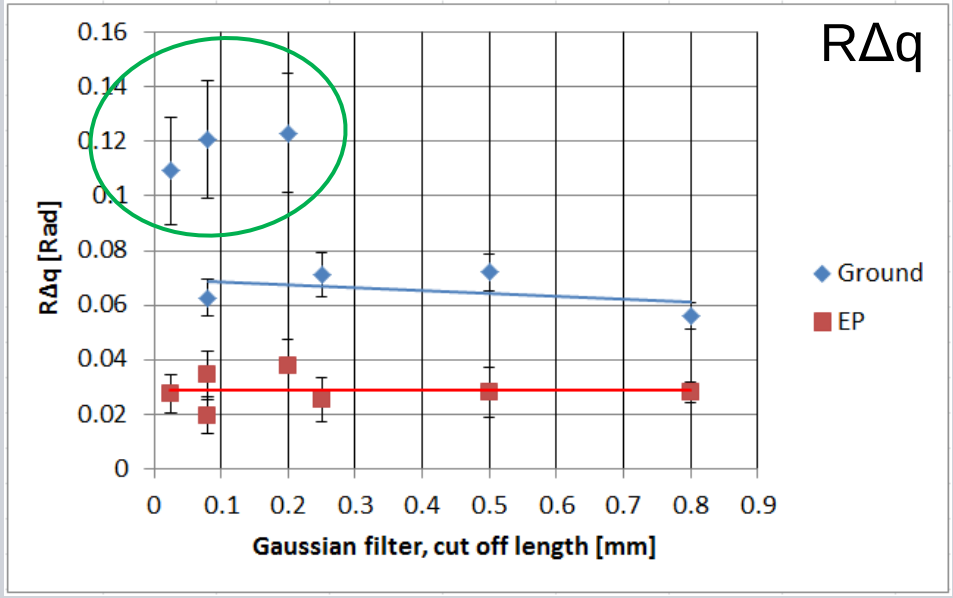






- ✓ EP impact on slope
- ✓ Slope is scale insensitive





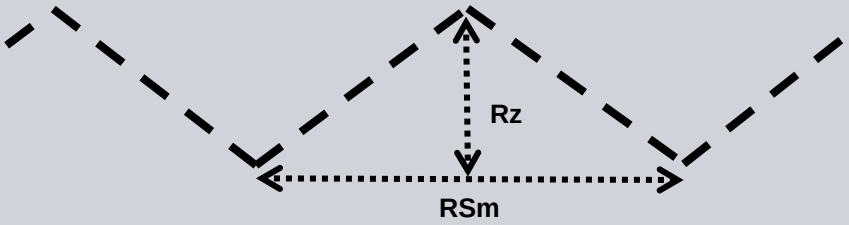
Results(2): Roughness slope & HL

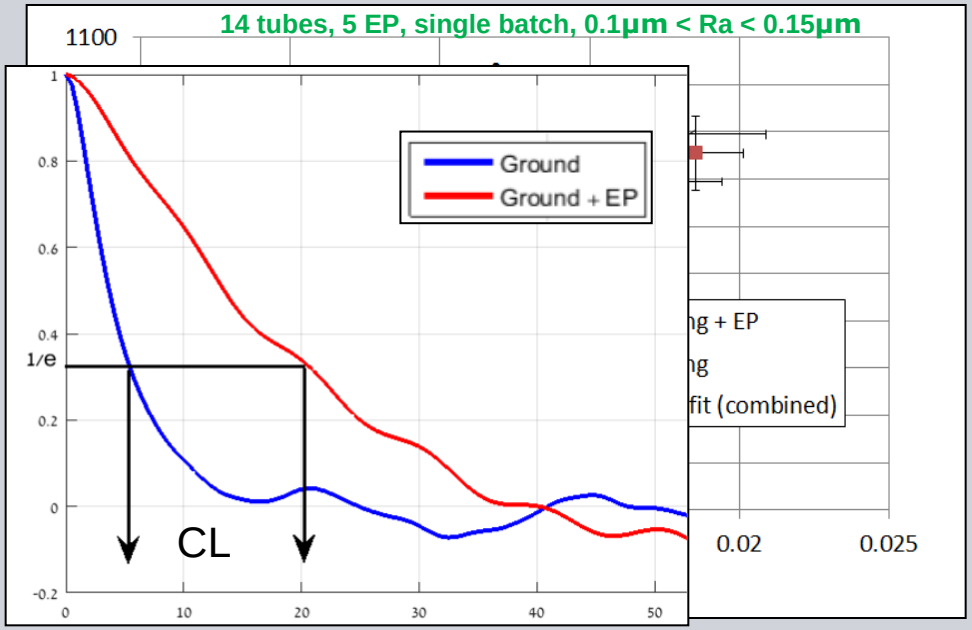
