Linear-mode APDs in standard CMOS

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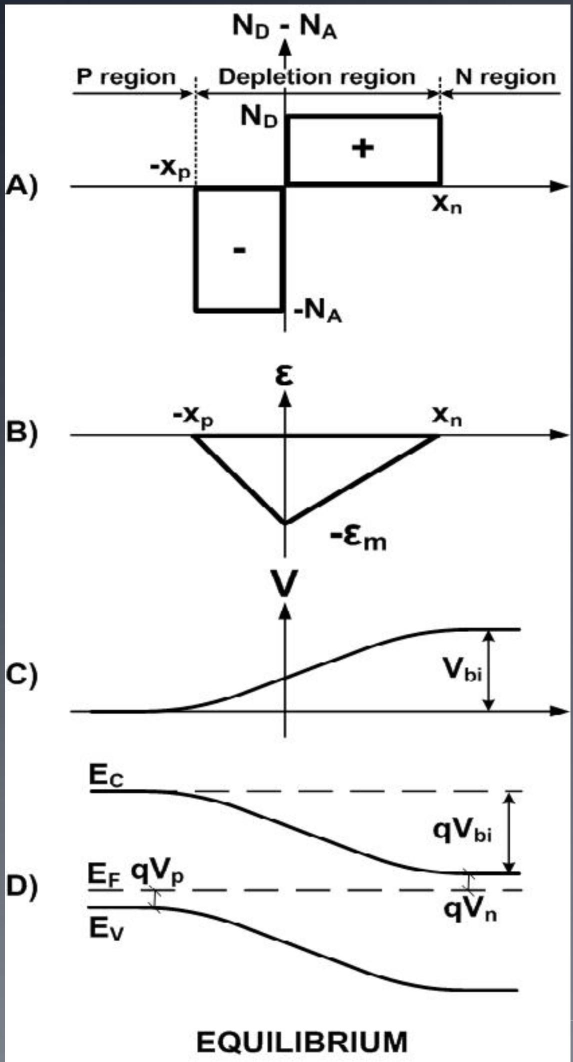
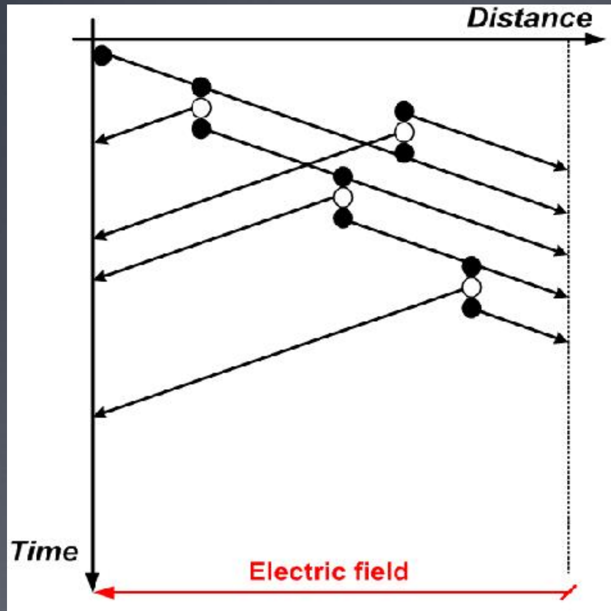
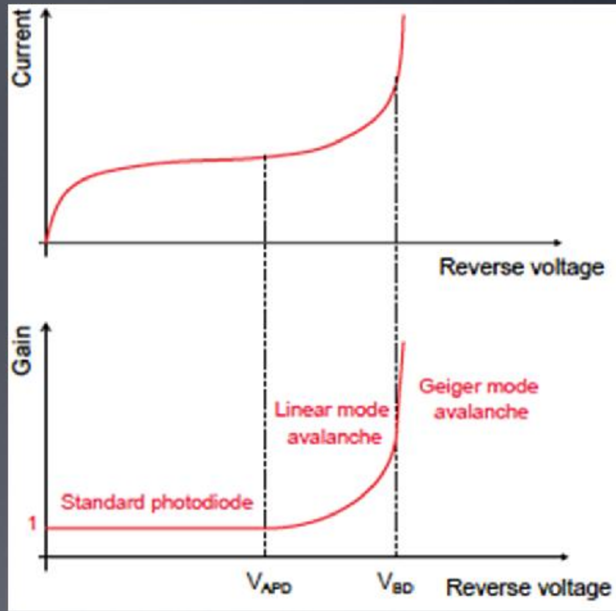
Outline

- Introduction
  - Introduction to APDs
  - Why linear mode?
- Experimental
  - The device
  - The setup
- Characterization (1 and 2)
- Conclusions

