On possible development of MAPS (monolithic active pixel sensor) based on spherical p-n junction

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CMS collaboration, CERN
SPD collaboration, JINR

Outline

- Designs of MAPS (Monolithic Active Pixel Sensor)

- Designs of SiPM (Silicon Photomultiplier)
  - Based on planar p-n junction − modern SiPMs
  - Based on spherical p-n junction − Tip APD

- On possible design of MAPS based on spherical p-n junction

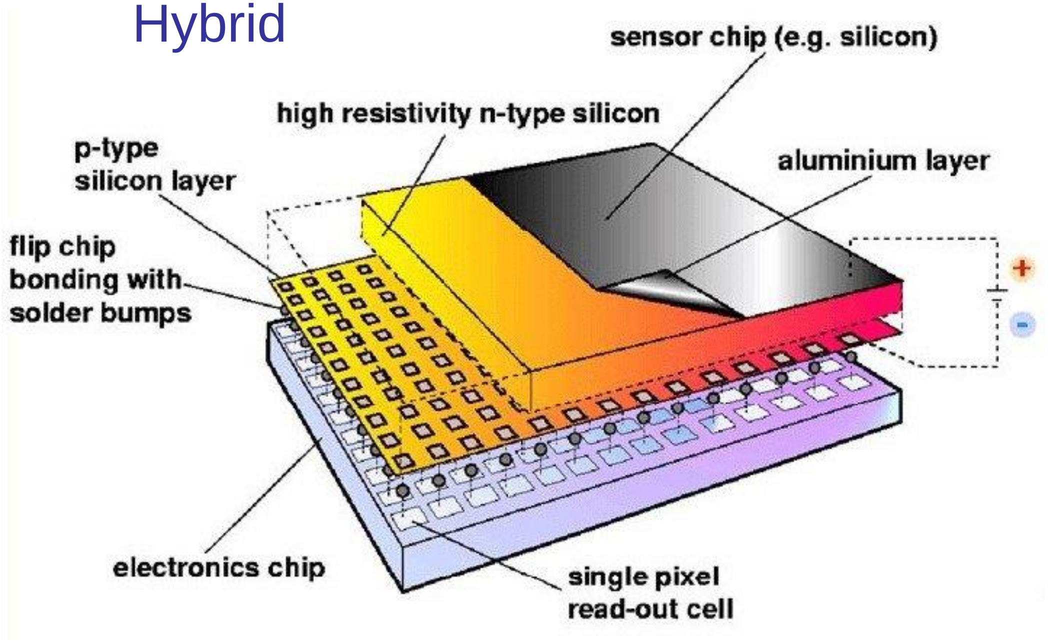
- Status of R&D on Tip APD in the Lebedev Physical Institute

Monolithic vs Hybrid

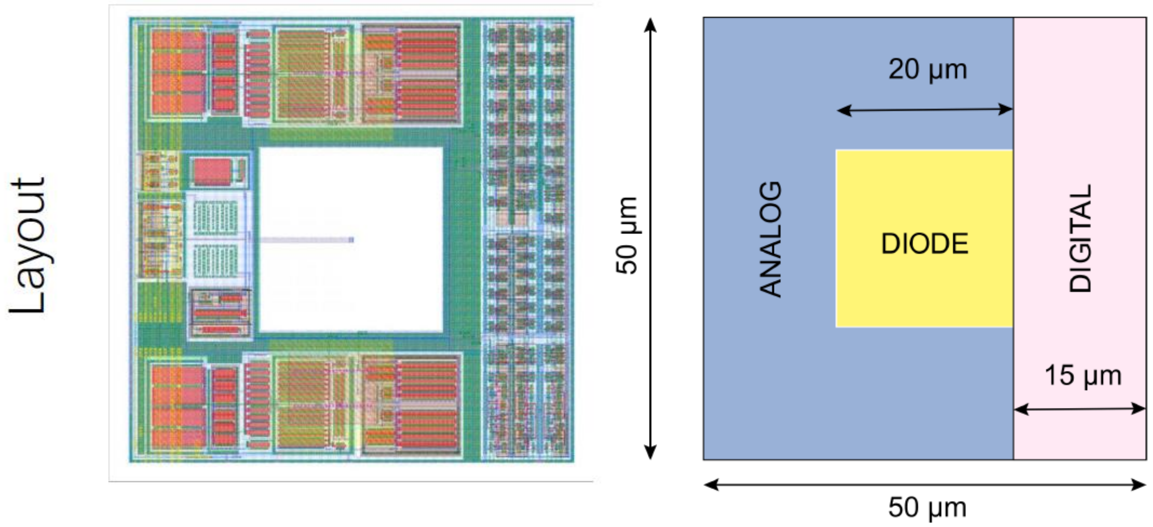
- Hybrid = sensor chip + FEE chip coupled by flip-chip integration
  - Became obsolete, large total thickness => particle scattering and resolution losses

- Monolithic = sensor region + FEE region on the same Si wafer
  - Many advantages, intense R&D at high-tech centers, reproduction started in China

