ISSW2024
Avalanche build-up field and its impact on the SPAD pulse width and inter-pulse-time distributions.

D. Rideau, R. Helleboid, G. Mugny, I. Nicholson*, A. Bianchi, D. Golanski, B. Mamdy, J-B. Kammerer**, S. Rink**, C. Lallement**, B. Rae*, W. Uhring**, S. Pellegrini*, M. Agnew*, E. Lacombe, J.R. Manouvrier, M. Al-Rawhani*.

STMicroelectronics, 1850 rue J. Monnet BP16, 38926 Crolles, France.
*STMicroelectronics, 1 Tanfield, Inverleith Row, Edinburgh, UK.
**ICube laboratory, Université de Strasbourg, 1 Pl. de l'Hôpital, 67000 Strasbourg, France.

denis.rideau@st.com

Agenda

1 Direct Time-of-Flight sensor:
General concepts of SPAD

2 A SPAD is a statistical device

3 VerilogA SPICE model

4 Experimental and model

Experimental results presented here are not representative of our best SPAD devices, but shown for modeling benchmarking purpose.

life.augmented

Measuring distance through history

Ivory Ruller from the 1800s.

Land surveyors chains around 1600

sliding scale from the 1700s.

measuring wheel from the 1800s.

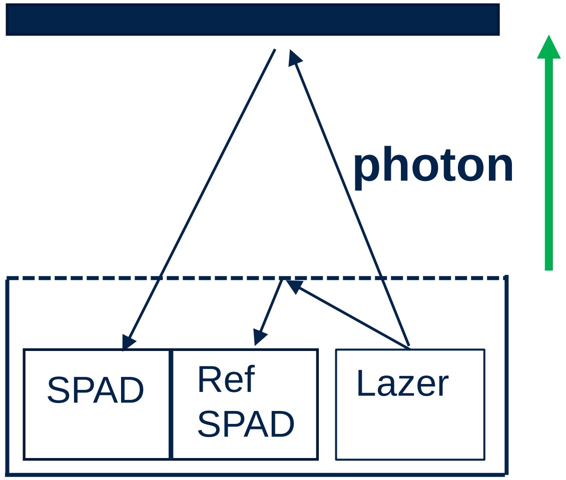
VL53L5CX
4th generation FlightSense™

[From History of Measuring Instruments - Malevus]

life.augmented

Direct Time-of-Flight sensor (TOF)

Principle of a TOF:



Light speed

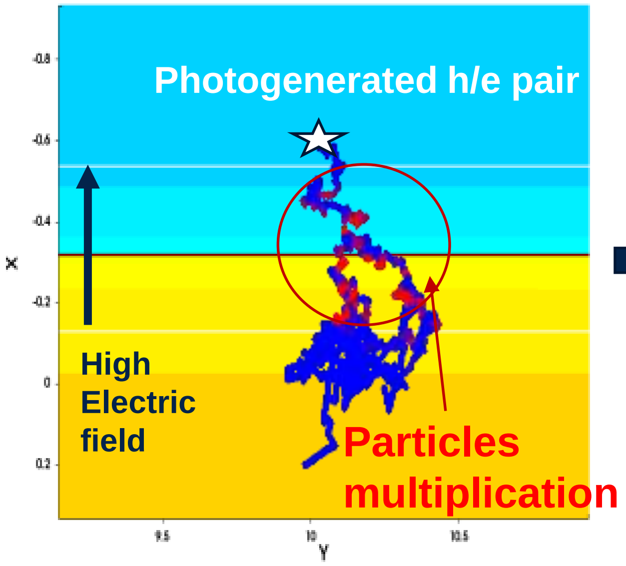
$$d = \frac{c * \Delta t}{2}$$

TOF

1m	➔ Δt = 3.3 ns
2m	➔ Δt = 6.7 ns
50m	➔ Δt = 167 ns
100m	➔ Δt = 333 ns

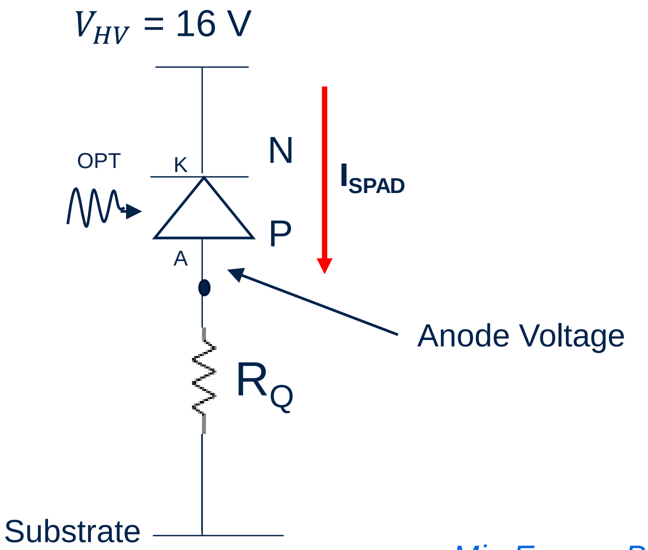
10 cm accuracy the needle chronometer moves by 1e-9 degree !

Direct Time-of-Flight sensor: (SPAD)



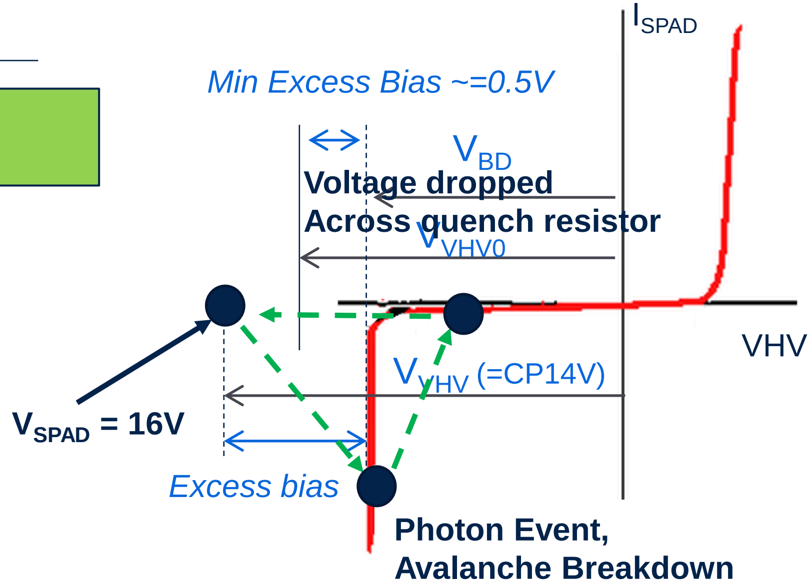
Avalanches by Impact Ionization in reverse biased diode

1 electron → 2ē → 4ē → 8ē → 16ē → 32ē → 64ē → … → detection current



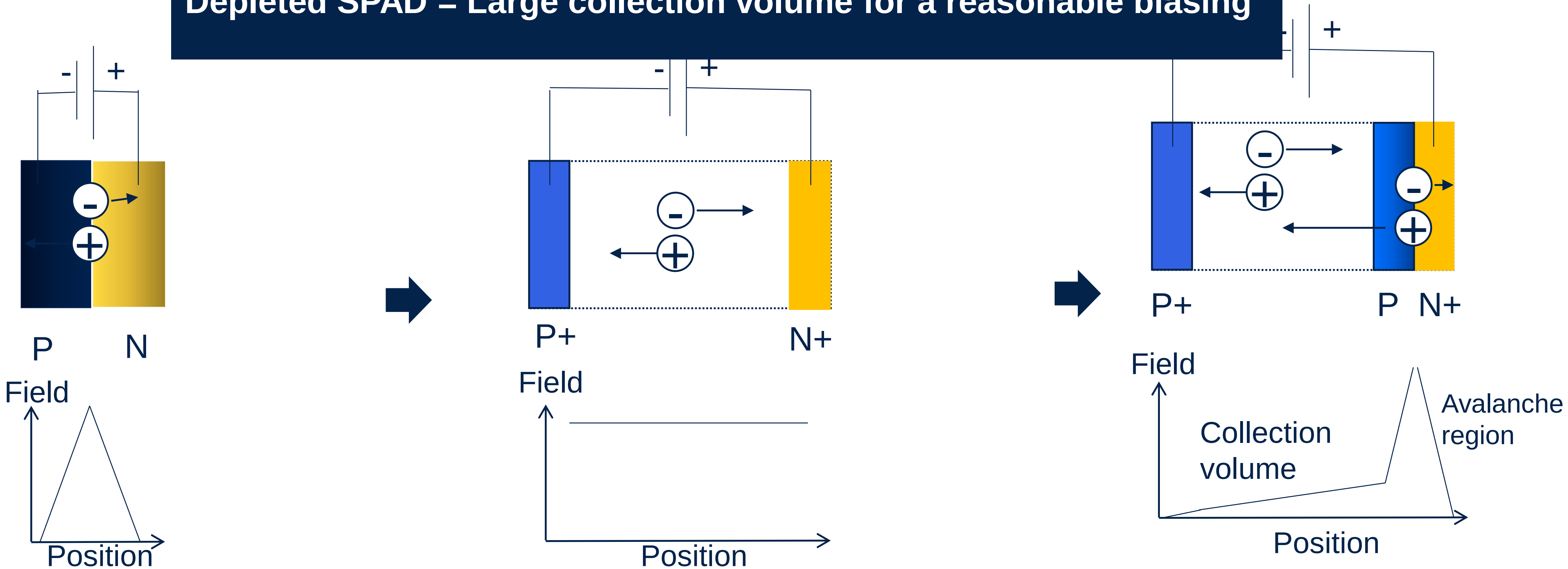
Need to be quenched!

Detection



Architectures for a SPA

Depleted SPAD = Large collection volume for a reasonable biasing



Biasing: 17V ➔ 18V
Collection Width: <1um

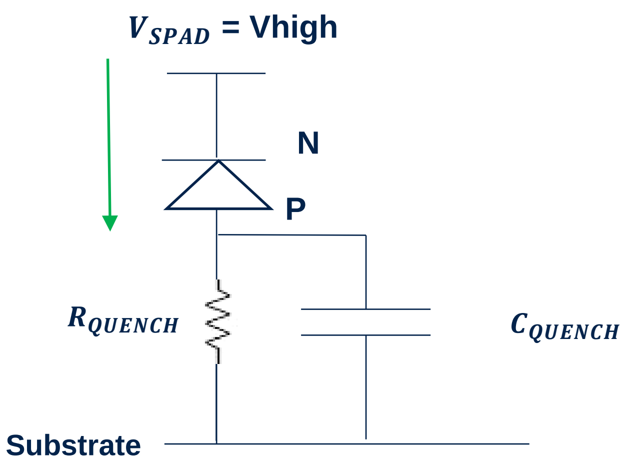
Biasing: 30V ➔ 40V
Collection Width: 5um

