Gain, noise, and collection efficiency of GaAs SAM-APDs with staircase structure by means of synchrotron radiation

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Introduction

- increasing demand for fast and efficient X-ray detectors
- silicon-based detectors widely employed, but are not efficient in hard X-ray range

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research of new materials
(Ge, compound semiconductors, …)

- we are developing

GaAs SAM-APDs
with staircase structure

Why GaAs?

	Si	Ge	GaAs
density [g/cm^3]	2.33	5.323	5.32
effective atomic number	14	32	32
electric-breakdown field [V/cm]	3×10^5	1×10^5	4×10^5
electron mobility [cm^2/Vs]	1350	3900	8000
band-gap [eV]	1.12	0.66	1.42

→ shorter attenuation length

→ shorter response time

→ possibility to operate at room temperature

Why avalanche?

low fluxes / single photon detection

↓

very weak signals (thousands of electrons)

↓

need for amplification

↓

impact ionization = internal amplification

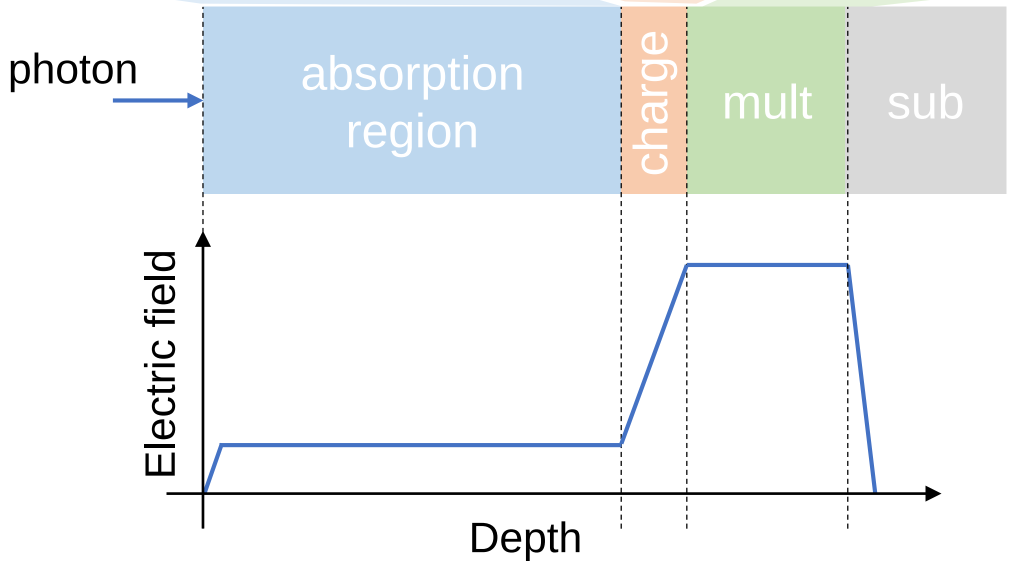
Why Separate Absorption and Multiplication?

photon absorption in a region with a high electric field = noise contribution

region for photon absorption
(with low electric field)
ABSORPTION LAYER

separation is obtained by a
highly **doped** layer
CHARGE LAYER

region for electrons multiplication
(with high electric field)
MULTIPLICATION LAYER



Why staircase structure?

multiplication in a region with similar electron/hole ionization coefficients
=
noise contribution

- $\alpha/\beta_{GaAs} \cong 1$ ➡ high noise ☹
- to reduce noise: band-gap engineering