Hybrid

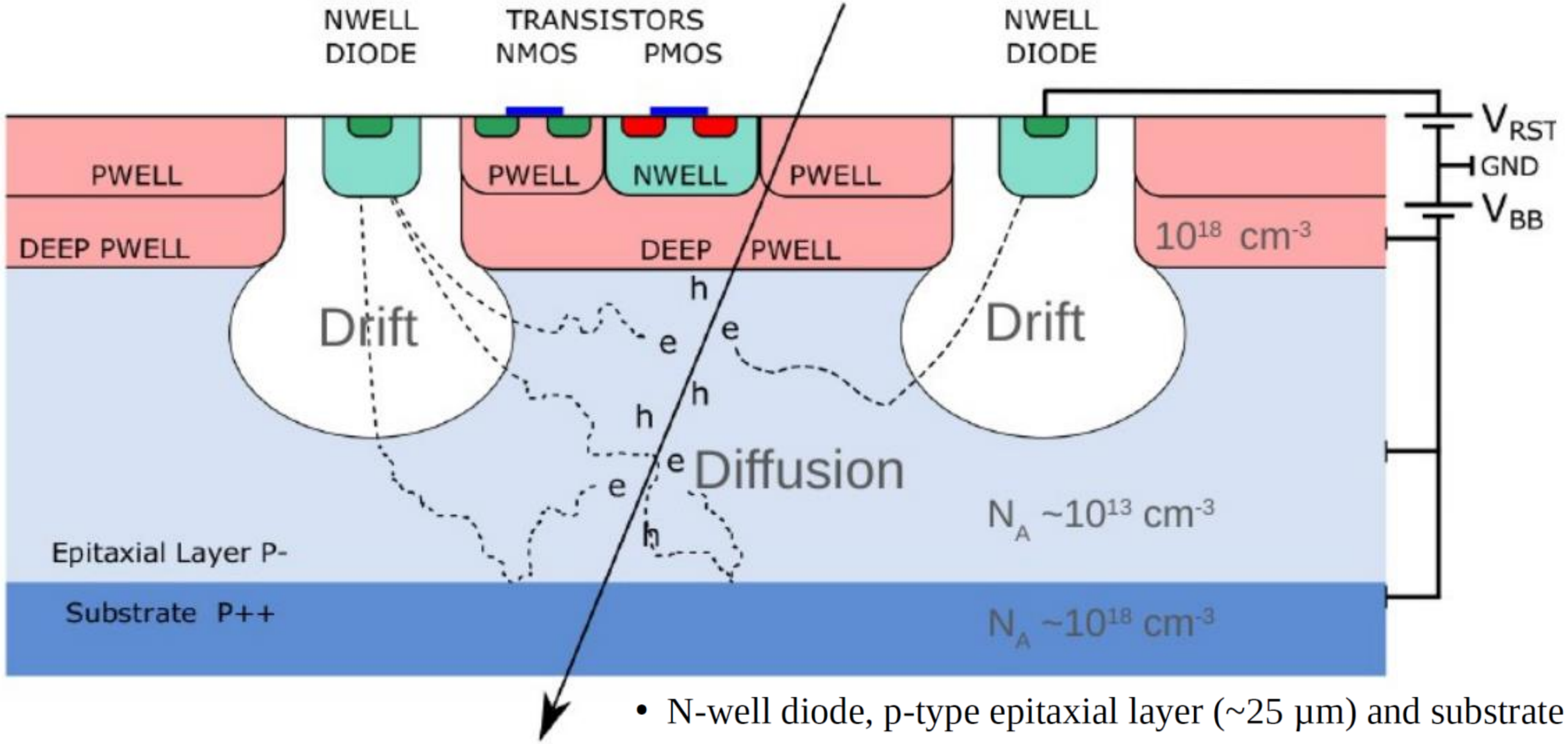


Monolithic (MAPS)



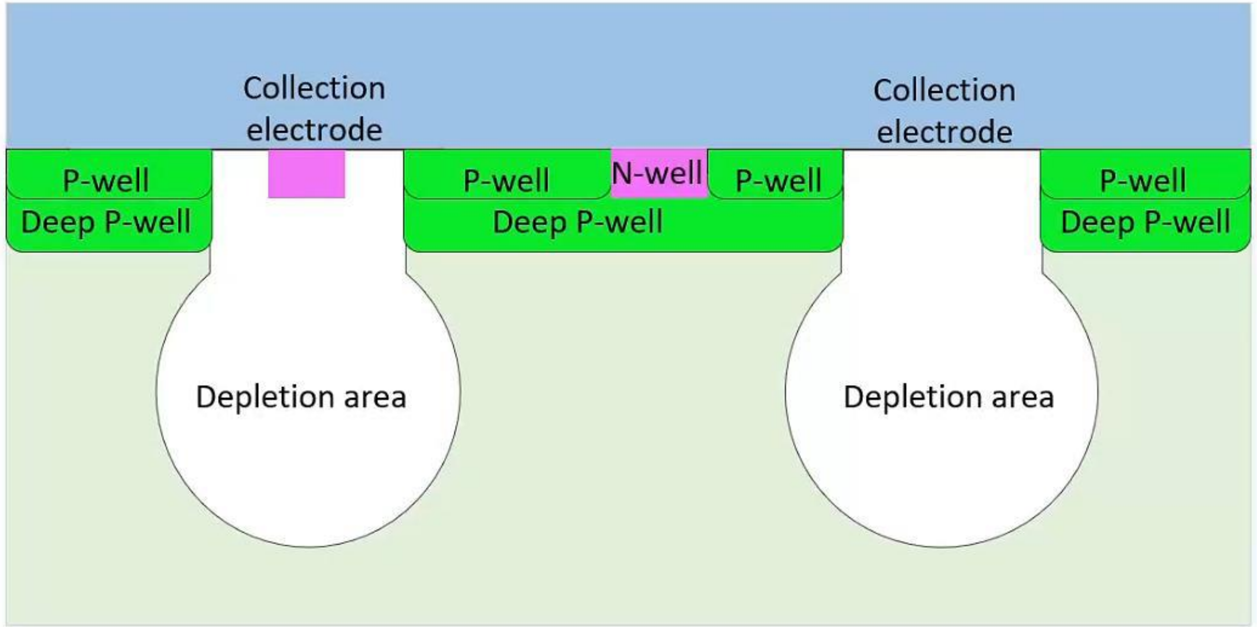
MAPS - ALPIDE

- Partial depletion => slow charge collection by diffusion, low radiation hardness



- N-well diode, p-type epitaxial layer (~25 µm) and substrate
- Diode size (2-3 µm) – very small than pixel size – low capacitance – high S/N
- Possible to reverse bias (up to -6 V)
- Drift e- reaching the collection diode induce a current signal at the input of transistors
- Deep PWELL shields NWELL of PMOS transistors
  – allows full CMOS circuitry in active area

MAPS - MICA



MICA MAPS pixel chip

- Domestic process
- Pixel Size: 27x31um^2
- Pixel Array: 512x980
- Front-end peaking time: < 2us
- Pulse discrimination time: 5-10 us
- ENC < 10e-
- Power consumption < 40mW/cm^2

- Le Xiao, The Research and Development of MICA Chip, Seminar on the Chinese-Russian Cooperation within the NICA MPD-ITS Project, VBLHEP JINR, 23 – 24 Jul. 2024.
- Yuri Murin, The MPD BP Installation Container; status and perspectives of the ITS, XIII-th MPD Collaboration Meeting, Dubna 23.04.2024.

