Kolymvari, Chania, Crete, Greece, 11.07.2019

Time response of avalanche photodiodes based on GaAs/AlGaAs with separated absorption and multiplication region

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Outline

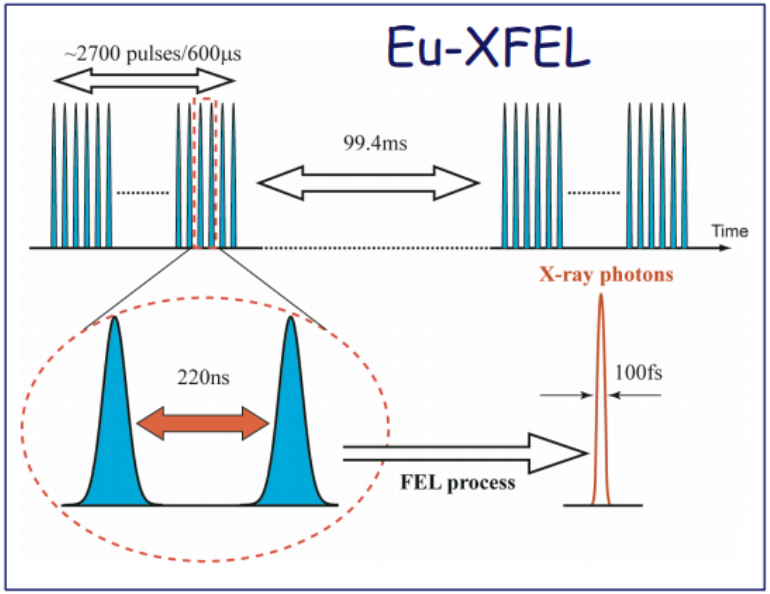
- Motivation
  - Why Avalanche PhotoDiodes (APDs)?
  - Why GaAs?
  - Why Molecular Beam Epitaxy?
- Results
  - Response of 3 different types of devices to a pulsed green laser
- Summary so far and what is next

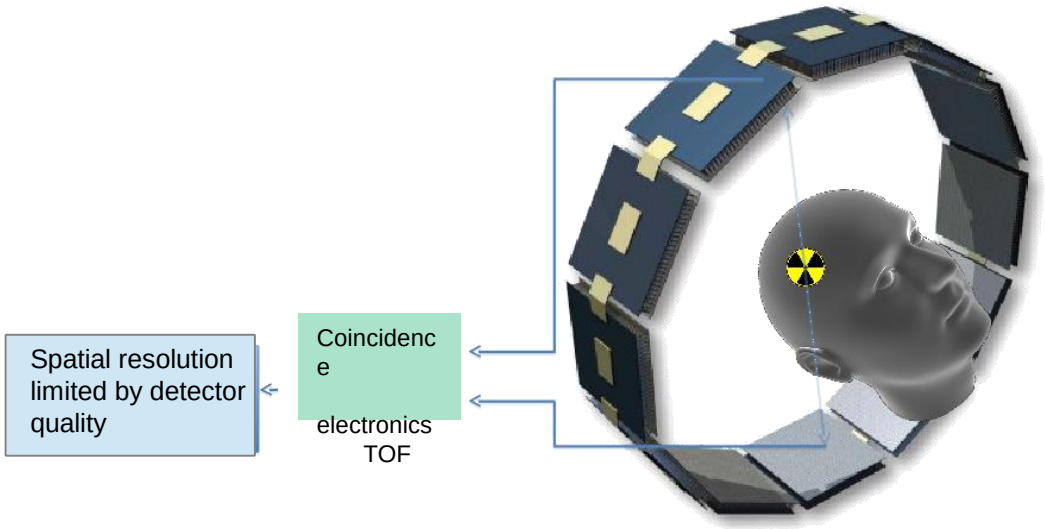
Time-resolved single-photon X-ray detectors

Single photon detectors:

- medical imaging, hazard detection, (bio)-photonics, high energy and astrophysics …
- the best-known is

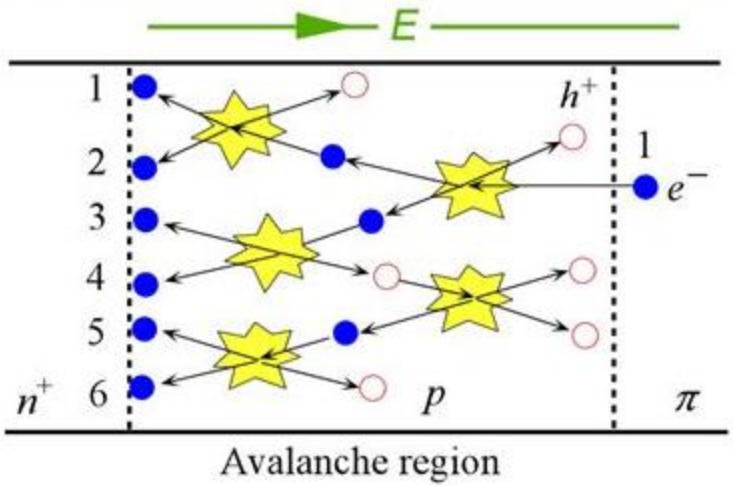
  Si avalanche photodiodes (APD's)





Why Avalanche Photodiodes?

- APD: electric field (>10^5 V cm^{-1}) → impact ionization of electrons and holes (avalanche effect)



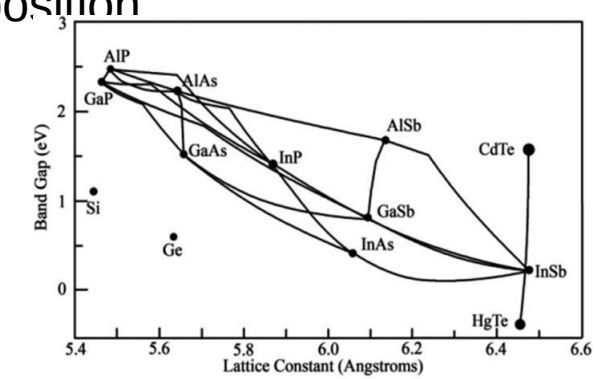
- High sensitivity, speed, gain and signal to noise ratio
- APDs for X-ray range traditionally based on silicon
- Next-generation of synchrotron light sources → GaAs/AlGaAs was proposed [1]

[1] F. Capasso, W.T. Tsang, G.F. Williams; *Staircase Solid-state Photomultipliers and Avalanche Photodiodes with Enhanced Ionization Rates Ratio; IEEE transactions on electron devices, vol. 30, n. 4: April 1983*