$$\text{Slope} = \frac{R_q}{CL}$$

Yang et. al. *(1995)*
Li et. al. *(2005)*

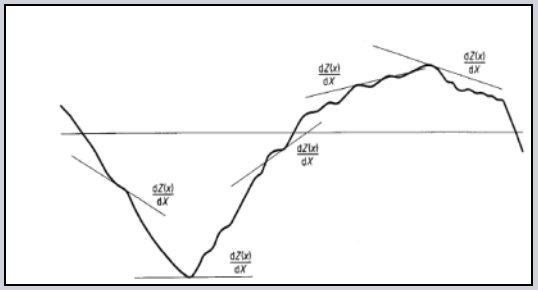
$$E_r = \frac{RS_m}{R_z}$$

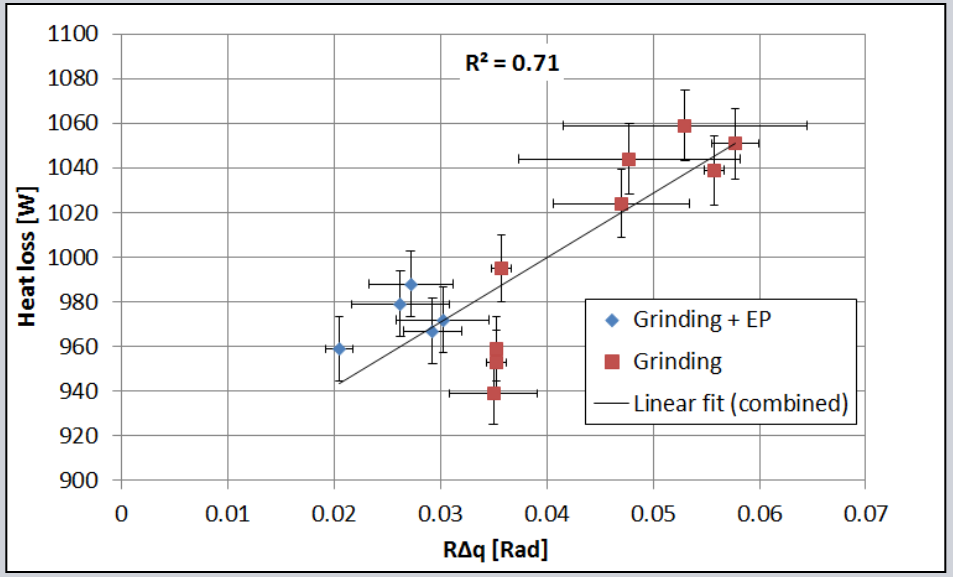
Wieczorowski et. al.(2006)



