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Degradation of solar cells due to in orbit electrostatic discharge?

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(Dated: September 2013; Revised May 14, 2014)

As the main activity of the ESA EMAGS3 study (published at 12th SCTC Kitakyushu, Japan) in orbit electrostatic discharge, called flash-over, has been simulated on a flight representative panel of dimensions 2 by 4 meters in an environment to achieve inverted gradient conditions on the solar cells.

Although not planned within the said study, electrical performance was measured after the panel has suffered from virtually hundreds of flash-over, some of them covering the whole surface. Comparison with the last measurements before testing revealed no degradation beyond measurement error. Obvious differences could be attributed to differences in the circuit. Accompanying experiments on single cells fully support this observation.

I. INTRODUCTION

Electrostatic discharges on the surface of solar panels attached to spacecraft have been investigated for several decades now [1–4]. One of the characteristic electrostatic effects considered being the discharge of the cover-glasses during a primary arc, the so called flash-over event.

While this effect was studied in many detail [5–8], questions – not to say controversies – keep going on about its relevance for degradation of cells on a solar array, the physical setup within a vacuum chamber, the experimental parameters, and – most important for industrial laboratory testing – its representativity with respect to space flight. Some experiments suggest flash-over to be responsible for degradation of solar array performance [7, 9–11], whereas other [8] clearly exclude this scenario for lack of energy.

Only recently realistic experiments on a representative large panel could be performed [12–14], which allowed for the first time to abstain from most of the experimental auxiliaries and assumptions needed during coupon experiments. The effort was funded by ESA and the work was carried by a team from ONERA and CNES, while Astrium (now Airbus Defence and Space) – besides having supplied the panel and its modification – and Thales-Alenia-Space, France participated on the elaboration of the test plan and provided detailed information.

The study primarily focused on a better understanding of the flash-over phenomenon and its characteristic parameters, the typical duration and amplitude of the flash-over current, which could be translated into a velocity of the discharge front along the surface and the area that could be discharged by a single flash-over.

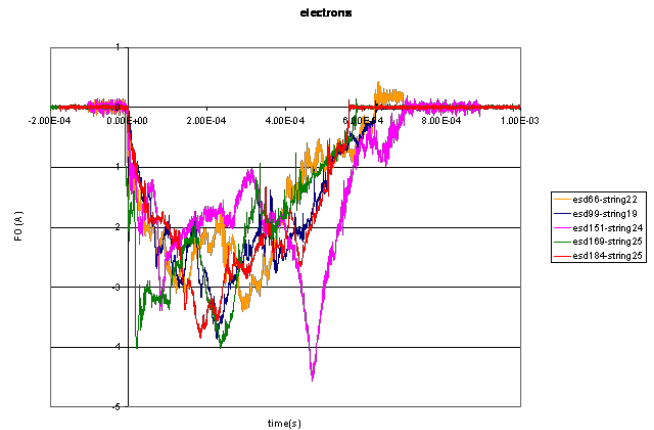


FIG. 1. Summary of flash-over transients detected during EMAGS3 study[13]

Thereafter the aim was to propose a simulation circuit that, based on the experimental results, could provide a most representative flash-over pulse shape to experiments on samples which are much smaller, typically coupons, and thus not capable to produce a full scale flash-over. While the individual shape of the pulses varied significantly as shown in fig. 1, duration and peak current kept to the same order of magnitude. So the proposed simulator consisted just of a simple R-L-C circuit, as shown in fig. 2.

It should be noted, that the elements of the circuit represent nothing other but the charged surface of the cover glasses and the part of the circuit of the discharge that is closed over the vacuum by the flash-over itself.

Already from first sight of the transients one could guess the way and speed the discharge took over the panel. The speed

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that could be read directly from the peak current on each string and its respective position [14] was about 4.5 km/s and thus much lower than 10 to more than 30 km/s reported by other authors[15, 16].

However Sarrailh et al[17] developed a more sophisticated physical model covering even details that would have been otherwise discarded as artefact or even may have let to the mentioned over estimation of the speed.

Since from our heritage no degradation is detected in space flight that would have to be correlated to electrostatic discharges alone, any indication of significant degradation during all of these experiments would have to be attributed to the test conditions rather than the tested effect.

At the beginning of the study it was therefore not planned to gain any information regarding degradation of the solar cells involved in the tests, because during the tests a lot of handling would possibly induce mechanical damage to the cells that would not affect the electrostatic behavior, but degrade the cells. So there was no reason to check the electrical health of the panel, and no electrical performance was measured before the modifications were applied, the last measurement was taken 2006 before storing the panel.

However, after the successful finalization of the study, ideas reappeared to check cell performance at least for any significant degradation.

To further supplement these measurements, to verify the operation of the flash-over simulator and to close the gap to multi junction solar cells, we performed some additional experiments on a typical coupon, thereby taking into account not only the worst case pulse shape but also concentrating 100 flash-over on a single cell.

II. EXPERIMENT

For the experiments during EMAGS3 a residual panel build by Astrium in late 2002 was modified to accommodate detection of discharge currents through each of the cell strings. With the modification almost all of the wiring was removed from the panel rear side and essentially replaced by just one wire per row of cells. Each row was short circuited from one end to its opposite, only the front side staid unchanged. It carries silicon cells 2wiTHI-ETA3 from AZUR Space Solar Power GmbH glued to the panel using Wacker RTV S691 silicone and DowCorning DC93500 for fixating the cover glasses to the cells. As manufactured to Astrium and today's Airbus DS standard design no glue was applied in any of the cell gaps and no insulation barrier existed at the triple point.

During the EMAGS3 study the panel suffered as much as 1400 discharges, only about 10 % of them discharged more than half of the panel and only 10 the full area[12].

Without reliable data from before the experiment, the latest electrical performance measurements dating back 2006 and a completely removed electrical circuitry where only the basic functionality could be reestablished under reasonable effort, the chances of getting reliable measurement data to be compared with appeared to be incredible low.

Nevertheless, by rewiring the panel sections on a break out

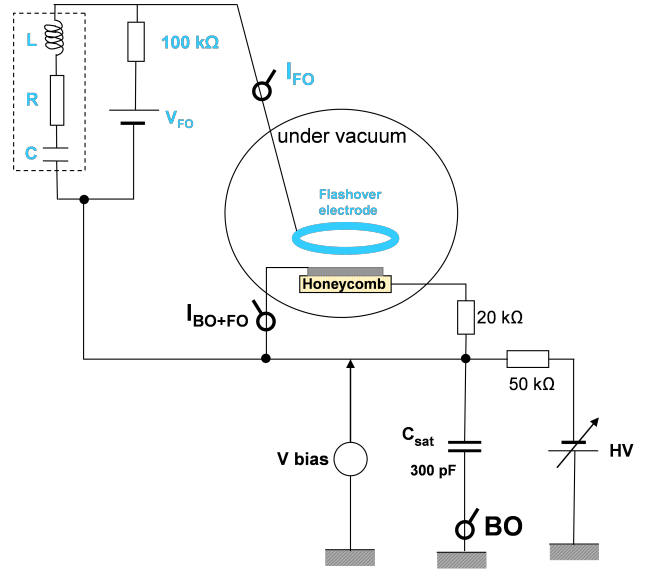


FIG. 2. Circuit for flash-over experiments[18]

box, barely restoring the electric circuitry, we performed the same measurements as in 2006 and to our enthusiastic surprise the IV-curves in fig. 5 fitted onto each other within 1 % at the characteristic points.

To support these encouraging finding a couple of samples on a panel structure like fig. 3 were prepared using solar cell assemblies (SCA) from both: Single silicon cells of same type as on the panel and 3G28 GaAs triple junction cells from AZUR Space, to be subjected to the flash-over generated by the proposed flash-over simulator to see if it has any effect on the cell performance and if it hence could be considered representative.

The experiments have been performed by ONERA at their facilities in Toulouse[18] using a circuit as described in fig. 2 designed to simulate the discharge of a whole panel. The coupons were placed in a vacuum chamber and the surface was charged by Argon plasma while being set at negative potential of up to -5kV to generate inverse potential gradient conditions. Above the coupon the flash over antenna was placed to gather any electrons emitted by the anticipated cathodic spot. To concentrate discharges on the area below the antenna, it was agreed to cover all other cell edges by insulating Kapton. Compared to the panel testing, were the cathodic spot nearly never occurred twice on the same cell, all the discharges were forced to happen on the 4 cm short edge of the cell. Thus one must consider these repeated discharges when comparing data to the real case.

In addition the parameter of the flash-over simulator, collected in table I, were chosen in a way to represent the envelope of all measured pulse forms, exceeding every worst case.

The electrical parameters of the components might appear a bit out-of-world compared to typical values for inductance and capacity of a panel. It must be recalled that the elements of the flash-over simulator represent no circuit element of the panel but the charged surface of the cover glasses and the part

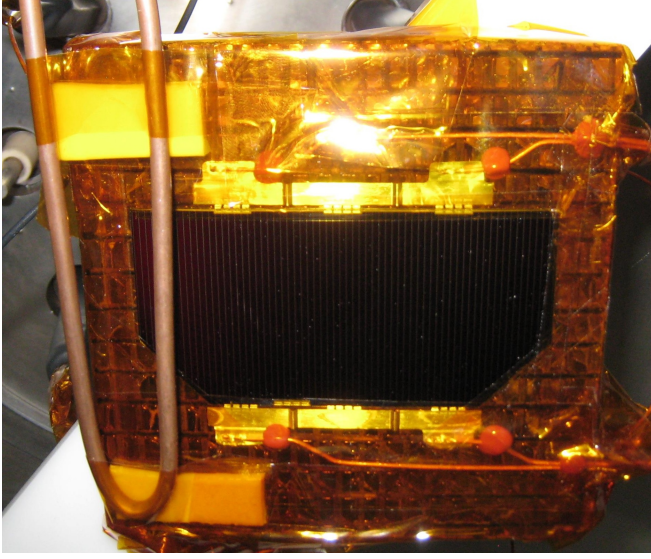


FIG. 3. Test coupon with AZUR Space Solar Power GmbH 3G28 GaAs triple cell in test chamber. The flash-over antenna is visible as a loop of copper strand

TABLE I. PARAMETER OF FLASH-OVER SIMULATOR

V_{bias}/V	500-800	900-1200	1300-1600	1600-2000
L/H	$6 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$
R/Ω	80	120	160	200
C/F	$3 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-6}$
V_{FO}/V	700	1100	1500	1800

of the circuit of the flash-over that is closed over the vacuum by the discharge itself. Especially the inductance has to be considerably high to spread the discharge of the capacitor to the desired duration.

Fig. 4 shows, respectively, a minimal, typical and maximal flashover current transient generated by the flash-over simulator during this tests.

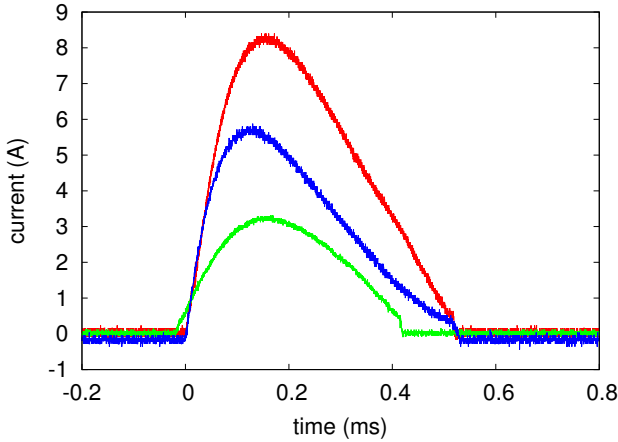


FIG. 4. Typical flash-over current transients

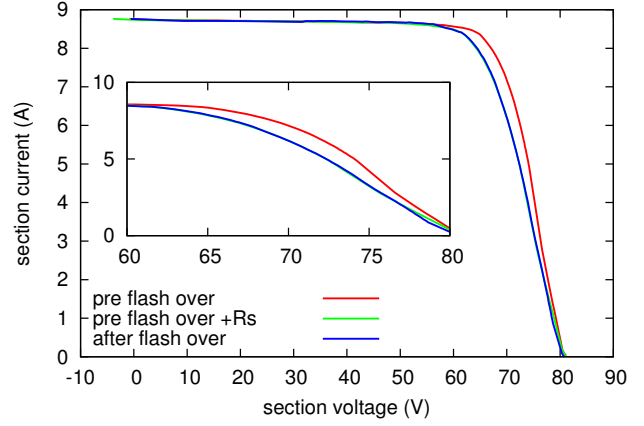


FIG. 5. IV Measurement on full section under one sun illumination. The inset gives a closer look to the right portion of the curve showing the effect of serial resistance of 0.35Ω associated with the additional cabling.

The characteristic parameters of the transients generated were an average peak current value of (5.3 ± 1.7) A on the GaAs cell and (5.1 ± 1.2) A on the silicon cell and an average duration of $(500 \pm 100) \mu s$ on both.

III. ANALYSIS AND DISCUSSION

A. Panel

The current voltage (IV) curves measured (long!) before the experiments almost lie on top of the newly measured – at least for the horizontal part of the curve. And we have to consider the different cabling and a lot of additional interconnectors in the circuit. As shown in fig. 5 the effect of 5 m additional cable having a resistance of 0.35Ω added to the measured data before test was sufficient to improve the correspondence to a perfect reproduction of the performance data before the test.