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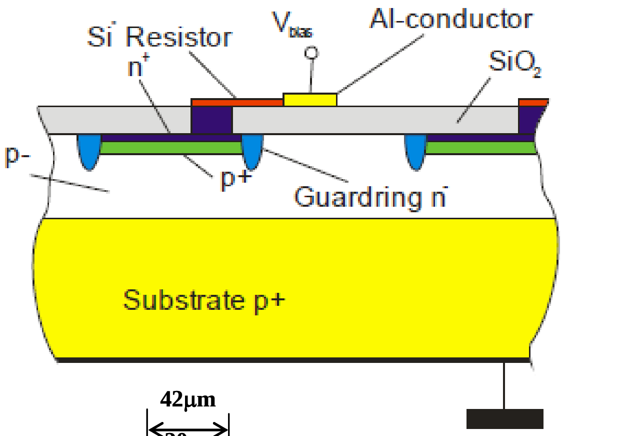
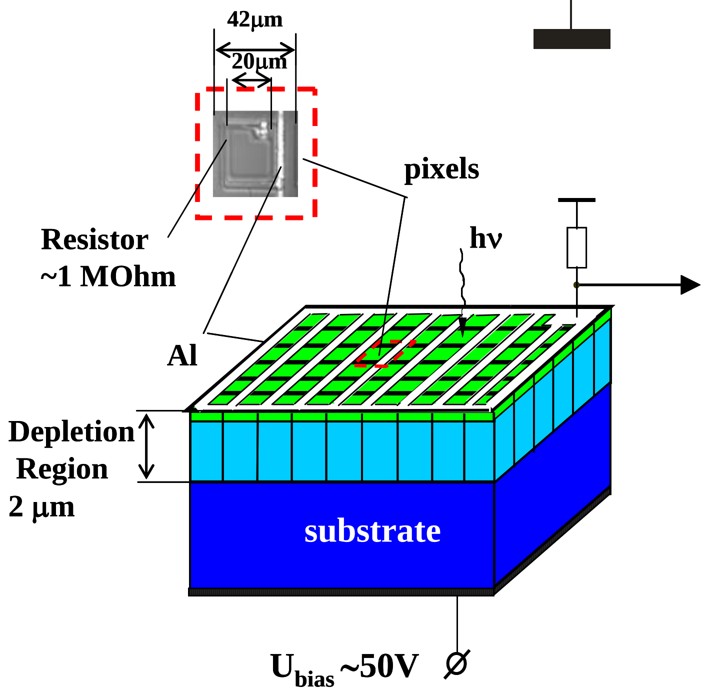
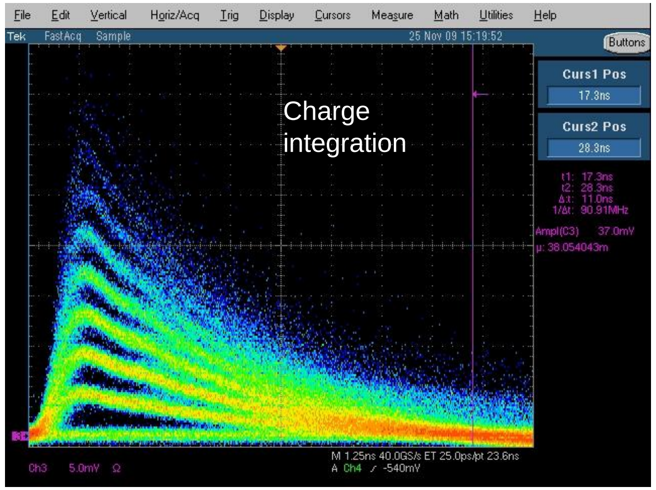
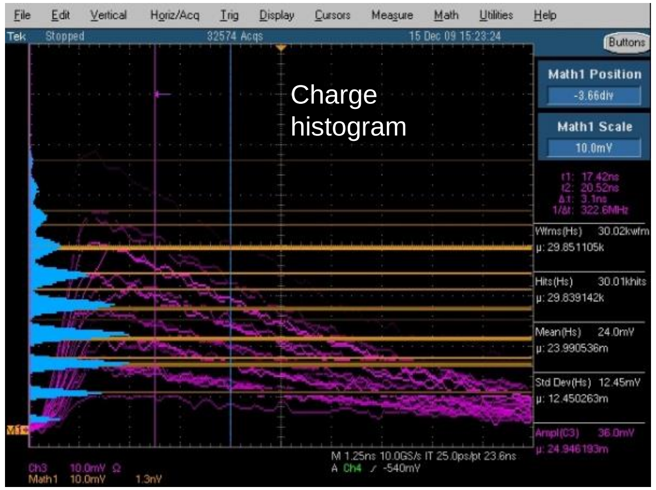
R&D on Silicon Photomultipliers:
MOS APD (1980s, LPI), MRS APD (1990s, INR/MELZ), SiPM (2000s, MEPhI)

