Device and method for a precise breakdown voltage detection of APD/SPAD in a dark environment

2nd International SPAD Sensor Workshop

Alexander Zimmer
Daniel Gäbler
X-FAB Global Services GmbH
8th – June 2020

Outline

- Motivation
- Technical issues on breakdown voltage measurement
  - Characterization
  - Application
- Functionality principle & simulation study
- Characterization results
- Conclusions

Outline

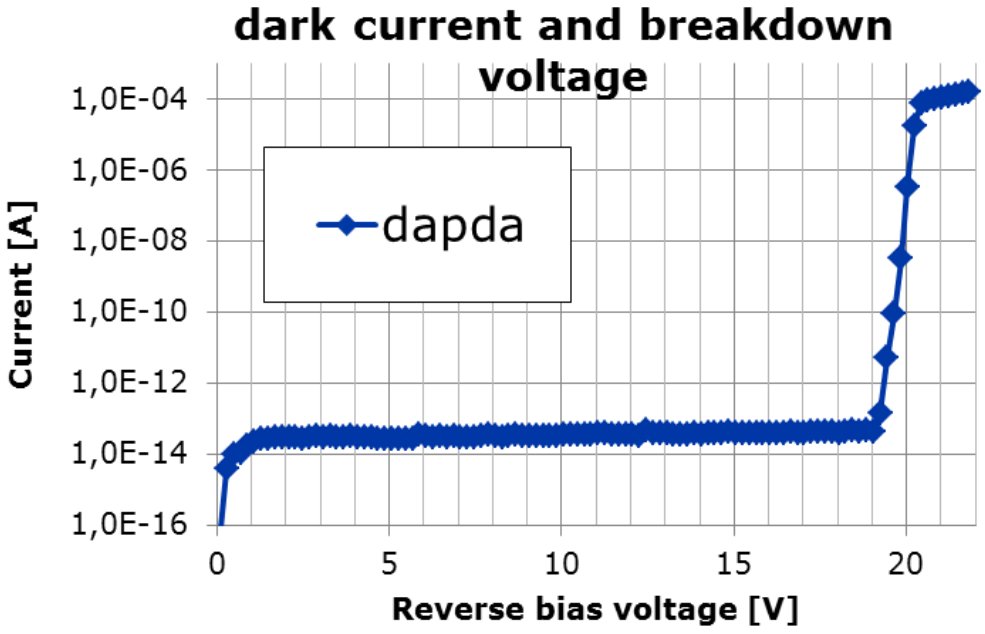
- Motivation
- Technical issues on breakdown voltage measurement
  - Characterization
  - Application
- Functionality principle & simulation study
- Characterization results
- Conclusions

Motivation

- What should be the objective of this talk?
  - Is it worth to talk about the device characterization of breakdown voltage?
  - It should be a simple number extracted from a IV -curve
  - CMOS foundry point of view but there is more behind them

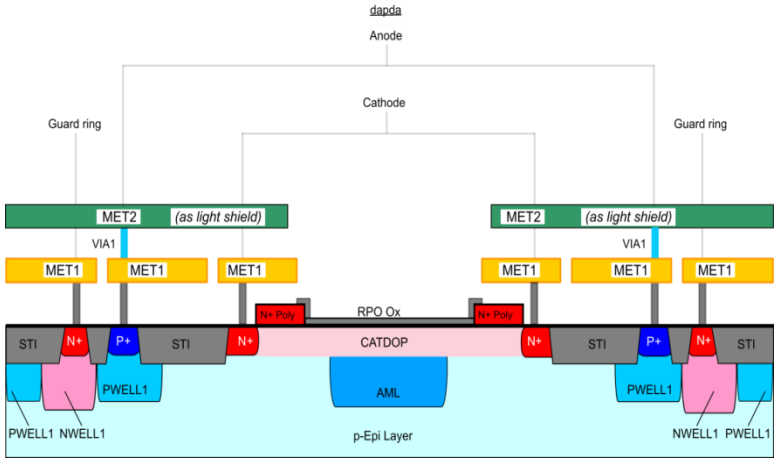
- Most important parameter to monitor the CMOS process
  - Shift in the breakdown voltage refer to issues in the process

- Therefore, the methodology how to extract the breakdown voltage or even the IV-curve is essential

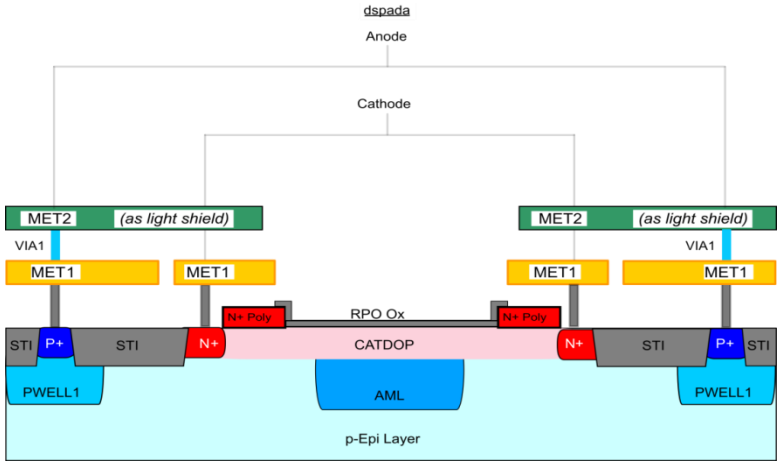


Motivation

- By choosing the "AVLA" process module
  - Enable the primitive device of avalanche photodiode and single photon avalanche diode
  - Necessity to monitor the process for both devices
    - Main criteria breakdown voltage for both devices



- Considering with one method two aspects:
  - Avalanche Photodiode:
    - High and stable gain multiplication needed
  - Single Photon Avalanche Diode:
    - Increased voltage swing for excess voltage required