B. Coupon

On the first glance the results appeared inconclusive: On both cells, there was no degradation in filling factor as it would be suspected if shunts were created, but current was reduced by about 1.4 % as in fig. 6. The dark IV curve of the GaAs cell fig. 7 shows no shunt at all, whereas on the silicon cell in fig. 9 a weak shunt of about 139Ω was created and could also be derived from the slope in fig. 8 but could not account for the loss in short circuit current. From dark IV-measurements in fig. 10 taken during the experiments after every 20 ESD inception we knew, that the shunt must have been generated after 40 and before 60 flash-over inceptions. Since the shunt resistance was stable before 40 and after 60 ESD, we deduce, that it has been generated most likely by one single event. Fig. 11 shows a chip out in the cover glass and a small disturbed area

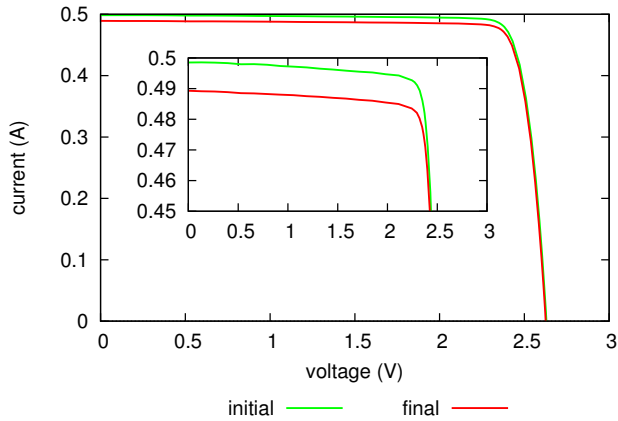


FIG. 6. IV curve of GaAs triple cell under one sun illumination. The inset shows a close up of the current branch.

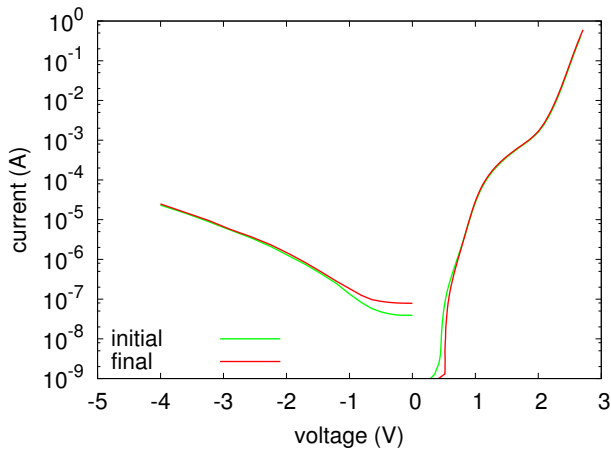


FIG. 7. Dark IV curve of GaAs triple cell

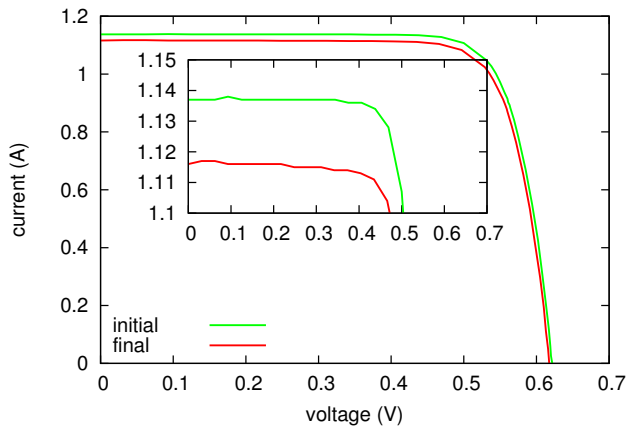


FIG. 8. IV curve of Si cell SCA under one sun illumination. The inset shows a close up of the current branch.

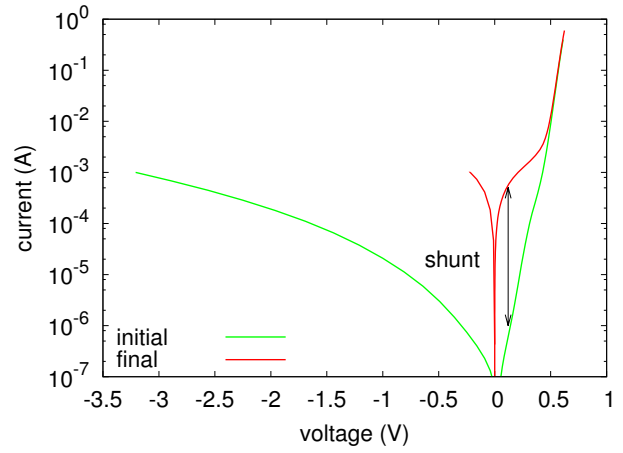


FIG. 9. Dark IV curve of Si cell SCA

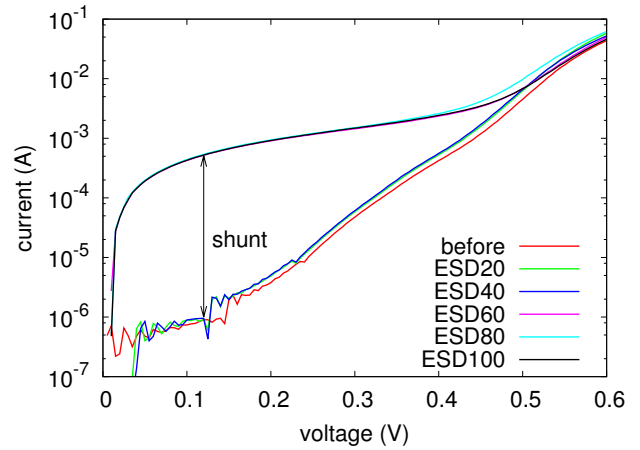


FIG. 10. Dark IV curve of Si cell SCA during ESD experiments

that might present the corresponding cathodic spot. But since this shunt cannot affect the short circuit current there has to be another cause for the observed reduction of current. A closer look to the surface of the tested silicon cell reveals degraded coating on about two thirds of cover glass. Considering du-

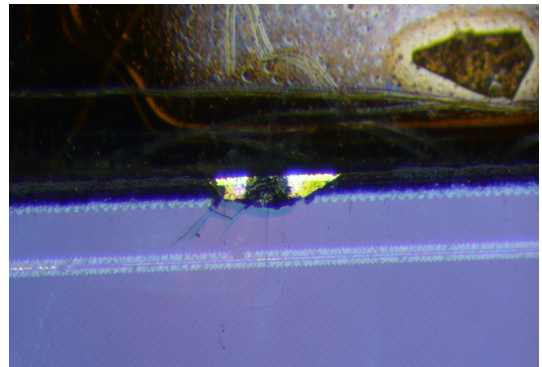


FIG. 11. Cathodic spot on Si cell

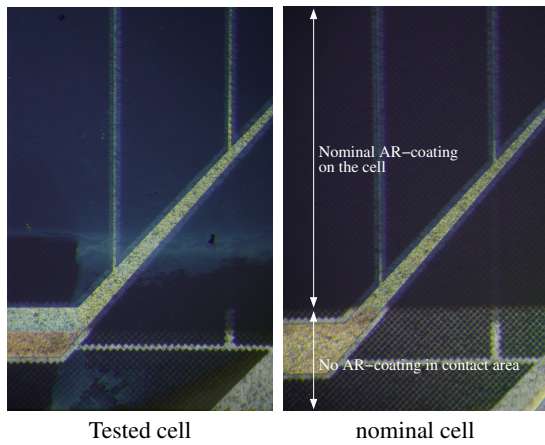


FIG. 12. Surface of Si SCA

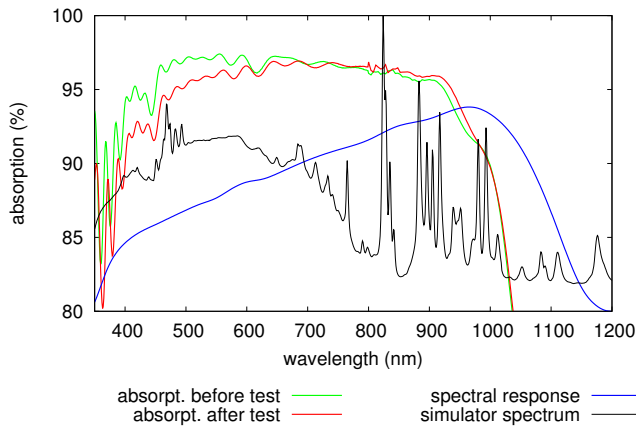


FIG. 13. Optical properties of Si cell SCA

ration of the exposure and density of the Ar plasma during the test together with typical sputtering rates, one would not expect a detectable sputtering of the coating.

In fig. 12 the tested cell shows a blurry fog on some parts compared to the dark sight of an unaffected one. By measuring absorption of the cells before and after the test, on both cells a slight decrease of absorption can be observed in the short wavelength part.

If we integrate the absorption with the spectral properties of the light source (a solar simulator) and the spectral responsivity of the cell, shown in fig. 14 and 13, the loss in absorption of 0.93 % for the GaAs cell could account for the loss in short circuit current that was measured. The silicon cell however shows loss of absorption of 0.41 % only, that appears too low to fully understand its loss in short circuit current.

One explanation could be the blurry appearance of the cover glass surface shown in fig. 12 that might reduce transparency to the lower cell without reducing absorption.

In any case, the degradation of the silicon cell is not ruled by a shunt, which would be the expected effect of ESD induced damage – but by a reduction of converted photons. In addition it occurred after 40 sever ESD events that would have

been equivalent to the discharge of a 8 square meter panel!

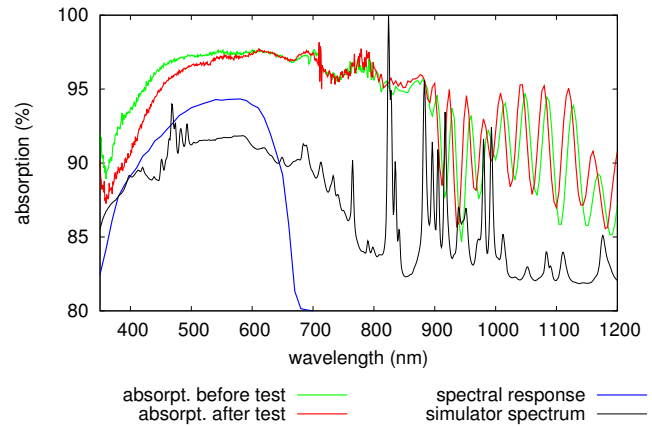


FIG. 14. Optical properties of GaAs triple cell SCA. Only the top cell as the current limiting cell has to be considered

Observations of discharges of this dimension was seldom all through the EMAGS3 experiments. And in contrast to the panel, were these discharges occurred on different places, they all occurred on the same edge of the same cell.

IV. CONCLUSION

Electrostatic discharges on solar generators in space are discussed as one of the major hazards to satellite missions, especially in geostationary orbits.

After having produced virtually hundreds of flash-over on a representative 2 by 4 meters panel, the electrical performance was not affected within measurement accuracy.

Further experiments on single cells and using a flash-over generator support this observation even under most sever – and unrealistic – conditions. Even though a silicon cell suffered from a small shunt after more than 40 flash over events, from the evidence of the IV curve we exclude shunting by ESD damage as the main cause of degradation. Especially the loss in short circuit current without significant loss in filling factor implies another root cause that may be found in the loss of absorption together with a more opaque surface.

ACKNOWLEDGMENTS

I want to thank the huge team from ONERA that performed the experiments in frame of EMAGS3 study spending 10 days at Ottobrunns iABG test facility while performing 8 hour shifts back-to-back around the clock, together with the team of iABG. Thanks to ESA for funding the EMAGS3 study [12]. Thanks to Marc, who pressed long enough to perform the final measurements on the panel. I would like to thank all my colleagues who have been working on the panel while by any step destroying part of their previous work!

The few results presented herein would not have been possible without their precise and dedicated work!

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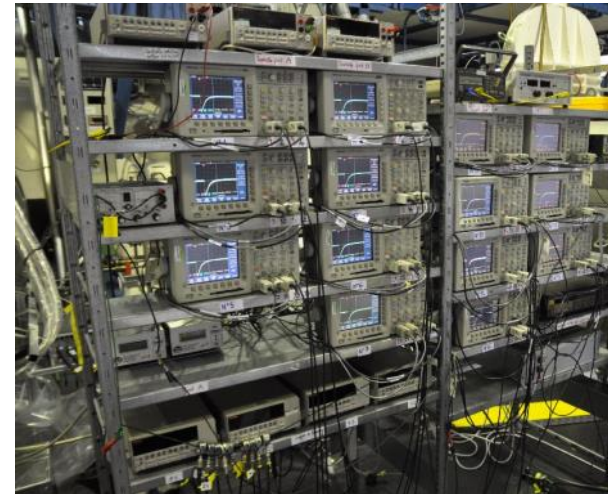
A follow-up from EMAGS3
#123

Andreas Gerhard, Wiebke Steins
Jean-Michel Siguier, Virginie Inguibert, Pierre Sarrailh, Marc Sevoz, Carsten Baur
Astrium, ONERA, ESA

EMAGS3: "Flash over on the big panel"

Tasks of the study:

- Inducing 1400 flash over on a standard 2x4m² panel
- Detecting pulse shape of more than 550 flash over
- Defining flash over simulator for ESD test on coupon level
- No measurement of degradation