Biasing: 17V ➔ 21V
Collection Width: 5um

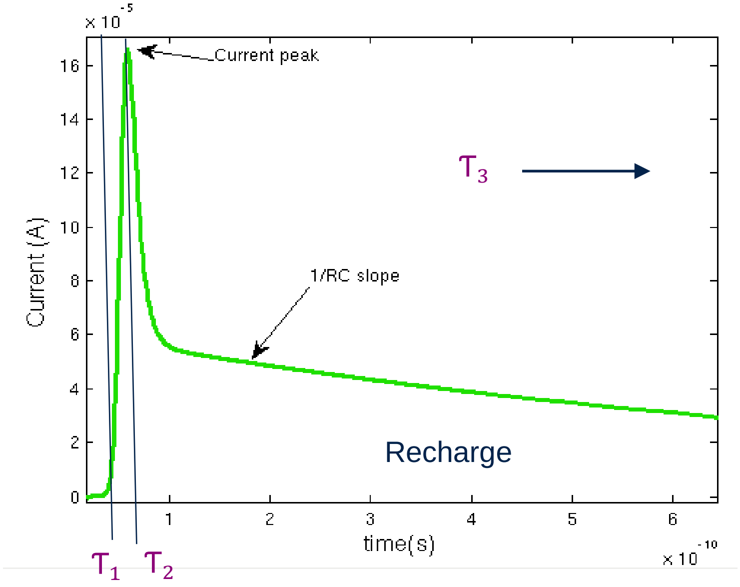
life.augmented

Direct Time-of-Flight sensor: the quench of a SPAD

Passive Quench circuit (Simplified Circuit)



Diode Current curve



Understanding the SPAD dynamics

7

Agenda

1 Direct Time-of-Flight sensor: General concepts of SPAD

2 A SPAD is a statistical device

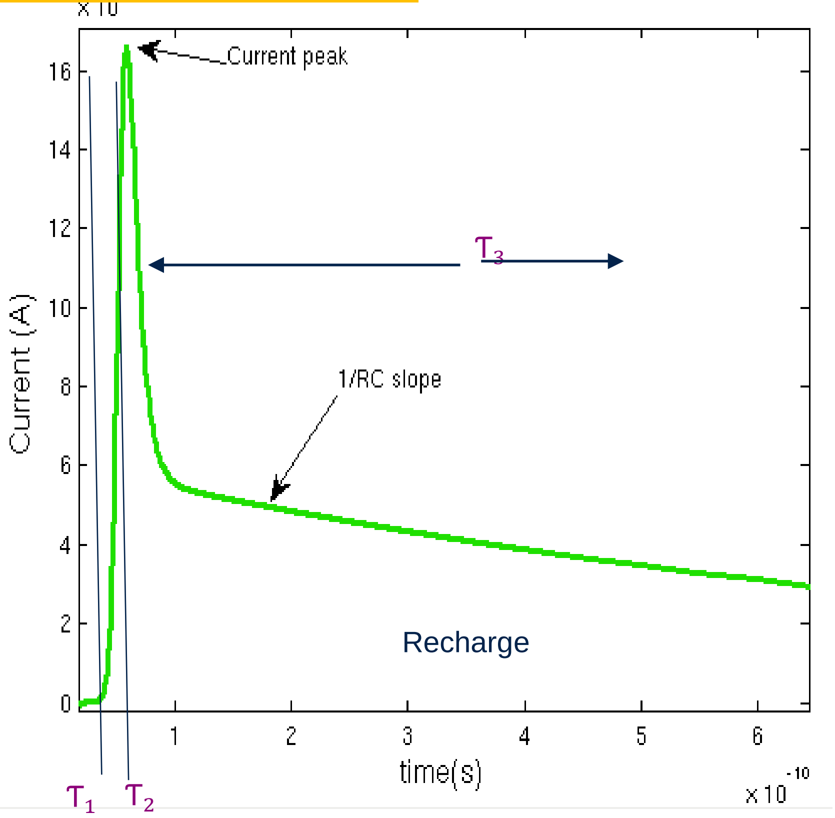
3 VerilogA SPICE model

4 Experimental and model

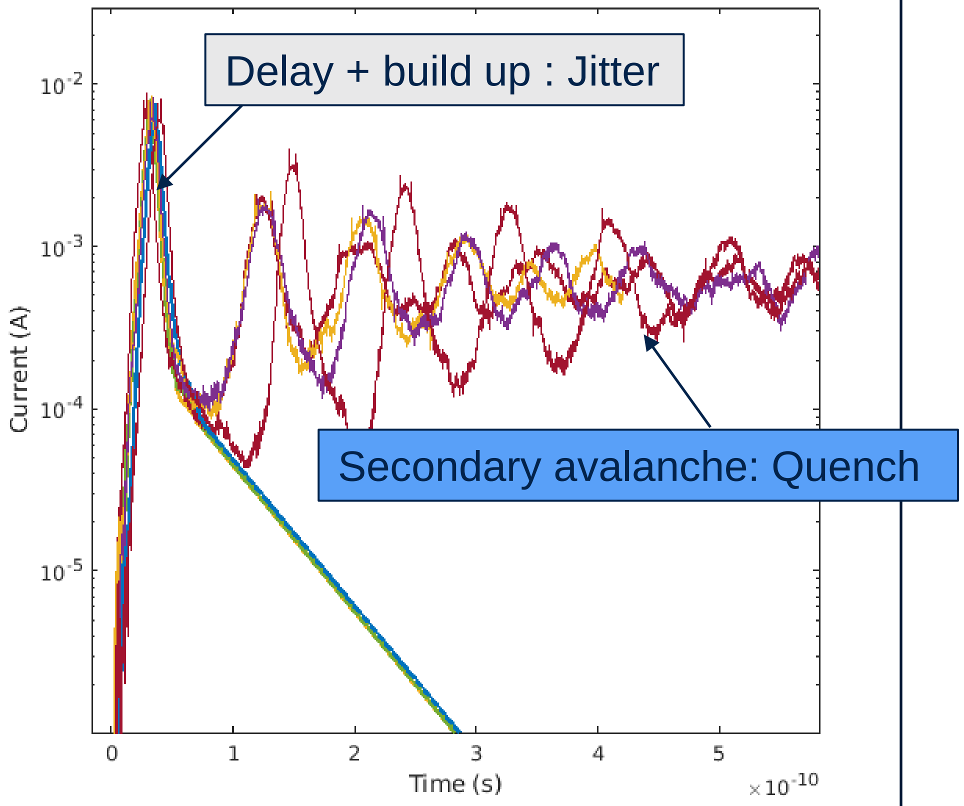
life.augmented

A SPAD is a statistical device

Deterministic simulation



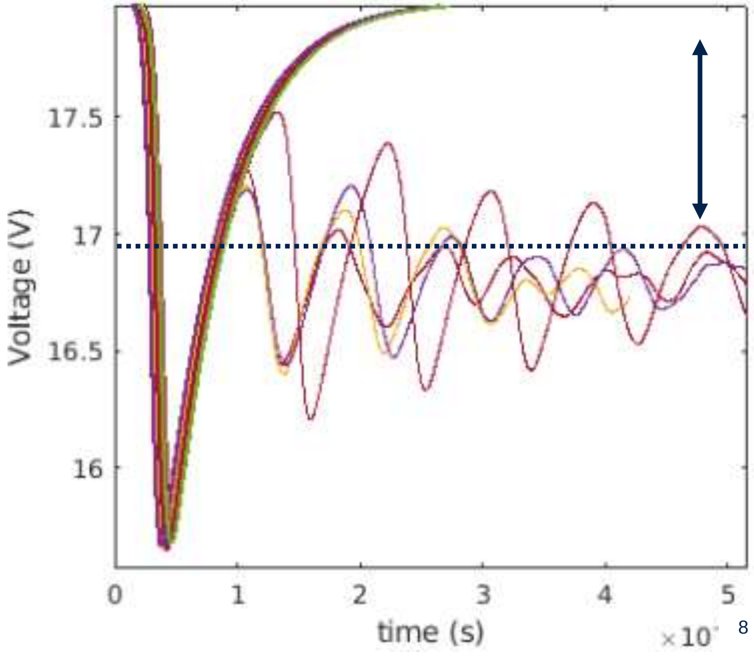
Statistical simulation



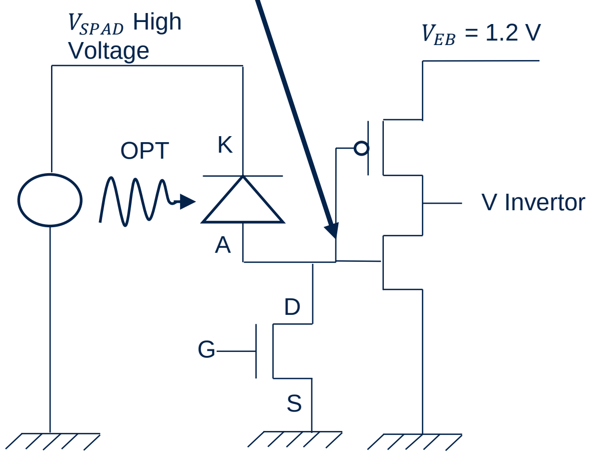
➔ Stochastics effects?

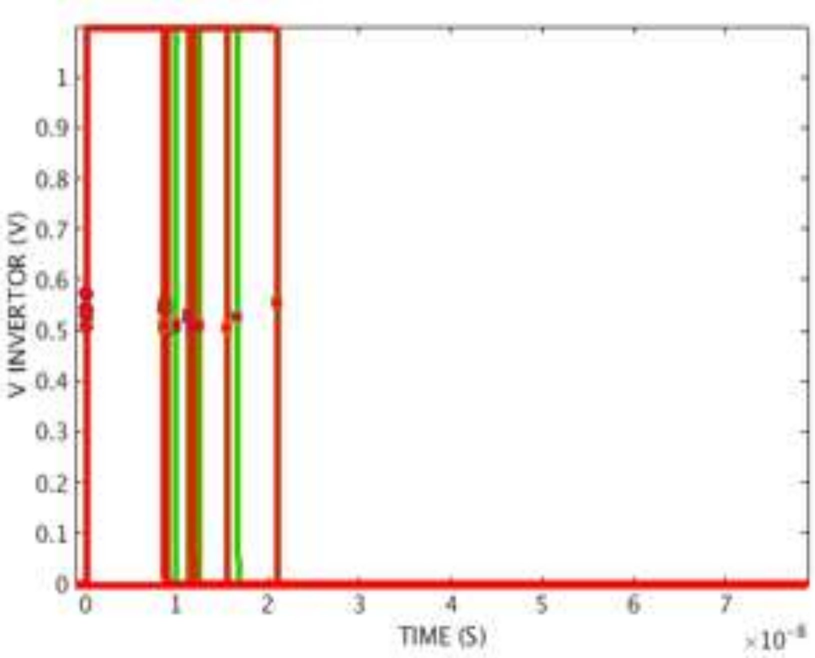
The quench of a SPAD:

When we can have a problem!



Invertor threshold

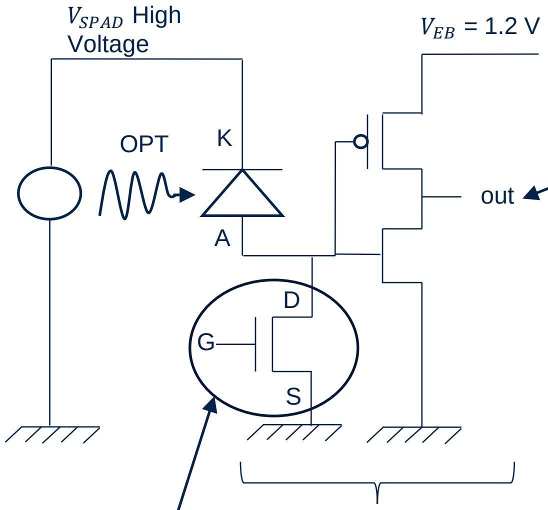




Pulse width vary!