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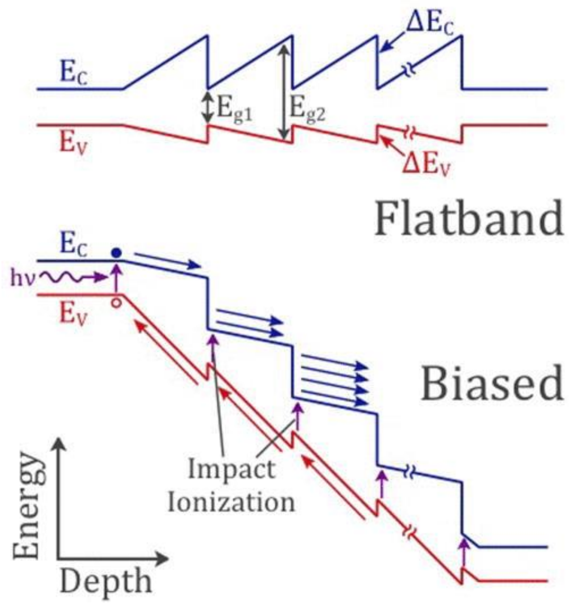
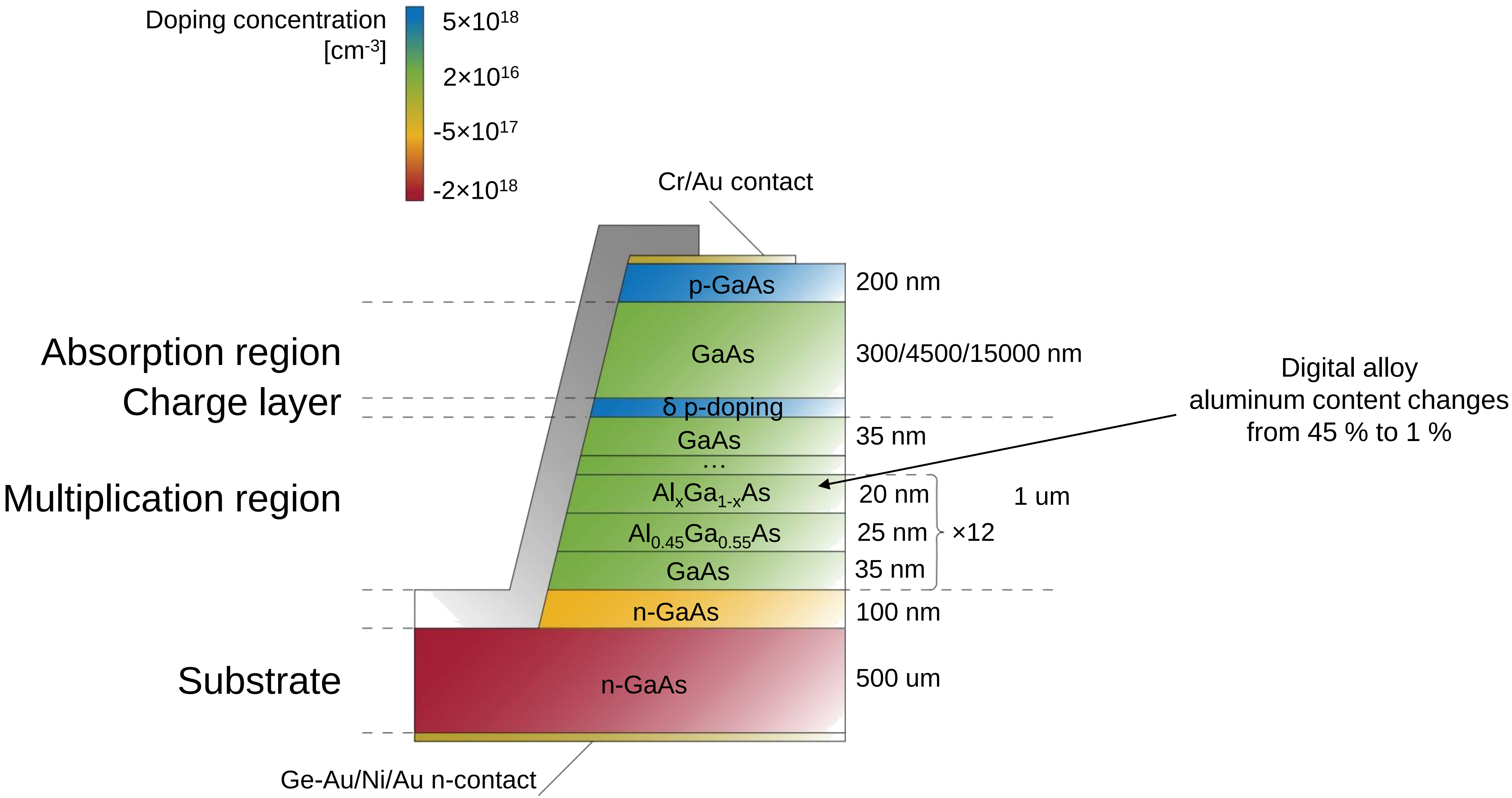
staircase structure
(impact ionization of electrons
at discrete locations)