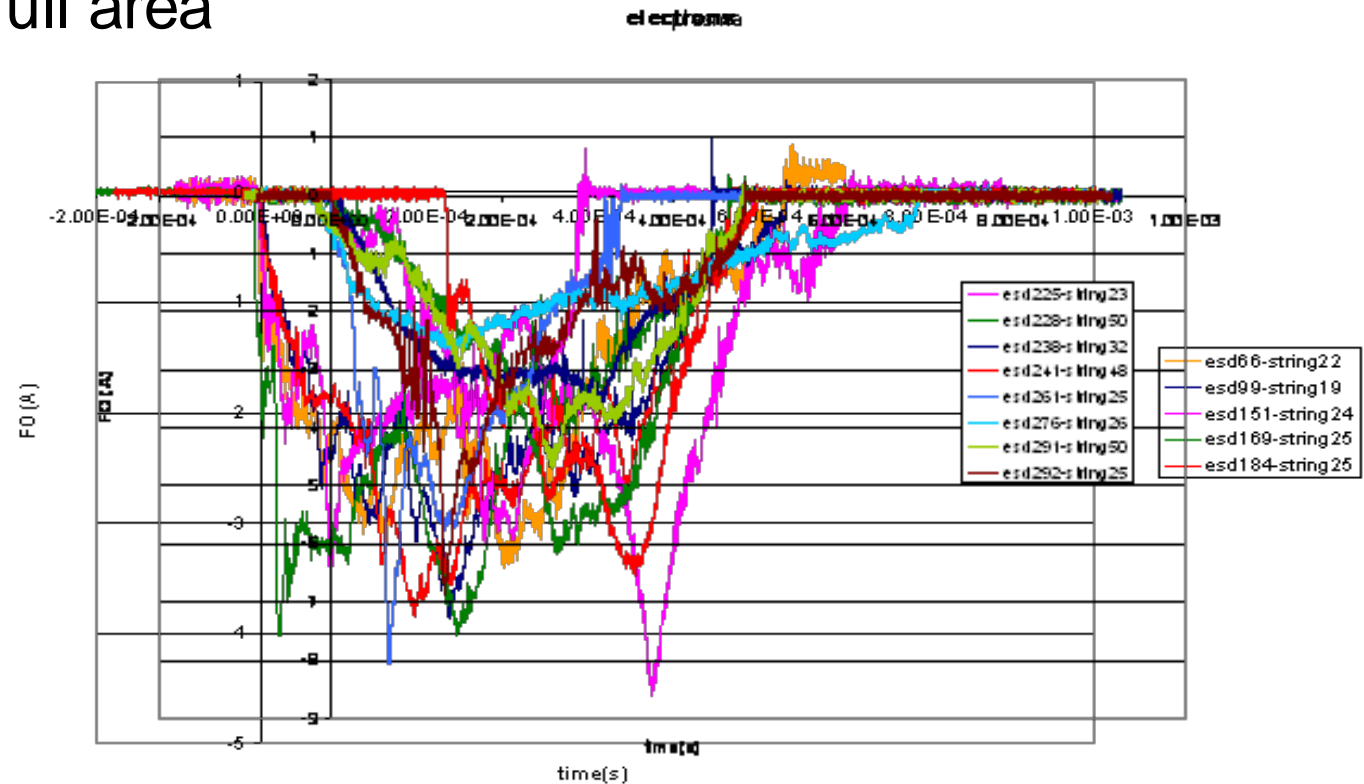
EMAGS3: "Flash over on the big panel"

Type of panel:

- Silicon cells: 2wiTHI-ETA3 from AZUR Space Solar Power GmbH
- Laydown: Wacker RTV S691 silicone
No glue in the gap!
- Cover Glass: Qioptic CMX100 AR/IRR
- SCA: DowCorning DC93500

EMAGS3: Characteristic of ESD

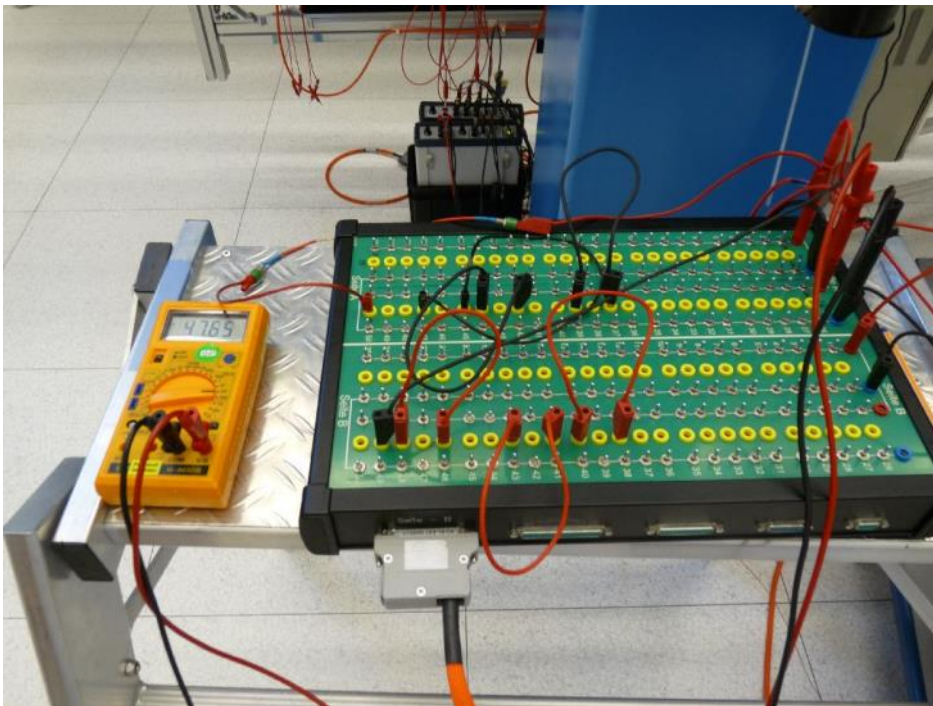
- About 1400 flash over registered
- Some 10% discharged full area
- Max current: 8A
mean: about 5A
- Max duration: 800 μ s
typical: 500 μ s



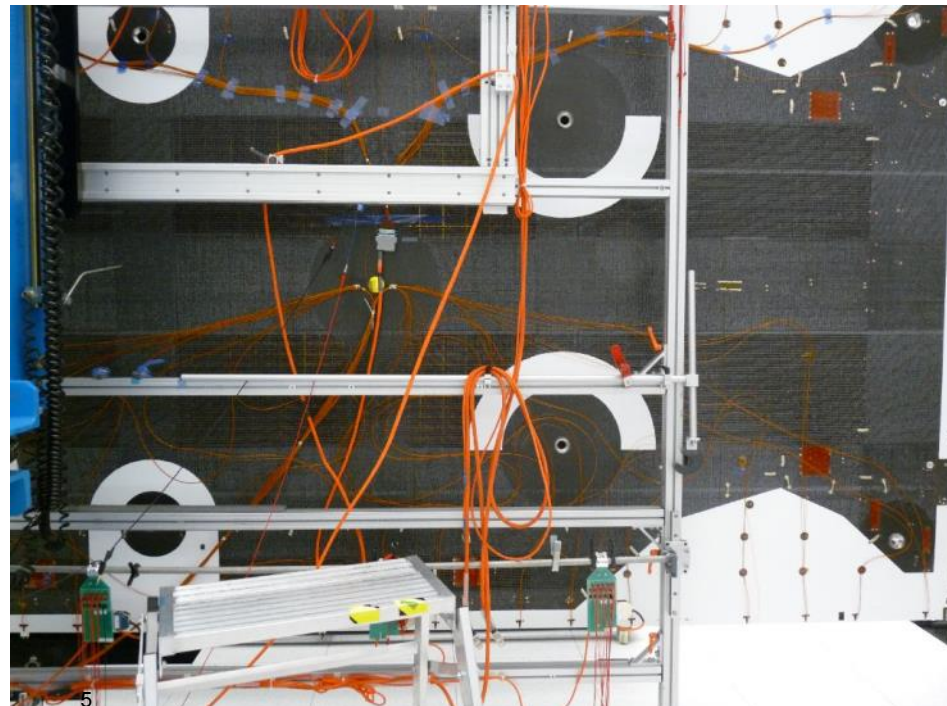
Virginie Inguibert, Pierre Sarrailh, J-C Mateo-Velez, J-M Siguier, Carsten Baur, Bernard Boulanger, Andreas Gerhard, Patrice Pelissou, Marc Sevoz, and Denis Payan, "Measurements of the flashover expansion on a real-solar panel—preliminary results of emags3 project," IEEE Transactions on Plasma Science 41, 3370–3379 (2013).

Re- measurement

- Panel manufactured 2002
 - Last electrical performance dated 2006 (before storage)
 - All circuit removed for ESD detection
- Circuit had to be restored to measure performance after ESD