The quench of a SPAD

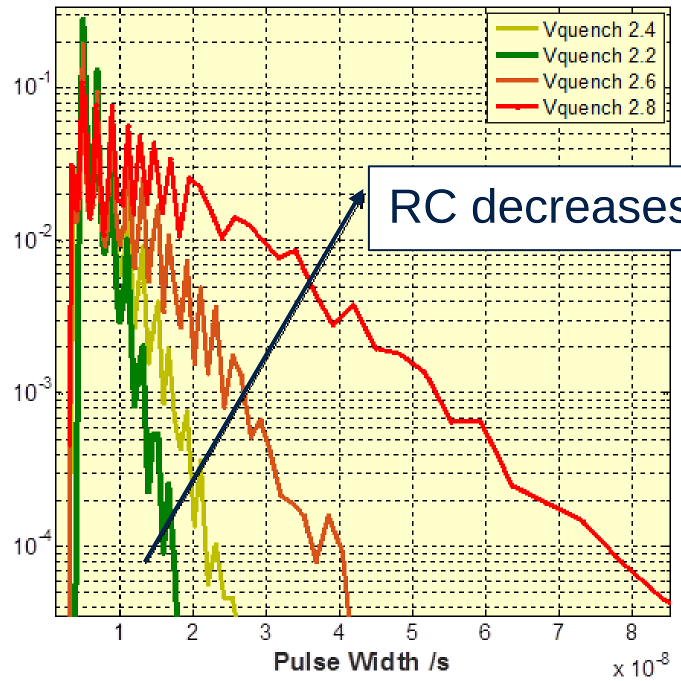
When the dead time of the quench circuit is too small secondary avalanches can occur



Pulse Shaper

Transistor as a quench resistor

Experimental Pulse Width

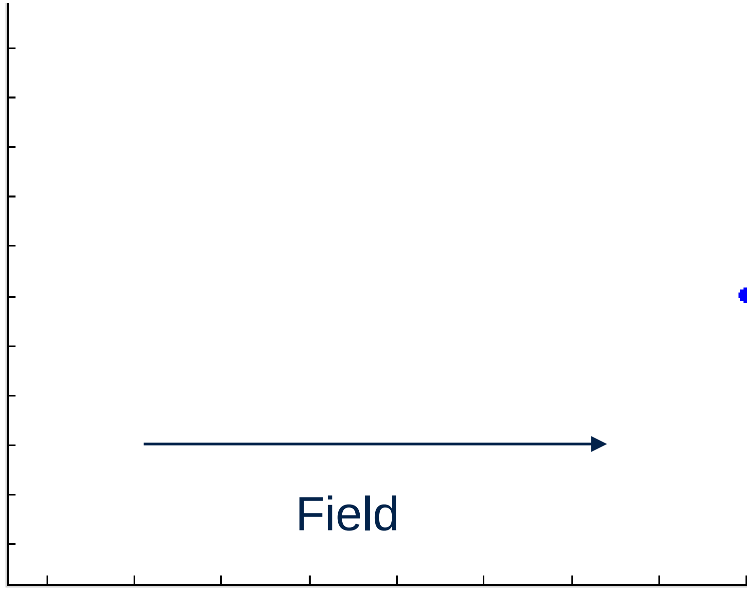


RC decreases !

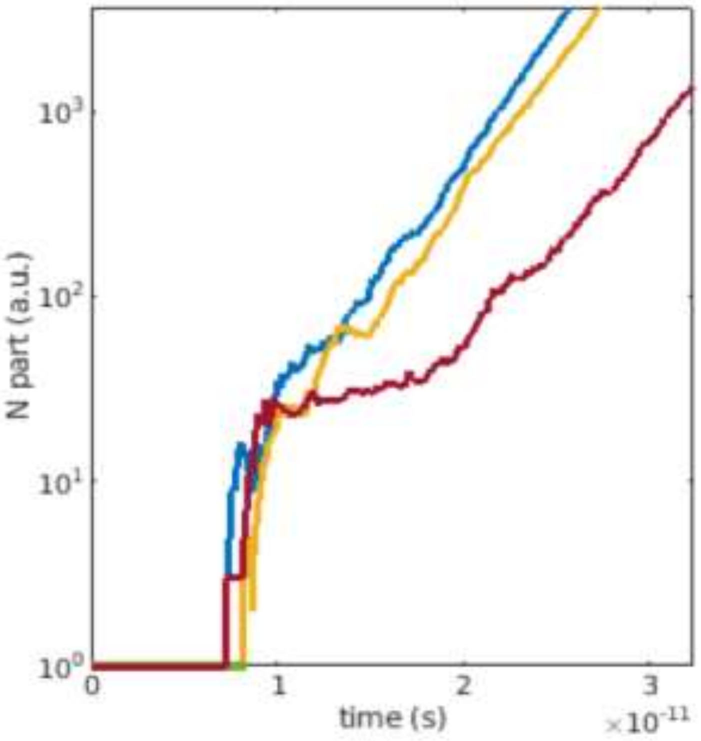
Quench circuit optimization:
➔ Pulse width vs dead time!

Stochastic: Impact ionization

The impact ionization is a stochastic process (Monte Carlo simulation – only electrons shown)



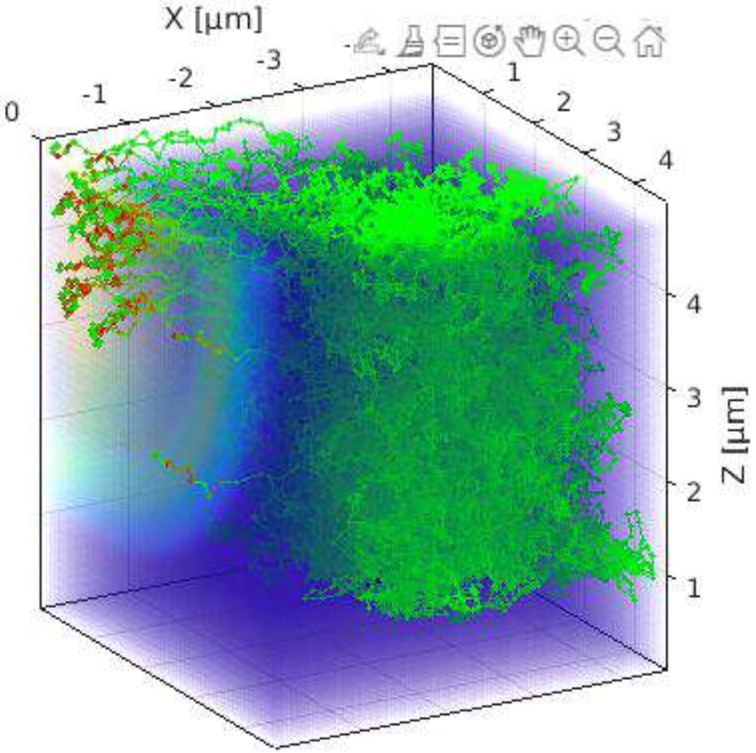
Increase of the number of particles in a PN junction (3 Monte Carlo simulations)



Stochastic: Where II occurs

Avalanche region and collection volume are separated

Electric field: transparent colors

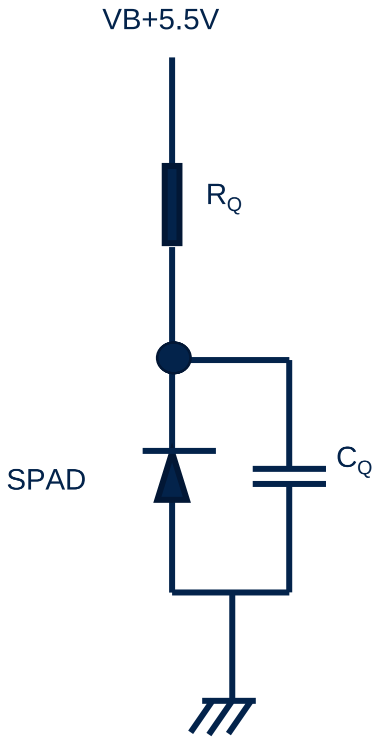


Carrier diffusion

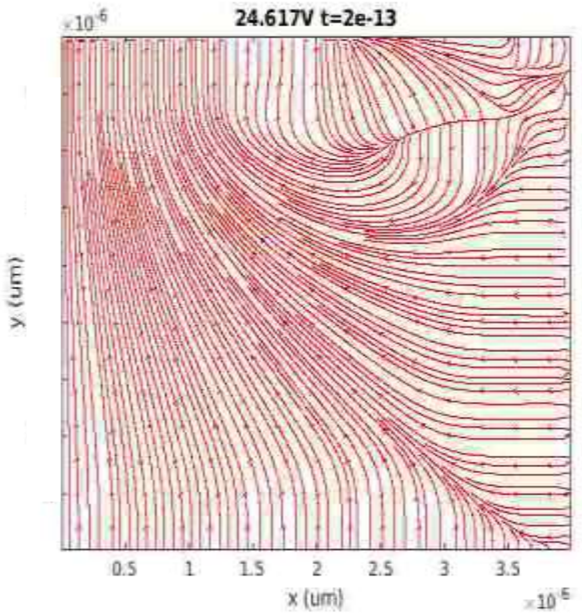
Electrons end in the N++ region

Electrons start here

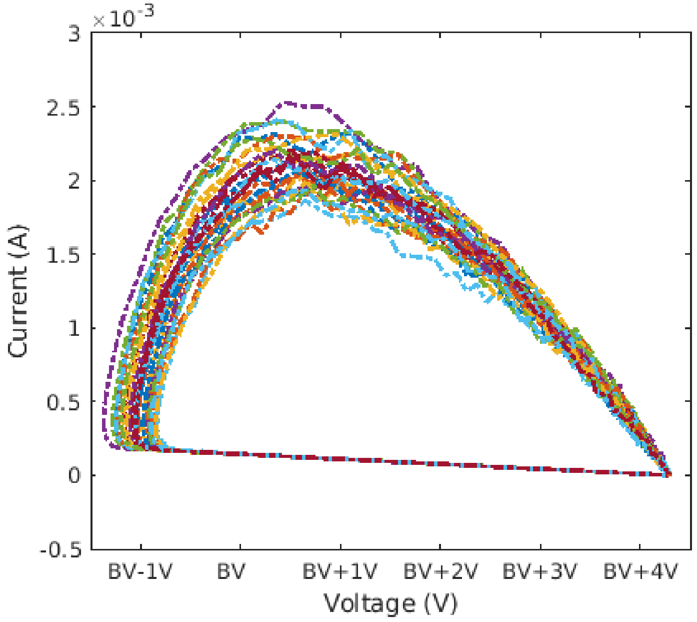
life.augmented



Electrons moving:



I-V response:

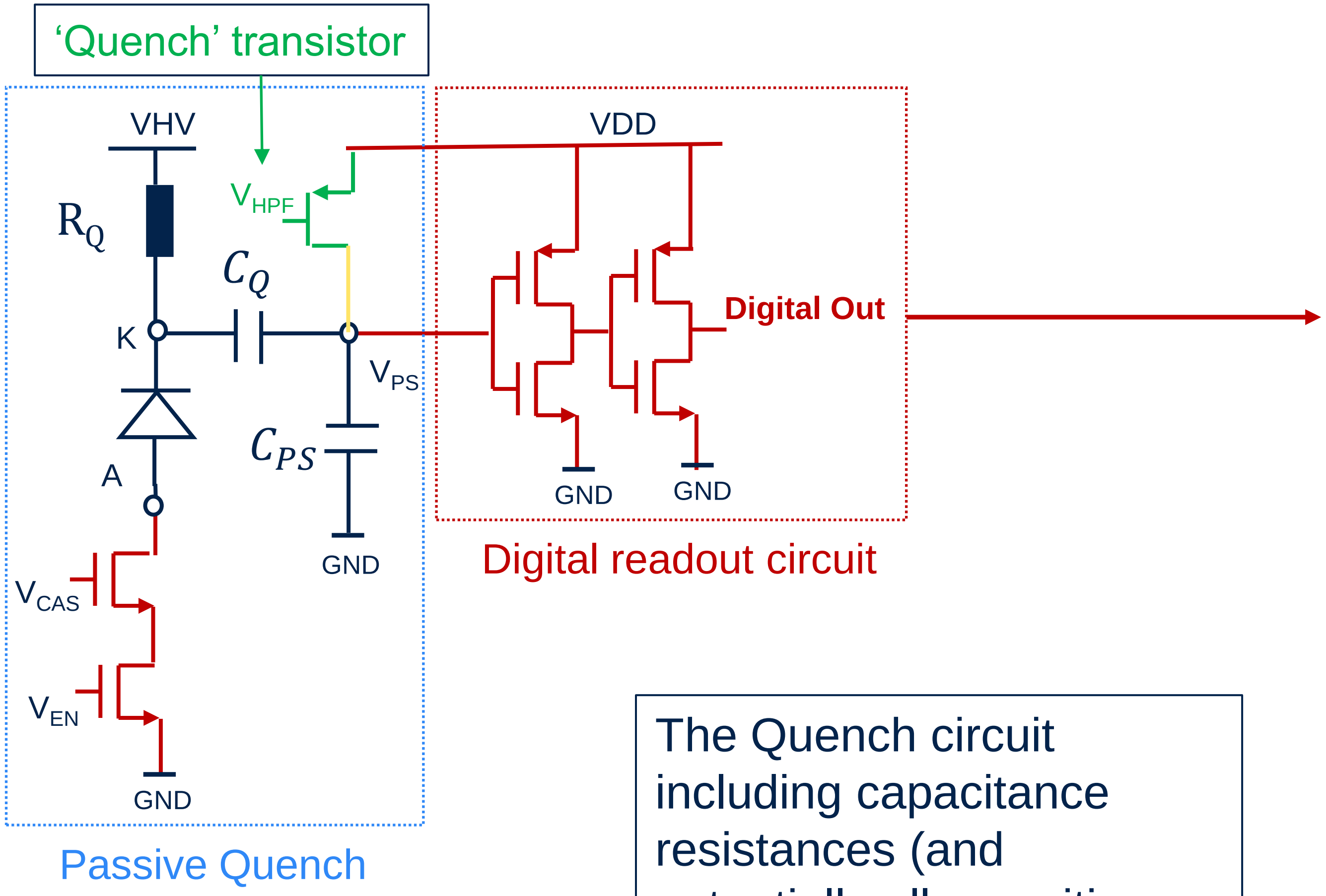


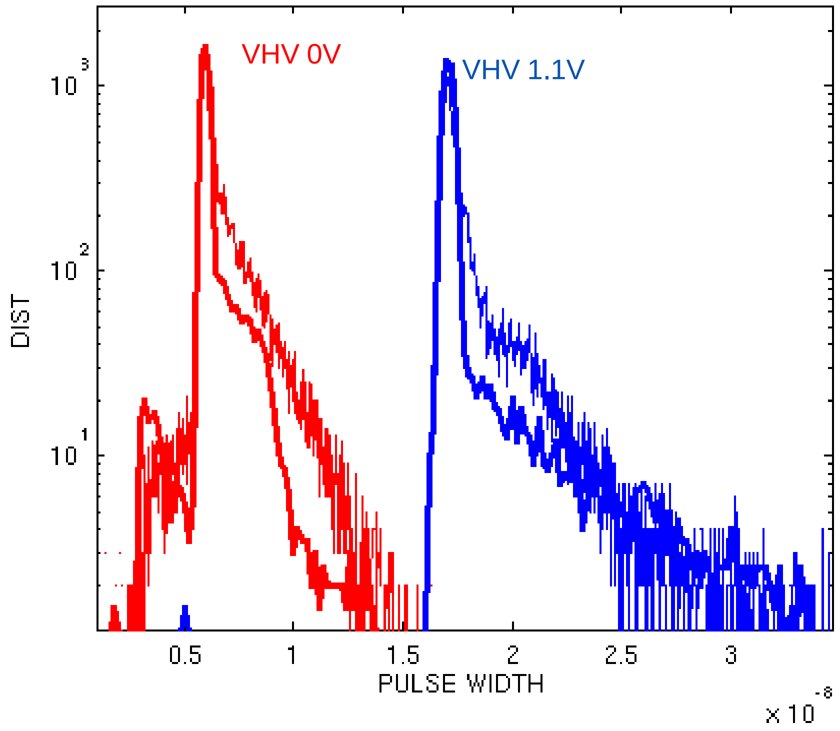
Quenching a SPAD = debiasing the diode to switch off the avalanche

Agenda

life.augmented

VerilogA model of a SPAD : goal



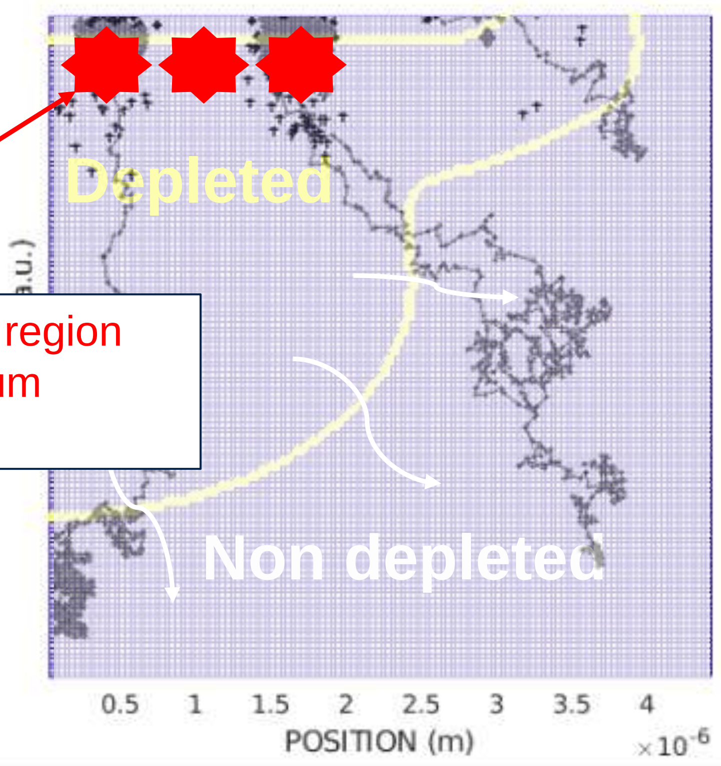


The Quench circuit including capacitance resistances (and potentially all parasitic capacitances)

At circuit level the digital output is monitored

life.augmented

VerilogA model for a SPAD



Created carriers in a thin region where the field is maximum

Toward a 1D model ! All the avalanche is 'collapsed' in 1 point of the device (where the electric field is maximum).

Ramo Currents Induced by Electron Motion*:

$$I_i = q\frac{v_i . ni}{w_i}$$

Electrons and Holes saturation velocity v_e and v_h

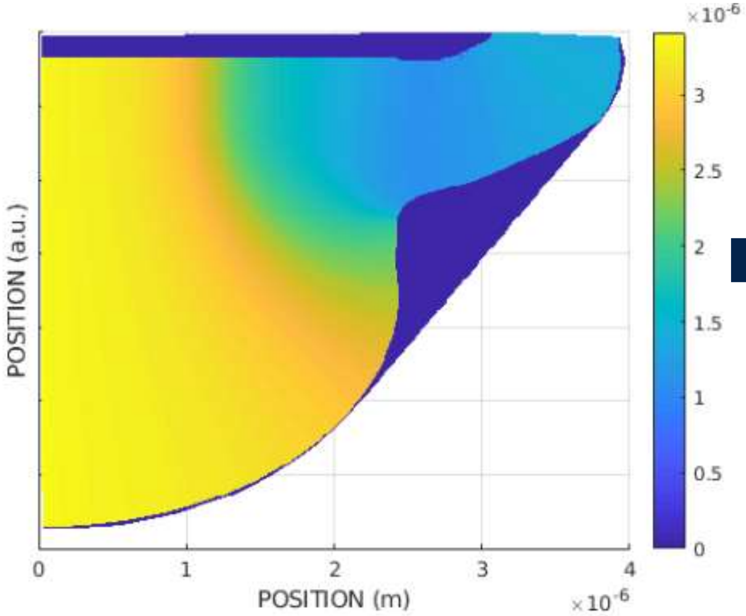
Ramo width w

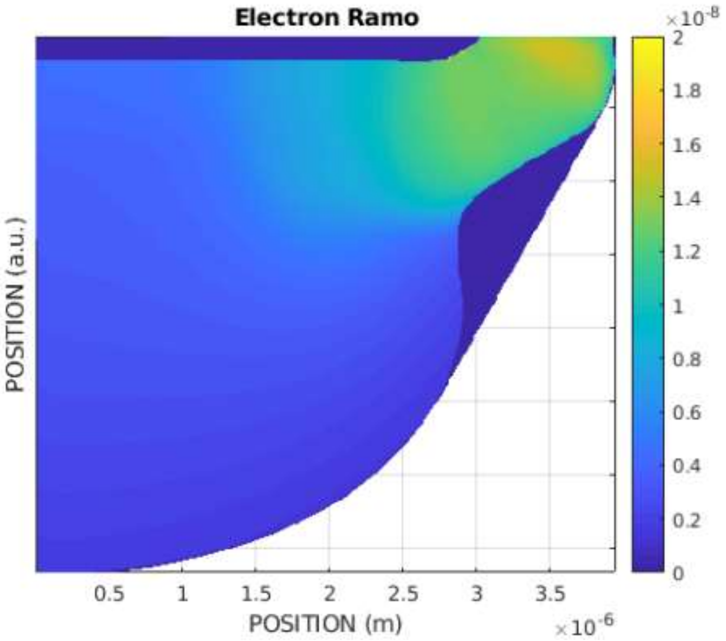
Currents Induced by Electron Motion*
SIMON RAMO†, ASSOCIATE MEMBER, I.R.E. 1939

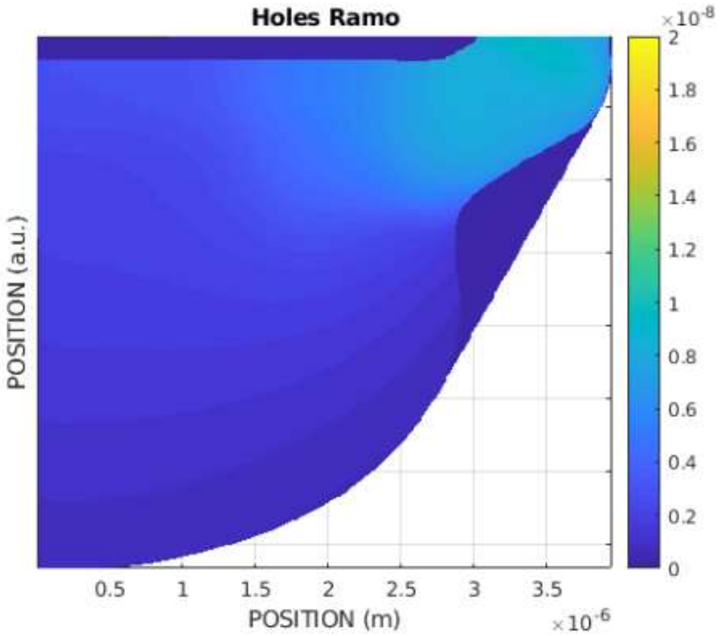
life.augmented

VerilogA model for a SPAD: effective Ramo Width

Effective Ramo width







One moving electron produces roughly 1e-8 A at the terminal.