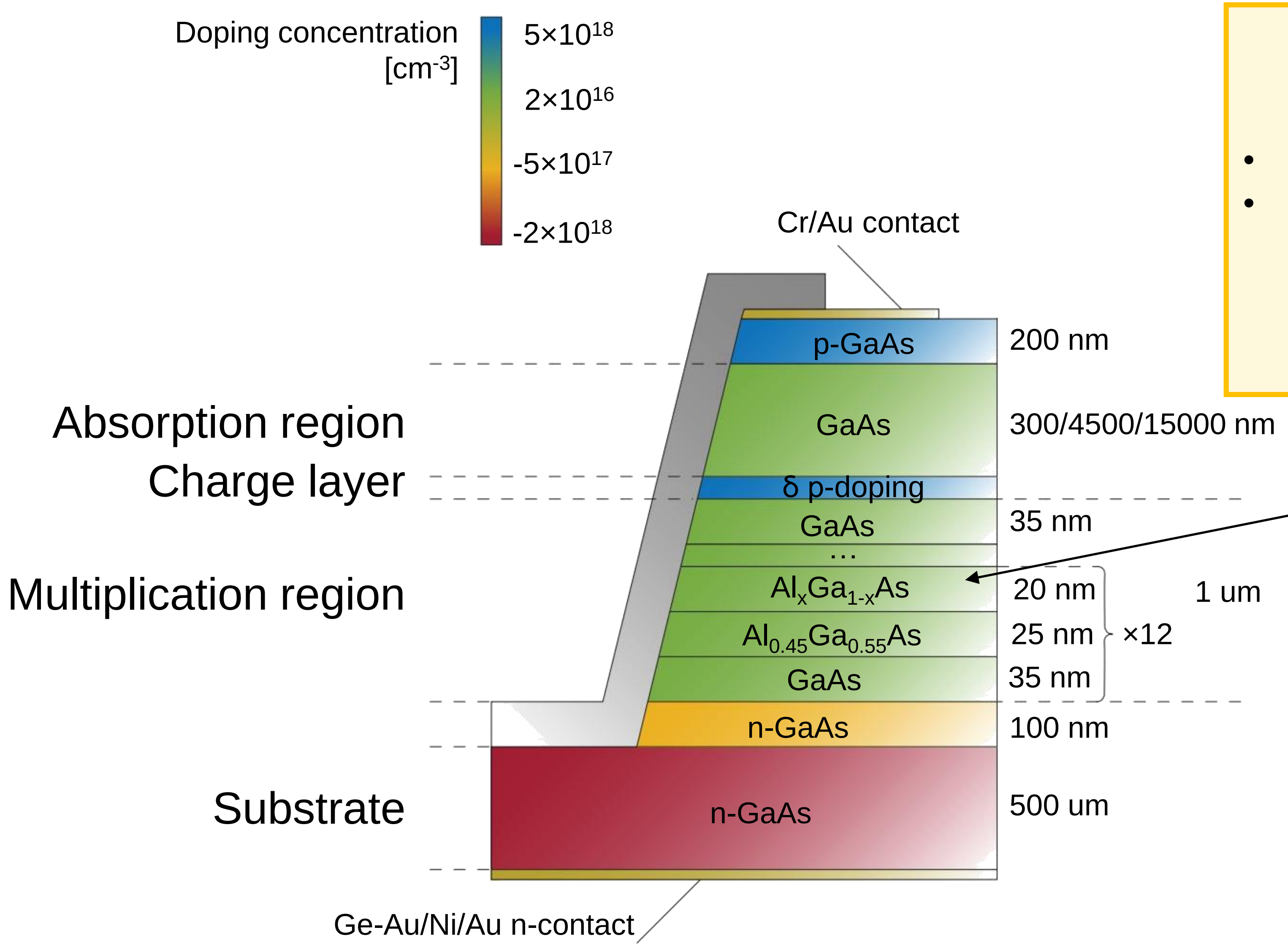


[David, J. The staircase photodiode. *Nature Photon* **10,** 364–366 (2016)]