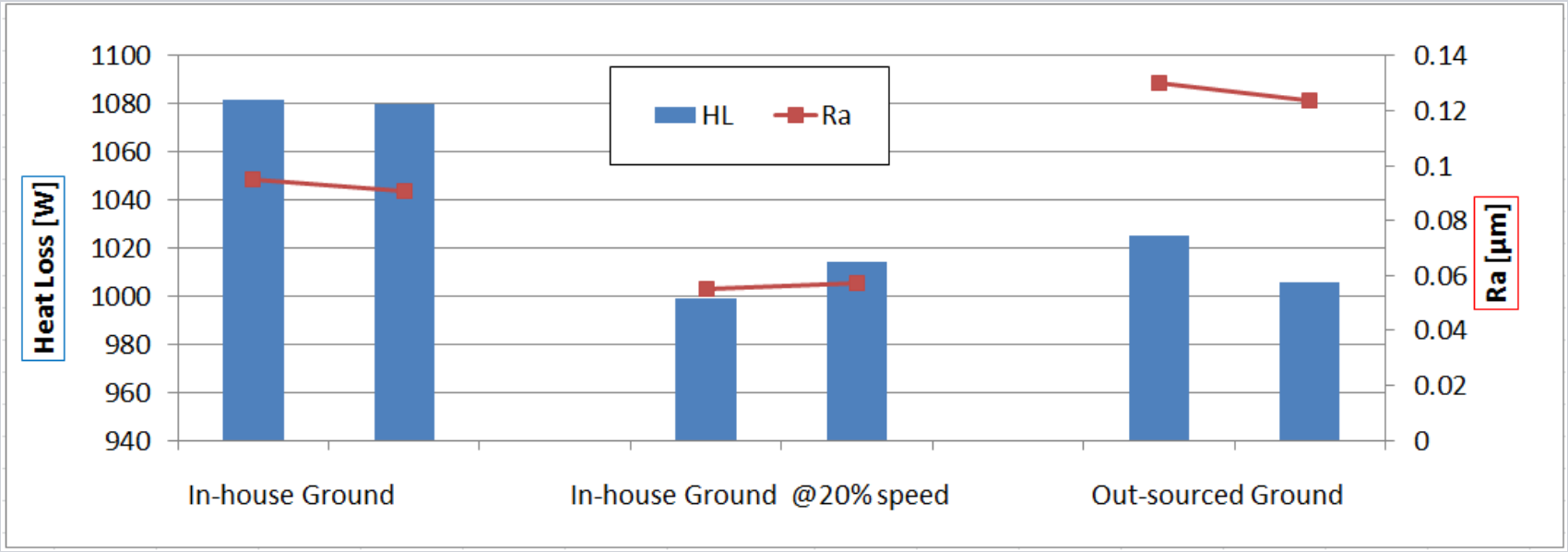


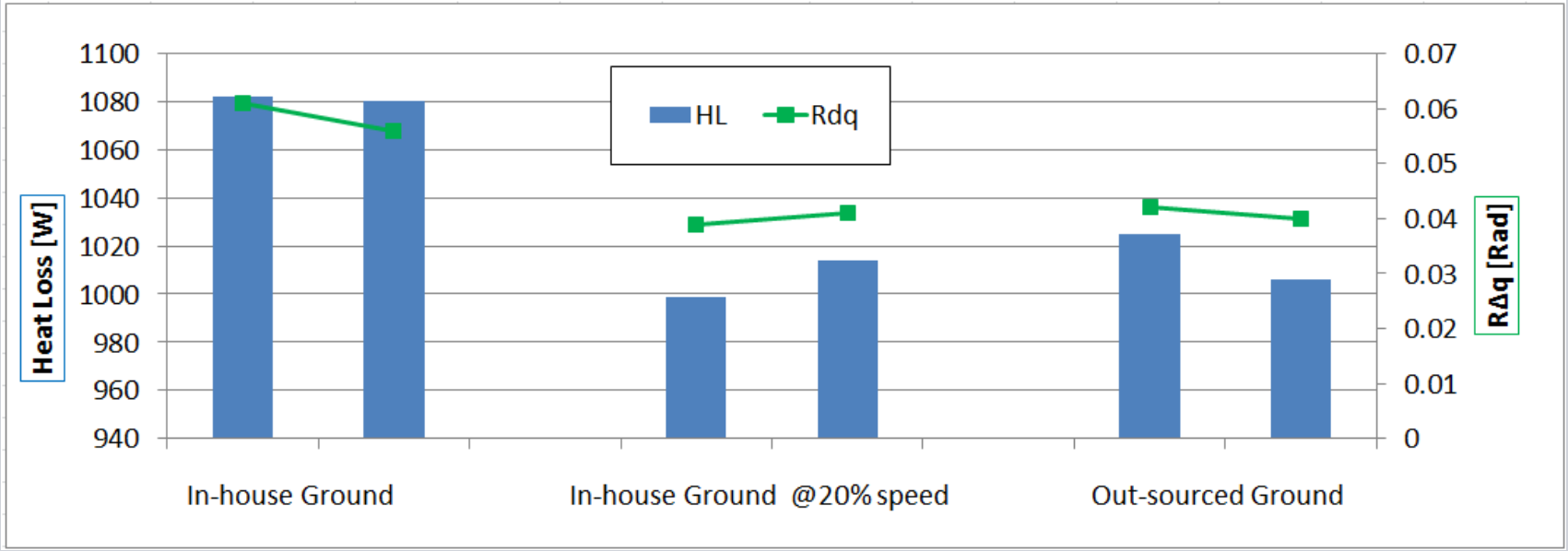
$$R\Delta q$$



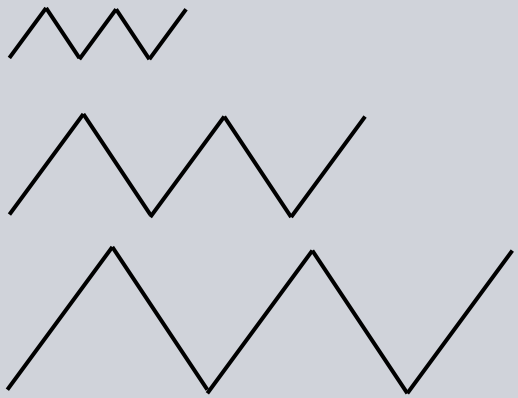