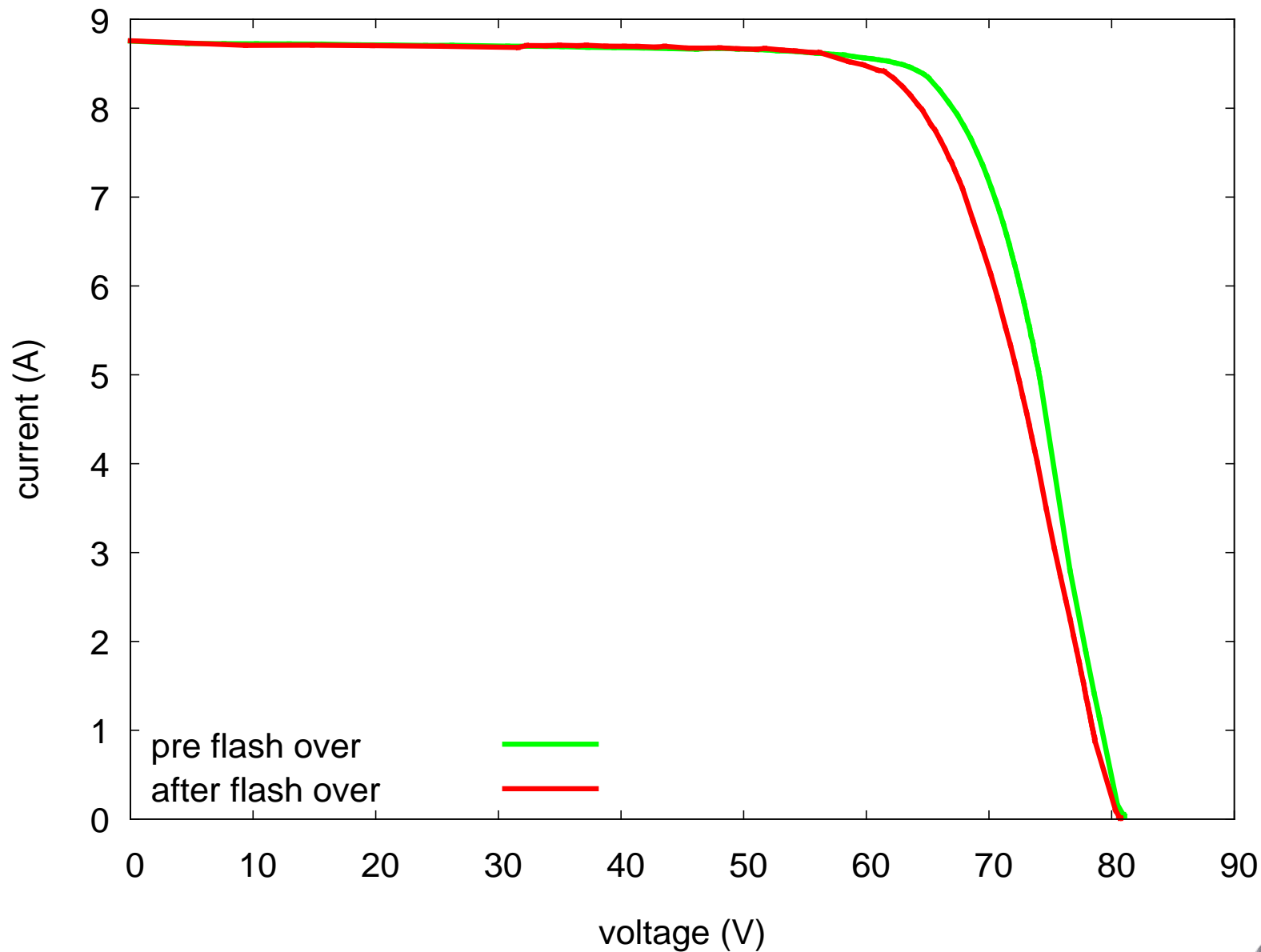


10 July 2014

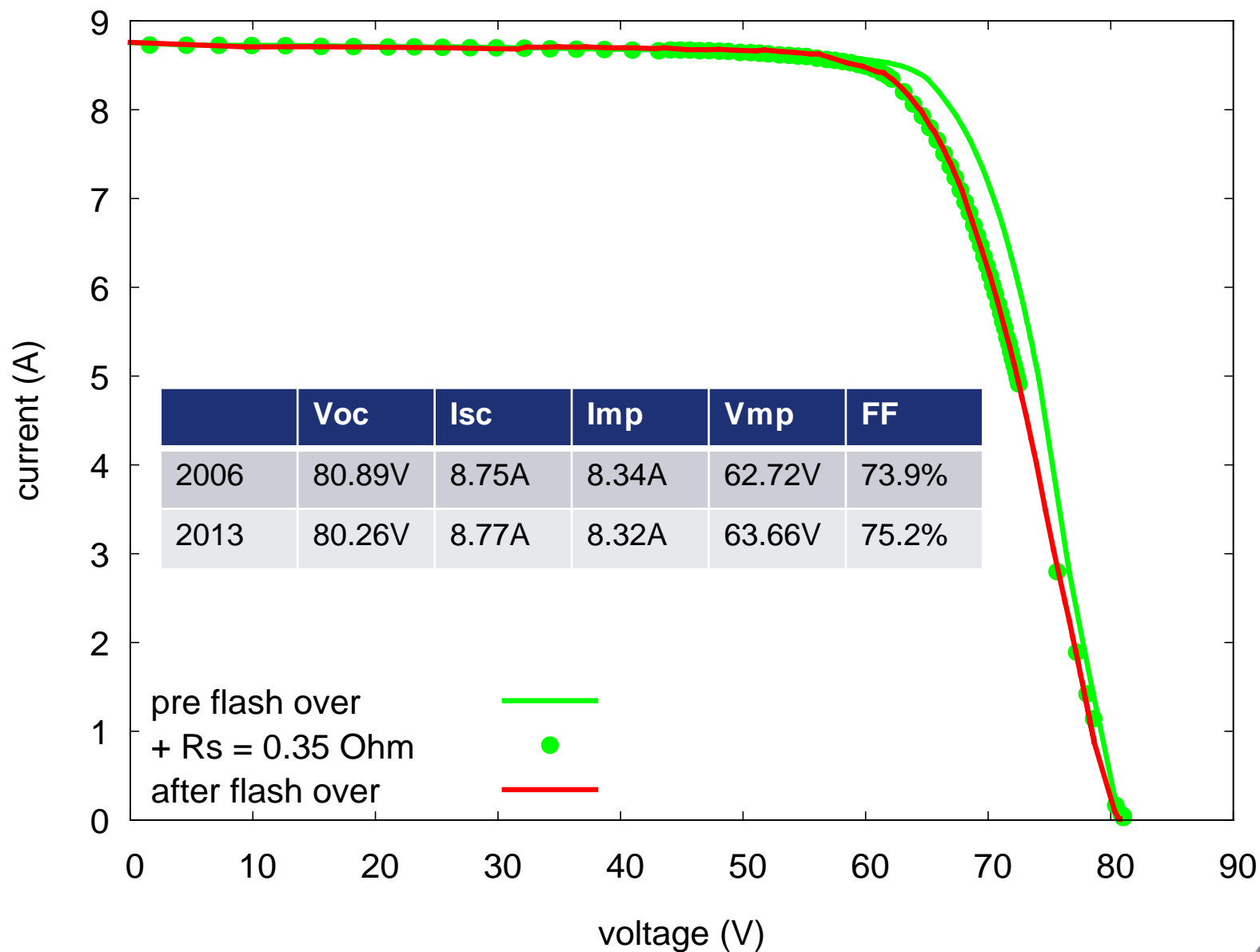


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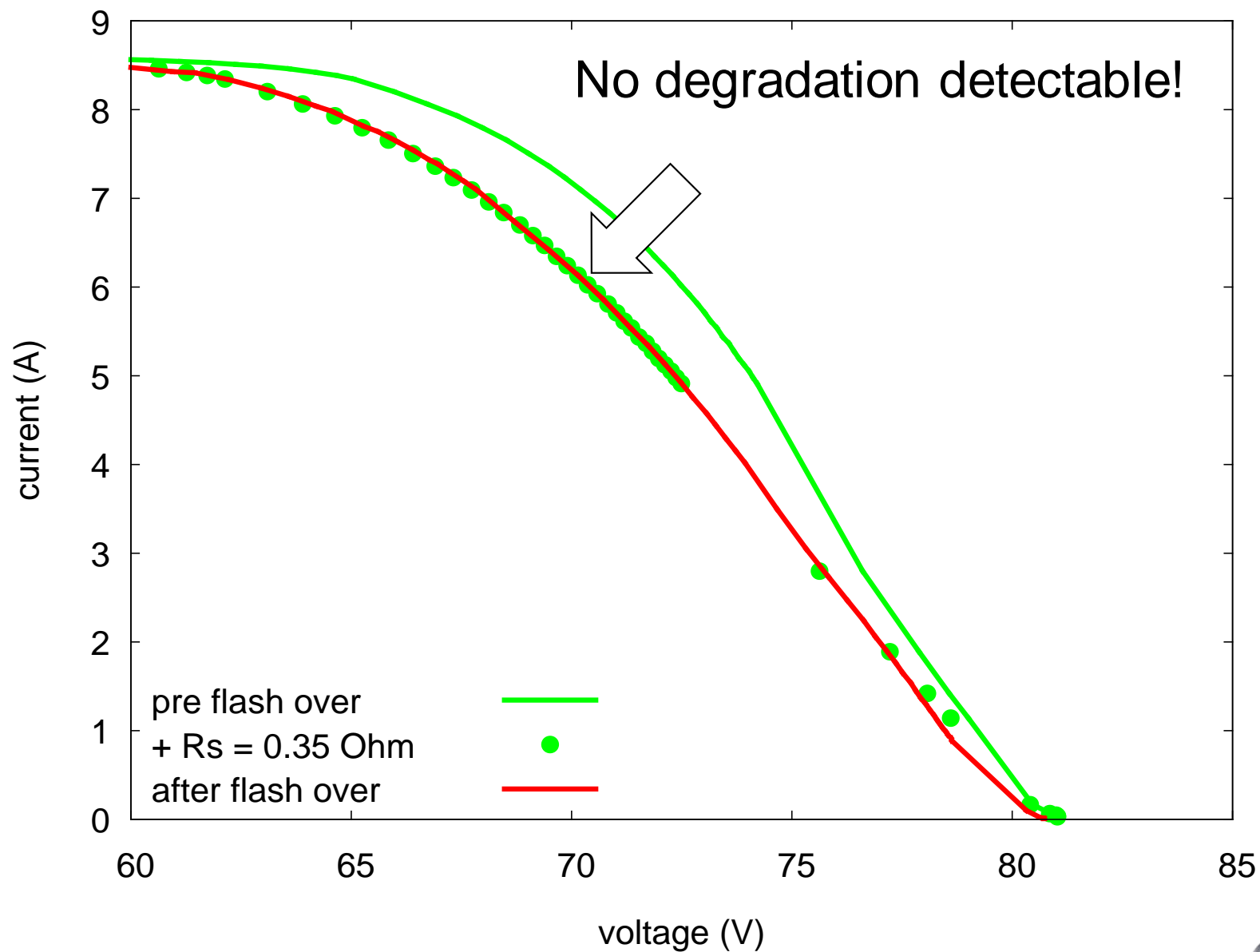
Electrical performance



Electrical performance



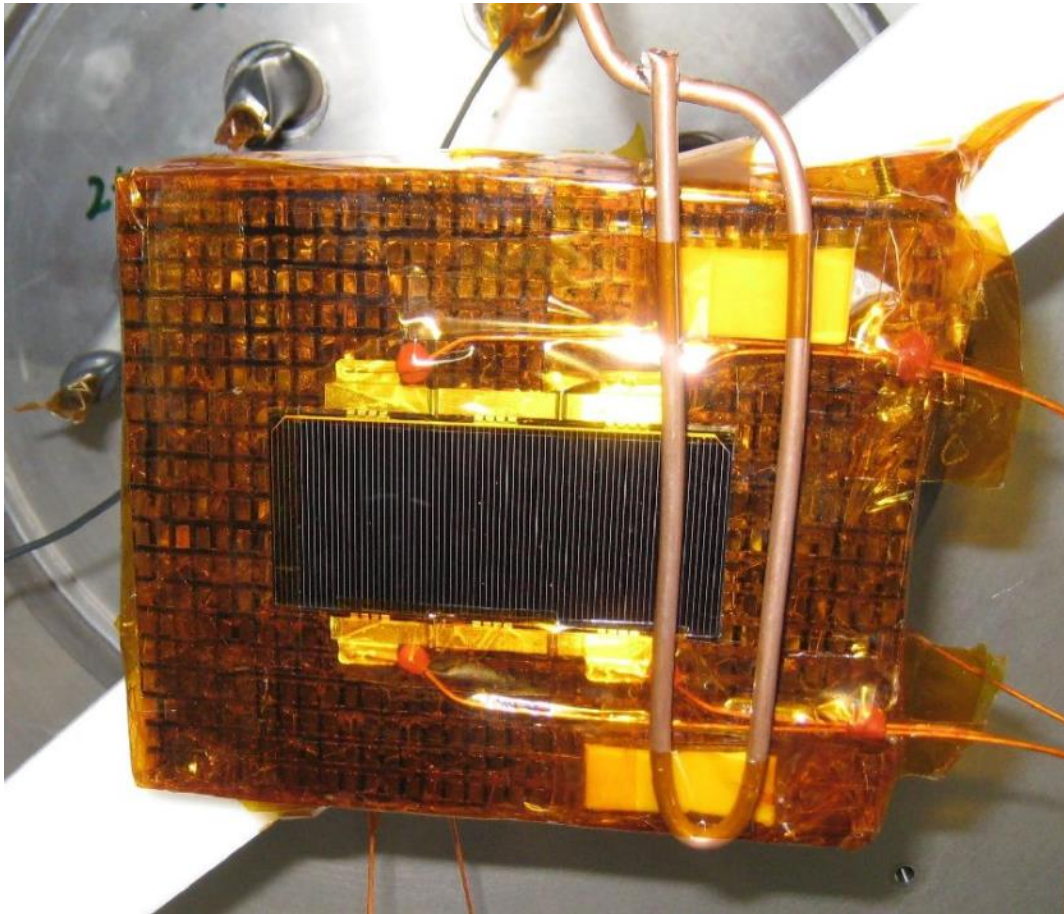
Electrical performance - Detail



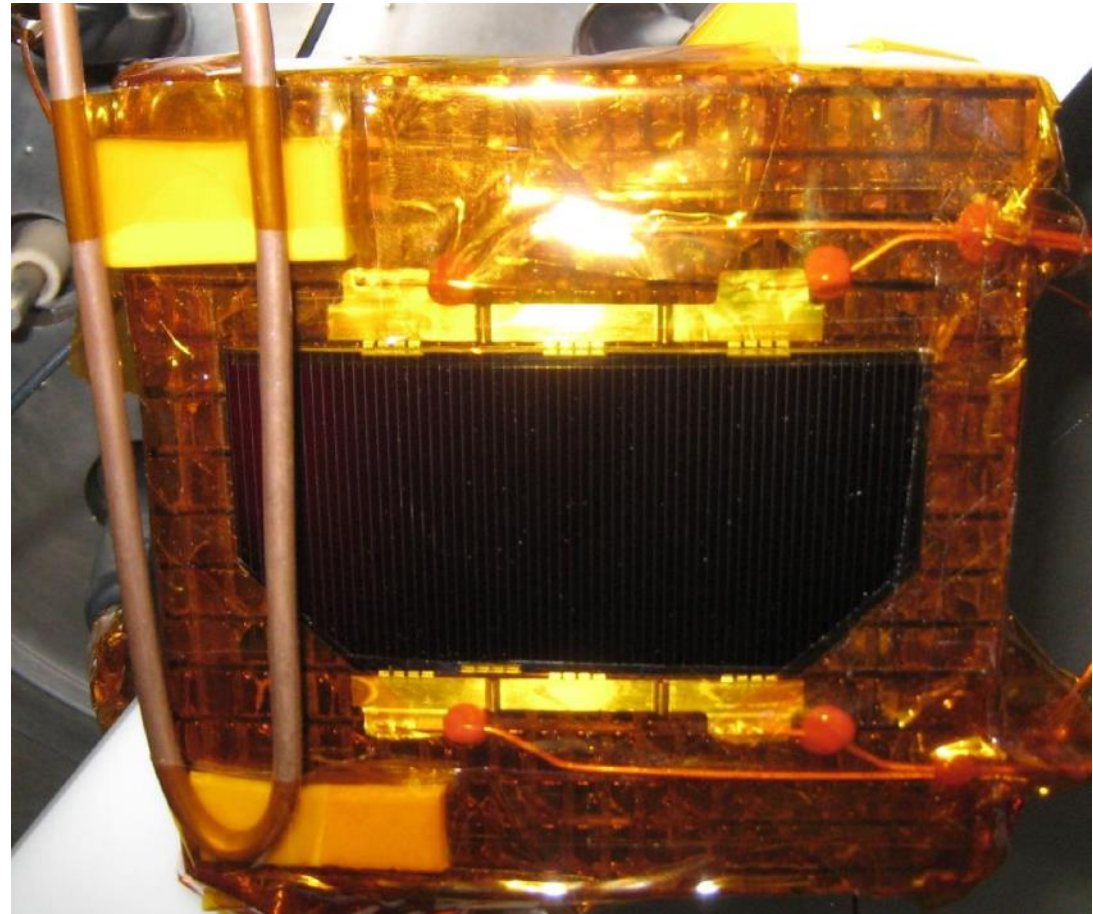
Coupon test

So far: Silicon cells
What about triple junction cells?