Avalanche PhotoDiode - APD







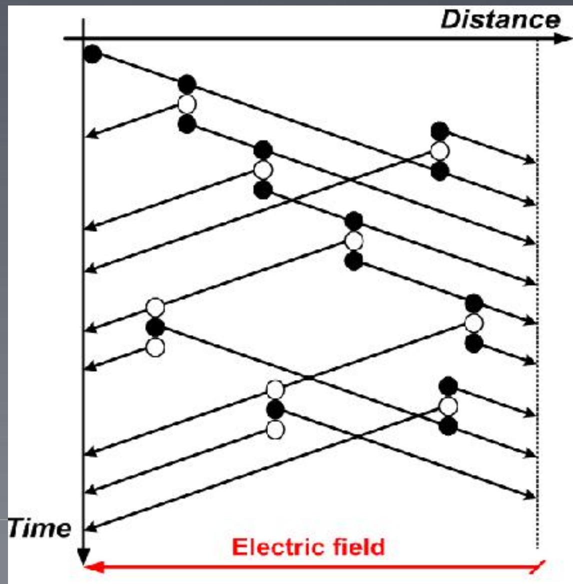
S. Sze 1981 "Physics of semiconductor devices"

e^--h^+ pair generation due to:

- External interaction:
  - Photon absoption
  - Minimum Ionizing Particle
- Noise:
  - Thermal release of charge
  - Tunnel effect

Operation modes

- An average field value of $3 \cdot 10^5$ V/cm is required to create one electron-hole pair per 1 micron travelled.
- Below the breakdown voltage, ionization rates balanced by extraction rate → carrier concentration & output current have finite gain, M (*10 - *100). Linear APDs
- For bias beyond breakdown, very high ionization rates → carrier concentration & current virtually infinite ($M > 10^6$). Geiger APDs, also known as SPADs



Why APDs?

- APD technology offers ideal properties for photon sensing applications:
    - low noise
    - high speed
- Geiger-mode APDs (SPADs) provide
    - high sensitivity
    - good energy resolution
    - digital answer
- SPADs have been monolithically integrated in standard CMOS processes.

Why linear mode?

- Linear-mode APDs allow (additionally)
  - determining the number of incident photons with great precision
  - low noise levels even at room temperature
  - demodulation together with detection
- Mainly manufactured by means of dedicated processes
  - cost consuming
  - poor reliability
  - high bias voltages to operate (typically between 100-200 V)
  - relatively low multiplication gains

We introduce a linear-mode APD fabricated in a standard 0.35 μm CMOS process for obtaining high multiplication gains.

Useful in several application domains such as image sensors, optical communications and quantum information.

Merit figures in linear mode

- As usual for other photodiodes:
  - quantum efficiency
  - dark current
  - bandwidth
  - gain
  - ...
- Statistical nature of impact ionization →
  actual number of e-h pairs per photon varies →
  multiplication noise higher than shot noise*M →
  Excess noise factor F = f (M,k) (McIntyre, 1966)