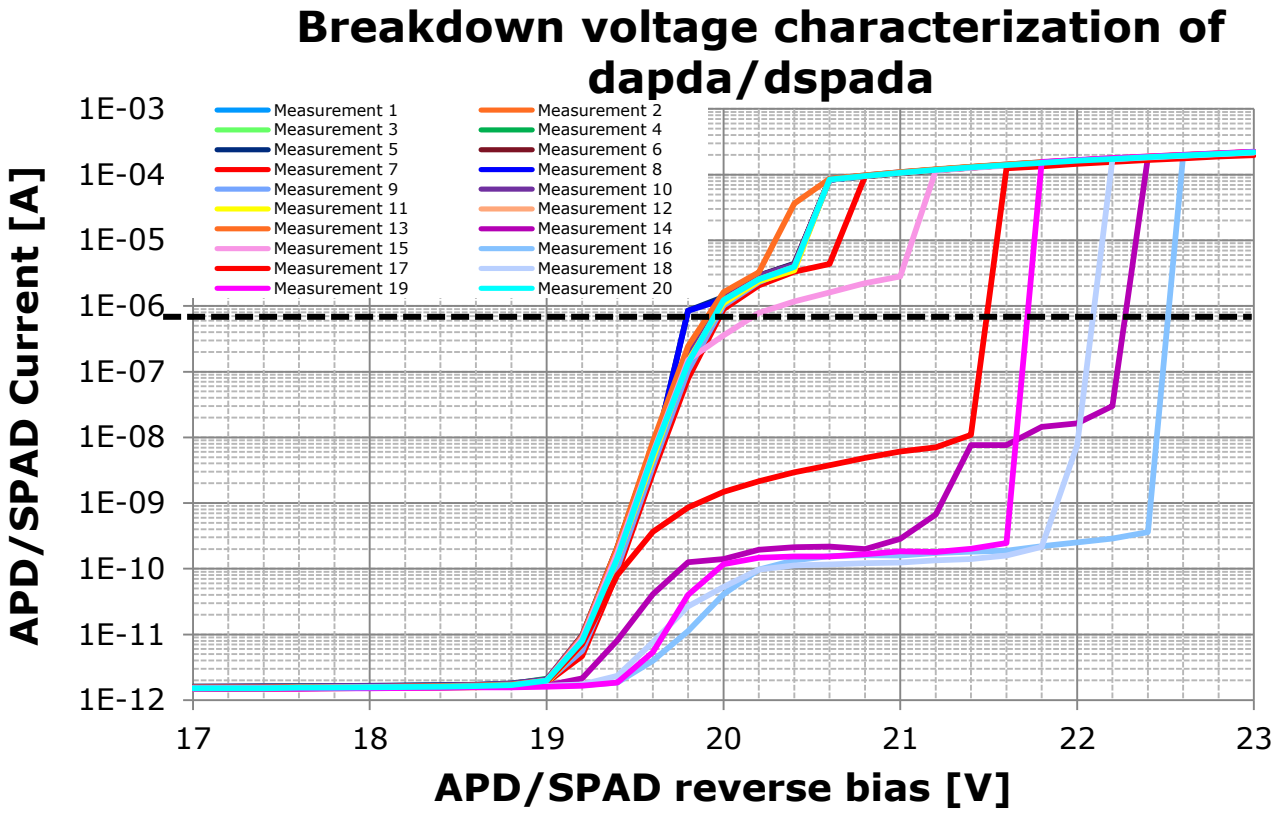
Name	Description	LSL	Low	Typ	High	USL	Unit
BVJ_DAVLA	Breakdown voltage @ Irev= 10 nA/µm², T= 27 °C	18.9	19.25	19.6	19.95	20.3	V

Outline

- Motivation
- Technical issues on breakdown voltage measurement
  - Characterization
  - Application
- Functionality principle & simulation study
- Characterization results
- Conclusions

State of the art BV measurement for primitive devices

- With current measurement principle it is very challenging to define <u>one</u> breakdown voltage value for avalanche photodiodes
- Not the appropriate measurement methodology
  - Need to consider timing dependency



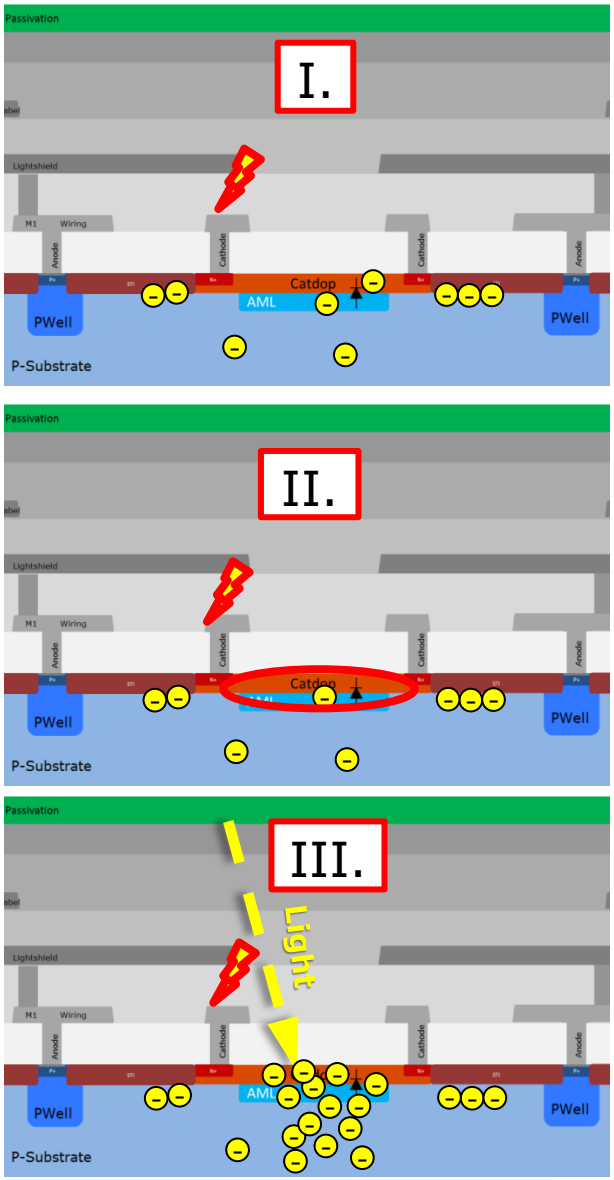
- Observation over 20 times measure the same device:
  - necessary to determine the breakdown voltage with a sufficient accuracy
  - No clear breakdown, array of curves observed

Measurement principle

I. Photodiode mode $V_{Bias} < V_{BV}$
- Steady measurement
- Current will be collected from diode surrounding
  - STI interface
  - Trap related
  - Diffusion from Epi material
  - Etc.