Results(3): Roughness slope, ground only

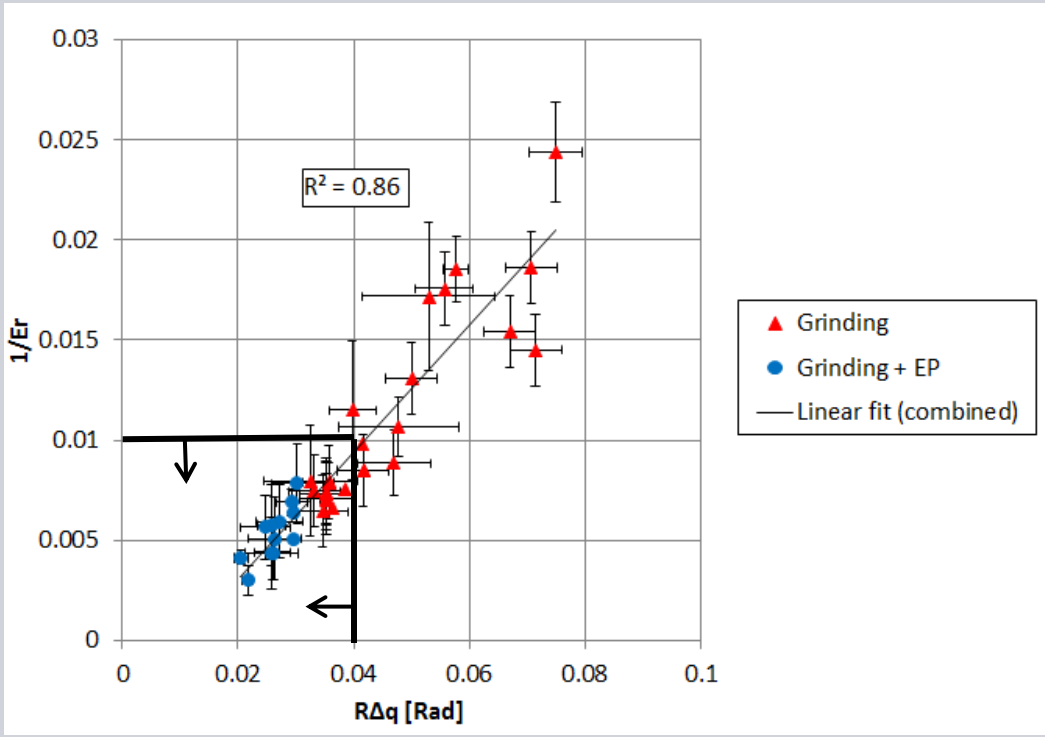




Results(4): Tube roughness spec.