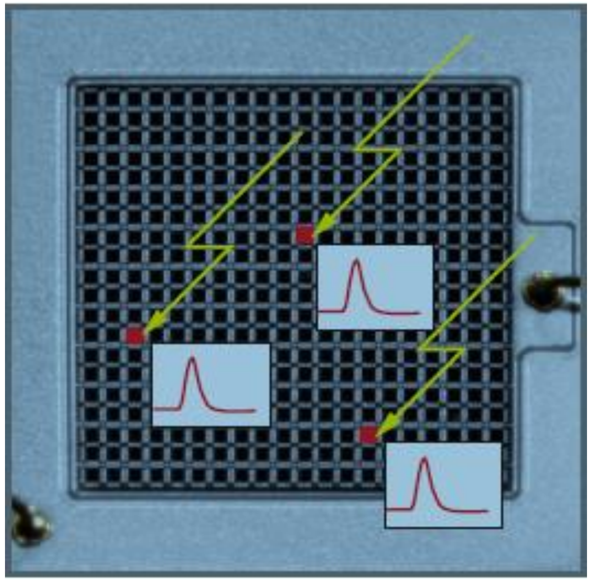


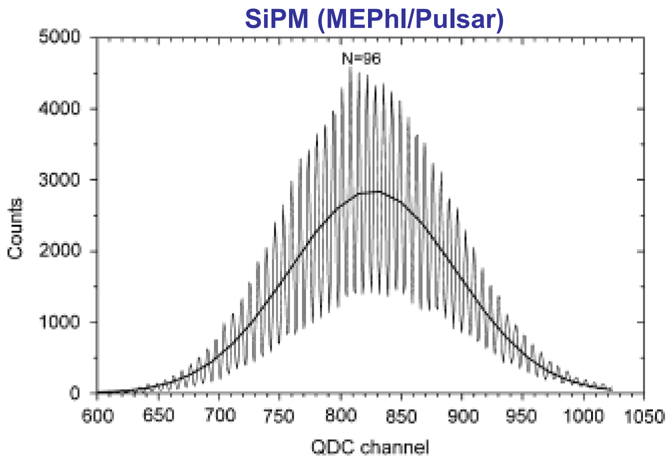


P. Buzhan, B. Dolgoshein et al, ICFA Instrum. Bull., 2001



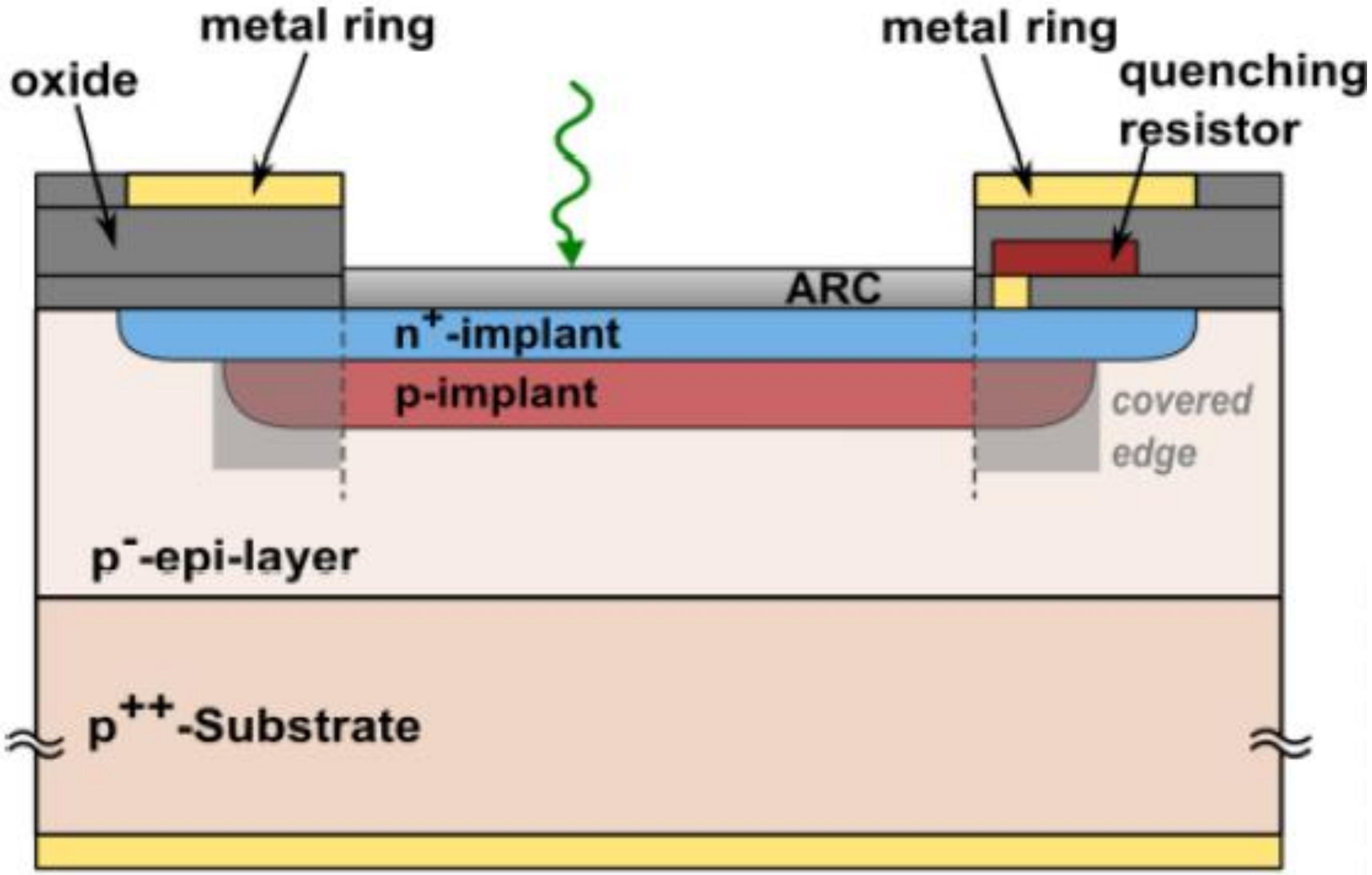






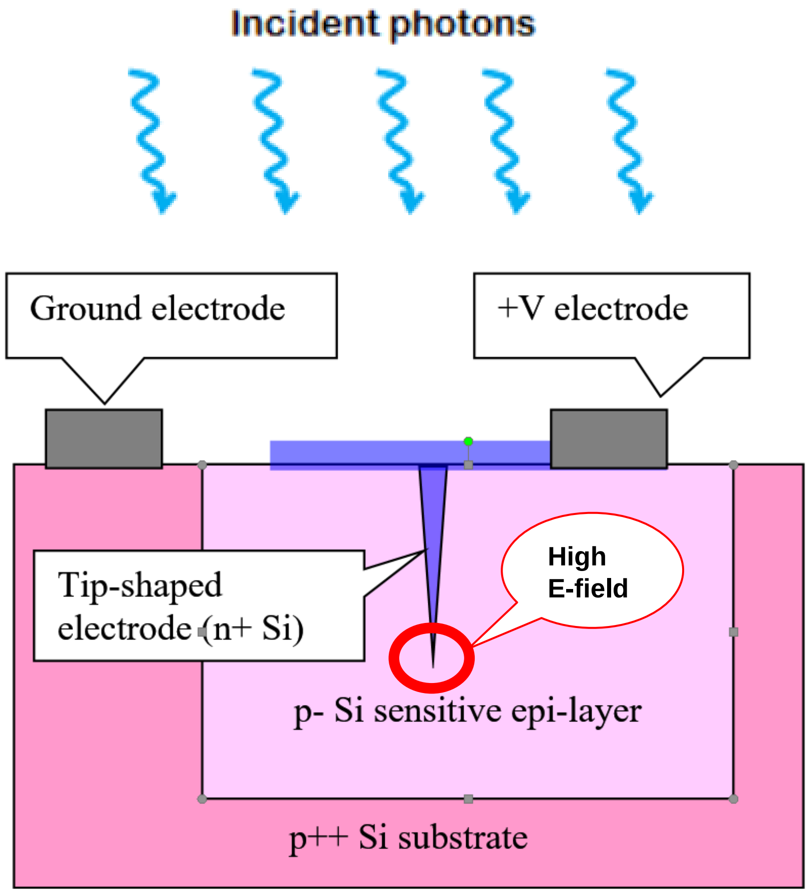