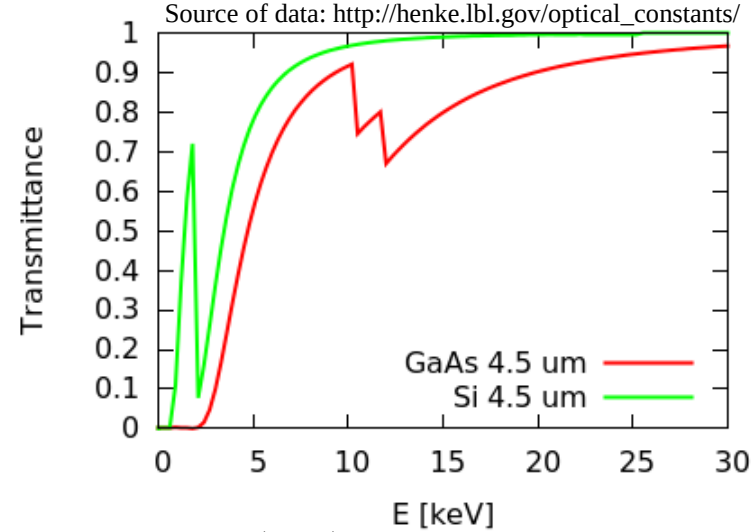
Why GaAs/AlGaAs?

	Band gap [eV]	Atomic number	Mobility of e- [cm²/ (V·s)]
Si	1.1	14	≤ 1400
$Al_xGa_{1-x}As$	> 1.4	31(Ga),33(As)	≤ 8500

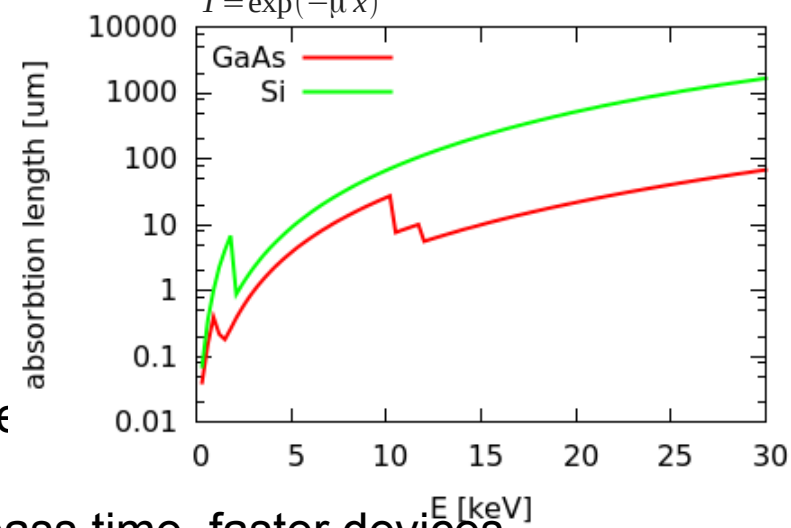
- Larger band gap → higher resistance to radiation damage, no cooling needed
- Band gap engineering: possibility to tailor material composition on nanoscale



Source of data: http://henke.lbl.gov/optical_constants/



$T = \exp(-\mu x)$



- Higher atomic number → higher absorbance compared to silicon

Active absorption layer can be thinner → short pass time, faster devices

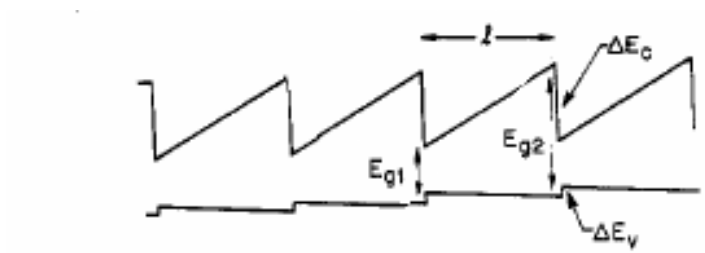
(for soft X-ray energies exceeding 11 keV absorption length is a factor of 22 shorter in GaAs than in

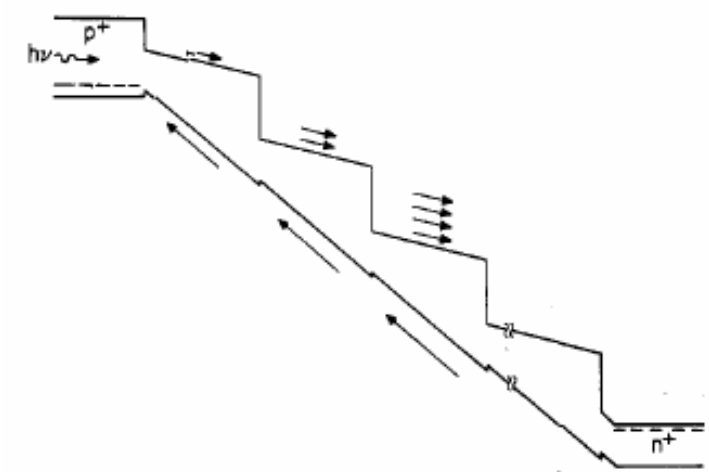
Stair case APD and noise

- Drawback of GaAs: same ionization ratio for holes and electrons
  → linear dependency of noise and multiplication factor [1]

+ This is the case for bulk! We can modify effective ionization ratios by band gap engineering

→ Stair case structure supports multiplication of electrons and suppreses multiplication of holes [2]