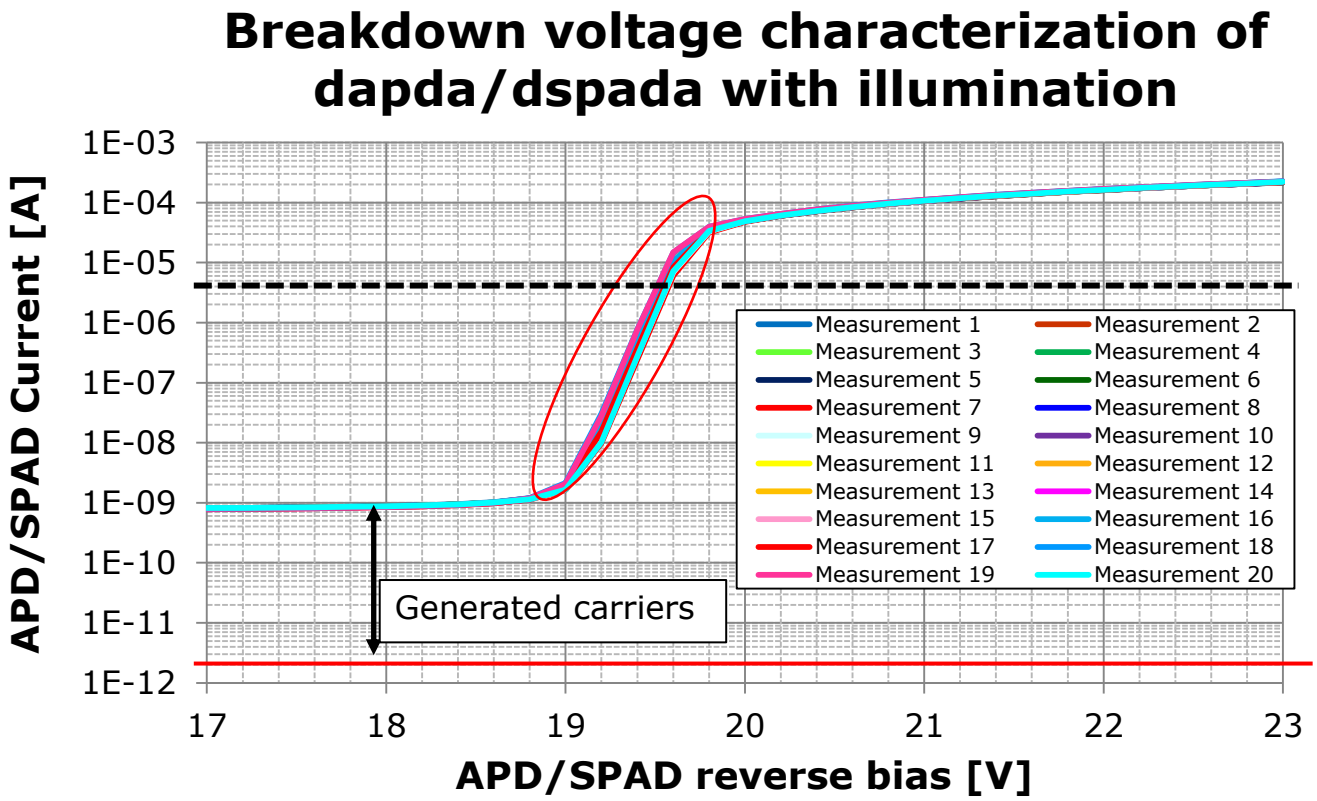
II. Diode breakdown $V_{Bias} \geq V_{BV}$
- A carrier is needed in the junction where the breakdown occur to trigger the avalanche
- Time dependent event:
  - If no carrier is triggering; the voltage could further increased until a carrier ignites the avalanche
  - Integration time during the measurement

III. Diode breakdown under illumination $V_{Bias} \geq V_{BV}$
- Still time dependent domain but:
  - Inducing carriers in the junction by illumination
    - Alternatively by temperature, defects etc.
  - Accurate triggering of the junction breakdown



Current solution (Characterization)

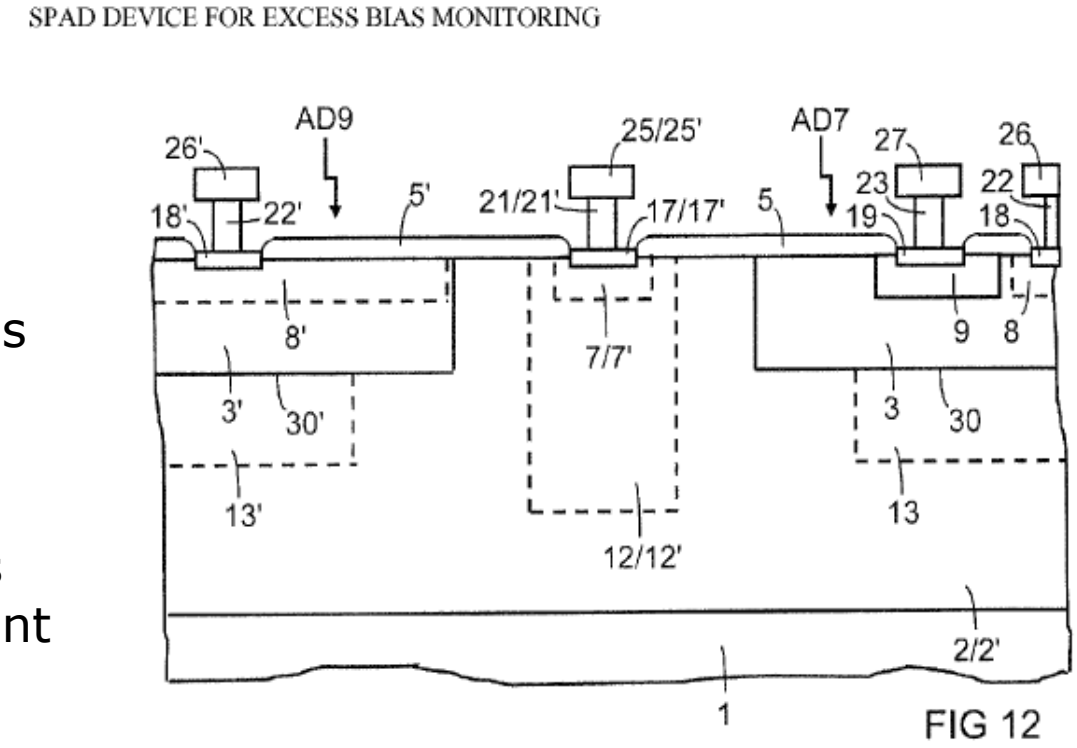
- For process control monitoring and characterization an illumination is done to shift the current level
- Increase in the amount of charge carriers
  - With increasing the amount of carriers a proper breakdown can be triggered