R. Mirzoyan et al., NDIP, 2008

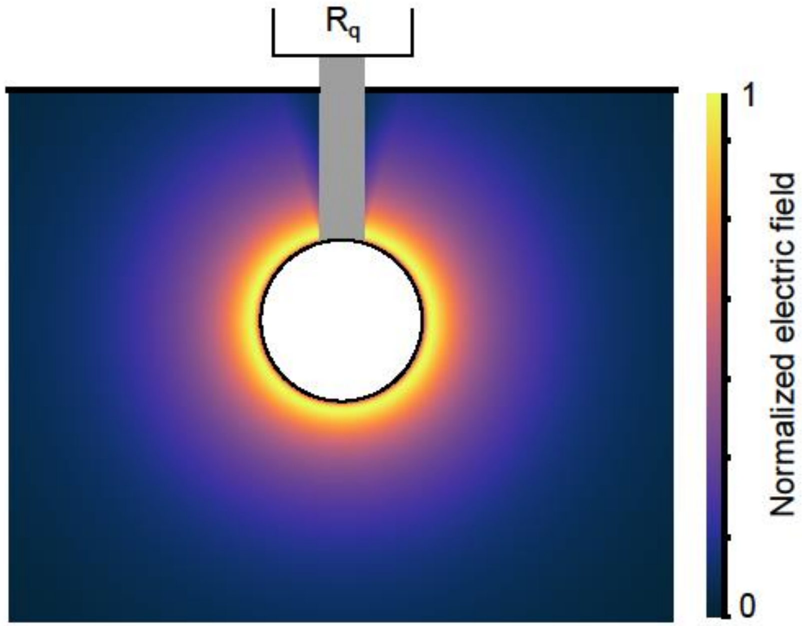
Modern SiPMs based on planar p-n junction: Hamamatsu, ST Microelectronics, Excelitas, On Semiconductor/ SensL, FBK/Broadcom



FBK

Non-planar SiPM design – Tip APD (TAPD)