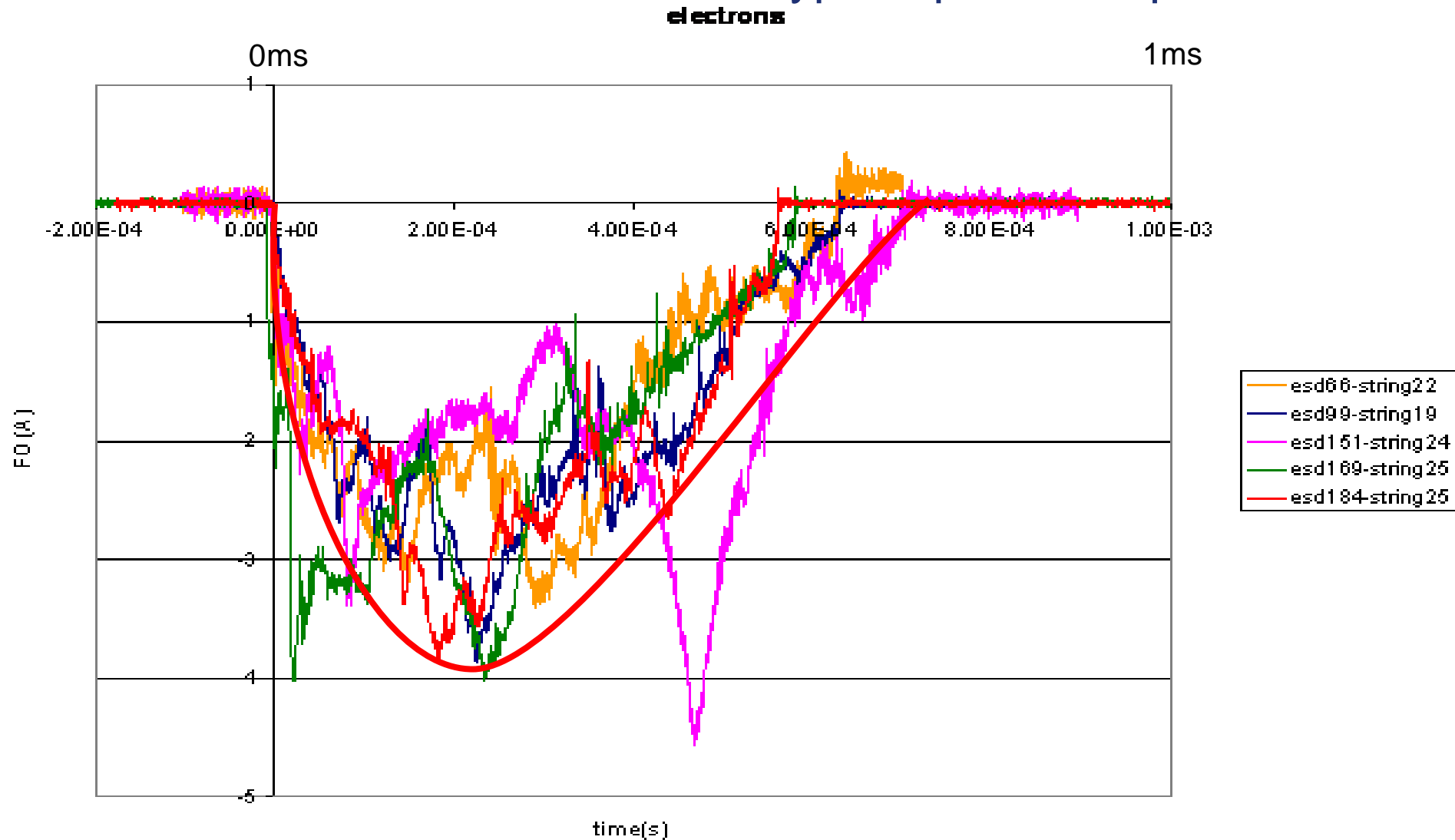
2wiTHI-ETA3 silicon



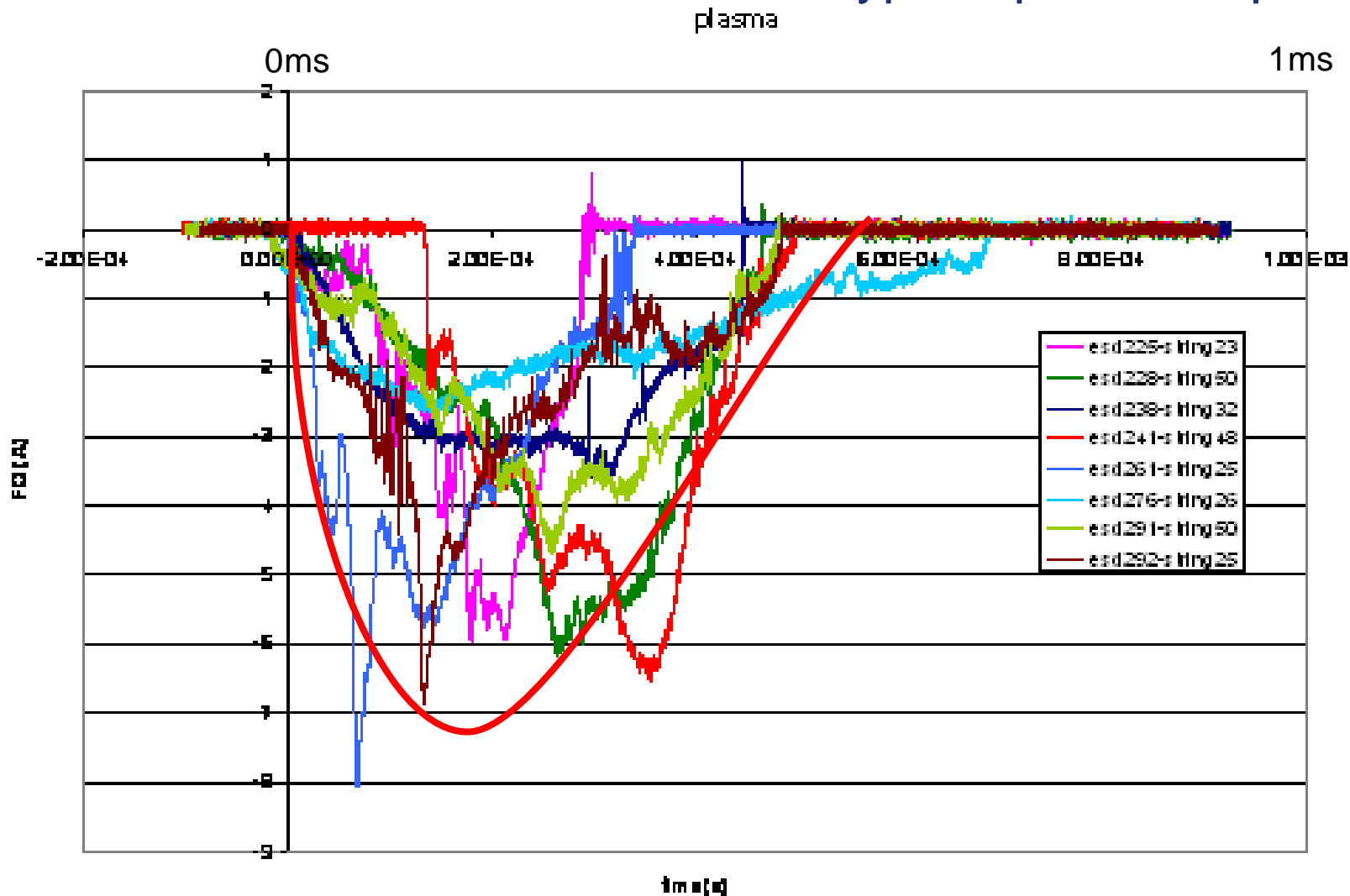
3G28 triple junction GaAs



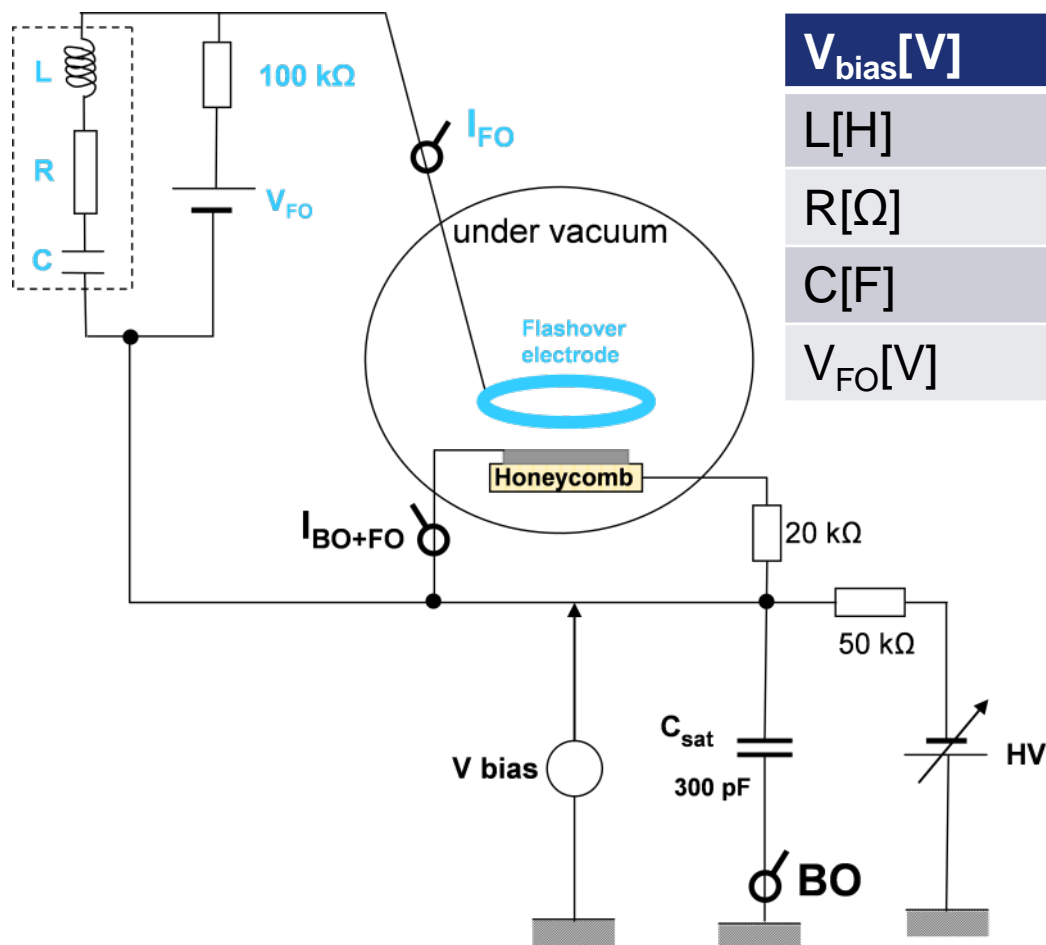
Flash over simulator: What's the typical pulse shape?



Flash over simulator: What's the typical pulse shape?