- Current status for the development:
  - Breakdown voltage measurements in lab are done under illumination with an optical fiber
  - For process control monitoring an optical test system was introduced with release of the devices

Further solutions

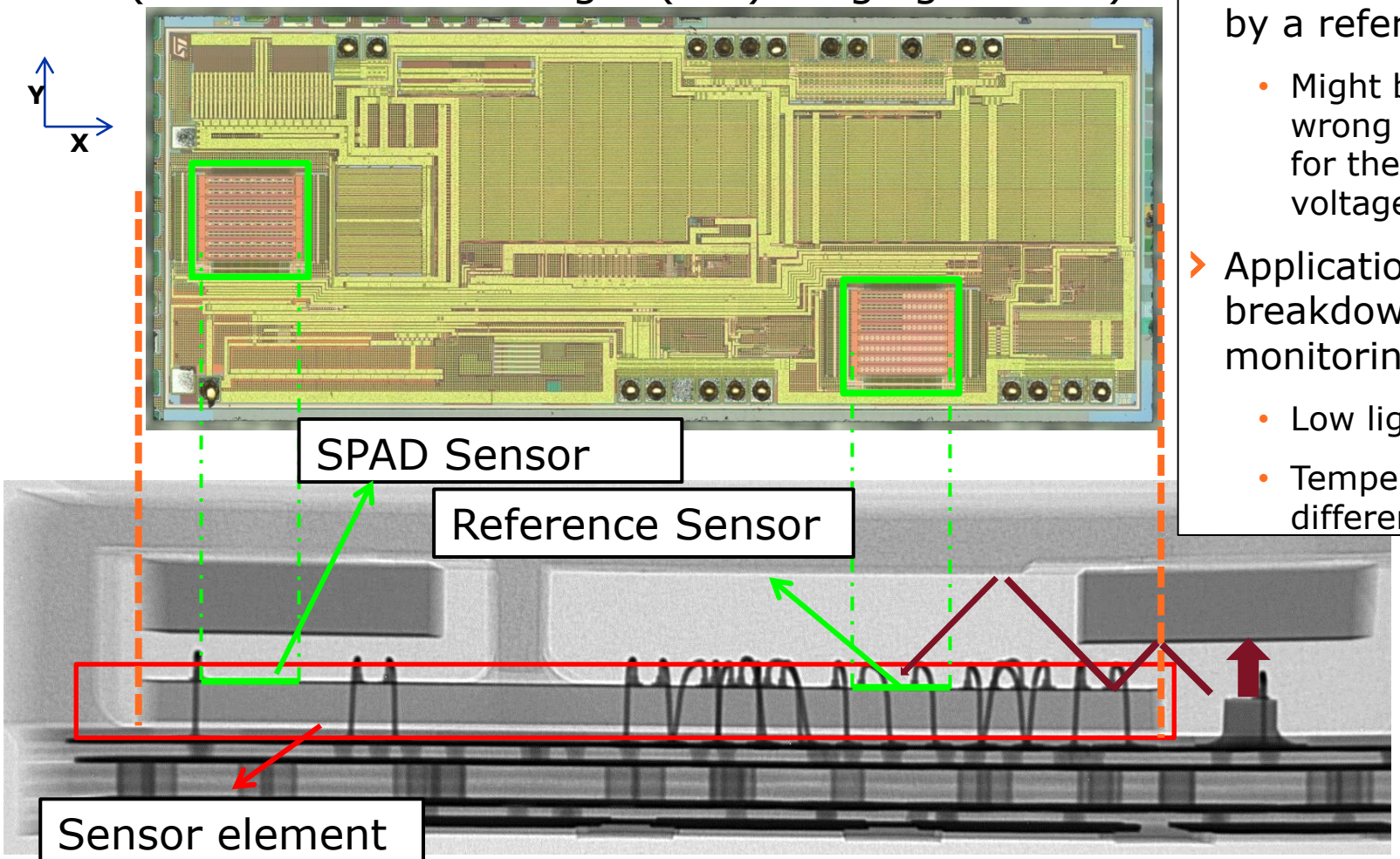
- Also other groups focus on the topic of breakdown voltage characterization in SPADs:
- "SPAD device for excess bias monitoring" from AMS
- extra high dark count SPAD device to control the excess voltage of the sensor element



G. Röhrer, et al. "SPAD device for excess bias monitoring" WO 2019/020472 A1, 31 January 2019

State of the art sensor Application

State of the art ToF sensor
(VL53L0X Time-of-Flight (ToF) ranging sensor)



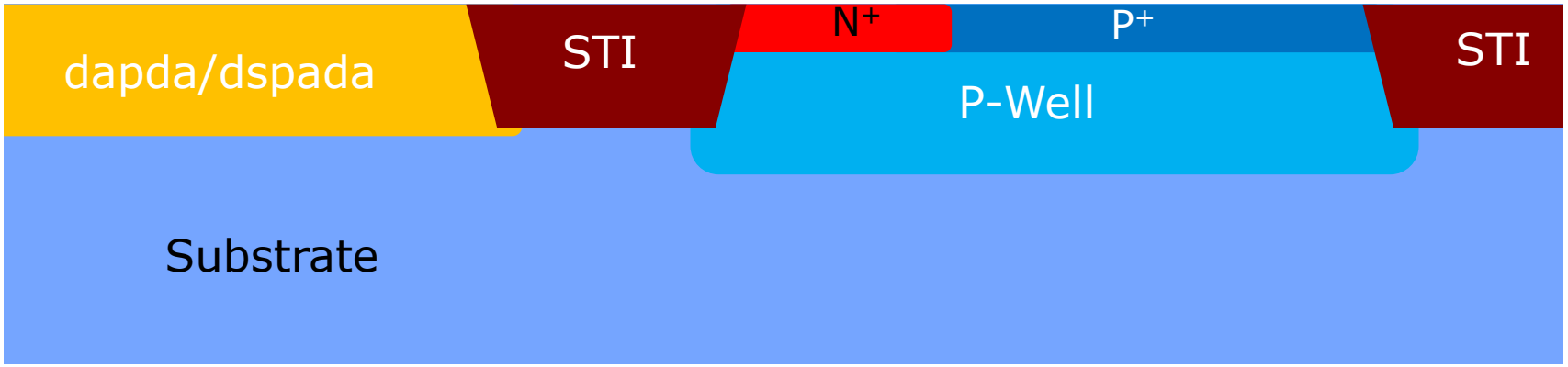
- Time-of-Flight sensor needs an adjustment by a reference SPAD
  - Might bring the wrong information for the breakdown voltage
- Application needs breakdown voltage monitoring
  - Low light condition
  - Temperature differences