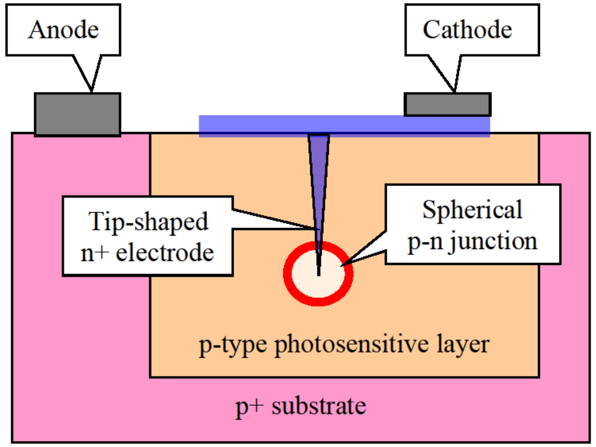




Advantages and drawbacks of TAPD

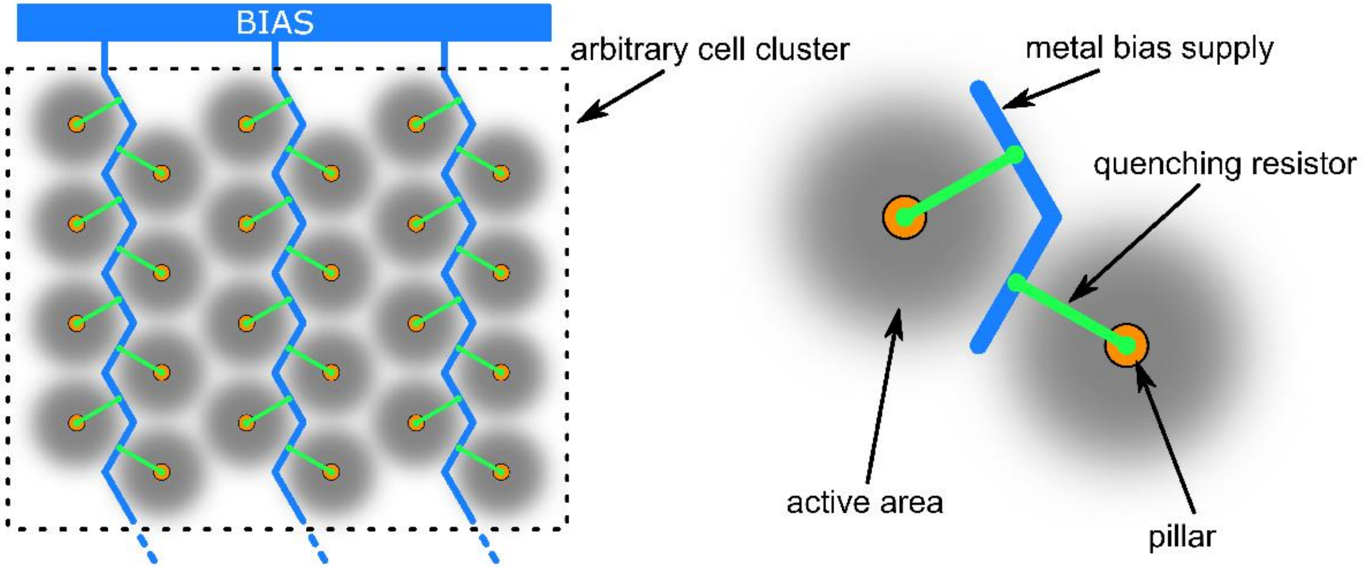
Advantages

- High efficiency (no cell boundaries) => high PDE;
- Low capacitance C =>
  - — fast timing response, fast recovery ~ *RC*,
  - — low readout noise ~ *C*;
- High Dynamic Range
- Low breakdown voltage =>
  - — low power consumption,
- Low size of high electric field region =>
  - — radiation hardness (TBD);