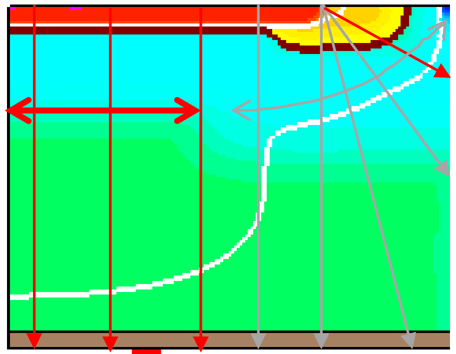
$$I_i = q\frac{v_i}{w_i}.\,n_i$$

Number of carriers

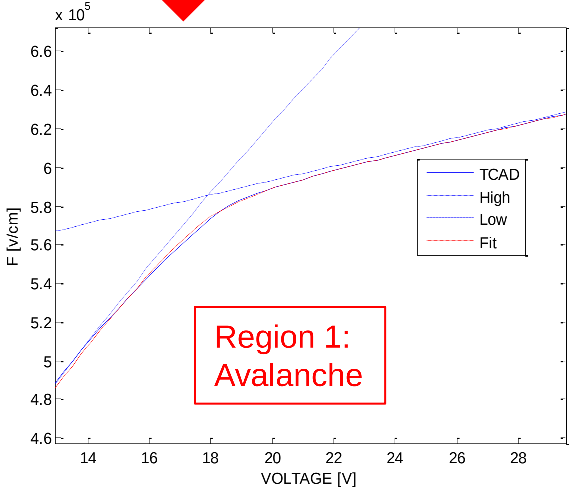
life.augmented

VerilogA model for a SPAD : the charges and capacitance

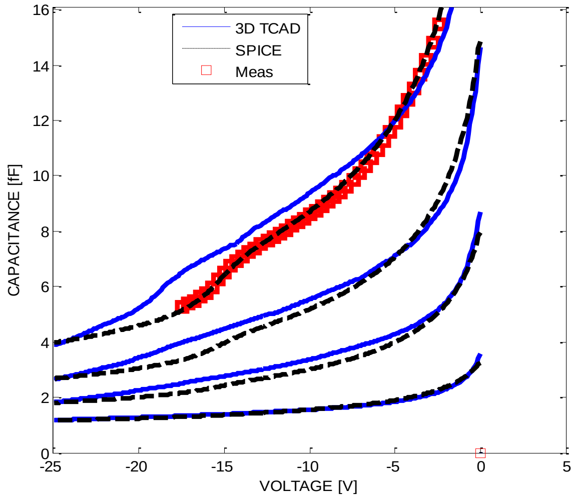
Field along the junction (TCAD simulation)



Region 2: Lower field

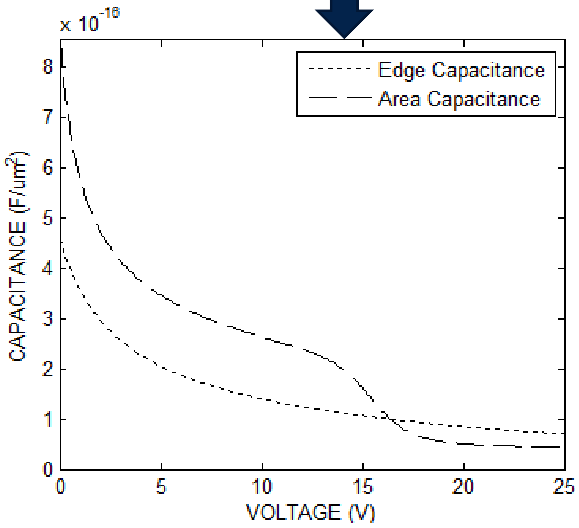


Junction Capacitance (TCAD simulation and measurements)



Field and capacitance linked by displacement curent:

$I_D = \varepsilon \partial_t F$ ⇨ $C_D = A \varepsilon \partial_V F$



life.augmented

VerilogA model of a SPAD: master equations

$$\frac{dn_e}{dt} = \frac{1}{q} M_e . I_e + \frac{1}{q} M_h . I_h - \frac{n_e v_e}{\boldsymbol{w_e}}$$

$$\frac{dn_h}{dt} = \frac{1}{q} M_e . I_e + \frac{1}{q} M_h . I_h - \frac{n_h v_h}{\boldsymbol{w_h}}$$

Depleted Region

Created electrons and holes by impact ionization

Electrons leaving the SCR

$\boldsymbol{\tau_i}$ is the 'evacuation' time

$$\frac{v_i}{w_i} = \frac{1}{\tau_i}$$

Electrons and Holes saturation velocity $\boldsymbol{v_e}$ and $\boldsymbol{v_h}$

Effective multiplication widths $\boldsymbol{w_e}$ and $\boldsymbol{w_h}$

Currents Induced by Electron Motion*
SIMON RAMO†, ASSOCIATE MEMBER, I.R.E. 1939

life.augmented

VerilogA model of a SPAD: master equations

$$\frac{dn_e}{dt} = \frac{1}{q} M_e . I_e + \frac{1}{q} M_h . I_h - \frac{n_e v_e}{\boldsymbol{w_e}}$$

$$\frac{dn_h}{dt} = \frac{1}{q} M_e . I_e + \frac{1}{q} M_h . I_h - \frac{n_h v_h}{\boldsymbol{w_h}}$$

Depleted Region

Impact Ionization model

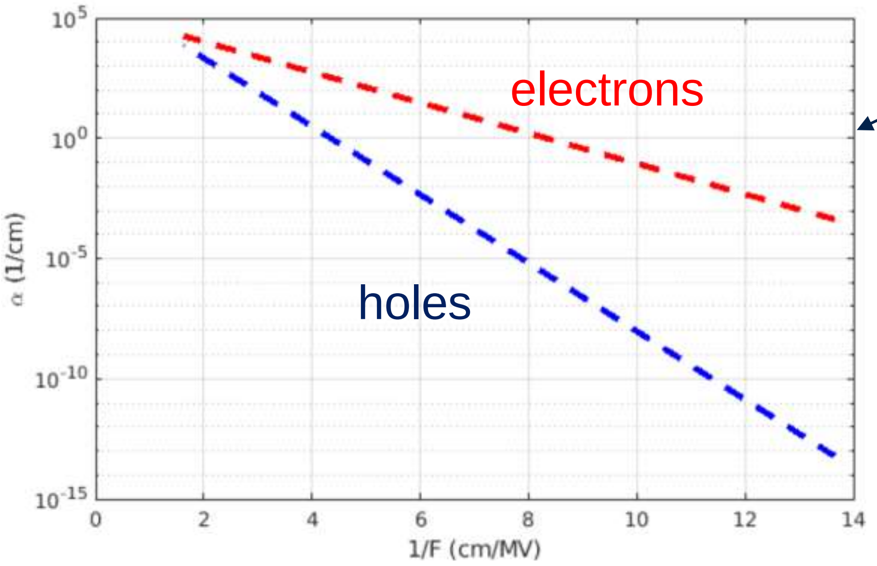
$$M_i = A_n(Fmax).w_i$$

Effective multiplication widths $\boldsymbol{w_e}$ and $\boldsymbol{w_h}$

Van Overstreaten Coefficients

$$A_n = \alpha_n . \exp\left(\frac{-\beta_n}{F_{max}}\right)$$

Maximum field in the junction



Maximum Field
5 Physical parameters
7 Device parameters

life.augmented

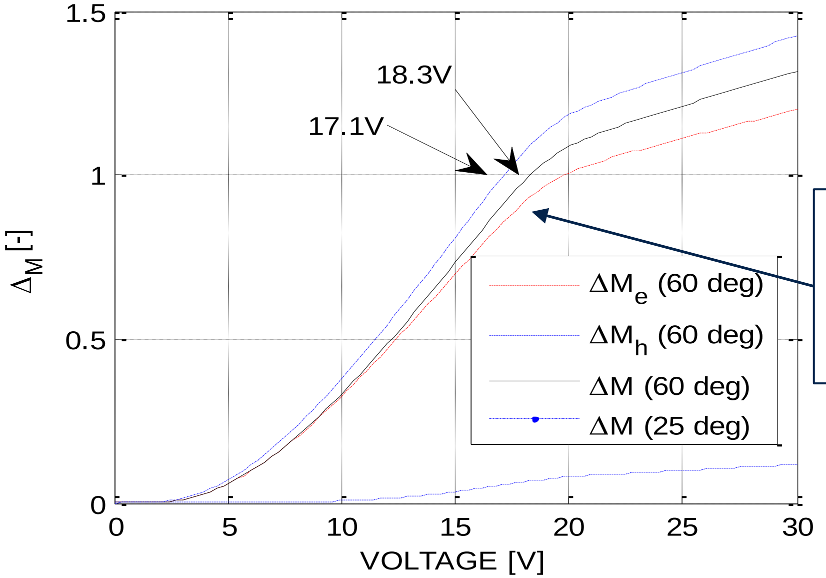
VerilogA model for a SPAD : Carrier multiplication

The avalanche is driven by the multiplication of carrier in an ‘infinite’ time.

➡ $I = Io(1 + \Delta M + \Delta M^2 + \Delta M^3 + \cdots)$

➡ $I = Io/(1 - \Delta M)$

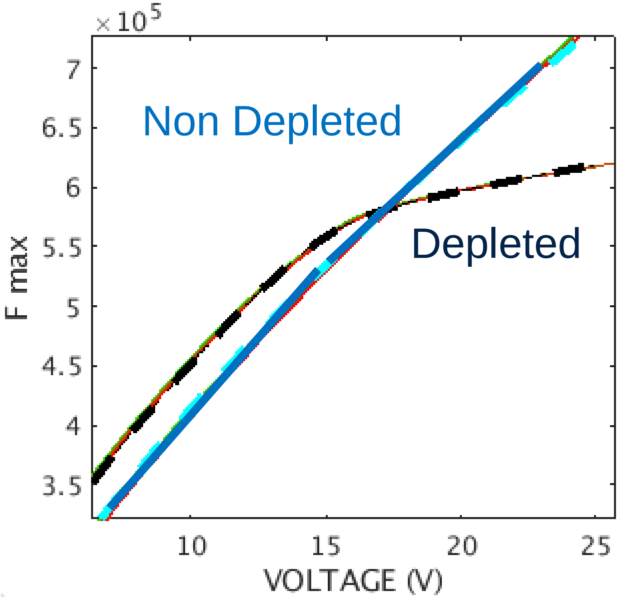
$\Delta M = [Mn + Mp]$

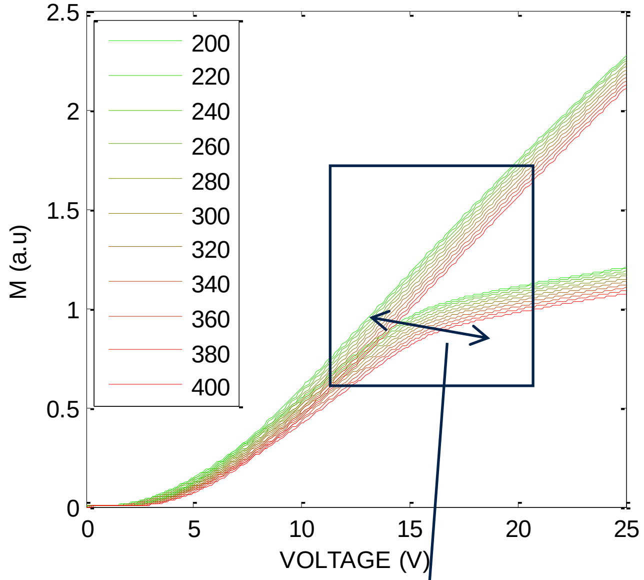


When M =1 the current is diverging. This is the BV and sets values for w_n and w_p parameters.