Outline

- Motivation
- Technical issues on breakdown voltage measurement
  - Characterization
  - Application
- Functionality principle & simulation study
- Characterization results
- Conclusions

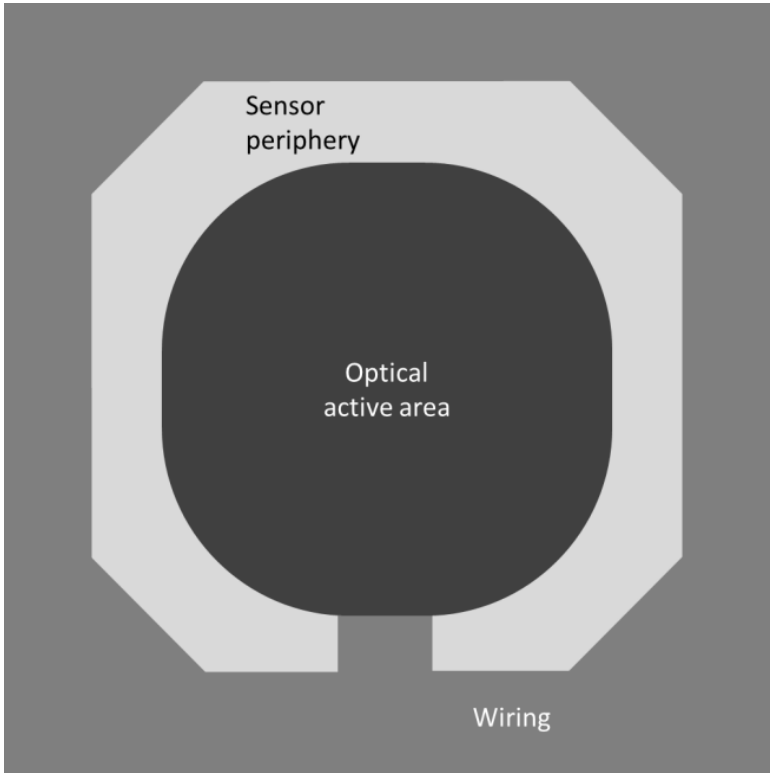
Functionality principle

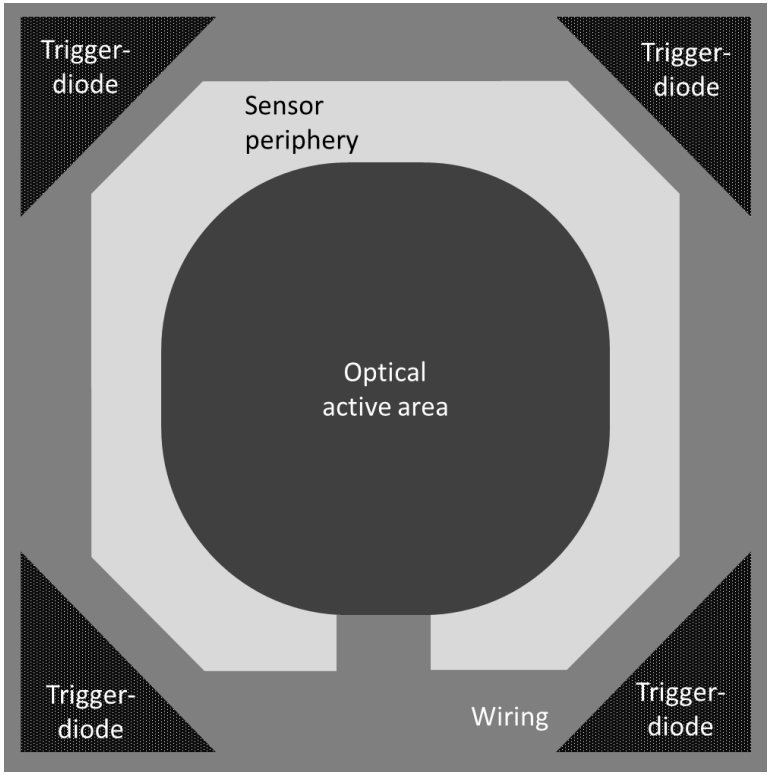
- With a trigger diode the illumination from outside would become obsolete
- Independent method also against breakdown voltage shift caused by different temperatures
  - In-situ measurement and switchable monitoring
- Trigger diode with an additional n^+ - implantation
- Boundary for simulation:
  - Reverse voltage 2.9 V at trigger diode (~1 mA), 0..32 V at Cathode, circular device, no light, 27 °C