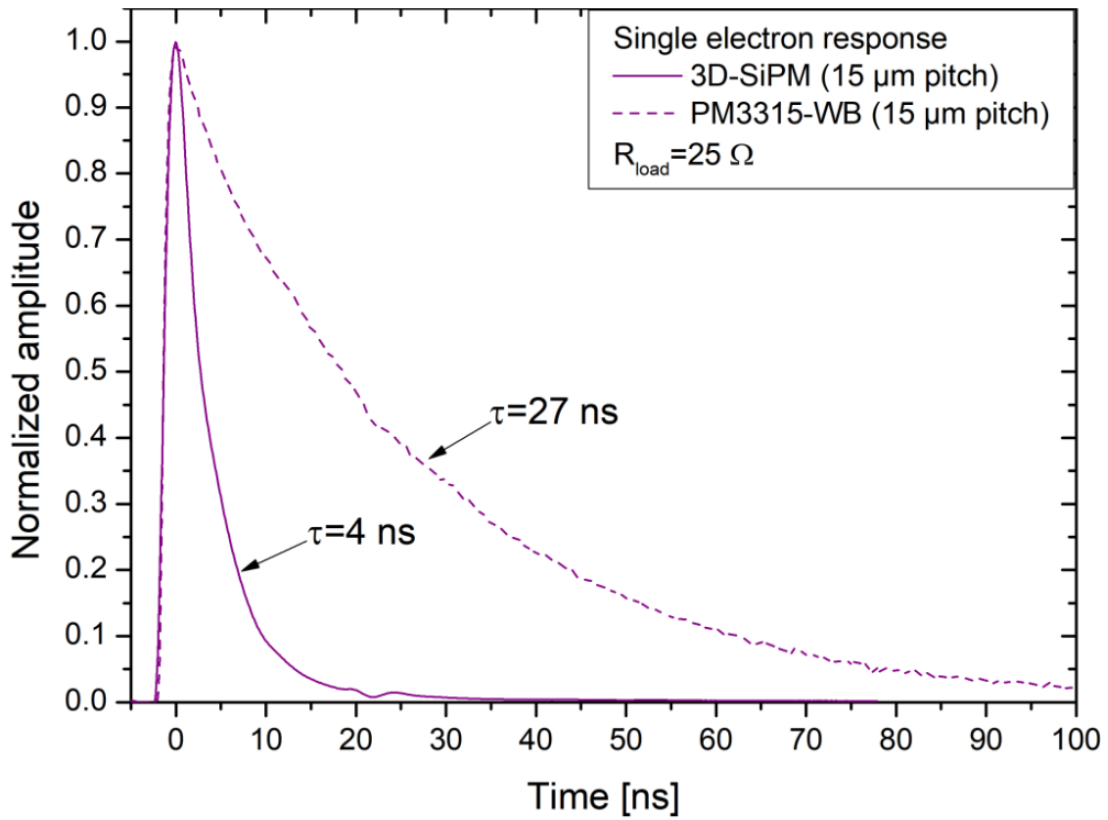
Drawbacks

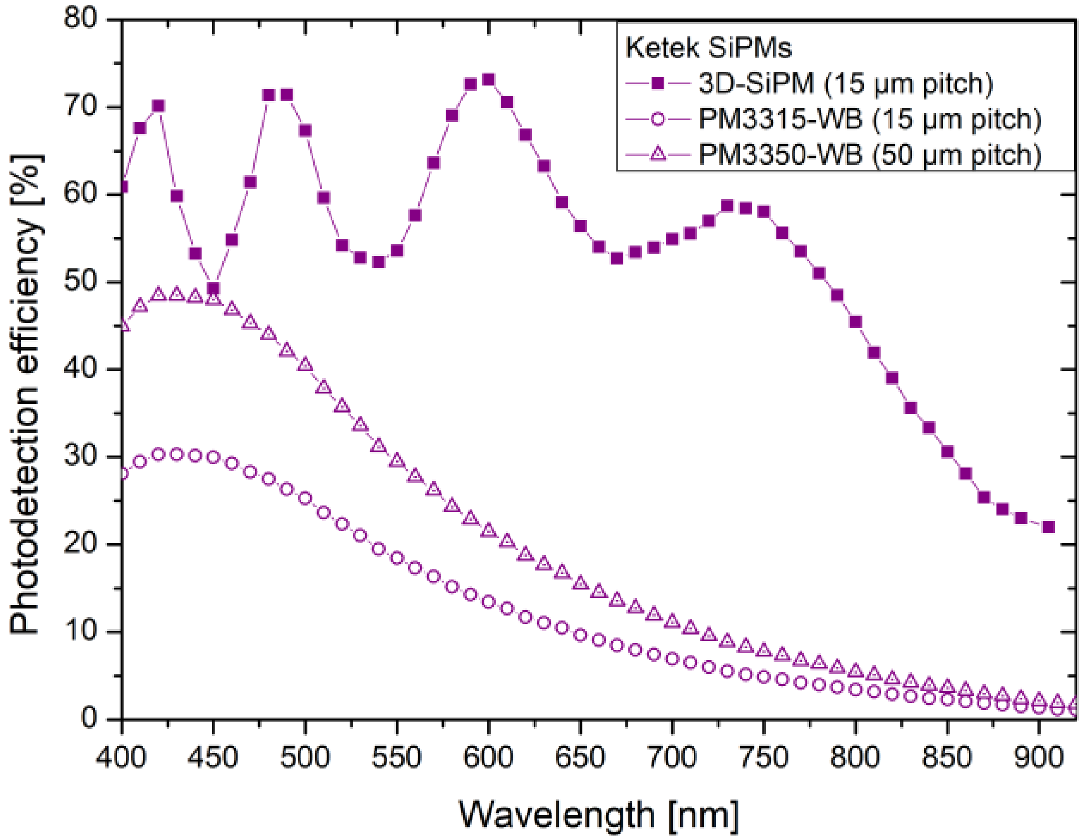
- High sensitivity of Vbd to the tip radius
- High risk of tunneling near the tip
- Questionable reproducibility of the tips



R&D on TAPD with KETEK, Germany, 2017 – 2020: record performance

- Single cell recovery time = **4 ns**
- Single electron response fall time = **4 ns**
- Max PDE = **73%** (608 nm)
- NIR PDE = **22%** (905 нм)