The detector – cross section



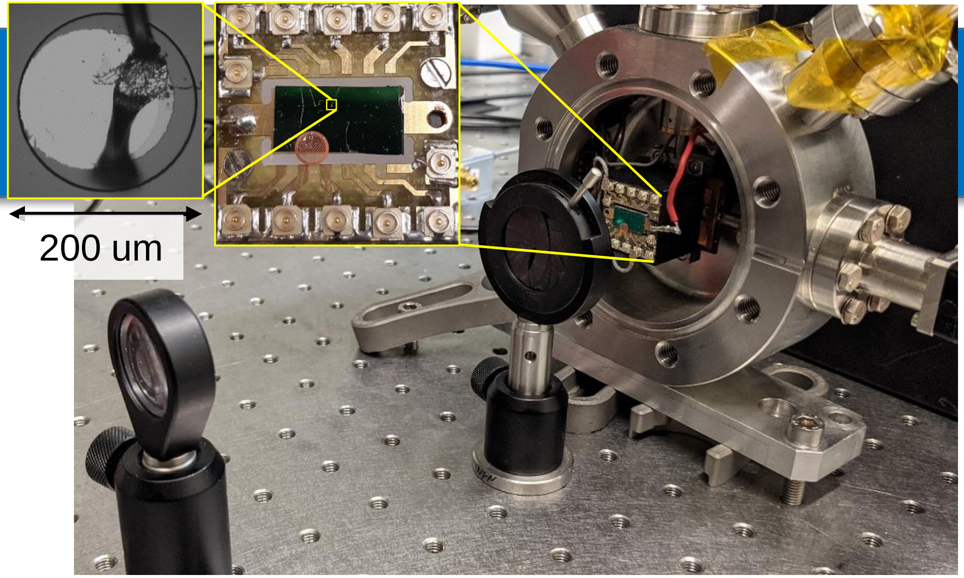
The detector – cross section



PROTOTYPES

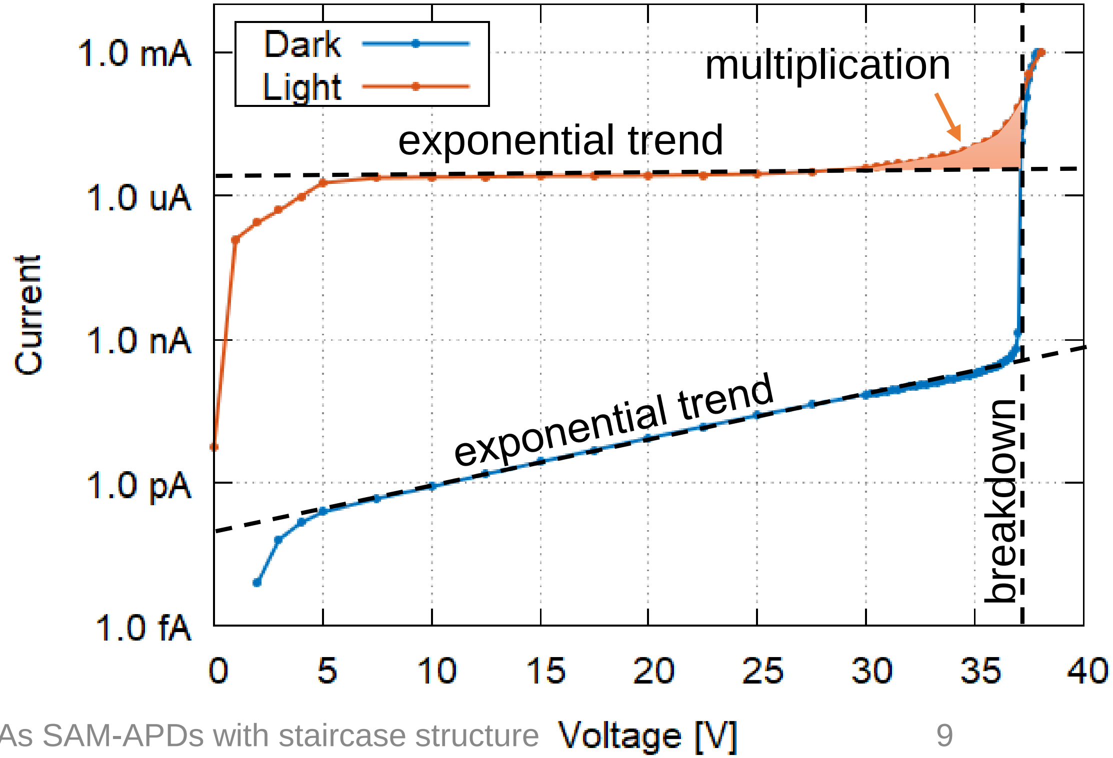
- not sufficiently thick for hard X-rays
- expressly developed to investigate recombination in:
  - metal-semiconductor interface
  - absorption region