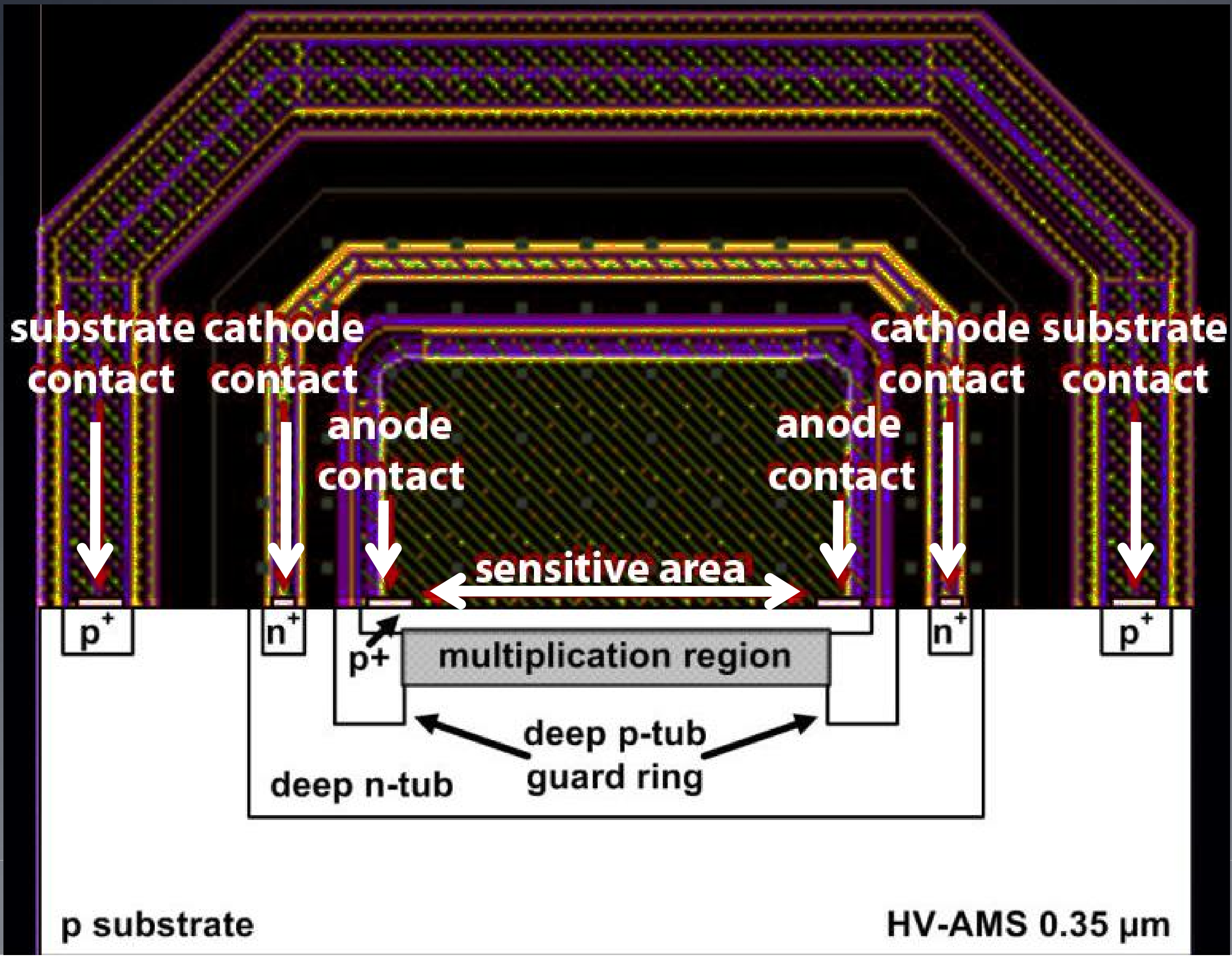
State-of-the-art

Reference	Node (µm)	Type	Guard ring	V_{APD} (V)	QE (%)	F @ M = 20
Biber 2001	2	p+/n-well	p-base	42	40@500nm	36000 @ 635nm
Biber 2001	2	n+/p-well	n-well	80	75@650nm	1800 @ 635nm
Rochas 2002	0,8	p+/n-well	p-well	19,5	50@470nm	7 @ 400nm
Stapels 2007	0,8	n+/p-well	n-well	n.a.	>60@700nm	5 @ 470nm
Stapels 2007	0,8	p+/n-well	p-tub	25	50@550nm	50 @ 470nm
Kim 2008	0,7	n+/p-well	virtual	11	30@650nm	n.a.
Panchieri 2008	0,35	p+/n-well	p-well	10,8	23@480nm	4,5 @ 380nm 6 @ 560nm

G.F. Dalla Betta et al., "Avalanche photodiodes in submicron CMOS technologies for high-sensitivity imaging" in "Advances in Photodiodes" InTech Ed. (2010)

The device

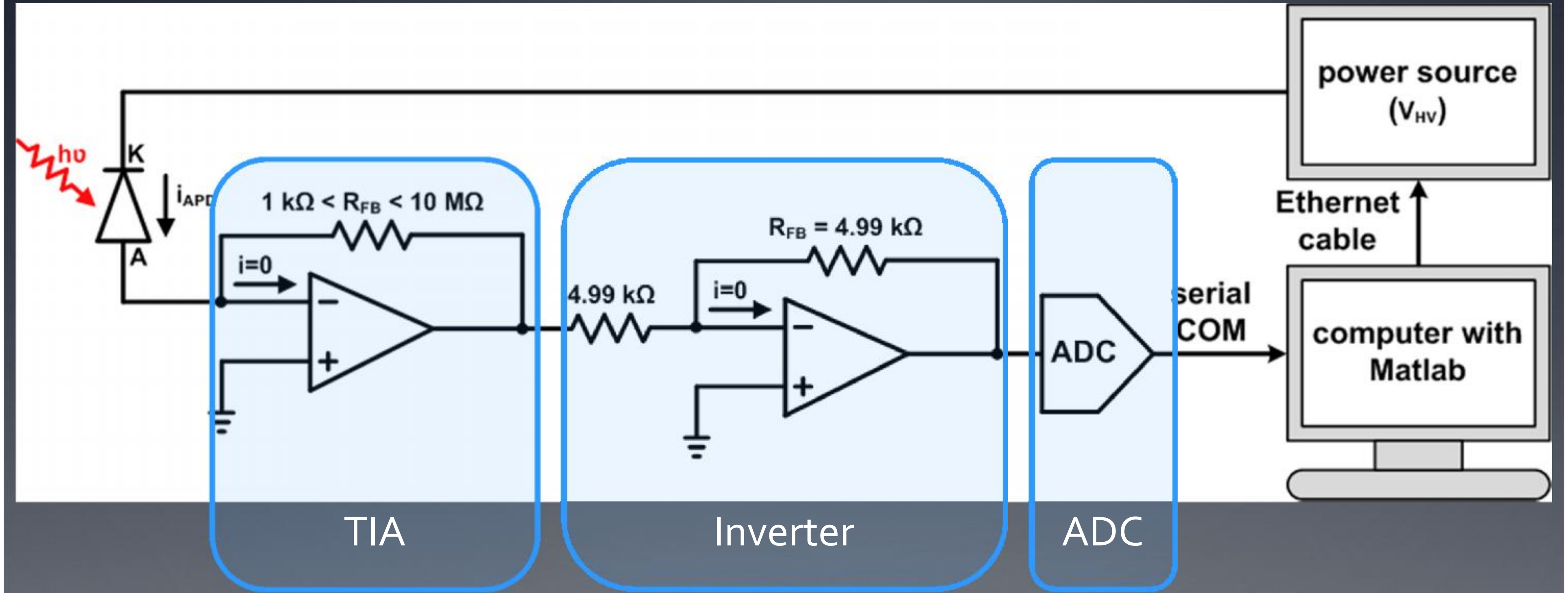
HV-AMS 0.35 µm CMOS process, without modifications through a MPW service by Europractice (20 µm x 100 µm).