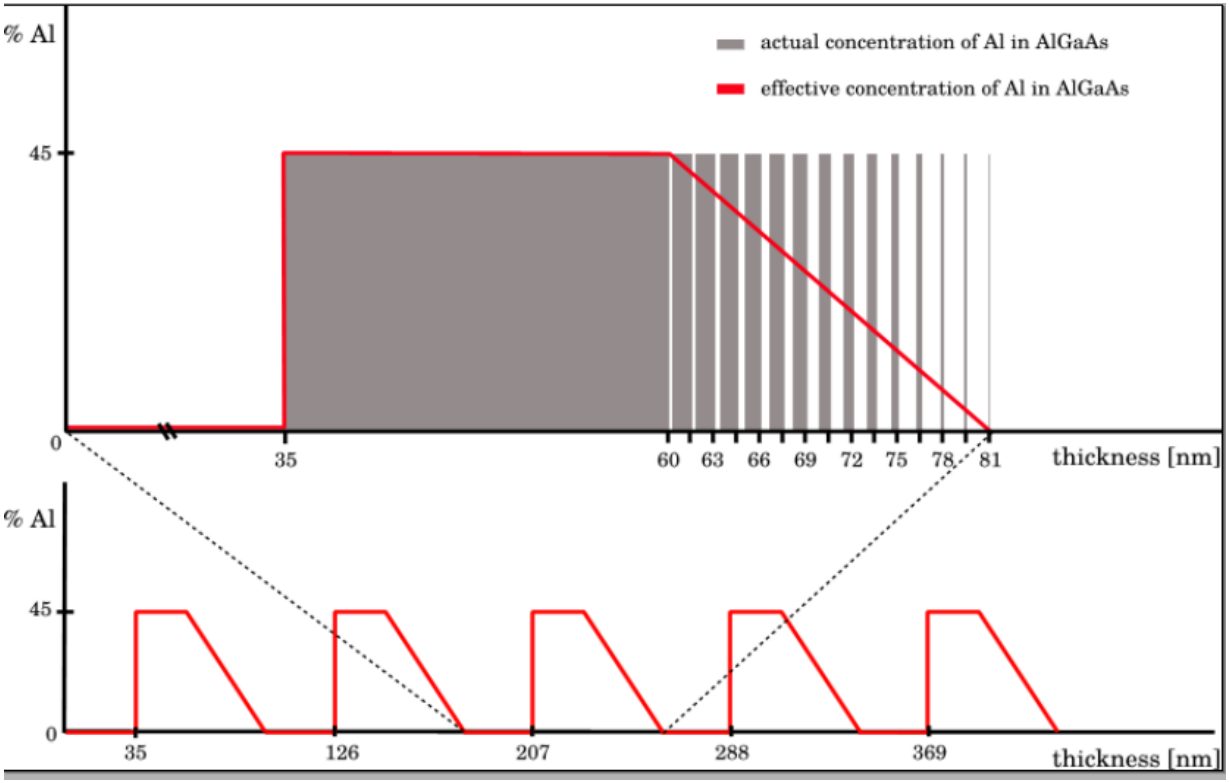
[1] R. J. McIntyre. Multiplication noise in uniform avalanche diodes. IEEE Transactions on Electron Devices, ED-13(1):164–168, Jan 1966.

[2] J.Lauter, D. Protić, A. Förster, H. Lüth; *AlGaAs/GaAs SAM-avalanche photodiode: An X-ray detector for low energy photons;* Nucl. Instrum. Meth. Phys. Res., Vol. 356, 1995, pages 324-329

MBE

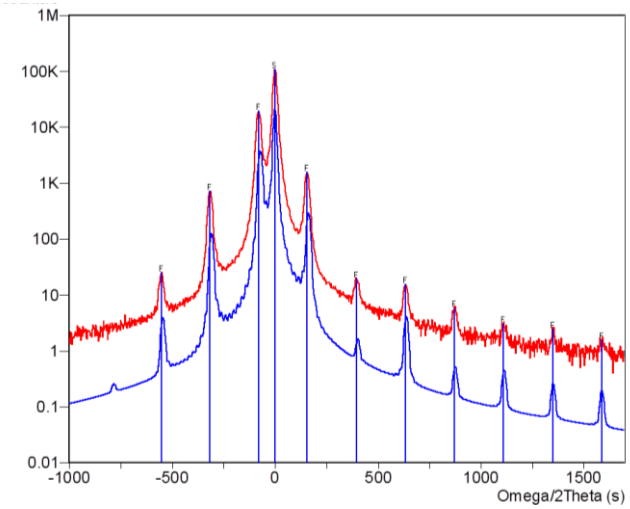
Molecular beam epitxy (MBE)

- Atomic layer precision
- Not able to grow layer with gradual composition → digital alloy