Characterization with laser



- Eph = 2.33 eV ➡
  - single e/h pair production
  - no photogeneration in the multiplication layer

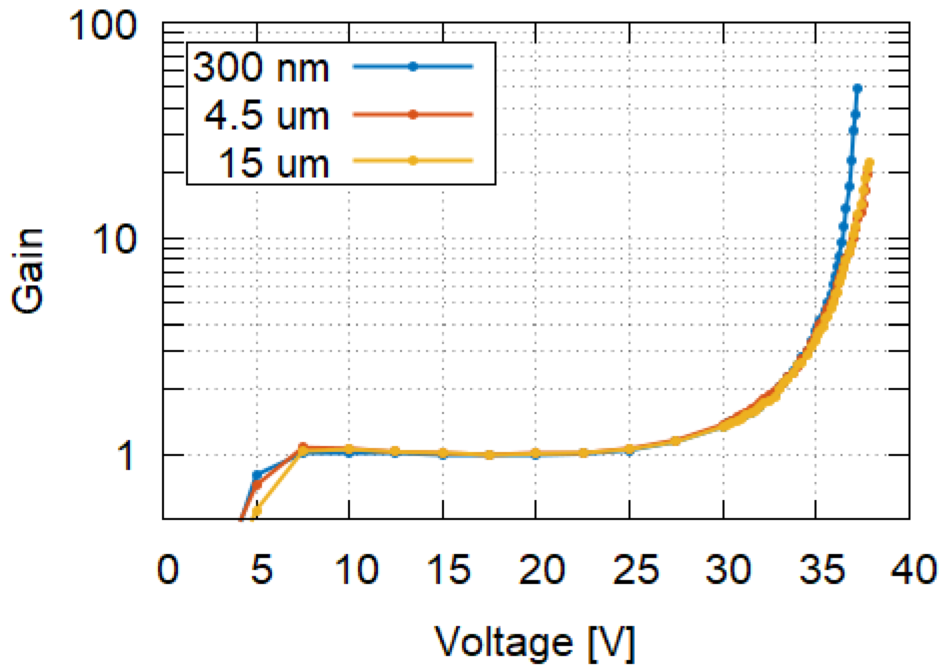
- initial exponential current growth due to lowering of the charge layer potential barrier
- $V_{breakdown}$ = 37 V
- multiplication from 25 V to breakdown



Gain

$$M(V) = \frac{I_m^{ph}(V) - I_m^{dark}(V)}{a \cdot e^{b \cdot V}}$$

- *a* and *b* are extracted from I-V measurements interpolating the initial exponential growth
- M_{max} = 50