Deep n-tub implantation (cathode) biased slightly below V_{BD}.

Photocurrent measured at the p+ implantation (anode).

Characterization 1



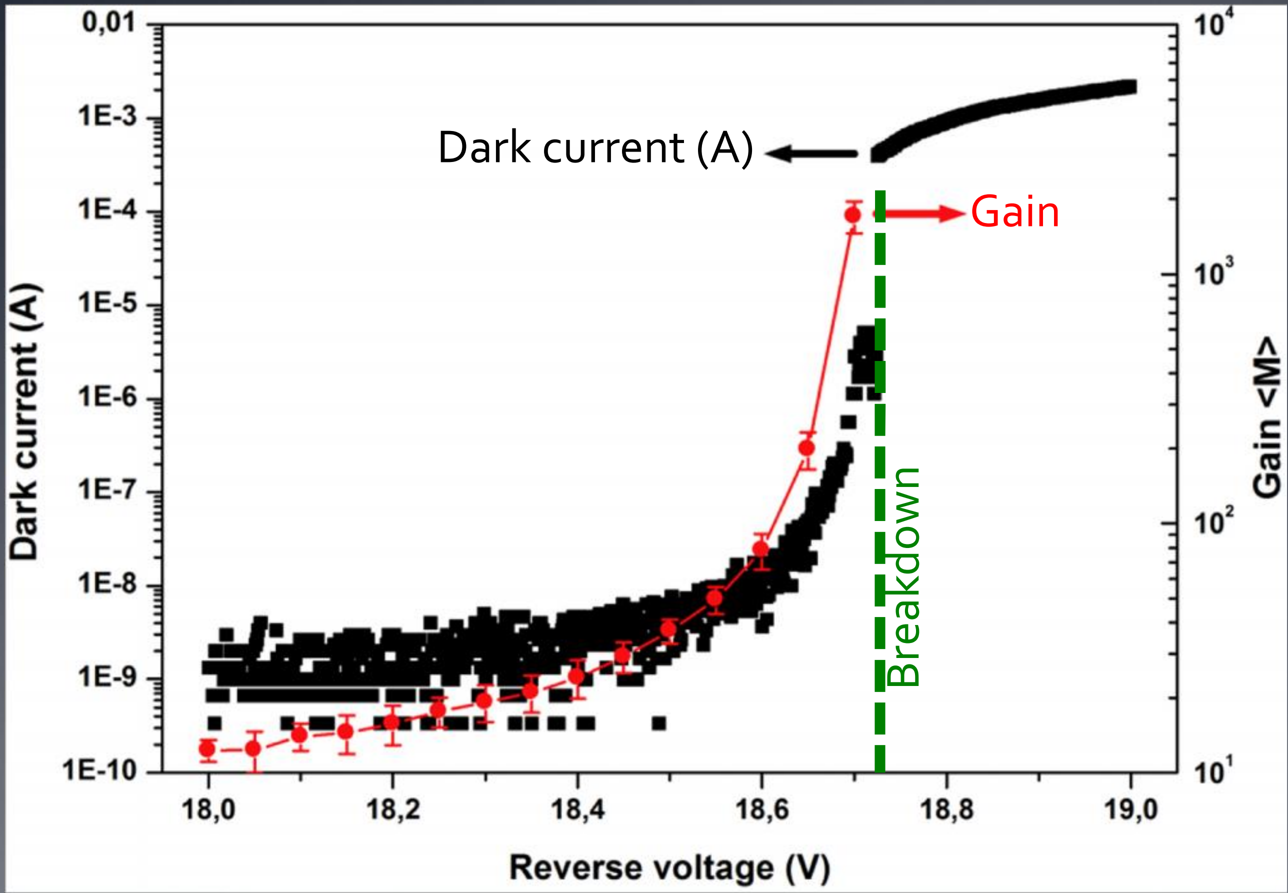
amplification system + digital data transfer

LPC662 by Texas Instruments + PIC32MX795 by Microchip

Complete setup

- A software self-developed in Matlab is used to receive and store the experimental data, in addition to control the power source (model N6705A by Agilent Technologies) by means of an Ethernet cable.
- To show the potential of this technology, the linear-mode APD was illuminated with an 880 nm LED (model SFH 485 by Siemens) at several optical powers.
- The experimental set-up was placed inside a black box to avoid any uncontrolled light sources.