- Slope is dimensionless parameter, Rz is provided in addition
- 1/Er and RΔq are linearly correlated and equally well



Roughness spec.

Rz < 1 µm & Er > 100

or

Rz < 1 µm & RΔq < 0.04

Conclusion

- Tube substrate roughness can be measured adequately by a 2D stylus portable profilometer
- Roughness slope (1/Er or RΔq) along with roughness height (Rz) show good correlation to HL for both: ground only and ground + EP tubes
- Proper grinding process makes the EP unnecessary
- No impact on solar absorptance was noticed
- Up to 1% improvement on total annual heat gain (and accordingly lower LCOE)
- Larger impact on higher operating temperatures (>400 C)

Thank you

Nakar, D., Feuermann, D. (2016). *Surface roughness impact on the heat loss of solar vacuum heat collector elements (HCE)*. ***Renewable Energy*, *96*, pp. 148-156**

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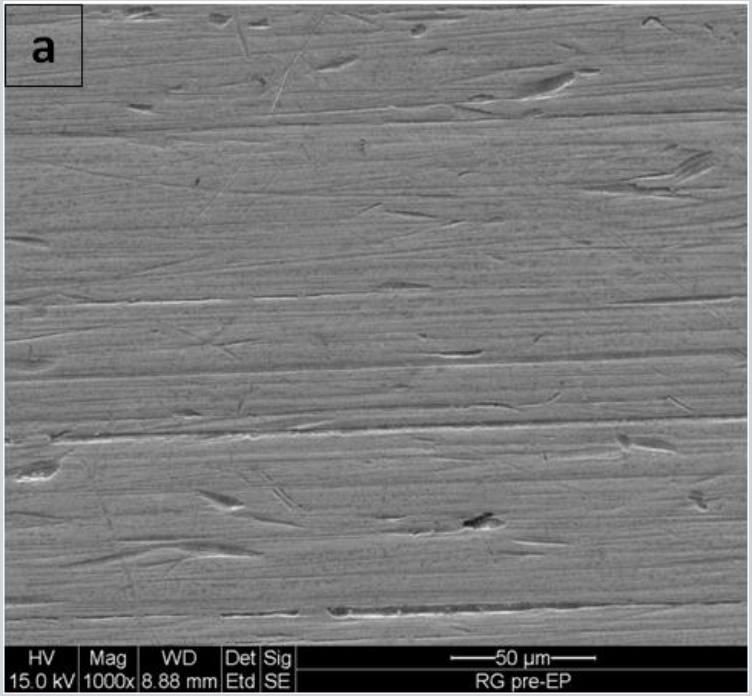
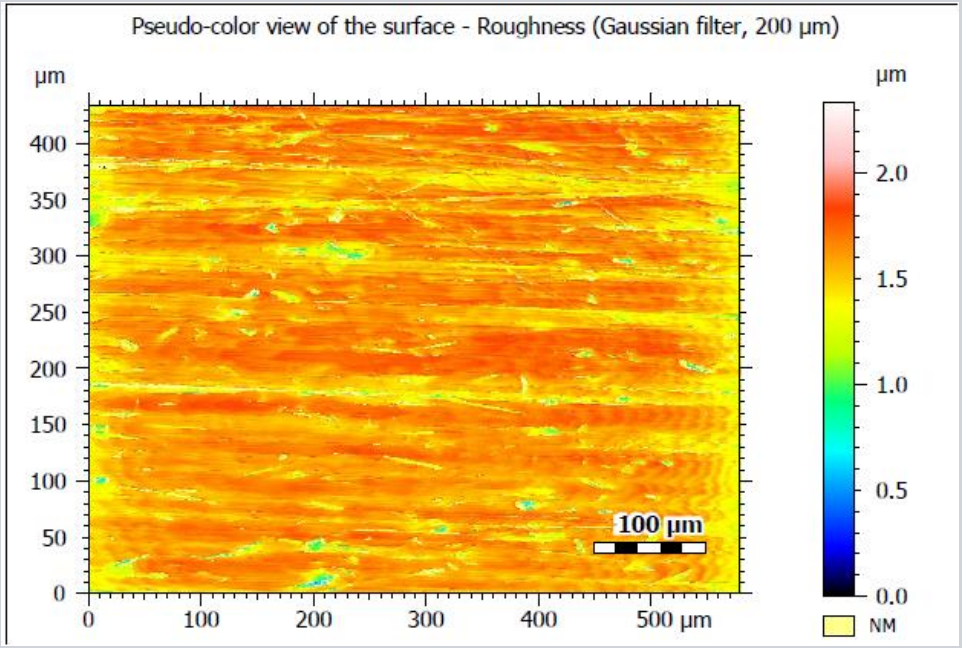
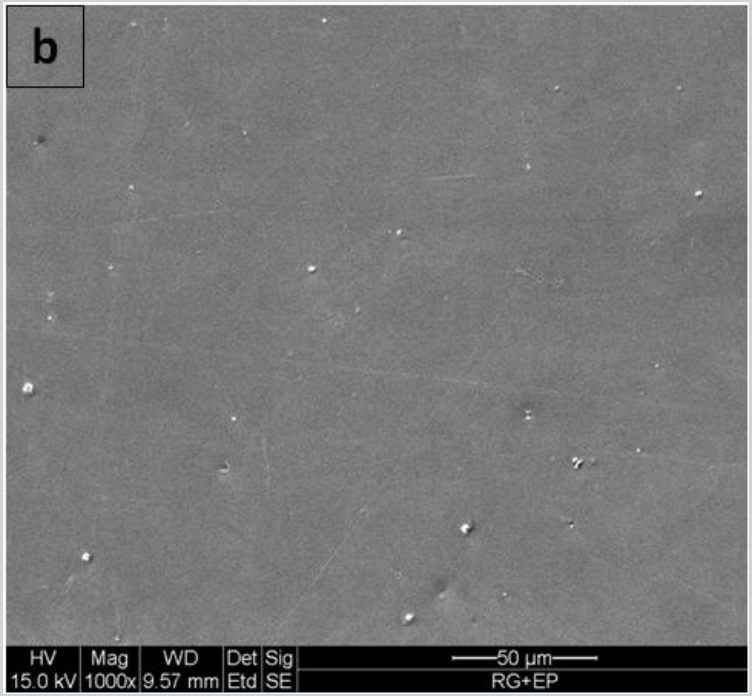
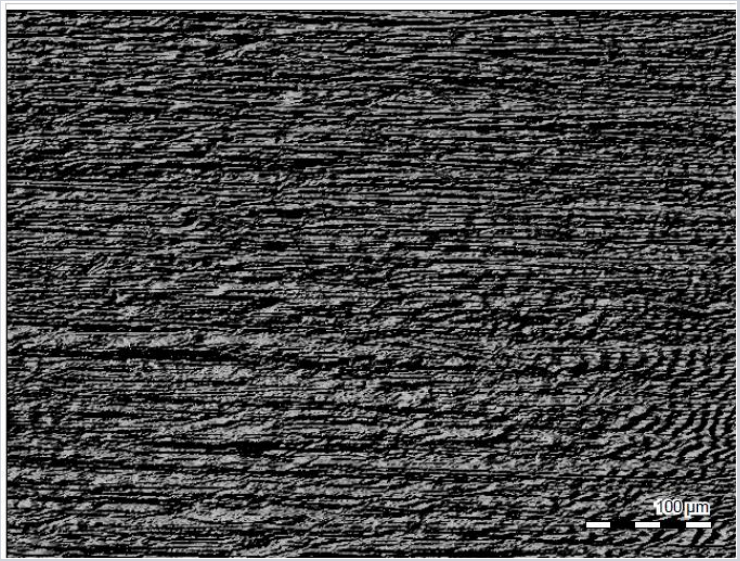