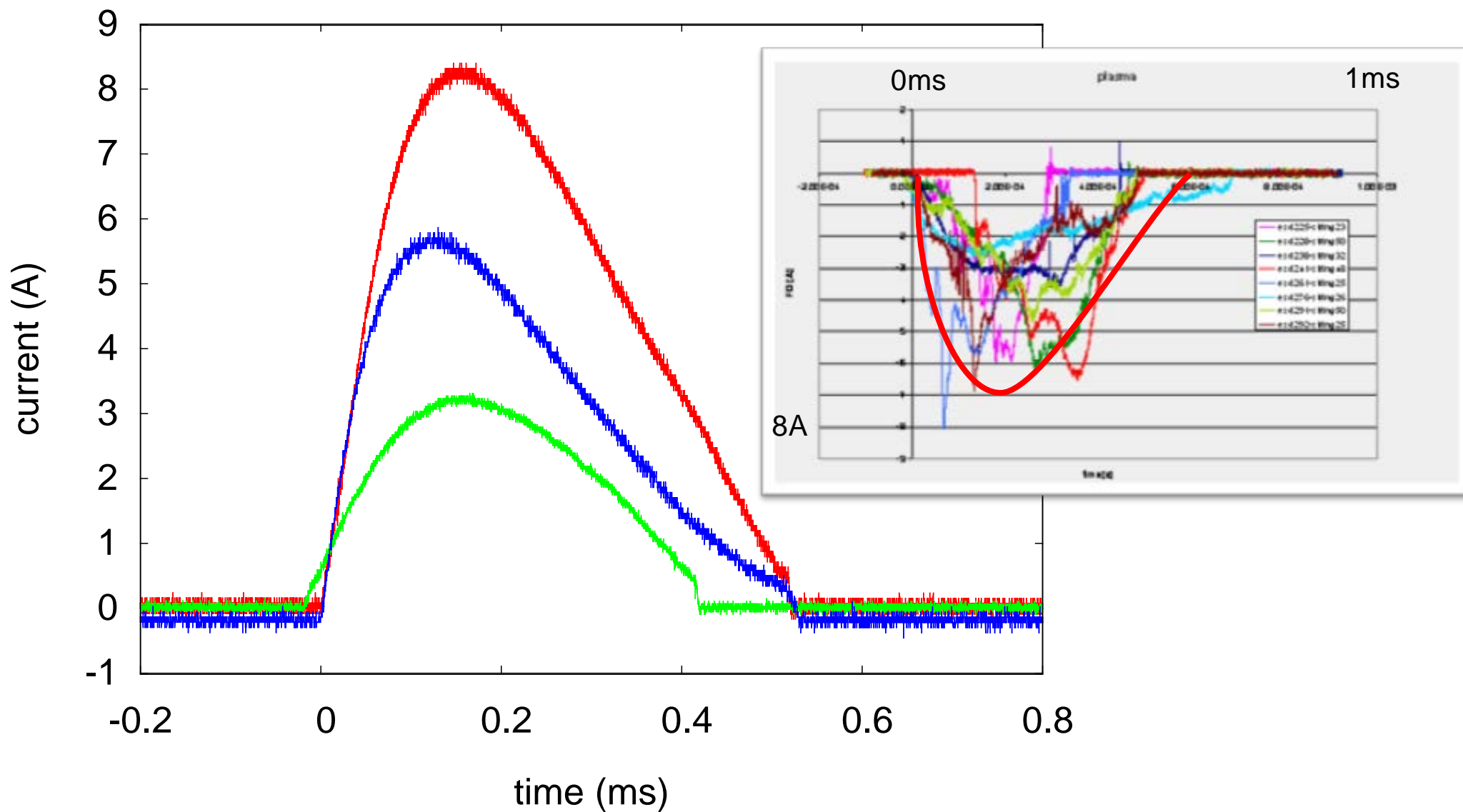


Flash over simulator: Circuit

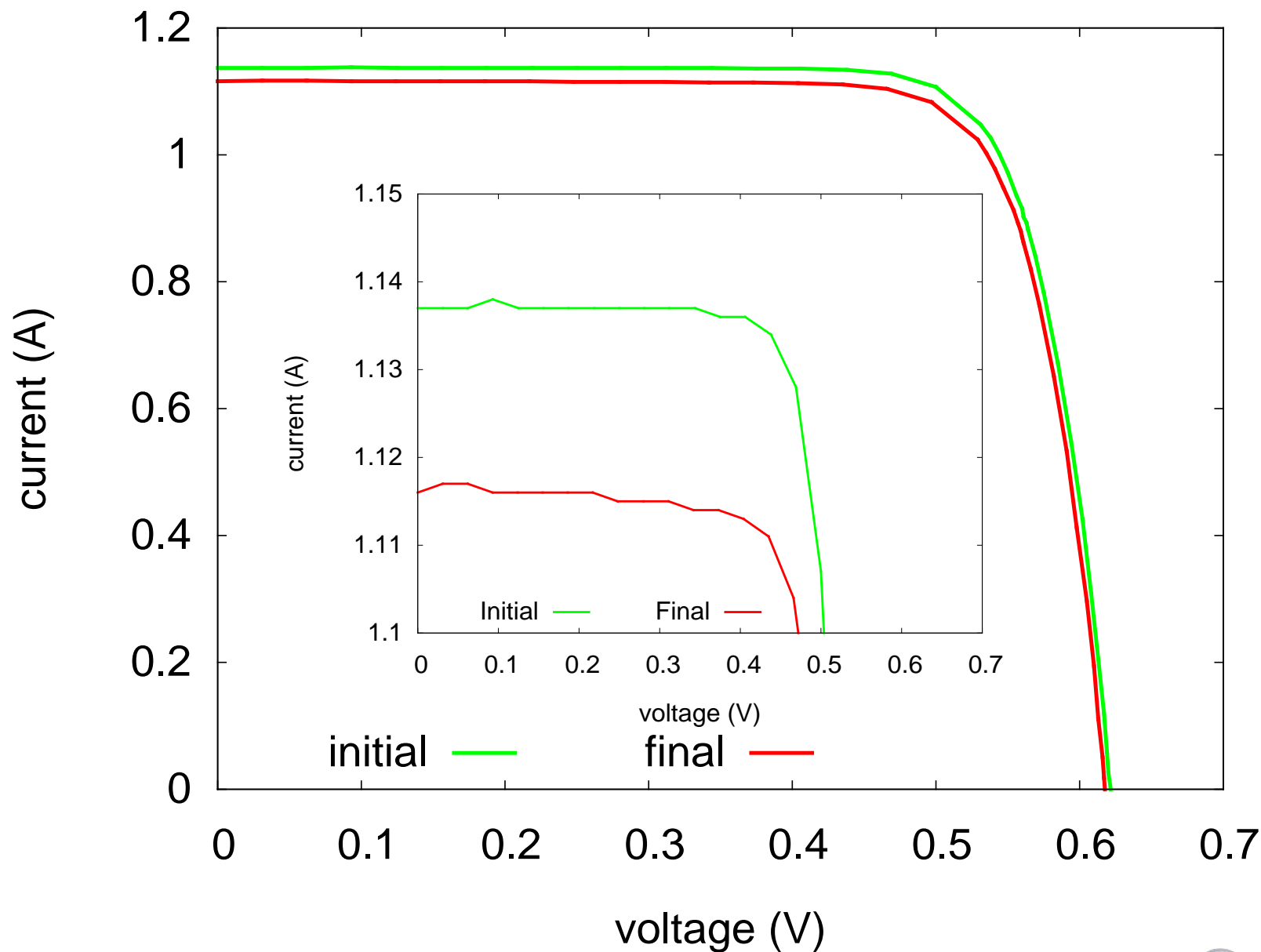


$V_{bias}[V]$	500-800	900-1200	1300-1600	1600-2000
$L[H]$	6×10^{-3}	1×10^{-2}	1.3×10^{-2}	1.3×10^{-2}
$R[\Omega]$	80	120	160	200
$C[F]$	3×10^{-6}	2×10^{-6}	1.5×10^{-6}	1.2×10^{-6}
$V_{FO}[V]$	700	1100	1500	1800