life.augmented

VerilogA model for a SPAD : Breakdown Voltage and Capacitanc

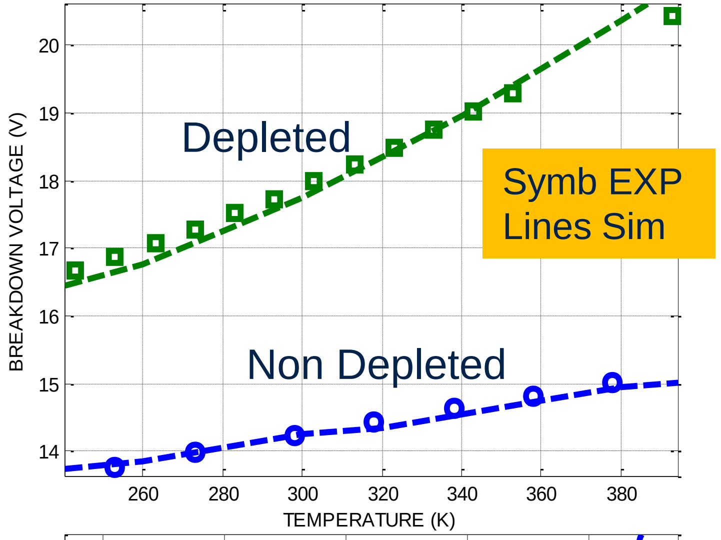


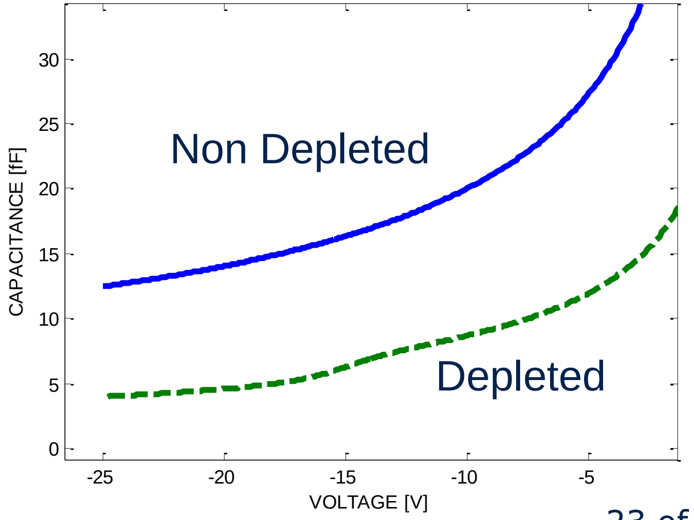


Voltage at BV:	$\Delta M = [Mn(F) + Mp(F)] = 1$

Multiplication factor vs Temperature ➔

- **Breakdown voltage**
- **Capacitance**

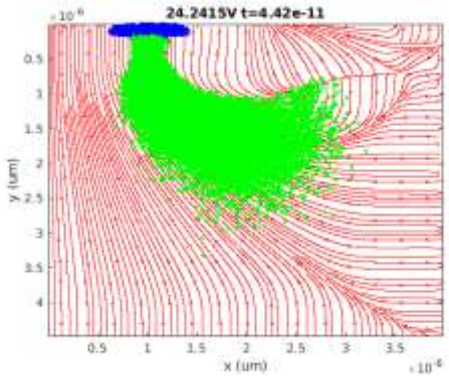


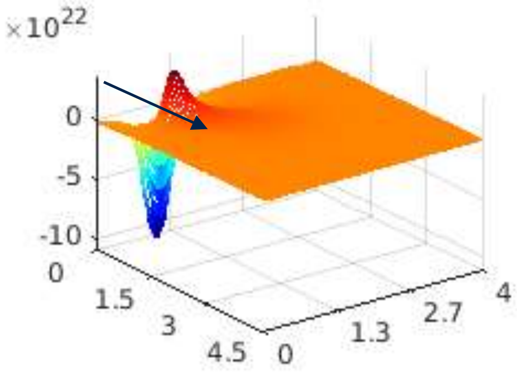


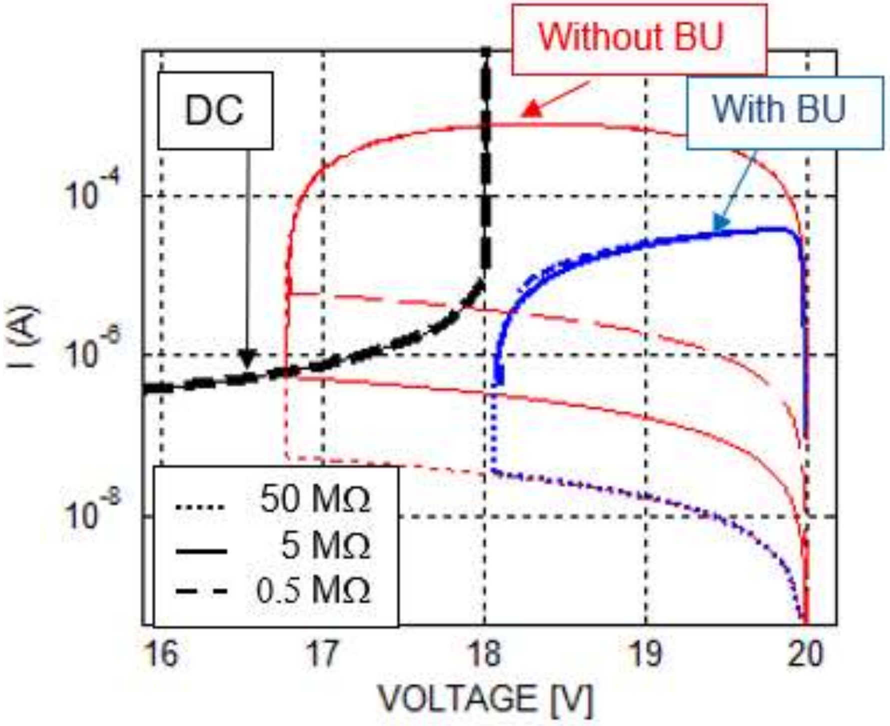
life.augmented

VerilogA model for a SPAD : bluid-up field

The additional charges create a dipole that tends to reduce the diode junction field !

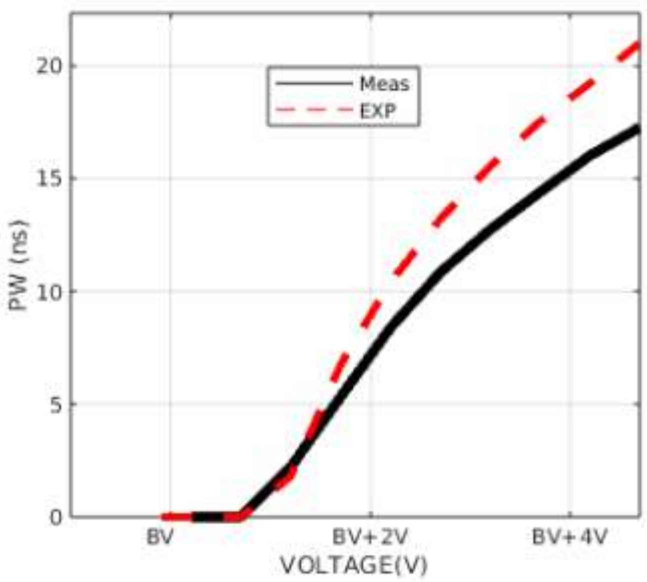




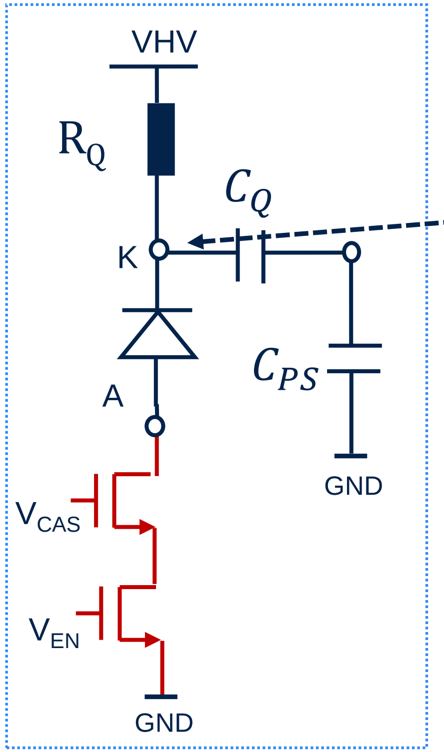


VerilogA model for a SPAD : parameters calibration

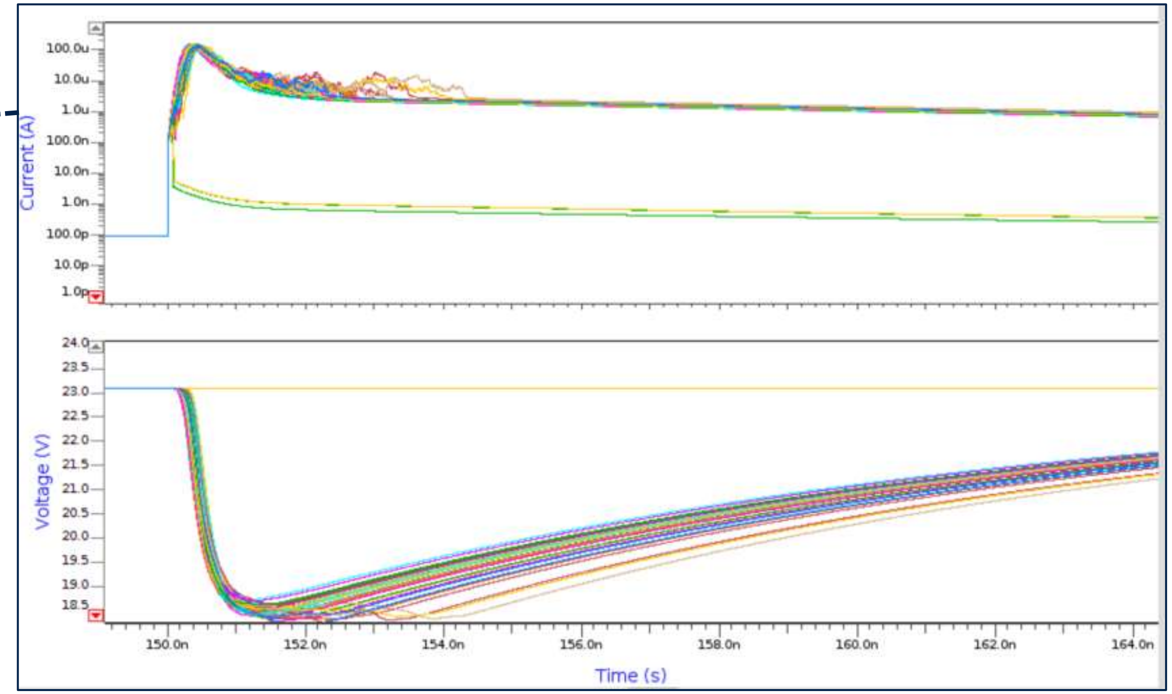
- An overall agreement bw model predictions and measurement is to be achieved combining several FOMs
- It requires some trade off sometimes !