Dark current & gain



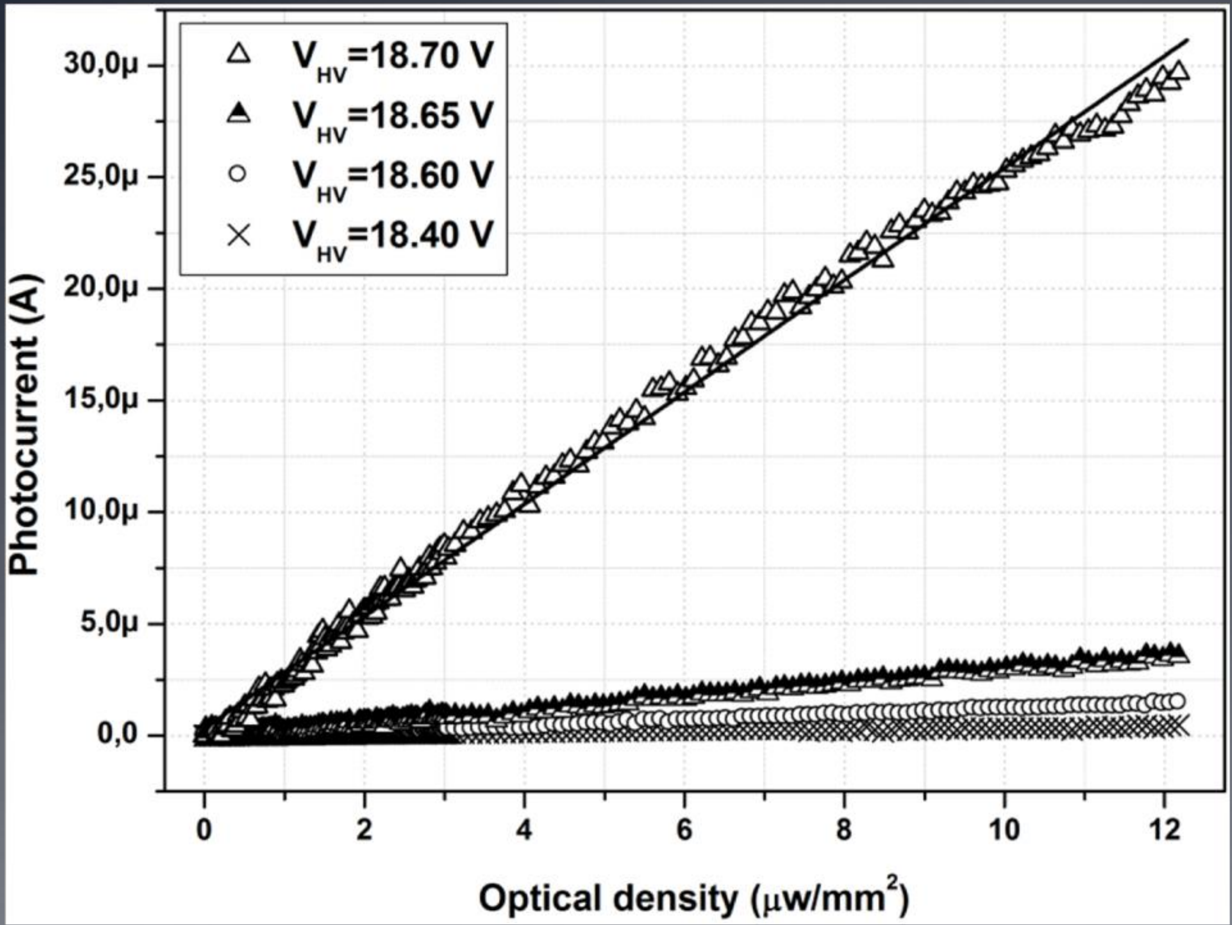
Breakdown voltage = 18.72 V.

Dark current = 1.2 nA for M = 12 and 2.9 nA for M = 21.

Normalized dark current density = 1450 nA/mm² (x200 what is reported for CMOS APDs at the same gain).

Maximum M = 1700 (@ 18.70 V).