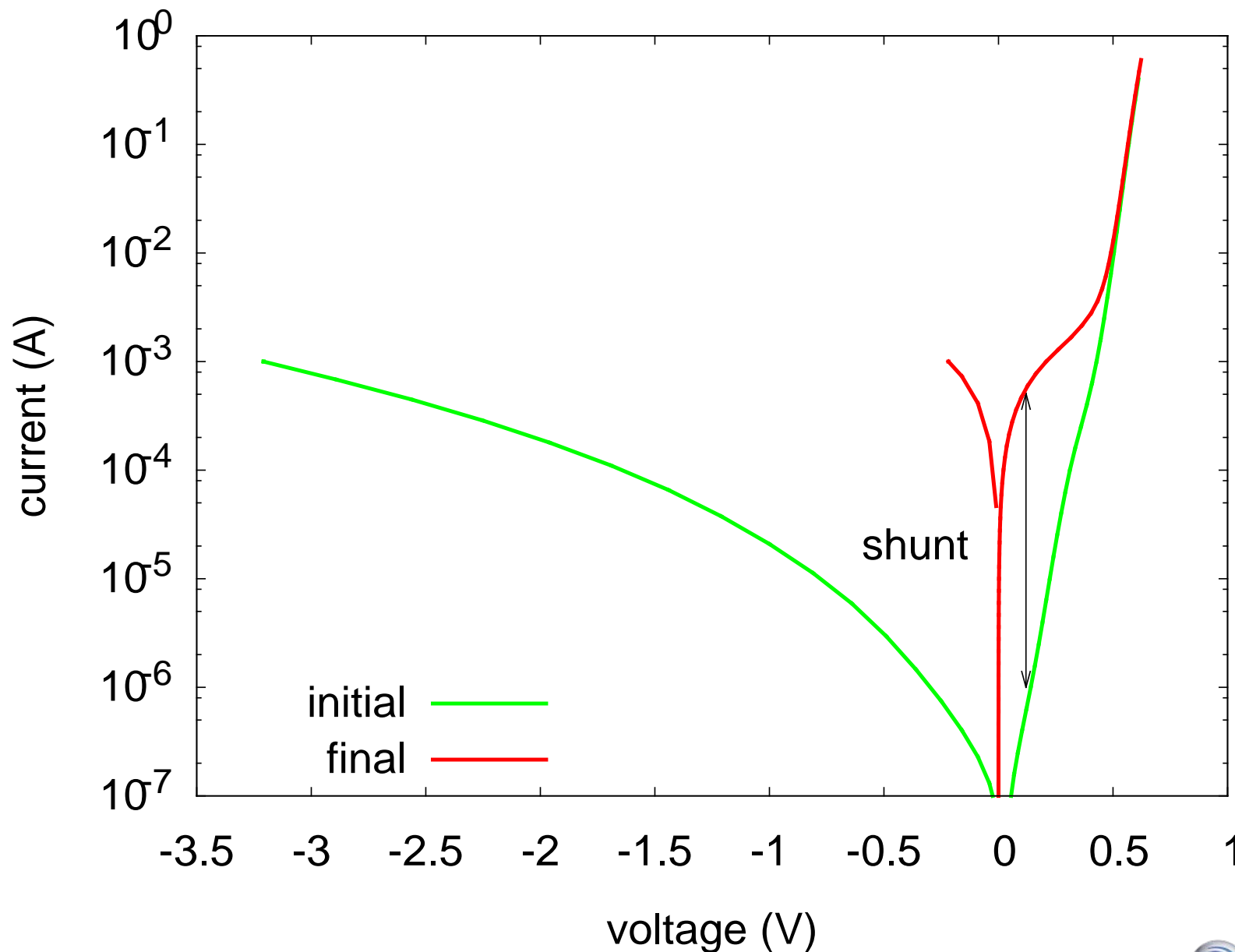
Flash over simulator: Pulse form



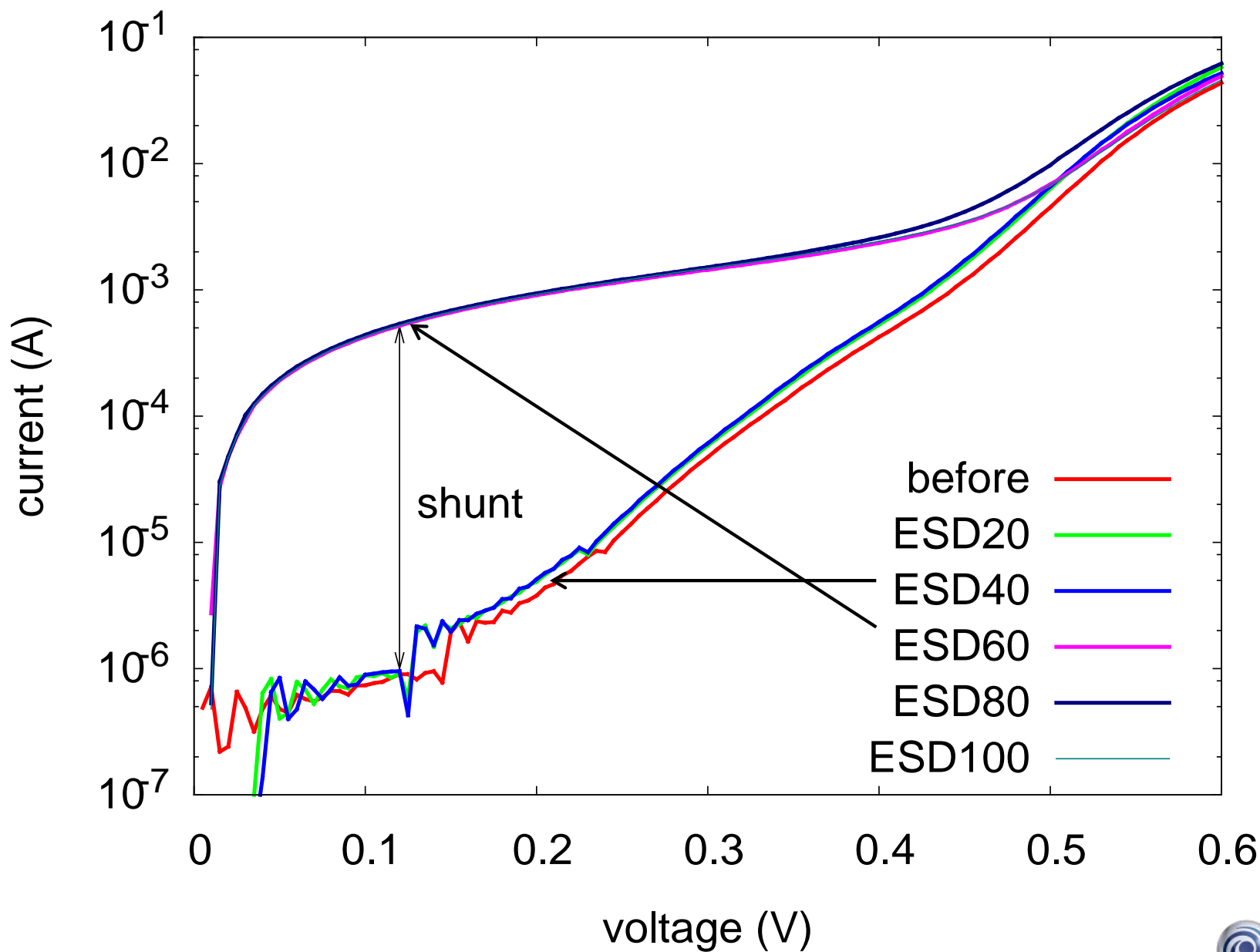
2wiTHI-ETA3: Degradation in efficiency



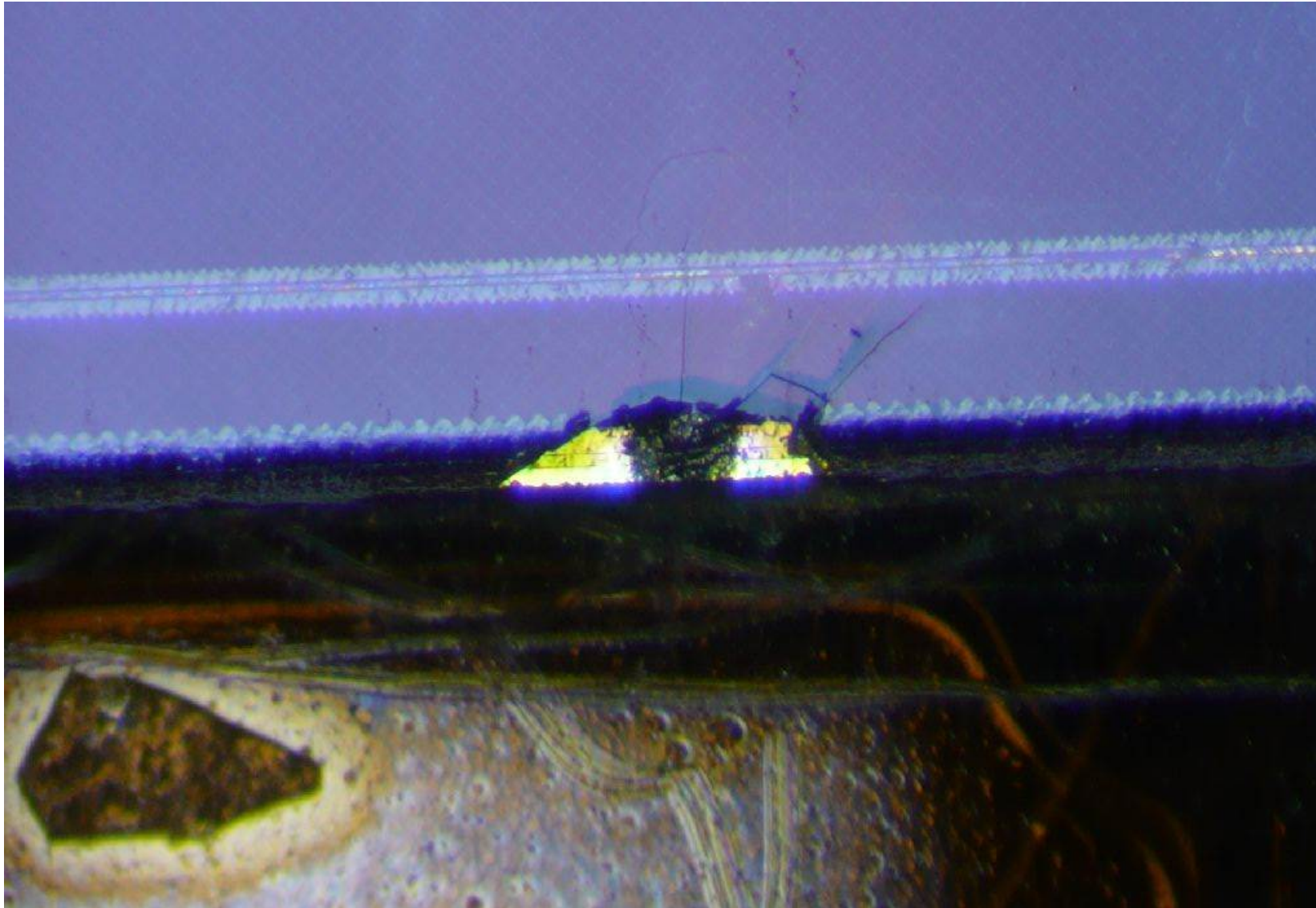
2wiTHI-ETA3: Dark characteristics



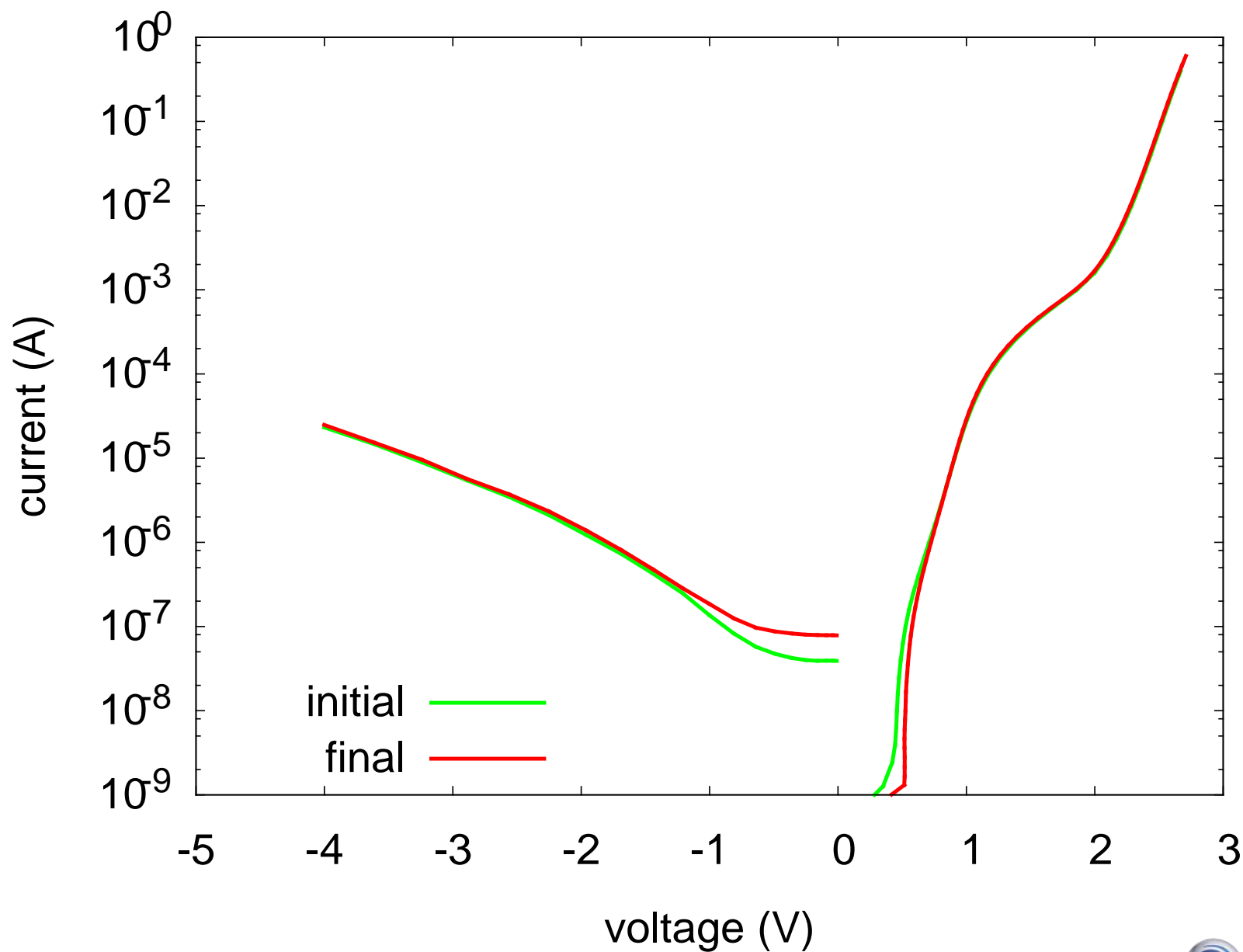
2wiTHI-ETA3: Dark characteristics during test



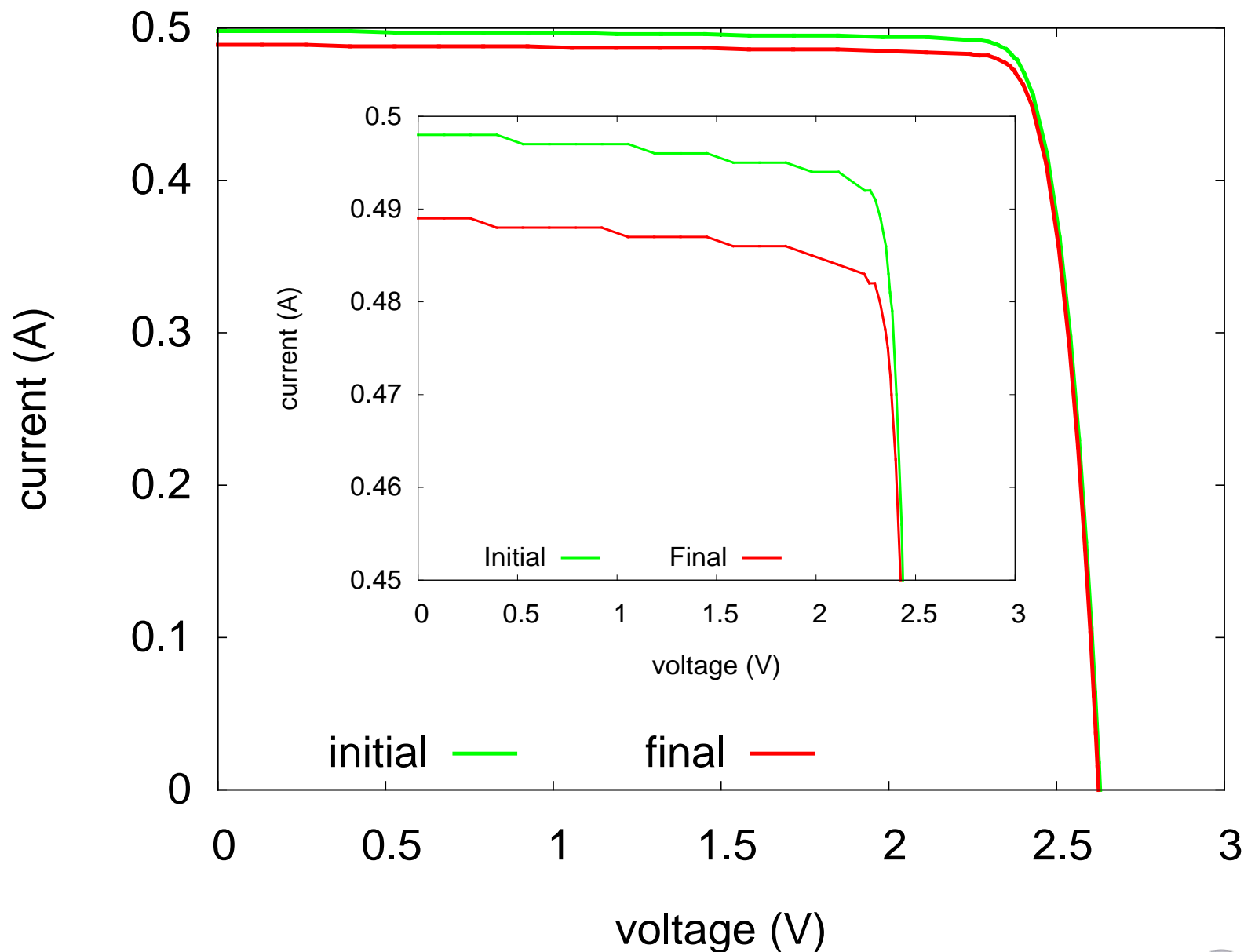
2wiTHI-ETA3: Cathode spot



3G28: Dark characteristics

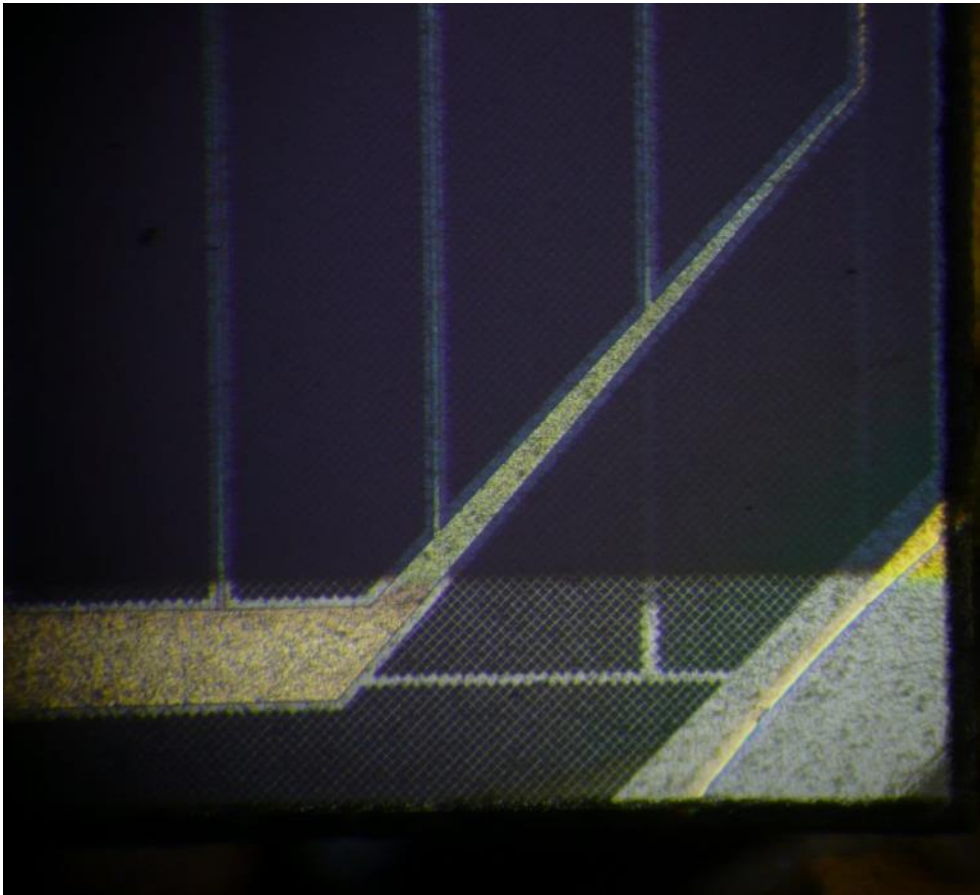


3G28: Degradation in efficiency - not in filling factor!