VerilogA model for a SPAD : avalanche current fluctuations

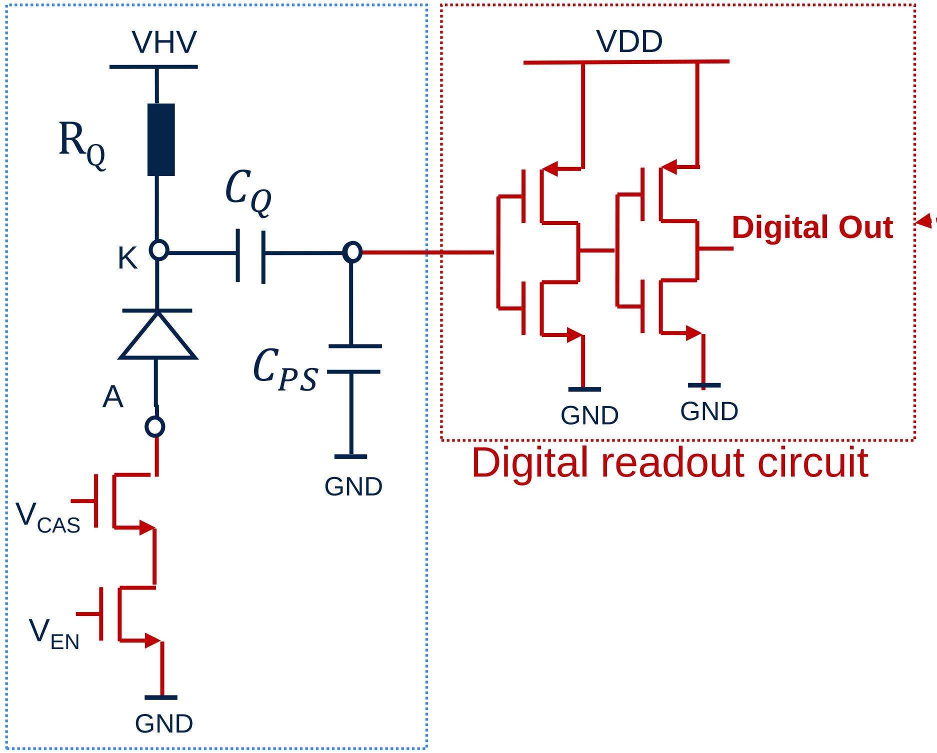


VerilogA SPICE model

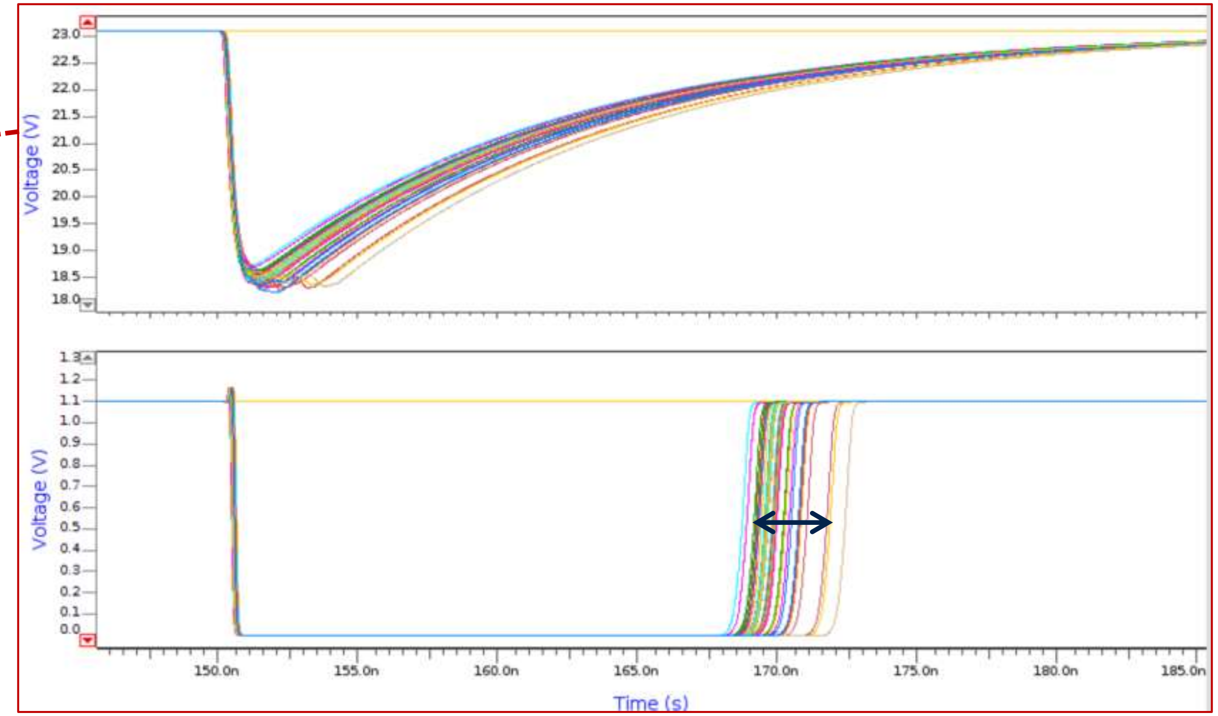


The II ionization is a statistical process ➔ The number of created carriers fluctuate ➔ Voltage curves exhibits a dispersion

VerilogA model of a SPAD: avalanche current fluctuations

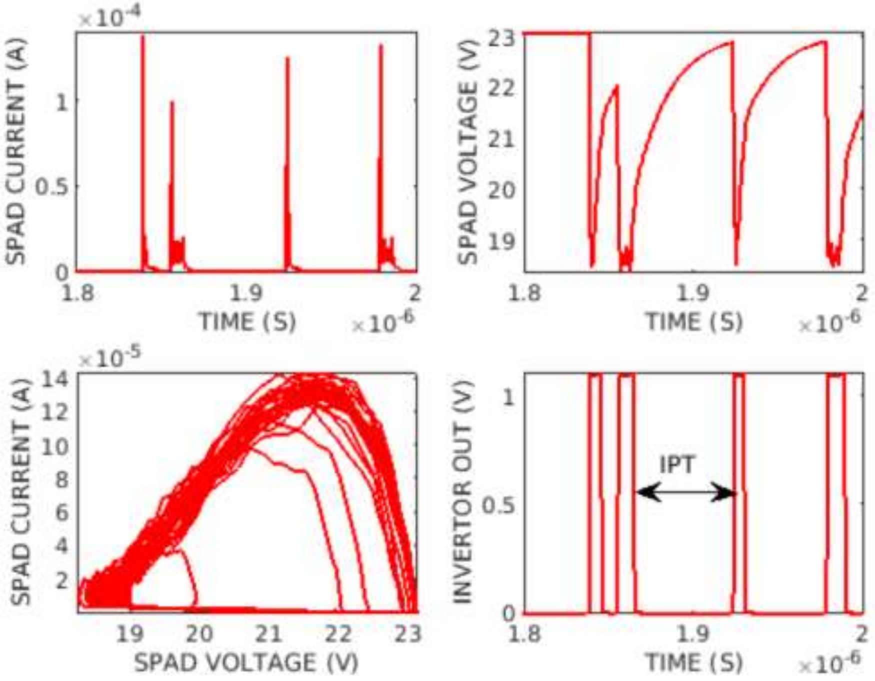


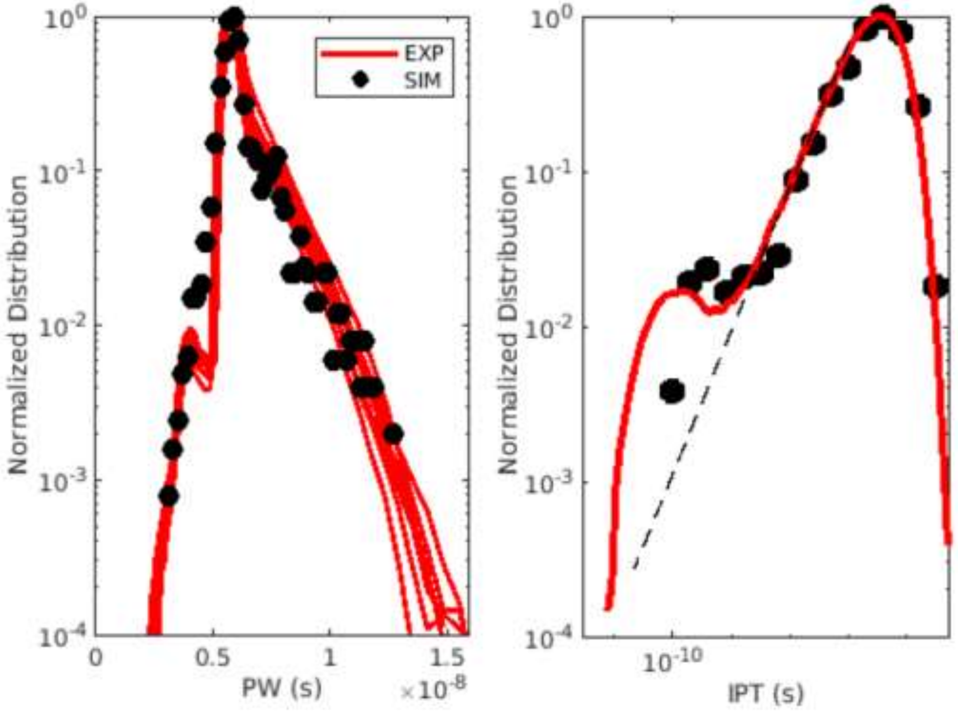
VerilogA SPICE model



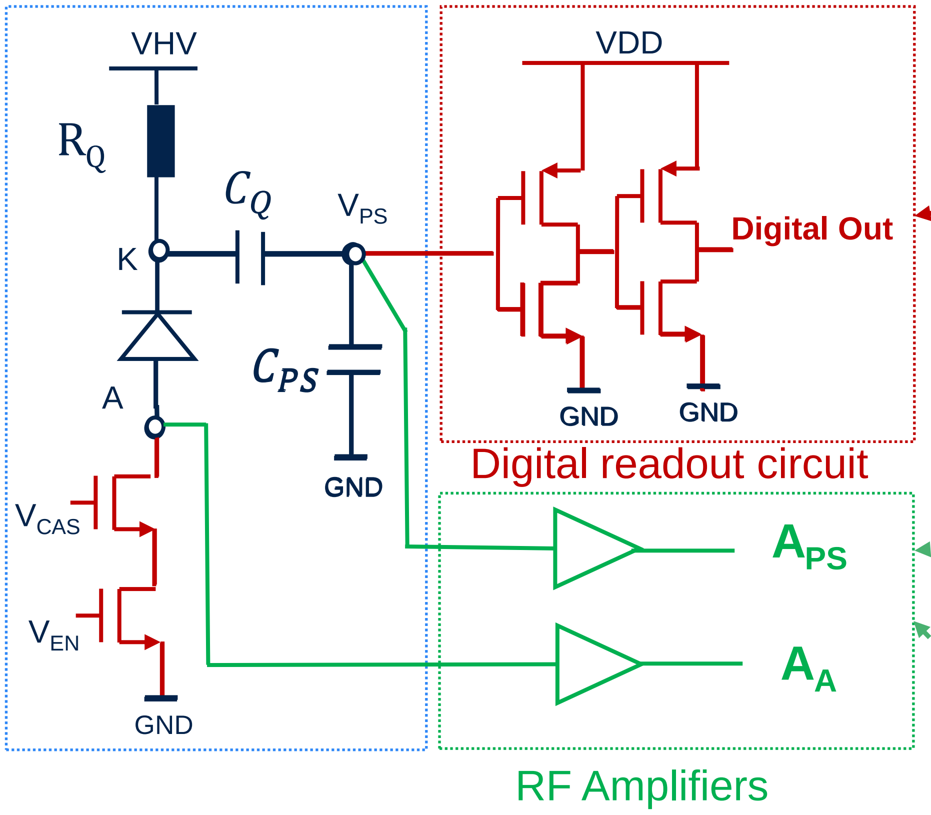
The II ionization is a statistical process ➔ The number of created carriers fluctuate ➔ Voltage curves exhibits a dispersion ➔ digital pulse width fluctuate