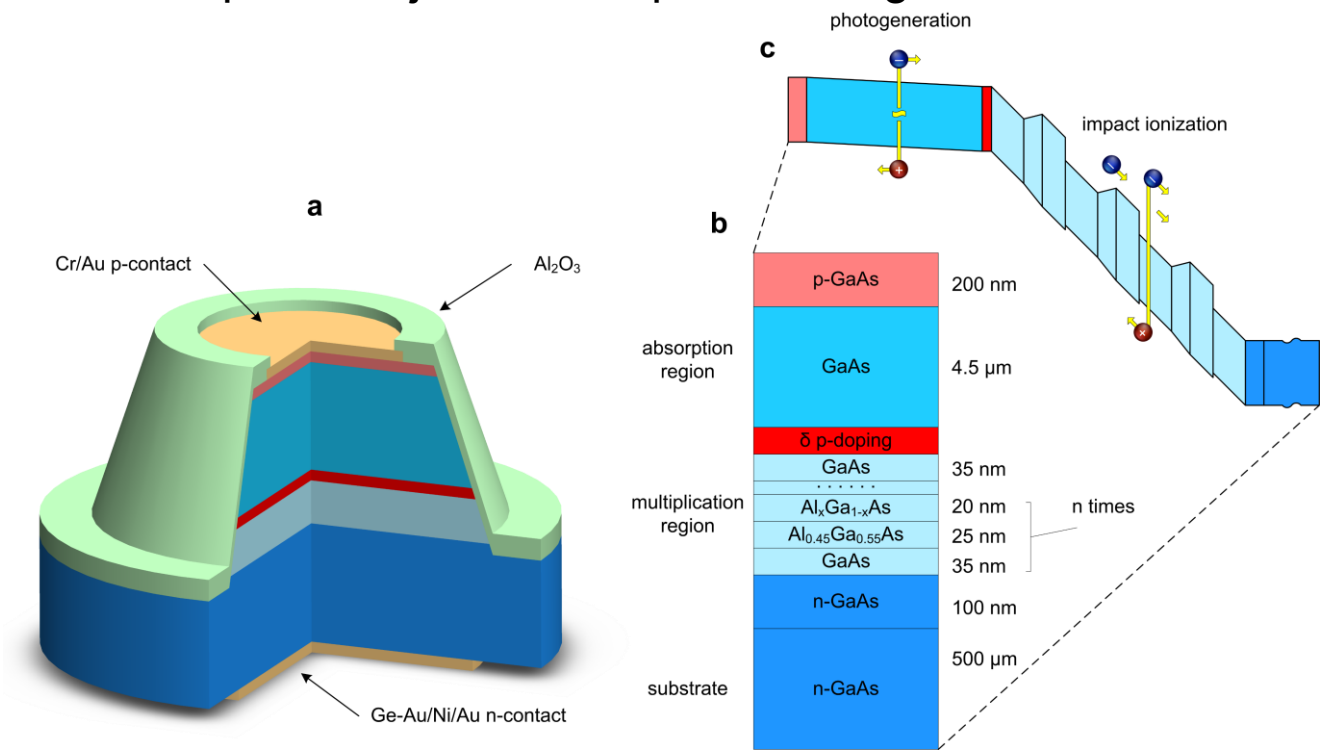
T (period) = 80 ± 1 nm

X (period) = 21.4% (nominal 19.3



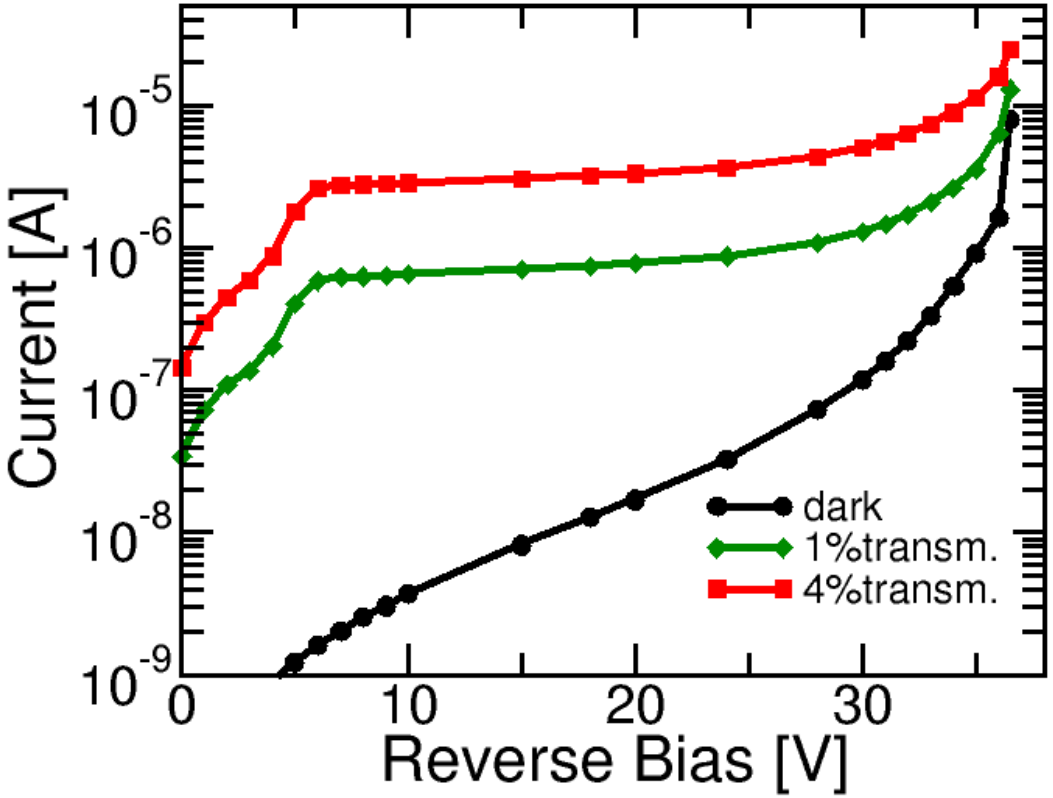
Separated absorption and multiplication regions

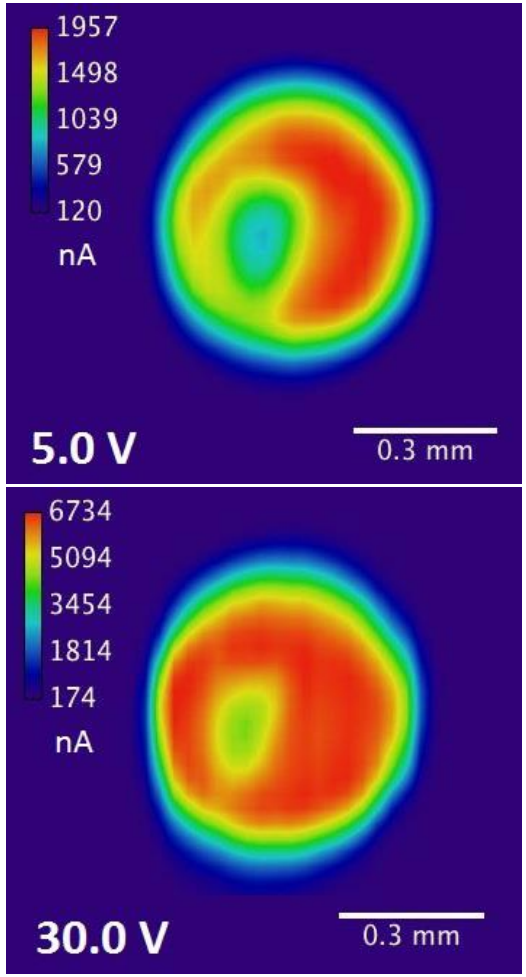
- To increase sensitivity (fraction of photons counted by detector) and suppress the noise we decided to use APD with separated absorption and multiplication (SAM) regions
  - Majority of absorption occurs in absorption region
  - Multiplication just in multiplication region → lower noise



T. Steinhartova, C. Nichetti, M. Antonelli, G. Cautero, R.H. Menk, A. Pilotto, F. Driussi, P. Palestri, L. Selmi, K. Koshmak, S. Nannarone, F. Arfelli, S. Dal Zilio and G. Biasiol,
Influence of δ p-doping on the behaviour of GaAs/AlGaAs SAM-APDs for synchrotron radiation, **J. of Instr., 2017**

Device response to Synchrotron radiation





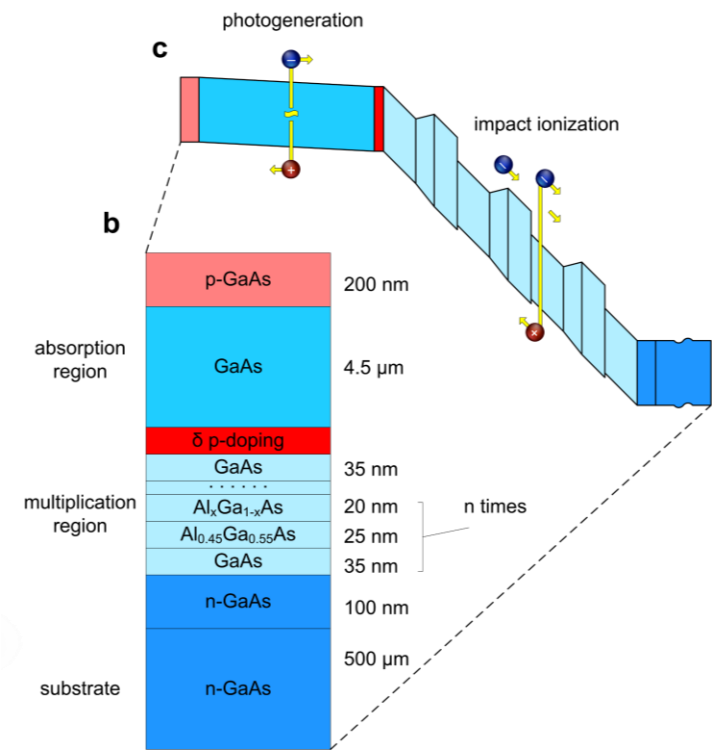
XRD2 beamline at Elettra Sincrotrone Trieste
(12.4 keV and 1.7×10^{13}ph/s over an area of 300x90 μm^2)