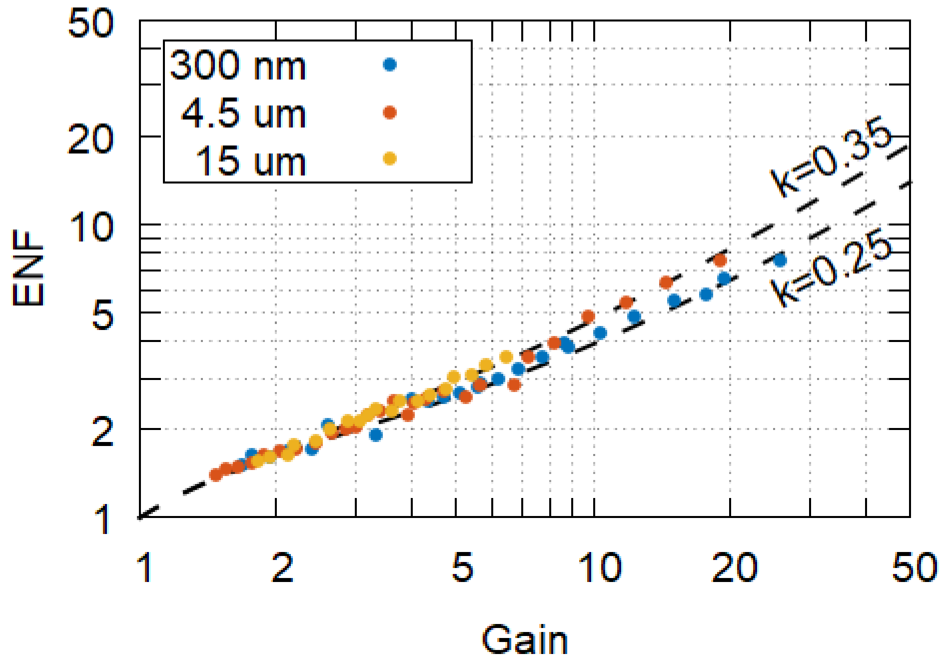


Excess Noise Factor

$$ENF = \frac{S_i \cdot B}{M^2 \cdot 2qI_{ph} \cdot B}$$

S_i: measured current spectral density
I_{ph}: DC value of photo-current with M = 1
B: system bandwidth

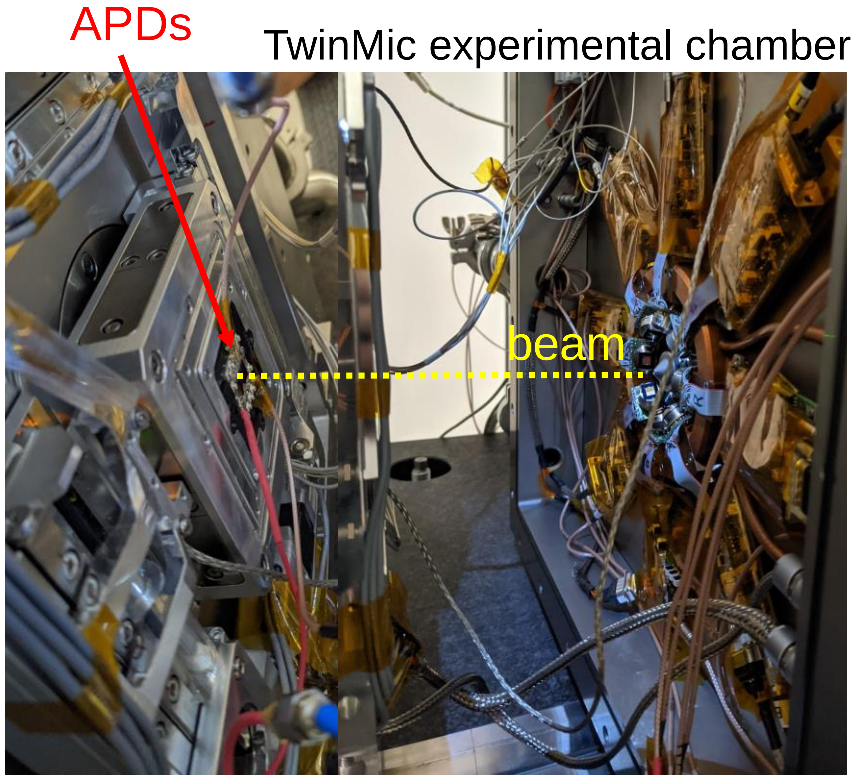
- $\alpha/\beta = k \in [0.25, 0.35]$



Synchrotron radiation measurements

- investigation of recombination in:
  - metal-semiconductor interface
  - absorption region

- TwinMic beamline (Elettra Sincrotrone)
  - photon energies = [400 eV, 2200 eV]
  - sub-micrometric monochromatic beam



Metal-semiconductor interface (1)

- chemical characterisation (As fluorescence)
- identification of areas not covered by top contact