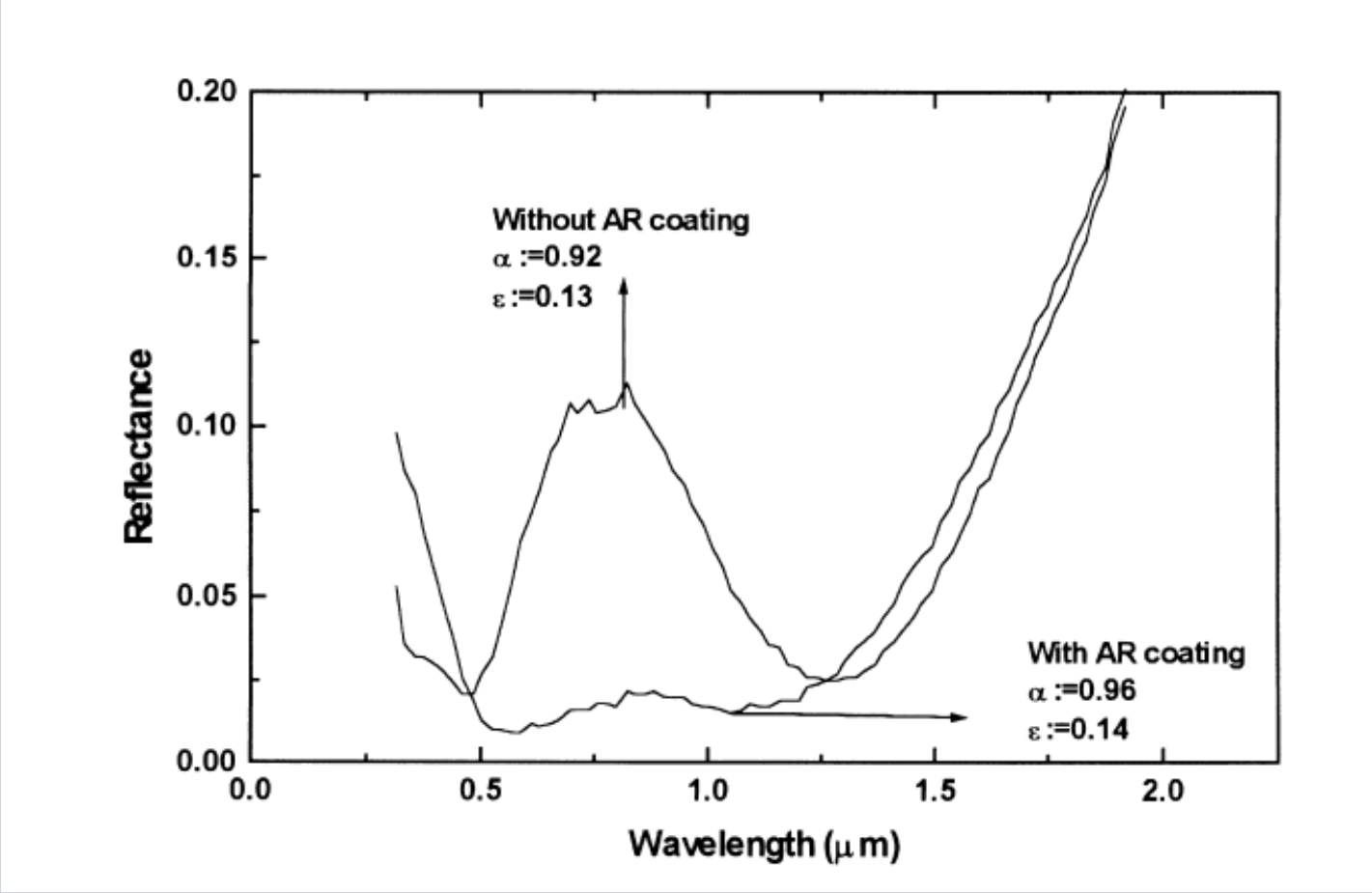

a
HV
15.0 kV
Mag
1000x
WD
8.88 mm
Det
Etd
Sig
SE
50 µm
RG pre-EP


Pseudo-color view of the surface - Roughness (Gaussian filter, 200 µm)
µm
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500 µm
100 µm
µm
2.0
1.5
1.0
0.5
0.0
NM


b
HV
15.0 kV
Mag
1000x
WD
9.57 mm
Det
Etd
Sig
SE
50 µm
RG+EP


100 µm

Absorptance (α)



Farooq, M et. al. (1998). High performance sputtered Ni: SiO 2 composite solar absorber surfaces. *Solar energy materials and solar cells*, *54*(1), 67-73.