C. Nichetti, T. Steinhartova, M. Antonelli, G. Cautero, R. H. Menk, A. Pilotto, F. Driussi, P. Palestri, L. Selmi, F. Arfelli and G. Biasiol, *Investigation of the Behaviour of GaAs/AlGaAs SAM-APDs for Synchrotron Radiation*, **AIP Conference Proceedings, 2019**

Samples

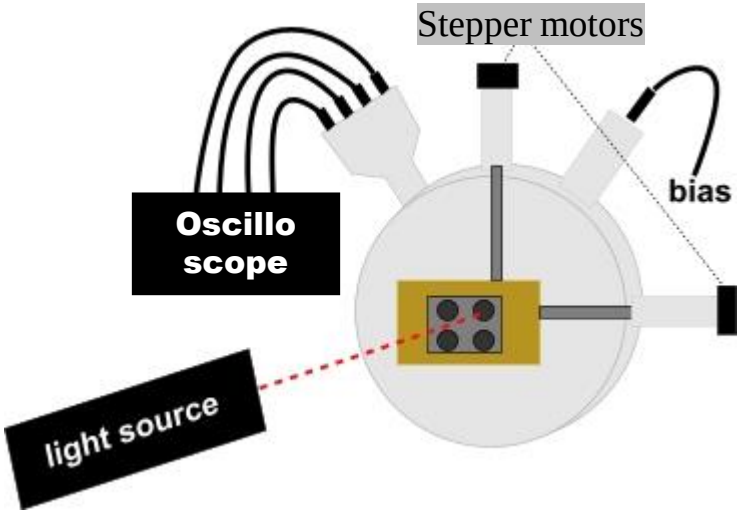
- Different number of steps in multiplication region
- The time response to pulsed laser of wavelength 532nm, pulse duration 10ps and repetition rate 40 MHz on set of reverse biases from 0V to voltage close to brake down voltage
- From each set 2 devices are selected
- Mesa diameter 200 µm

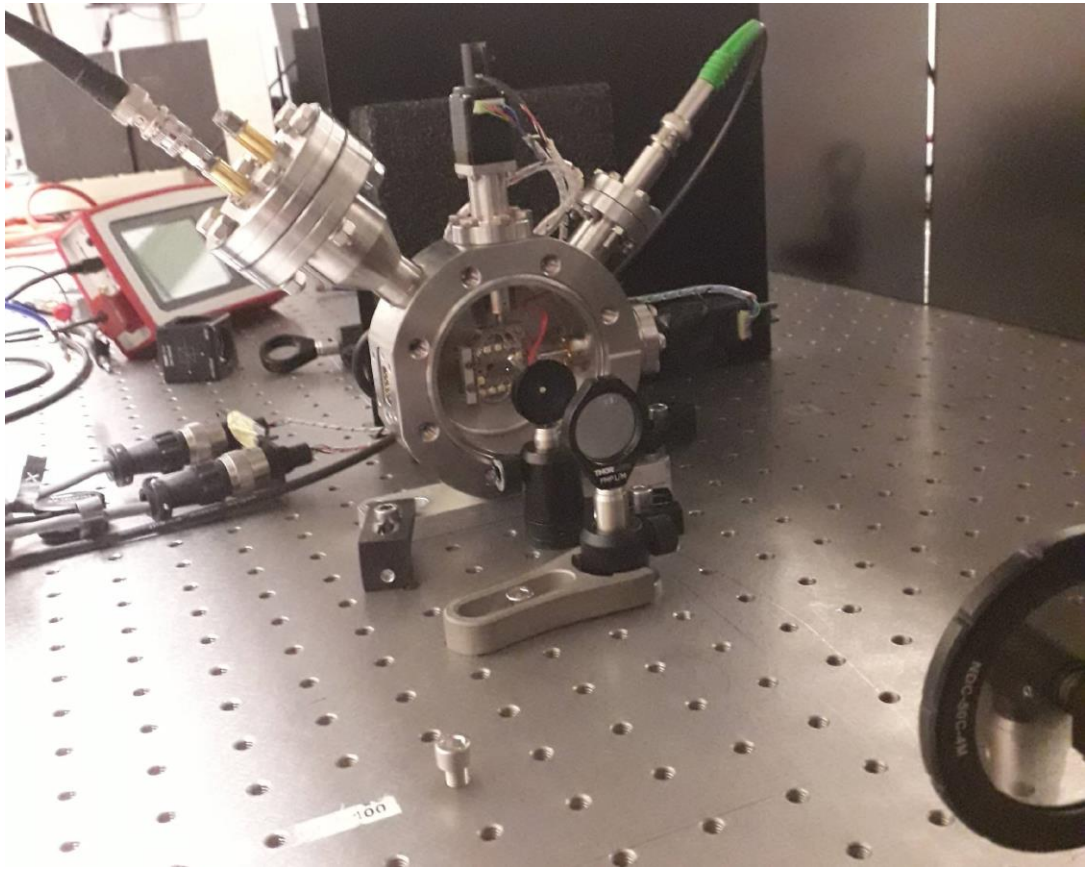
	6 steps	12 steps	24 steps
Capacitance [pF]	~ 6	~ 4	~2
V_{bd} [V]	19	38	60



Experimental set up

- Table-top pulsed laser (532 nm wavelength, 10 ps pulse duration, 40MHz repetition rate)
- Oscilloscope with analogue bandwidth of 12.5GHz