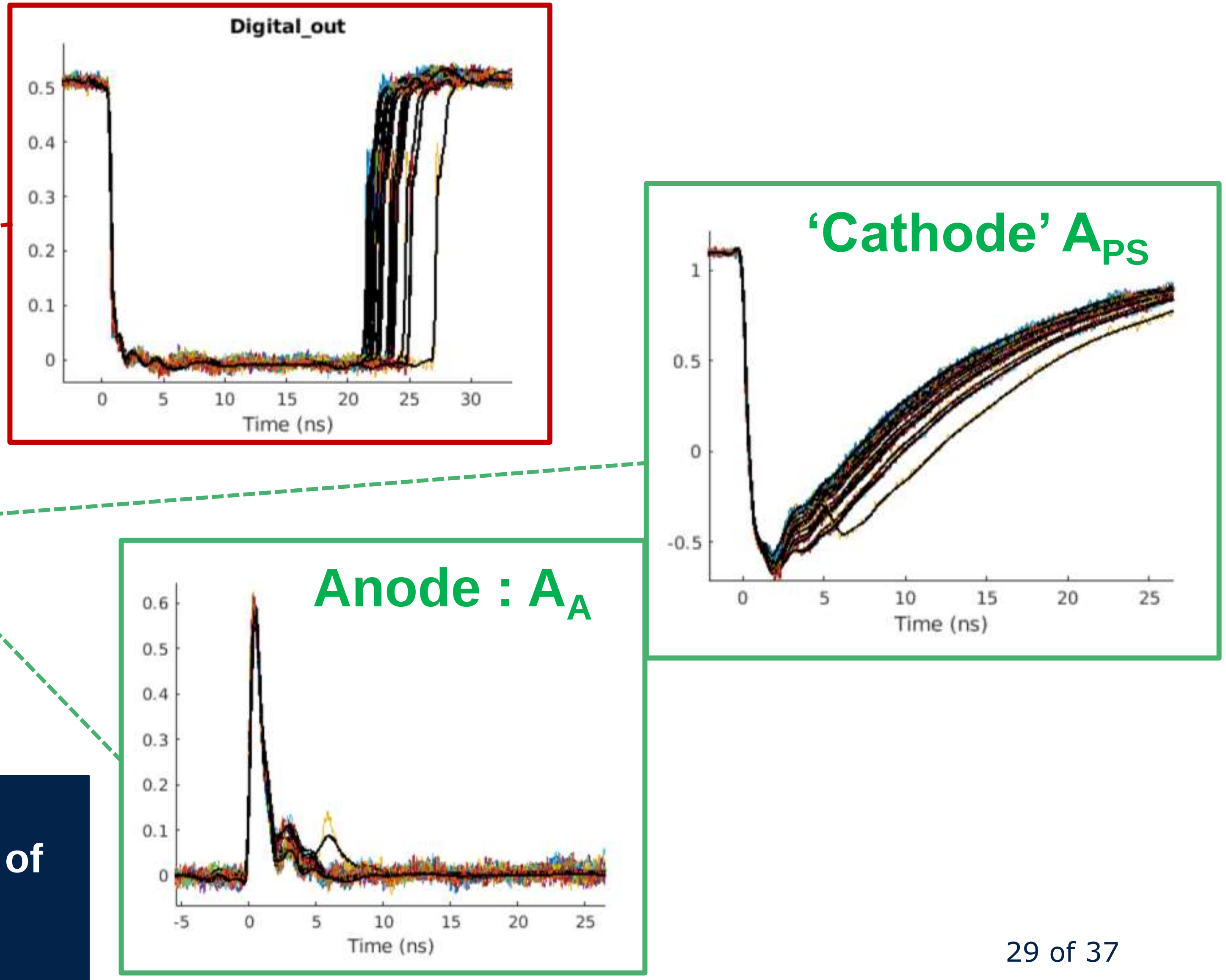
Model vs. measurements: PW distribution and IPT





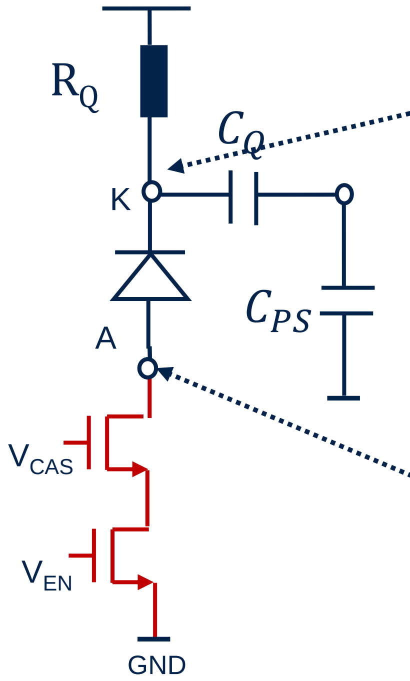
Comparison with measurements: transient setup

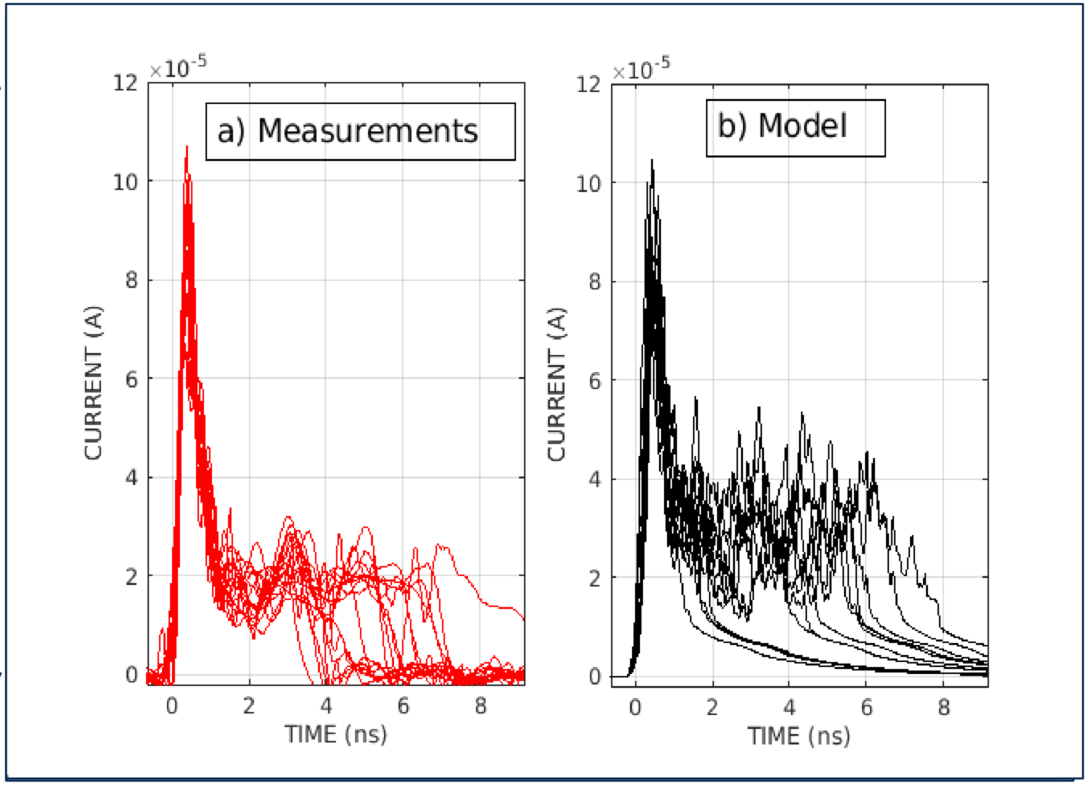




<u>ICUBE, Strasbourg collaboration</u>: RF Amplifiers make possible the monitoring of the Anode and the Cathode signals

Model vs. measurements: quench circuit





Faster RC time constant: 3ns

Faster recharge is not always a path for a "faster" SPAD

Agenda

1 Direct Time-of-Flight sensor: General concepts of SPAD

2 A SPAD is a statistical device

3 VerilogA SPICE model

4 Experimental and model

life.augmented

Conclusions

- Direct Time-of-Flight sensor:
  - General concepts
  - A statistical device!

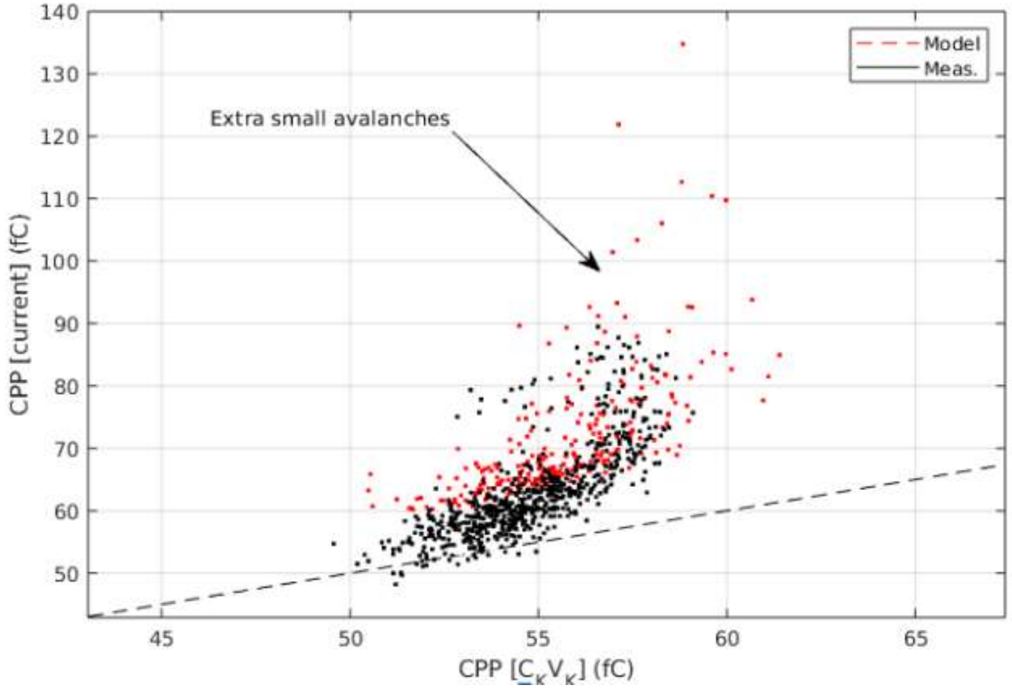
- VerilogA SPICE model
  - Quench Circuit
  - Model Equations
  - Measurements and Model

life.augmented

Questions?

denis.rideau@st.com

Charge per pulse



Agenda

#	Topic
#	Topic
#	Topic
#	Topic
#	Topic
#	Topic
#	Topic
#	Topic

life.augmented

Section title

life.augmented

Our technology starts with You

Find out more at www.st.com

life.augmented