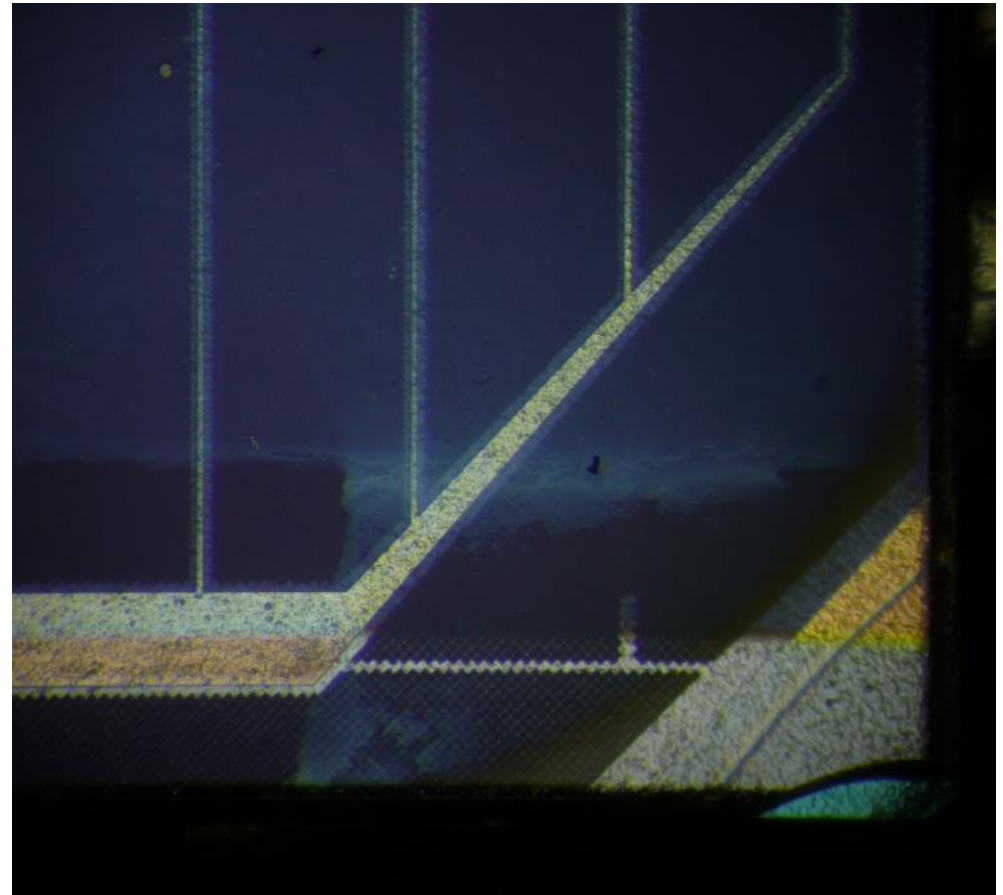


3G28: Degradation of AR coating

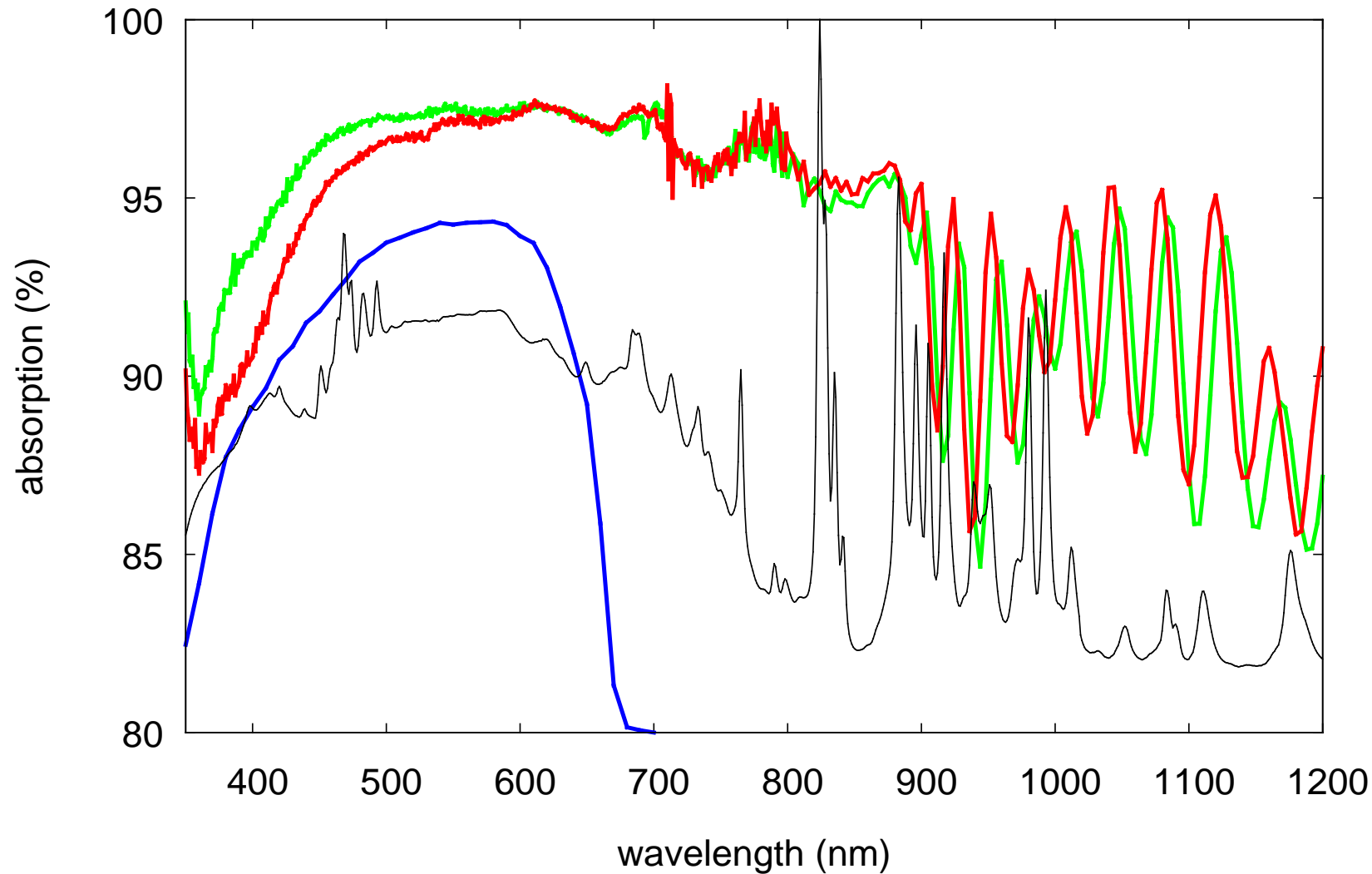
New cell



After experiment



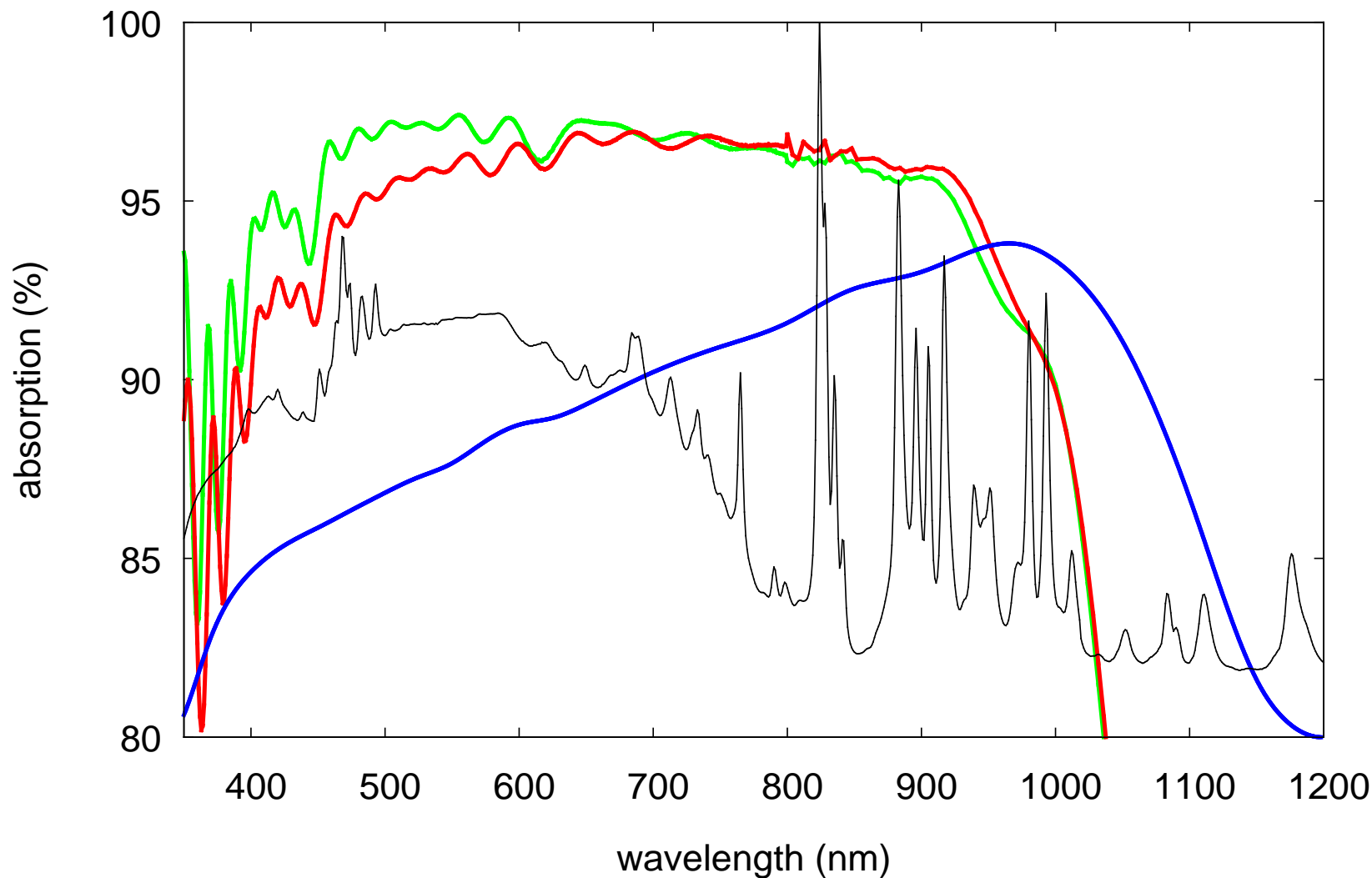
3G28: Degradation of AR coating



absorpt. before test —
absorpt. after test —

spectral response —
simulator spectrum —

2wiTHI-ETA3: Degradation of AR coating



absorpt. before test —
absorpt. after test —

spectral response —
simulator spectrum —

Conclusion

- No degradation of a real panel suffering 1400 flash over (some 10% of them full area!)
- Flash over simulator performed as expected
- Coupon experiments showed degradation in current only (not by shunting but change of optical properties)
- Small shunt on silicon cell after 40 flash over

Outlook

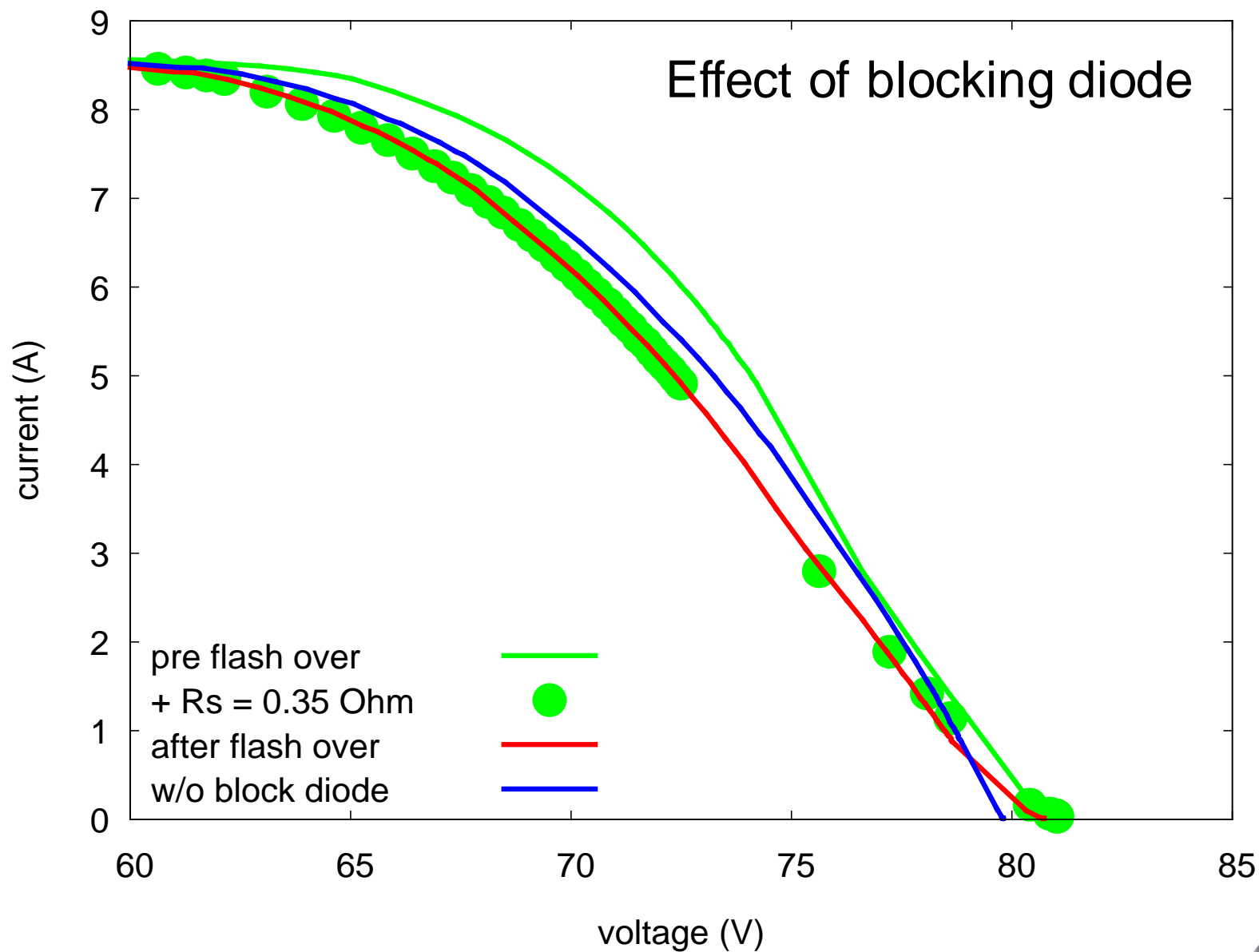
- Need for better statistics on coupon level
- Identify root cause for optical degradation
- Explore effect of flash over simulator on secondary arcing experiments

Thanks to

- Team of ONERA performing EMAGS3 study
- Team of iABG
- ESA for funding EMAGS3 (ESTEC Contract No. 22771/09/NL/GLC)
- Marc for pressing long enough to perform the final measurements on the panel.
- All my colleagues at Astrium for re-working and re-re-working the panel

...and thank you!

Electrical performance - Detail



Electrical performance