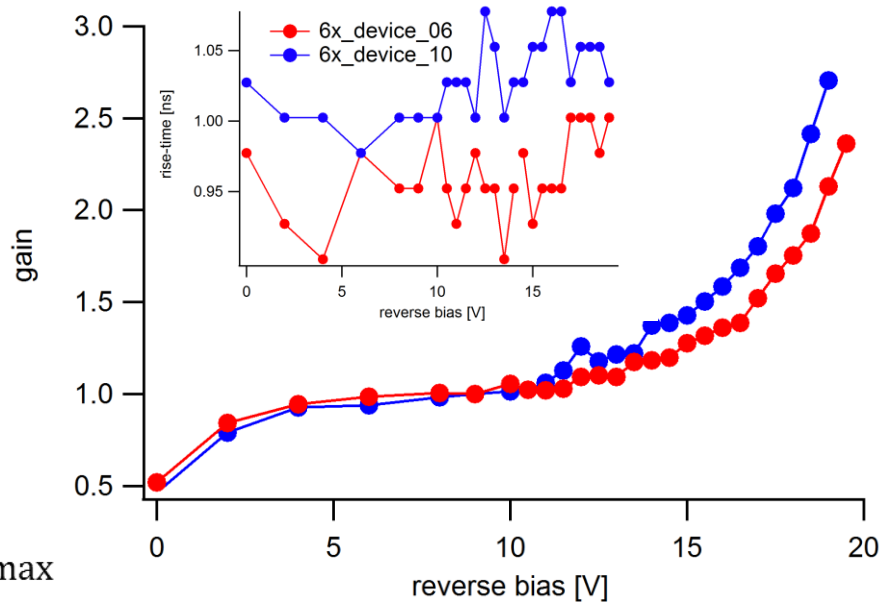
Devices with 6 steps

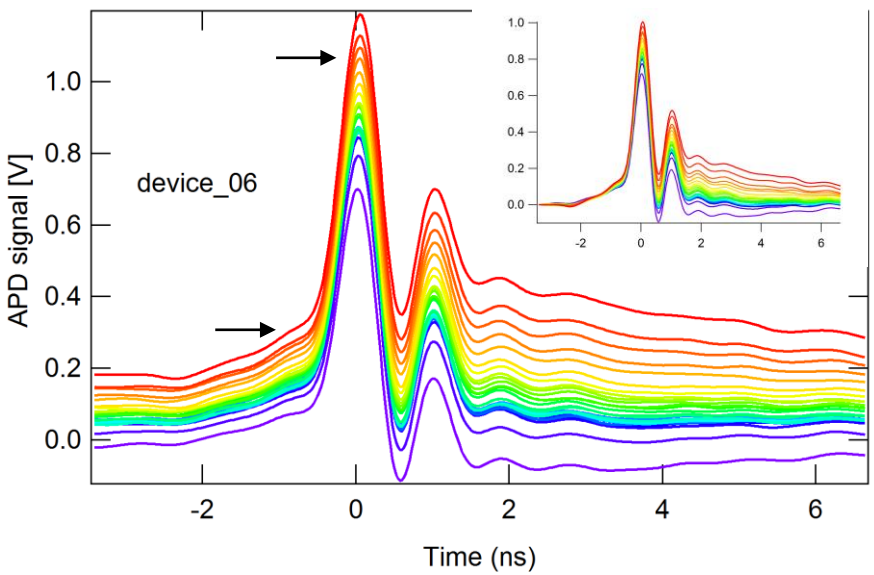
	6 steps	12 steps	24 steps
gain	~ 2.75		
Rise time	~ 1ns		

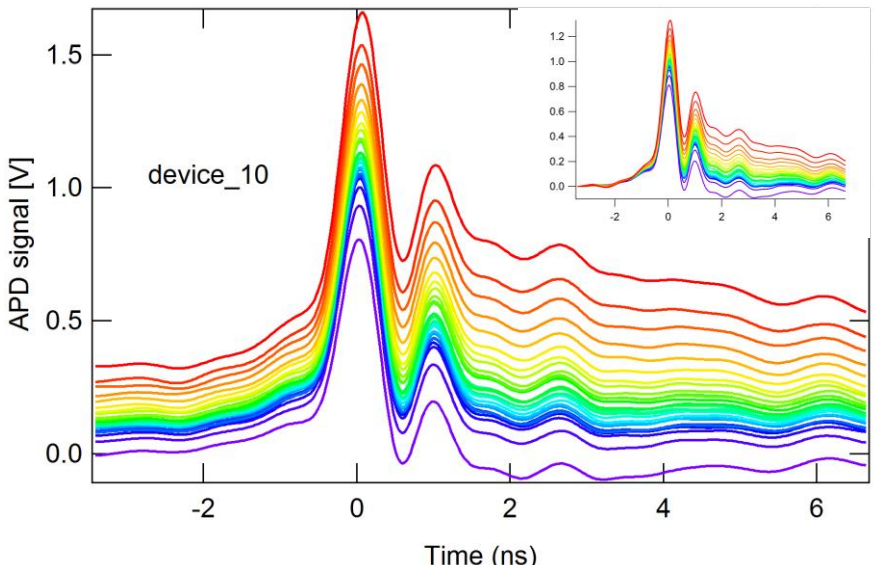
$$\text{Gain} = \frac{charge\ over\ time\ window\ (V)}{charge\ over\ time\ window\ (V_0)}$$