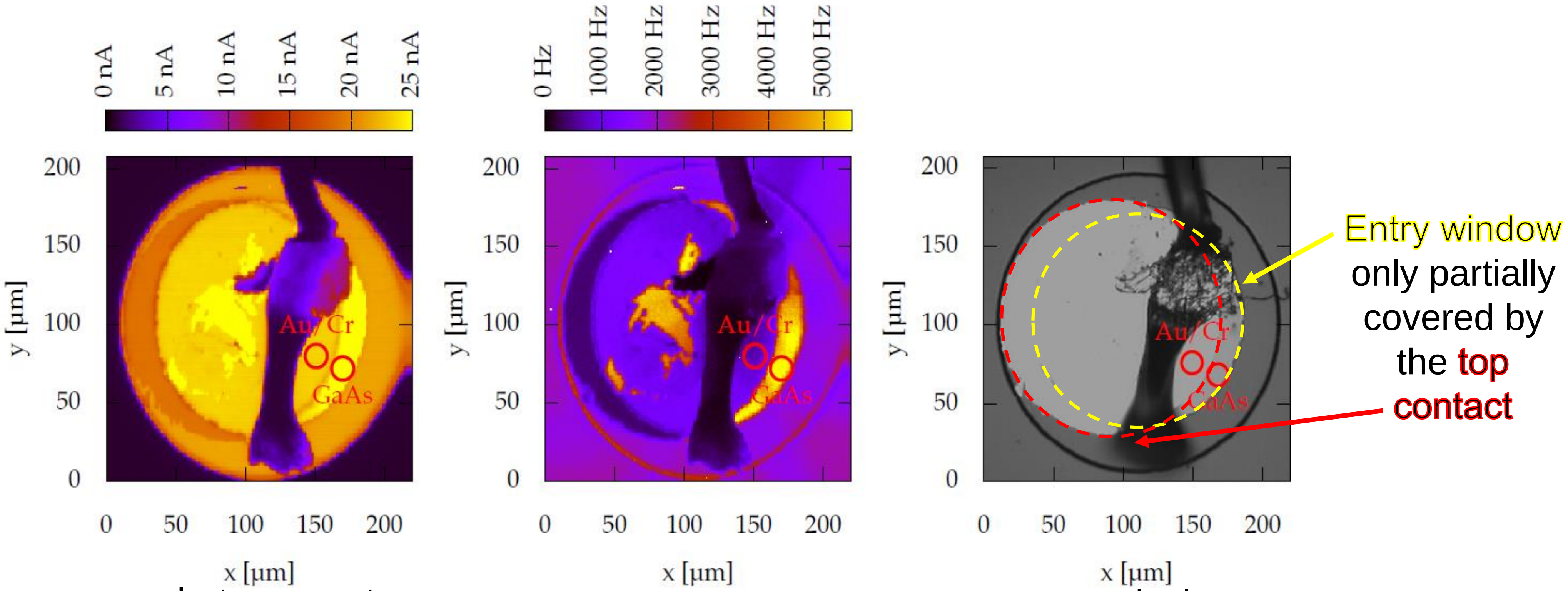


photo-current As fluorescence optical

Metal-semiconductor interface (2)

- current measured when the radiation entered:

	through Cr/Au	directly in GaAs		
Energy [eV]	I_m^{Au} [nA]	I_m^{GaAs} [nA]	T_m [%]	T_{th} [%]
940	64.187 ± 0.025	119.793 ± 0.025	53.58 ± 0.02	51.8 ± 0.3
1090	81.903 ± 0.025	125.670 ± 0.025	65.17 ± 0.02	62.0 ± 0.3
1500	232.192 ± 0.025	318.681 ± 0.025	72.86 ± 0.01	79.3 ± 0.2
1705	293.290 ± 0.025	378.027 ± 0.025	77.58 ± 0.01	84.6 ± 0.1
2010	278.579 ± 0.025	322.070 ± 0.025	86.50 ± 0.01	89.1 ± 0.1

measured and theoretical transmissions have a similar trend and their values are comparable

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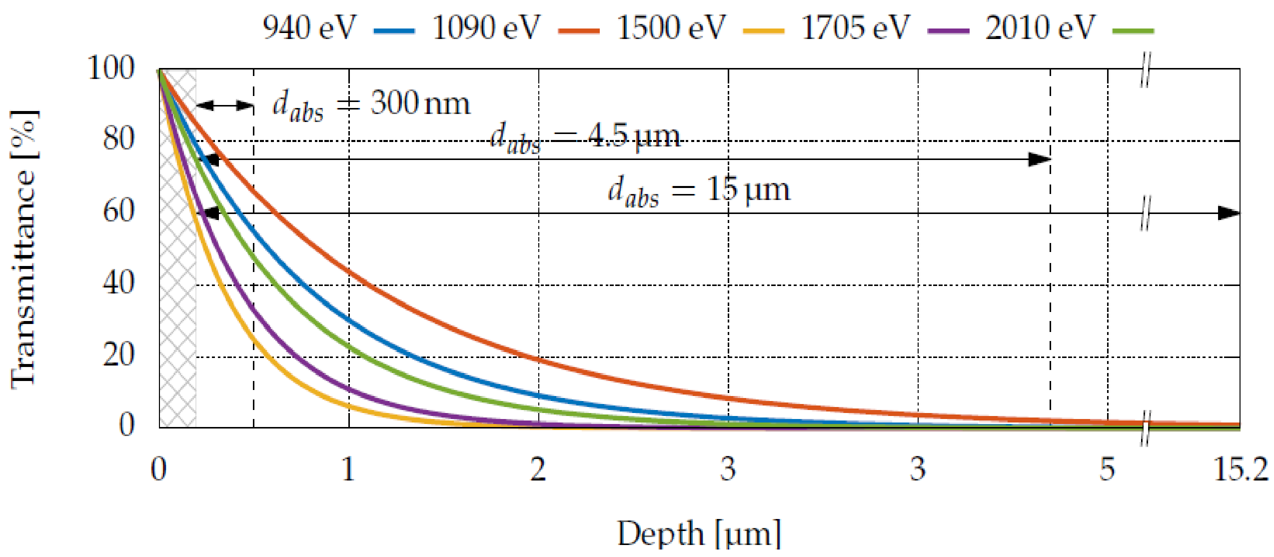
traps and defects at the interface have a small effect in the charge loss