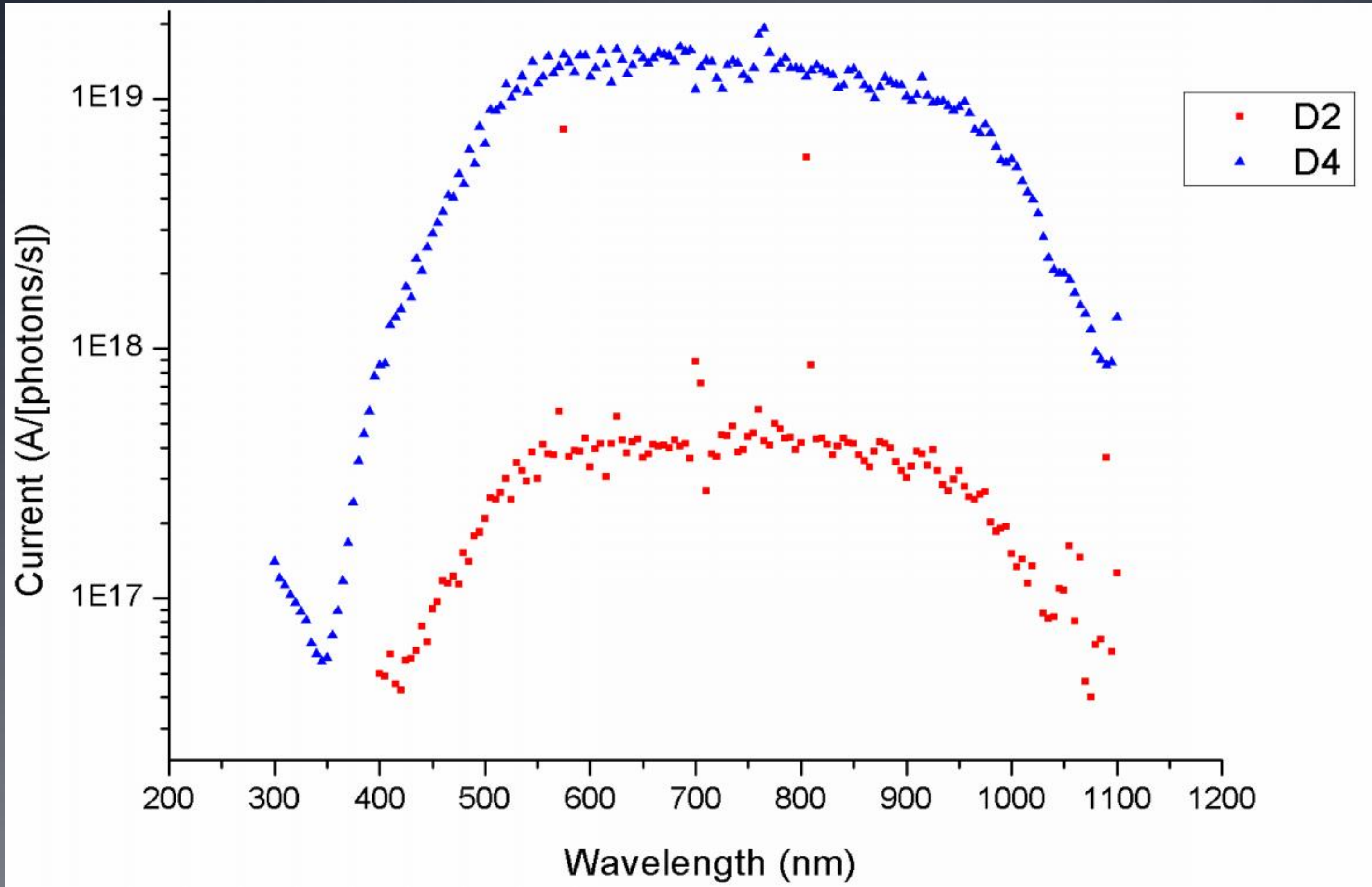
Photocurrent



Excellent linearity

Increasing with M, and then with V_{HV}

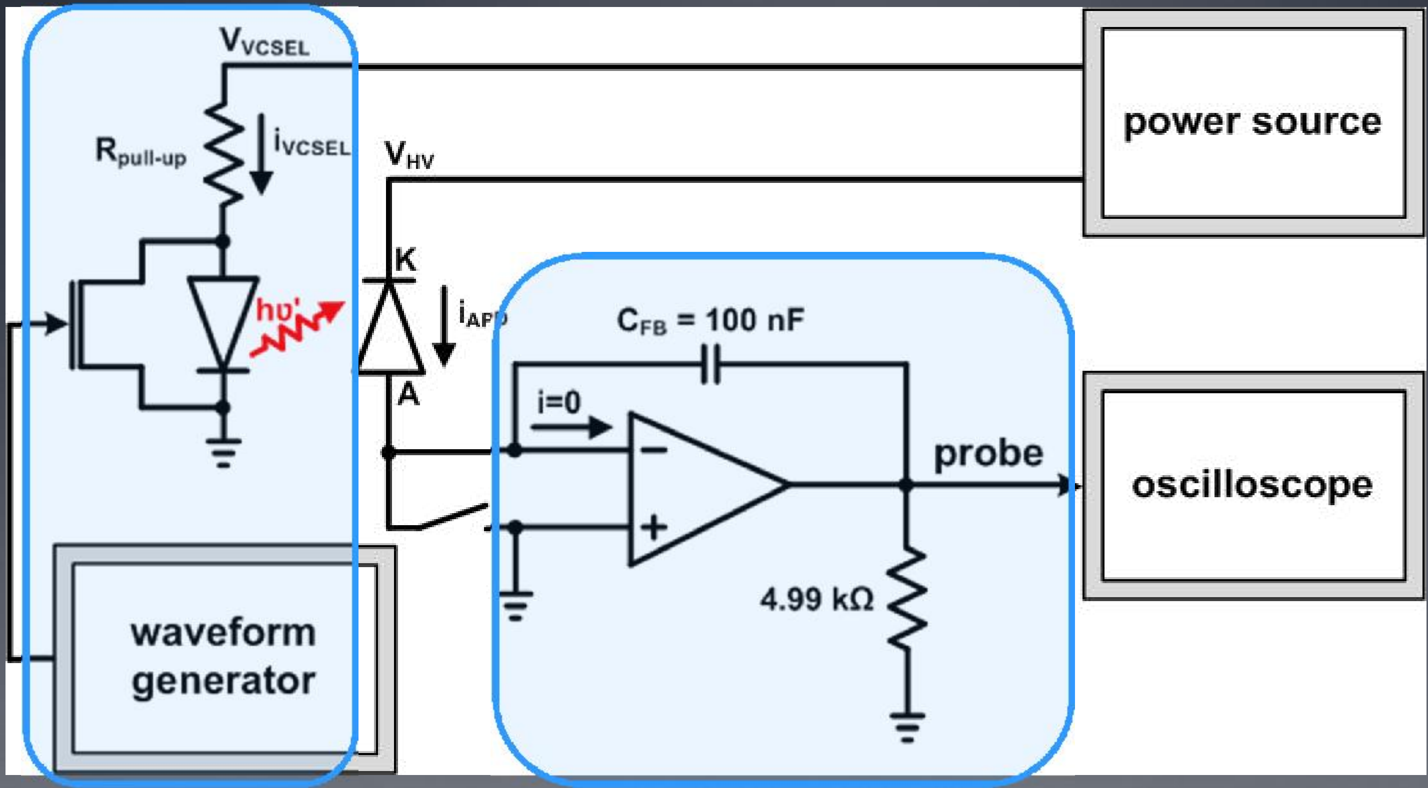
Spectral response



Good detection for 500-1000 nm.

Minima for 350 and 1100 nm (425 and 1075 nm for reduced area)

Characterization 2