V_0 = voltage at which we do not observe multiplication

rise time = time from min + 0.1 of max to min + 0.9 of max

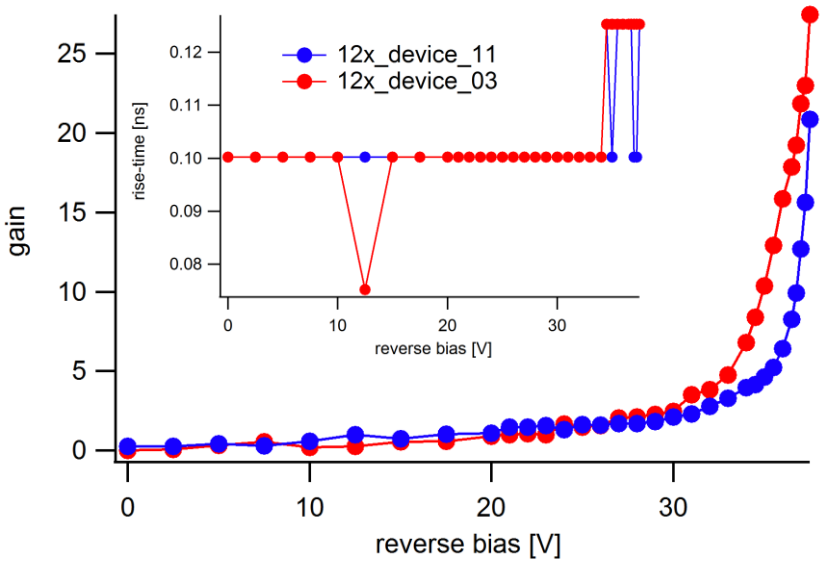


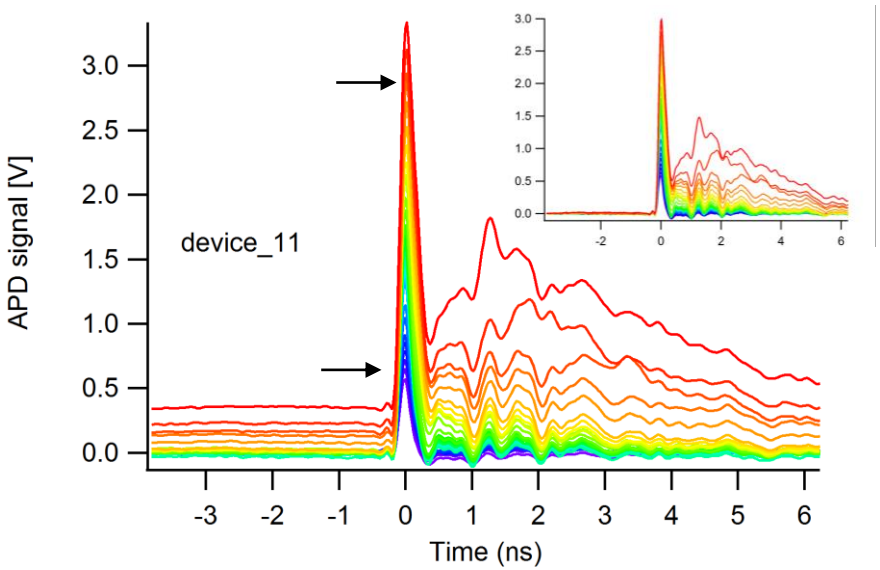


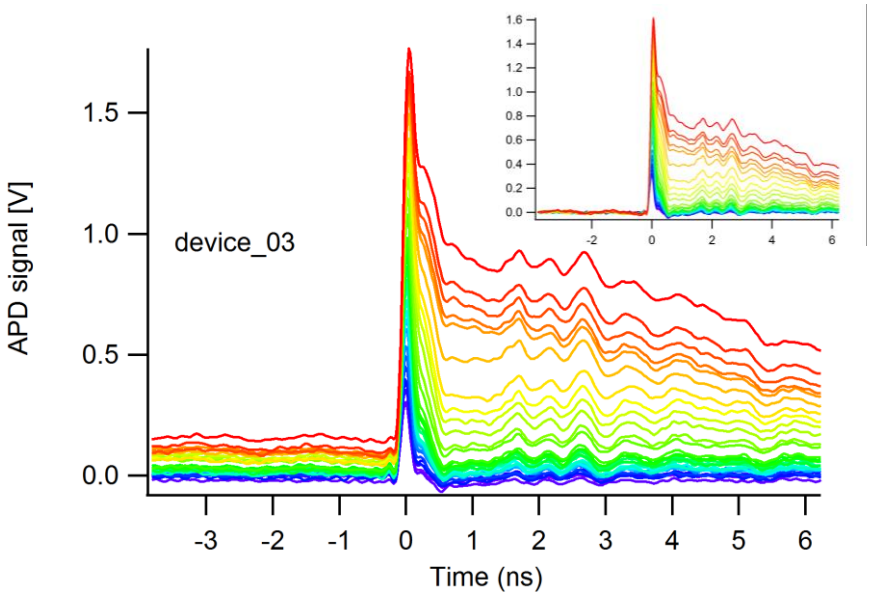


Devices with 12 steps

	6 steps	12 steps	24 steps
gain	~ 2.75	~ 25	
Rise time	~ 1ns	~ 100 ps	

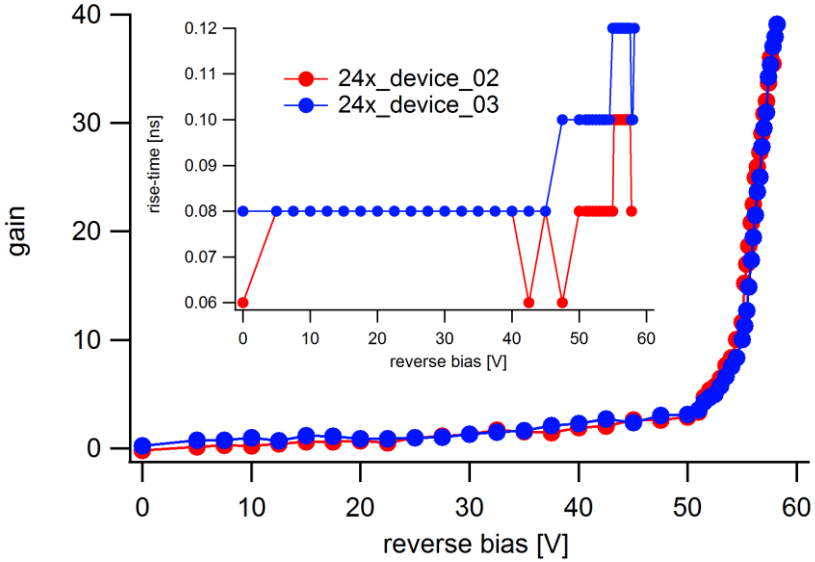


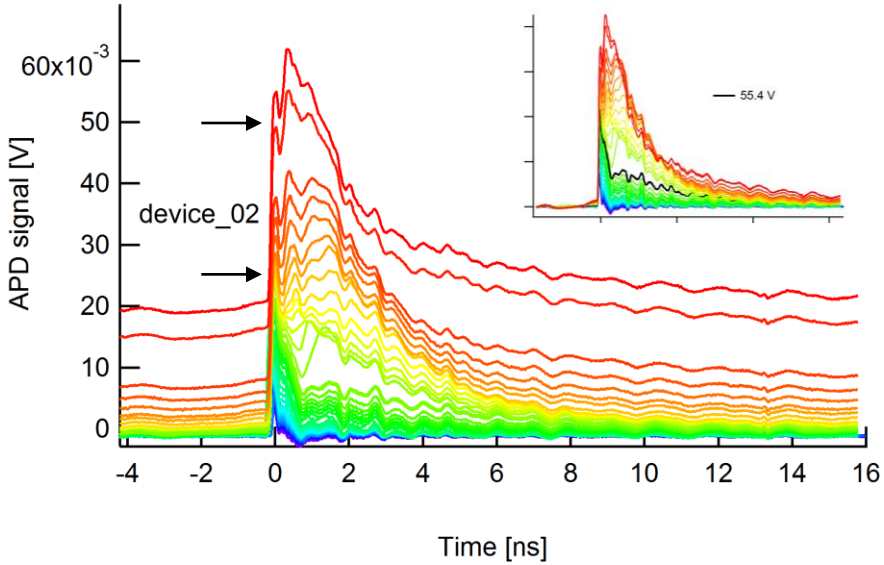


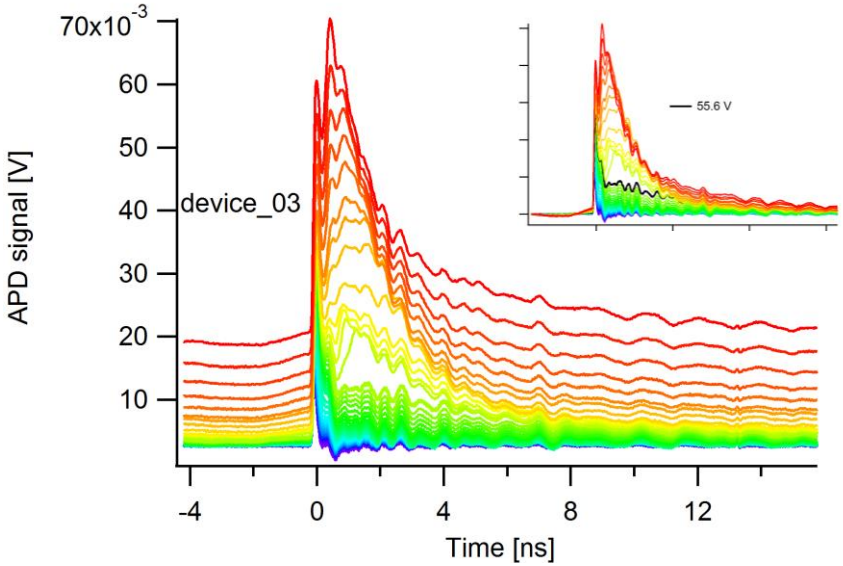


Devices with 24 steps

	6 steps	12 steps	24 steps
gain	~ 2.75	~ 25	~ 40
Rise time	~ 1ns	~ 100 ps	~ 80 ps