Recombination in absorption region (1)

- 5 energies (940 eV, 1090 eV, 1500 eV, 1705 eV, 2010 eV)



transmittance as a function of depth

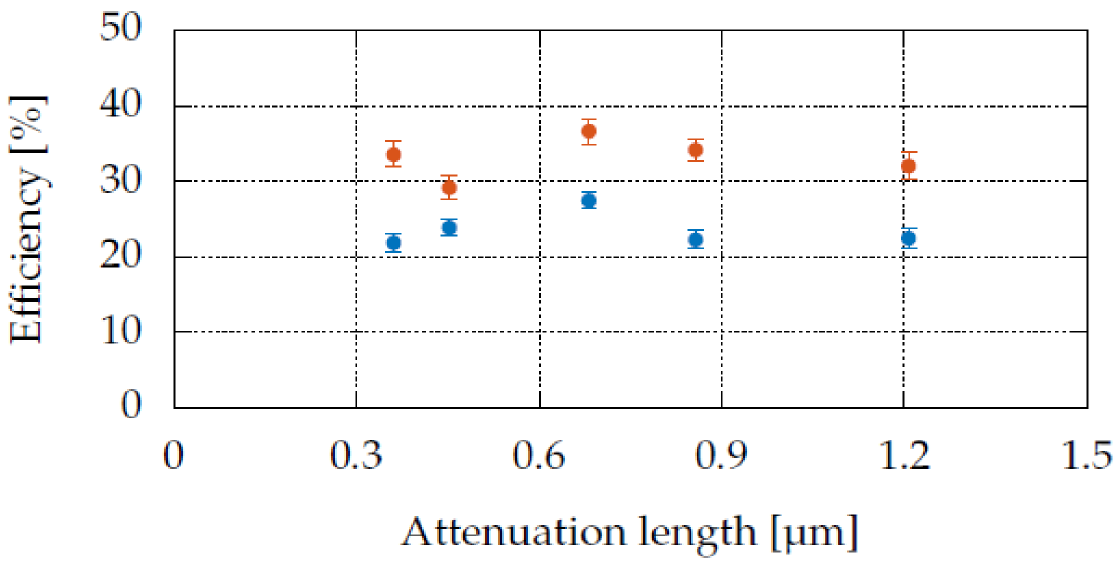
carriers produced at different distances from the multiplication layer

- measurements on 4.5 and 15 um-thick devices only
- expected current

$$I_{th}(E_{ph}) = \Phi_0 \cdot \frac{E_{ph}}{E_{e-h}} \cdot q,$$

Φ_0: photon flux [photons/s]
E_{ph}: photon energy [eV]
$E_{e\text{-}h}$: average energy to produce e-h

Recombination in absorption region (2)



- no dependence on the attenuation length -> negligible recombination during electron travelling through the absorption region
- variations due to systematic error (reposition of the sample)

Conclusion

- GaAs valid alternative to Si, but careful design required for noise reduction
- ENF can be greatly reduced by band-gap engineering
- negligible effect in charge collection efficiency of:
  - recombination in metal-semiconductor interface
  - recombination in absorption region

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International Workshop
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on Radiation Imaging Detectors

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Thank you for your attention