lightning + integrator

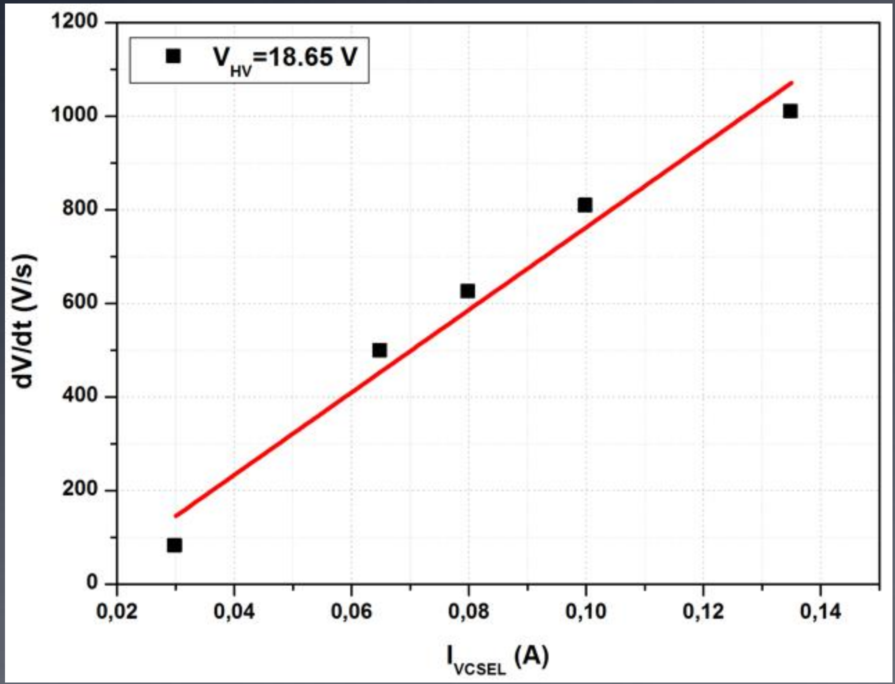
VCSEL array by eMCORE (850 nm) + LPC662 by TI

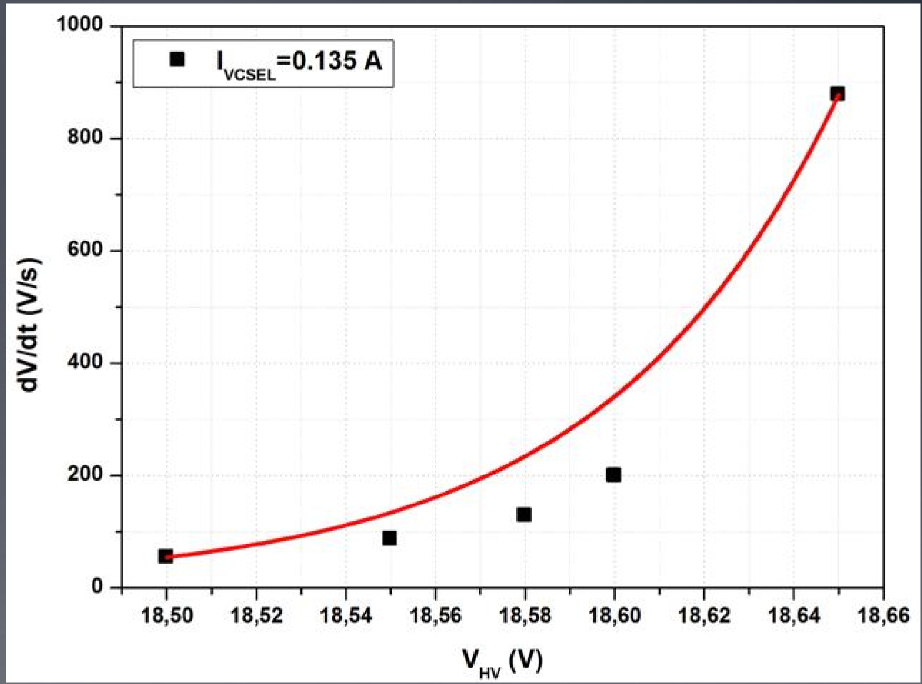
Integrating the current

APD pulsed with t_{on} = 3 ms and V_{HV} = 18.7 V, only once. VCSEL continuously ON. C_{FB} = 100 nF. Uniform variation.