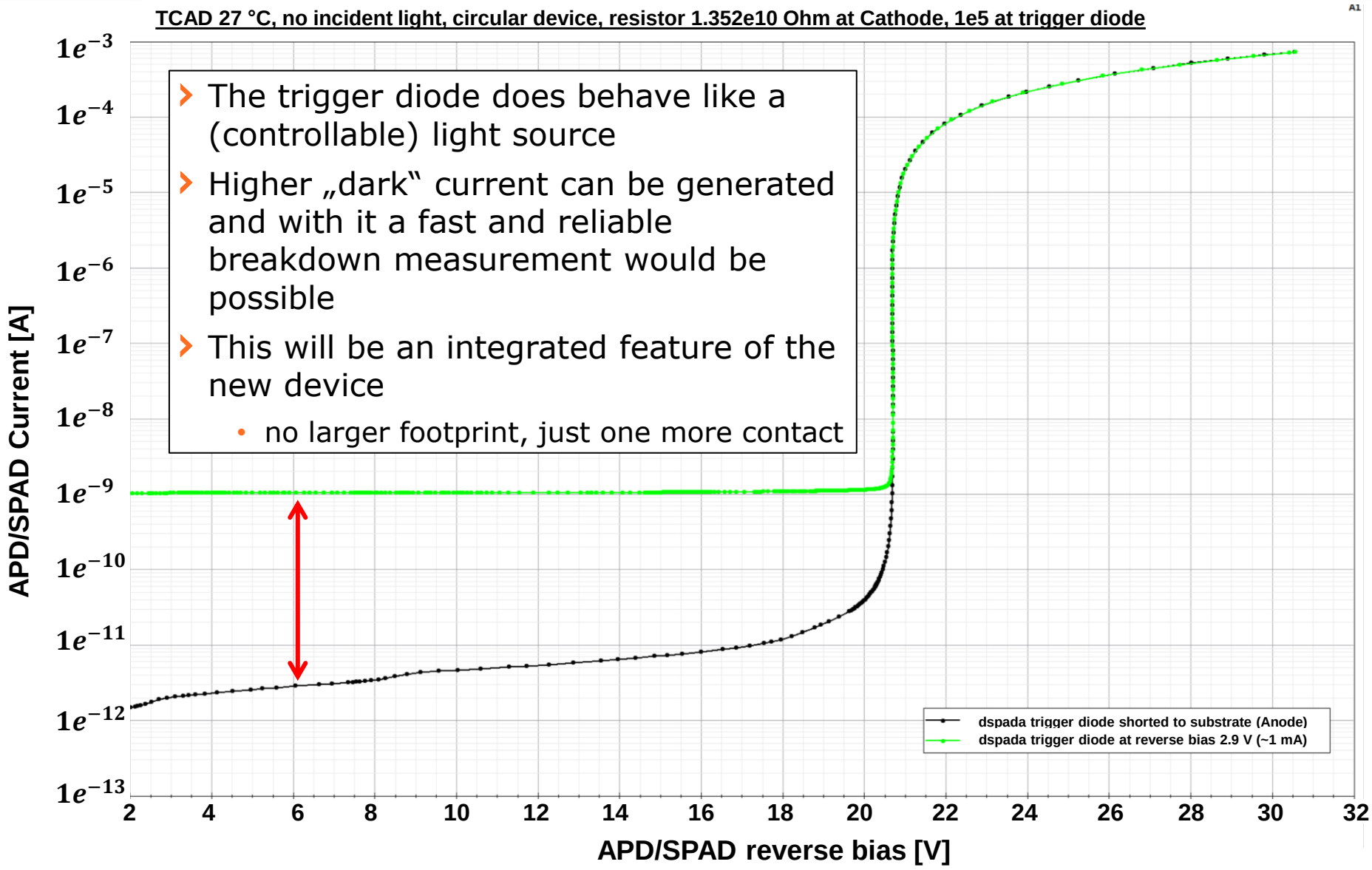
Design

- Compared to the existing design there is no impact on the footprint or the fill factor of the sensor device
- The trigger diode is placed in the corners were no impact is given to the existing design
- No additional process steps are required