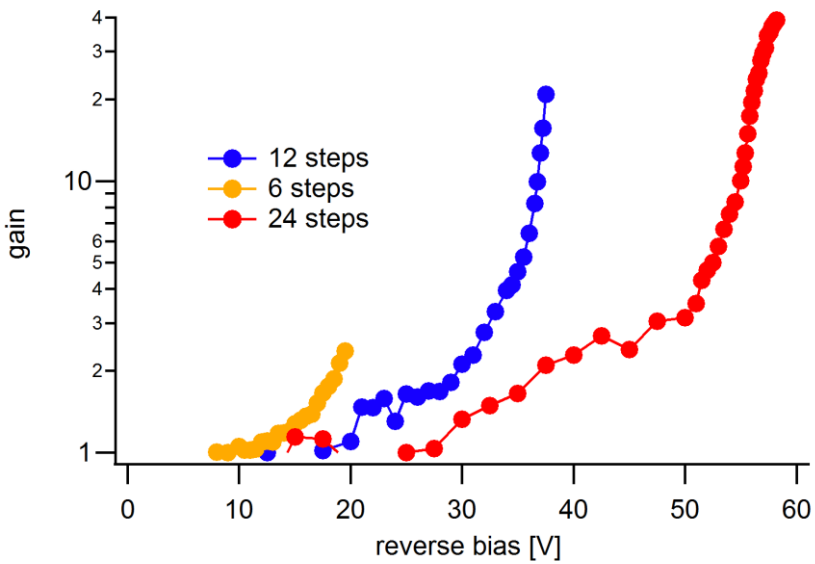






Summary

	6 steps	12 steps	24 steps
gain	~ 2.75	~ 25	~ 40
Rise time	~ 1ns	~ 100 ps	~ 80 ps



- Further :
  - More focus on the devices with 24 steps
  - Thinning down the back side of device (substrate)

Thanks

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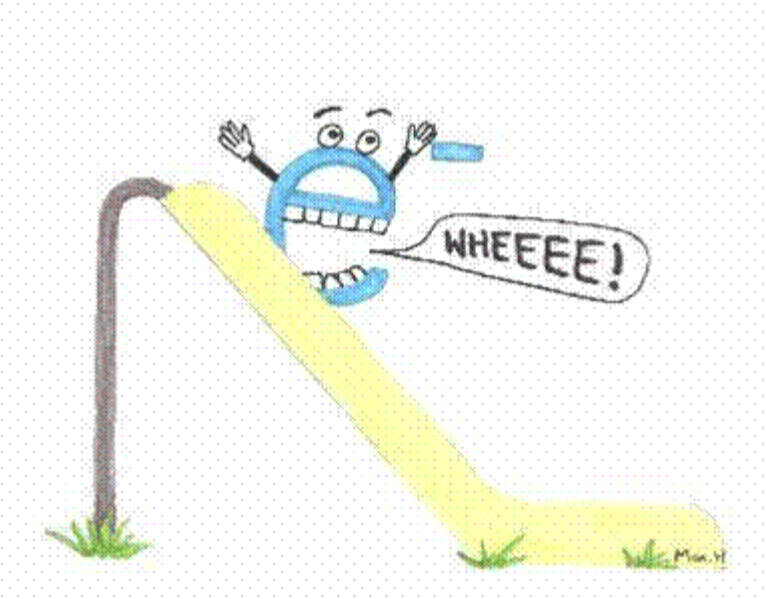
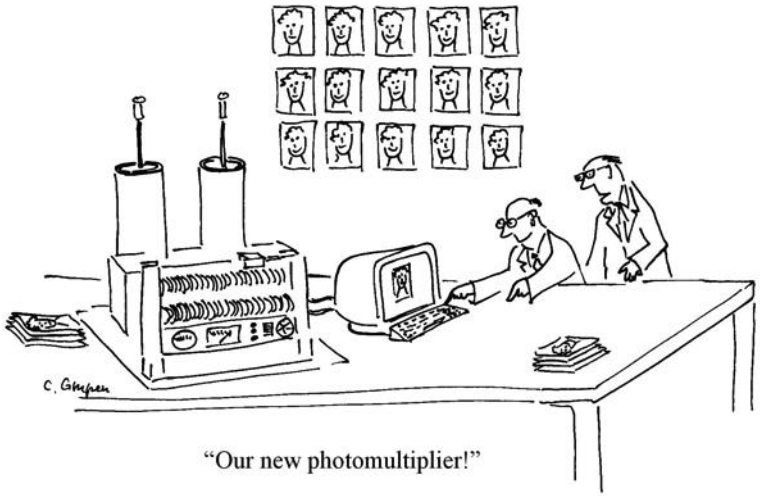
Dipartimento Politecnico di Ingegneria e Architettura - Università di Udine

Università di Trieste

and to you for your attention!!





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