APD biased to 18.7 V. VCSEL pulsed (green, active time is 10 ms approx.) with 135 mA. C_{FB} = 100 nF.

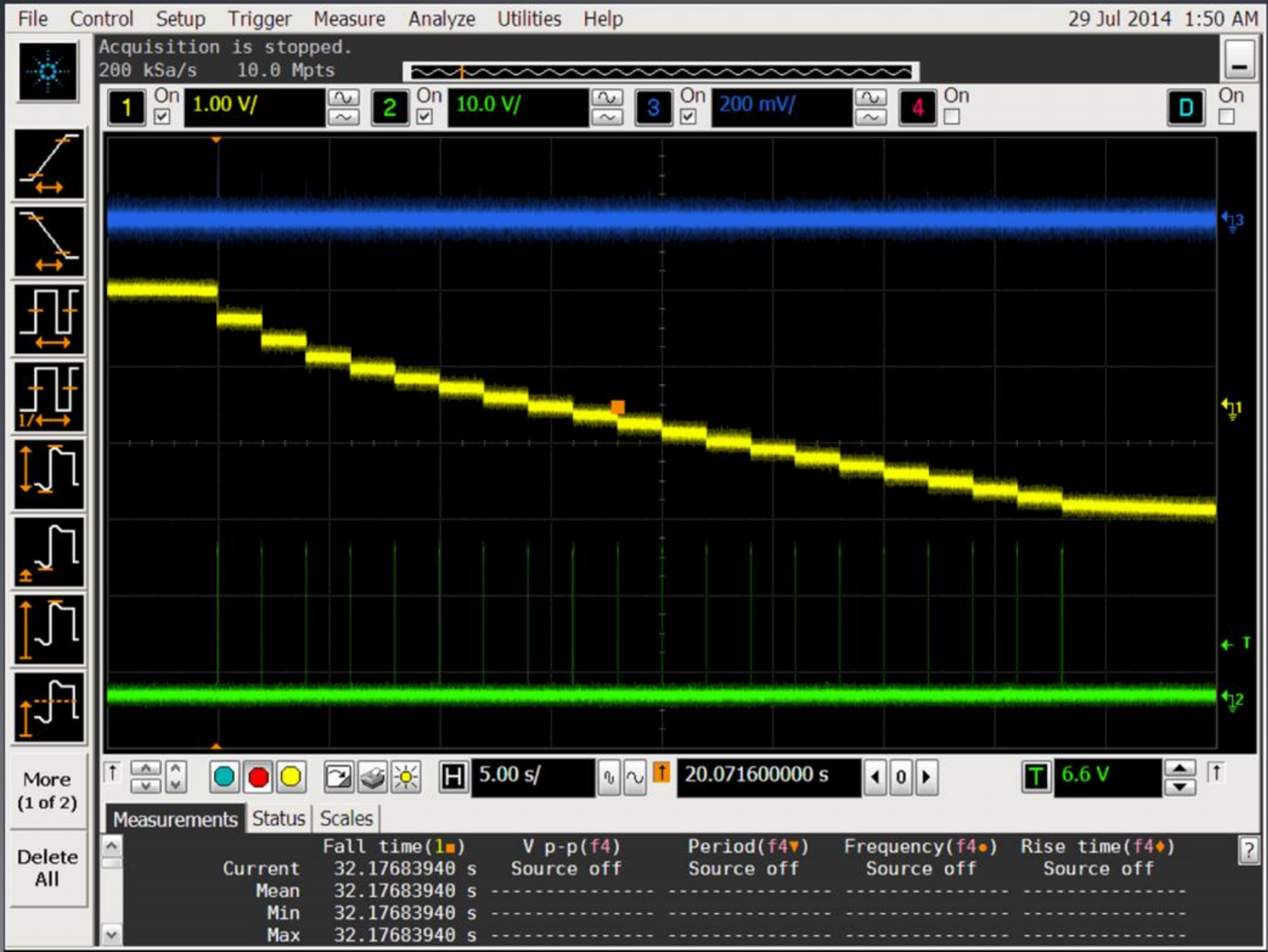
Integrated current





- dV/dt linear with the intensity at the VCSEL.
- Large variation with biasing at the APD.

High range precision



Conclusion

- A linear-mode APD fabricated in a conventional 0.35 µm CMOS process is reported and characterized.
- The experimental characterization shows high multiplication gains and excellent linearity between the incident optical power and the generated photocurrent.
- Linear-mode APDs fabricated in standard CMOS processes can be used for effectively counting the number of incident photons in many applications

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Thank you !!!

- Questions?