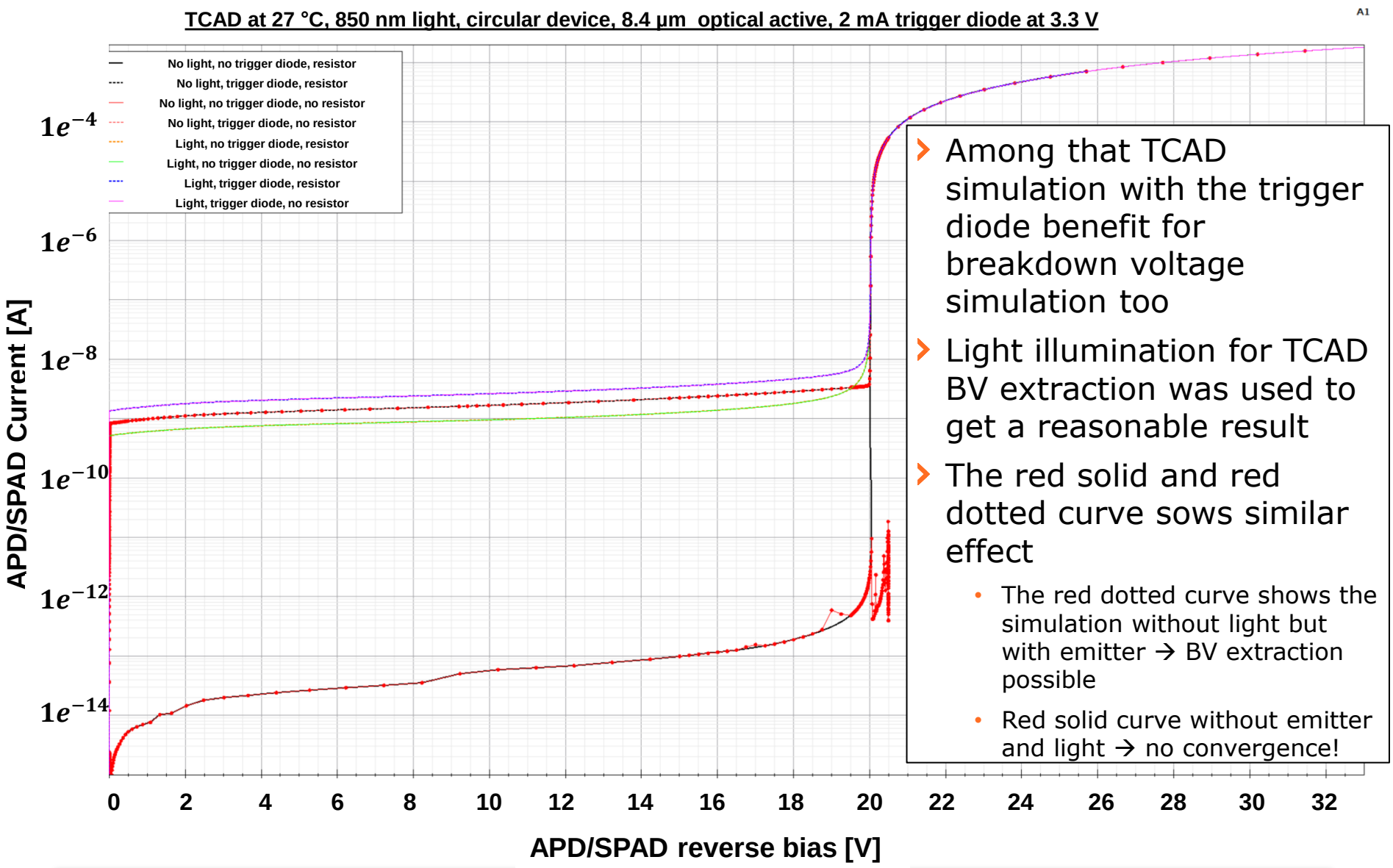




Simulation study



Simulation study



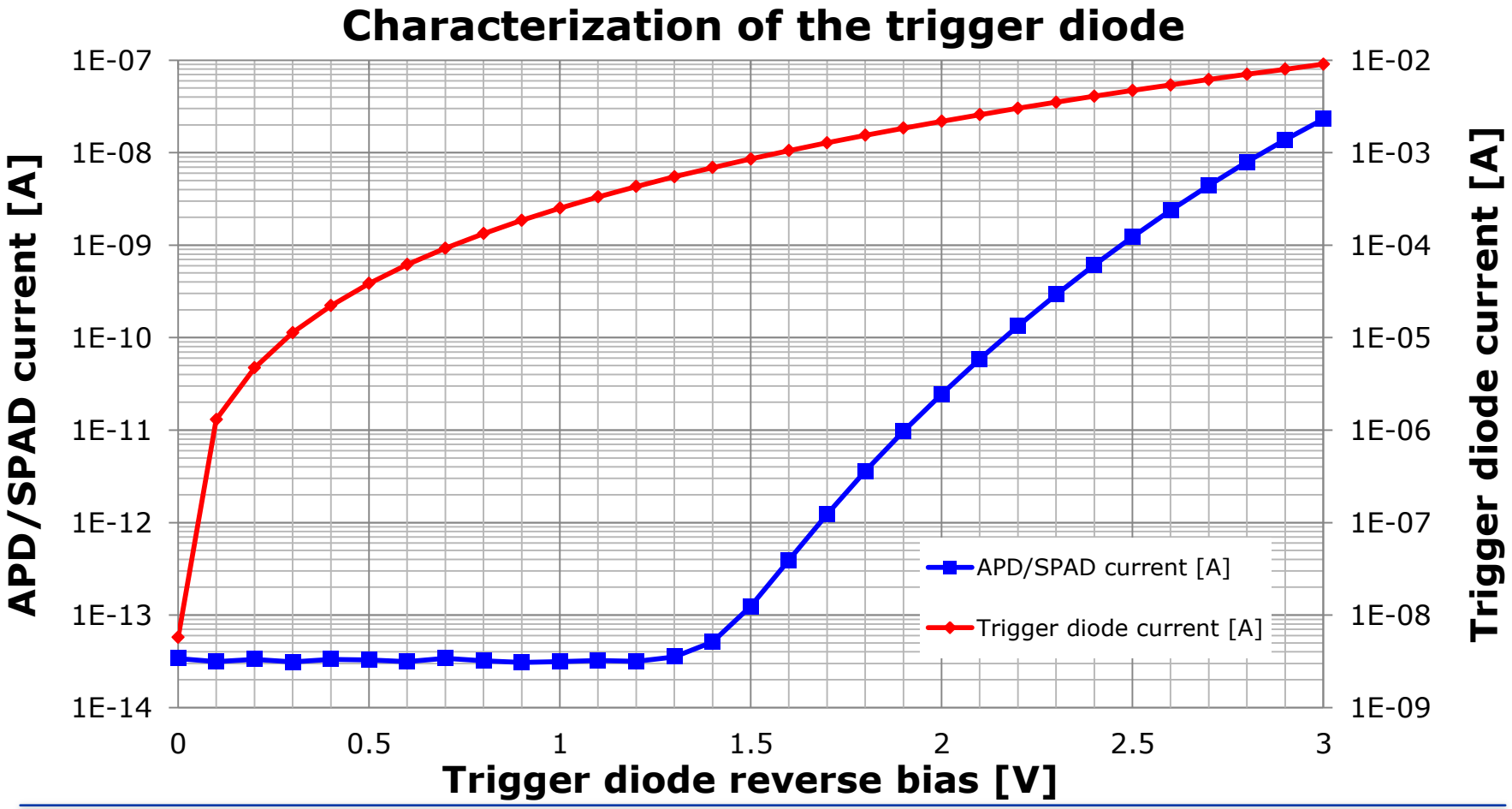
- Among that TCAD simulation with the trigger diode benefit for breakdown voltage simulation too
- Light illumination for TCAD BV extraction was used to get a reasonable result
- The red solid and red dotted curve sows similar effect
  - The red dotted curve shows the simulation without light but with emitter → BV extraction possible
  - Red solid curve without emitter and light → no convergence!

Outline

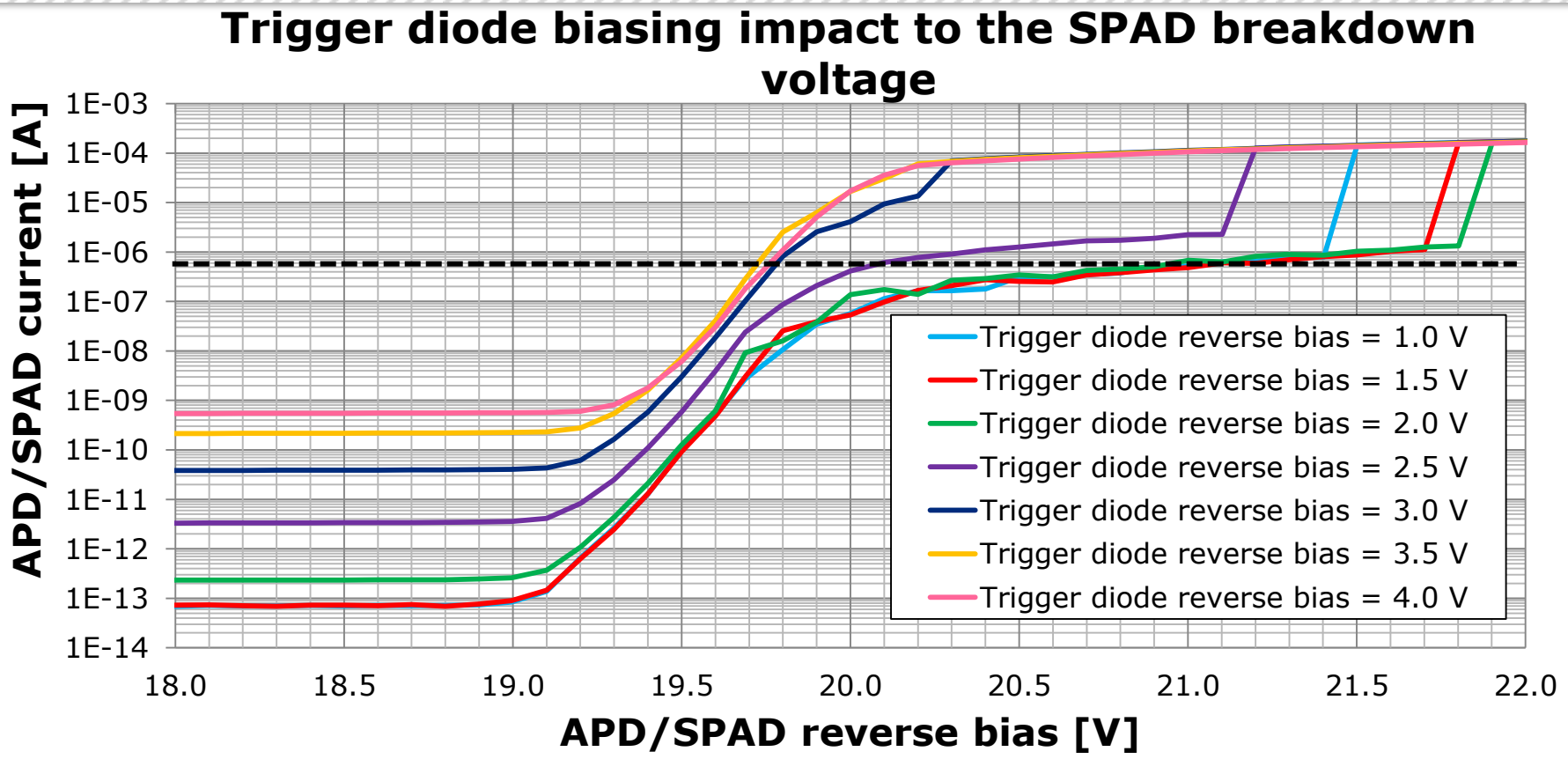
- Motivation
- Technical issues on breakdown voltage measurement
  - Characterization
  - Application
- Functionality principle & simulation study
- Characterization results
- Conclusions

Characterization Results

- Functionality test:
  - Implementation to improve the measurement methodology
  - Increased APD/SPAD current in dependency to the reverse voltage could be observed

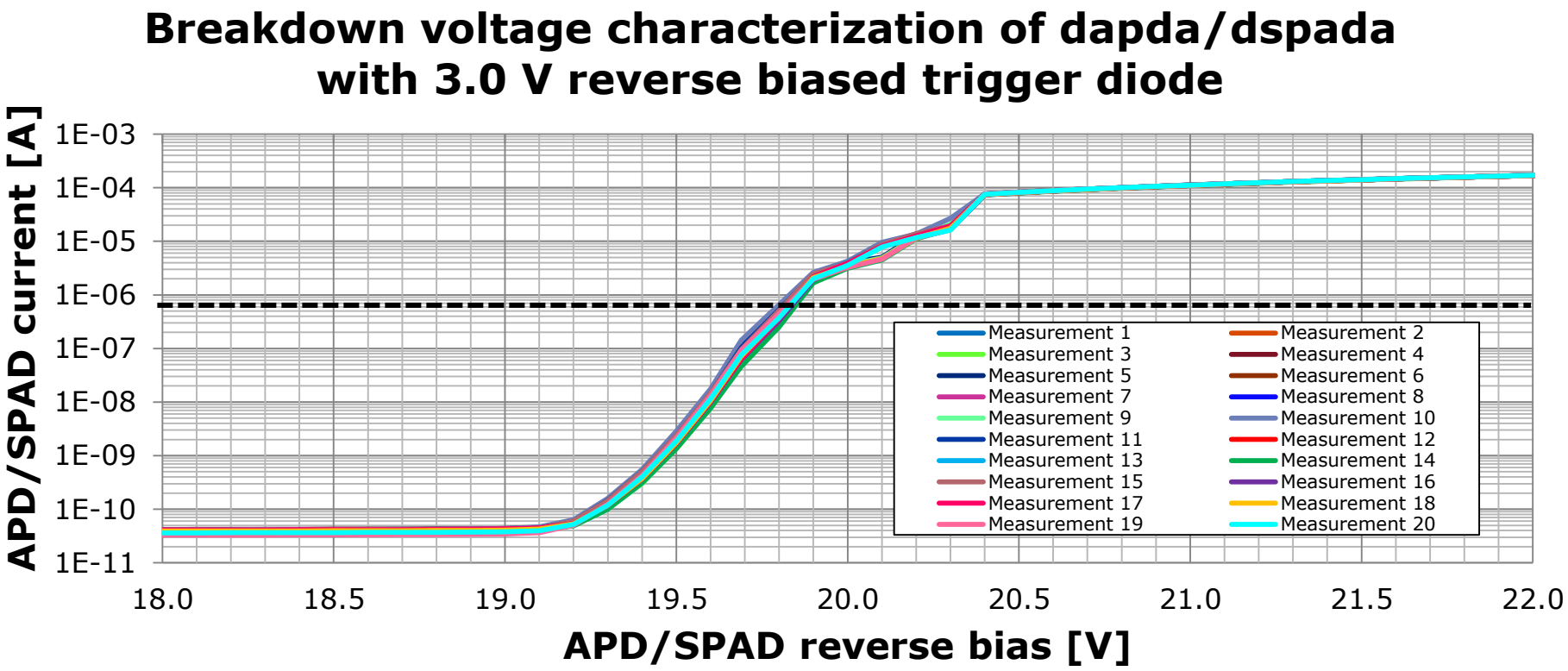


Characterization Results



- Furthermore, the impact of the bias voltage of the trigger on the IV-curve and on the breakdown voltage could be observed
  - The higher the reverse bias of the trigger diode the more comparable measurement environment could be placed as the device would be illuminated

Characterization Results



- Also a characterization of 20 SPAD devices with a reverse bias of 3.0 V shows the improvement of the BV measurement
- It is possible to measure an IV curve and determine the breakdown voltage of small (10 µm) SPAD devices

Outline

- Motivation
- Technical issues on breakdown voltage measurement
  - Characterization
  - Application
- Functionality principle & simulation study
- Characterization results
- Conclusions

Conclusion

- A new device for breakdown measurements was implemented to improve the breakdown voltage measurement (patent pending)
  - Makes the current solution with illumination during measurement obsolete
- With this new device it is possible to get precise values for the breakdown voltage (two operation modes: BV extraction and sensing)
  - Part to part or temperature related breakdown voltage deviation can be detected without impact on the device (just short timeslot required)
- Beneficial for the usage of avalanche photodiodes and/or single photon avalanche diodes
  - Multiplication control of APDs (precise adaptive bias)
  - Wider range for excess bias on SPAD (excess bias can be exactly regulated)
- No impact to the device footprint, no additional process effort, no impact on the device performance (if trigger diode is unbiased), works stable with low voltage <3 V.

Acknowledgement

- Daniel Gäbler for the support around this topic (simulation, design etc.)
- Hannes Schmidt for characterization support
- Opto process development team


FAB
THE MORE THAN MOORE FOUNDRY.
Thank you for your attention.