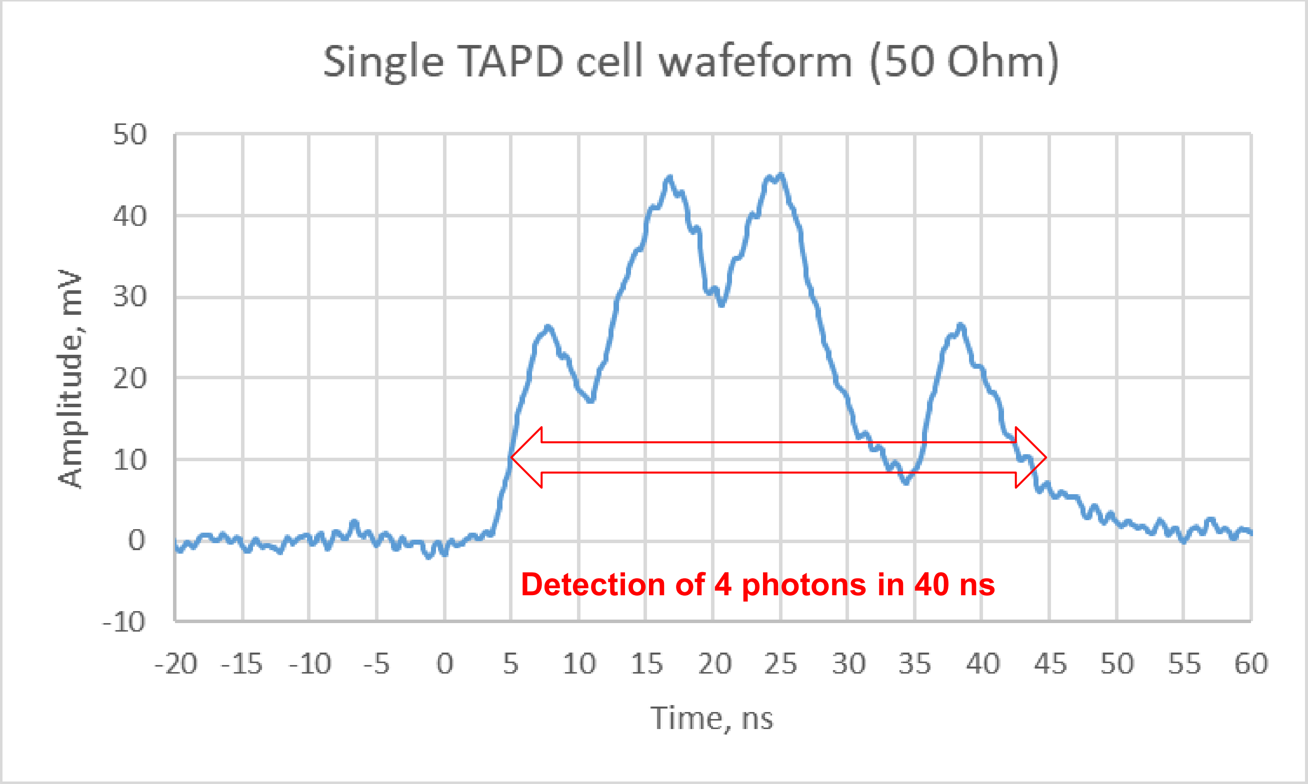


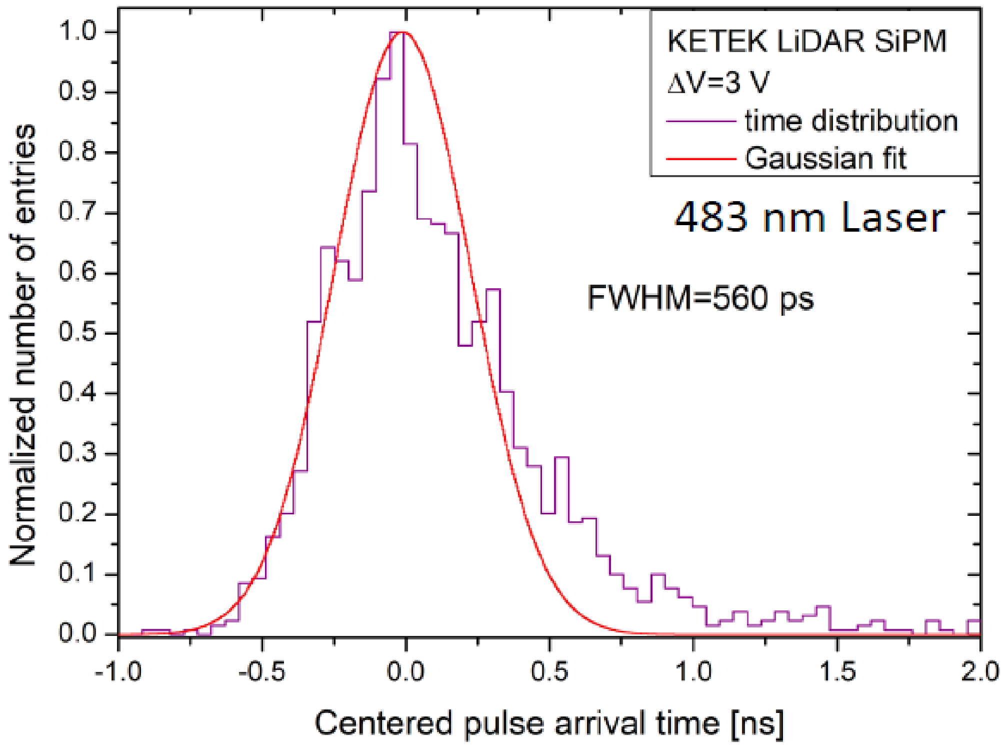


E. Engelmann, W. Schmailzl, P. Iskra, F. Wiest, E. Popova, S. Vinogradov, Tip Avalanche Photodiode—A New Generation Silicon Photomultiplier Based on Non-Planar Technology, IEEE Sens. J. 21 (2021) 6024–6034. doi:10.1109/JSEN.2020.3041556.

TAPD timing performance

- Single cell photon counting ~ 100 MHz/pixel
  - Cell size / pitch = 15 um
- Single photon time resolution ~ 0.5 ns
  - Partial depletion





S. Vinogradov, Tip Avalanche Photodiode—A spherical-junction SiPM concept, Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 1045 (2023) 167596. doi:10.1016/j.nima.2022.167596.

Подтверждение радиационной стойкости TAPD (2022)

- Исследования UHH/DESY Detector Lab
- Облучение тепловыми нейтронами 1 МэВ
- Дозы до 10^{12} см$^{-2}$
- Сравнение с планарными SiPM
  - KETEK MP15: 15 мкм ячейки, 1x1 мм^2
  - Типичная для SiPM рад. стойкость
- Рост темнового счета (при $\Phi=10^{12}$ см$^{-2}$)
  - TAPD – **10^3 раз**
  - KETEK MP15 – 10^5 раз

J. Römer, E. Garutti, W. Schmailzl, J. Schwandt, S. Martens, “Radiation Hardness of a Wide Spectral Range SiPM with Quasi-Spherical Junction”, *NDIP* (2022) / NIMA (2023). http://arxiv.org/abs/2209.07785.

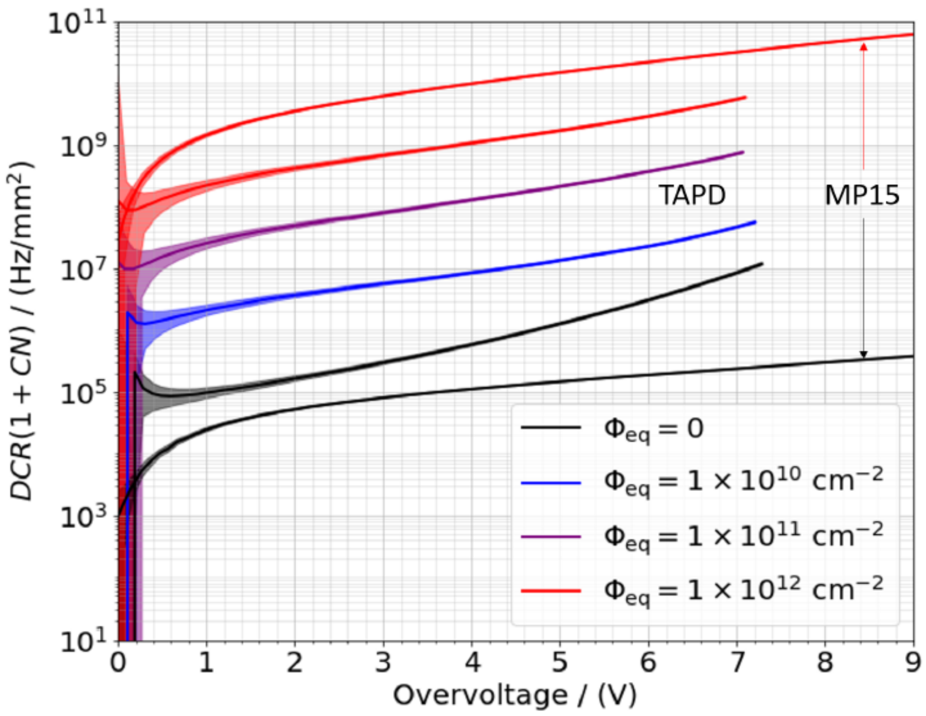


Figure 7: The dark count rate at 20 °C calculated using Eq. 7 normalized to a detector area of 1 mm^2 for the TAPD 0.6 µm and the MP15. The overvoltage is given as $V_{over} = V_{bias} - V_{BD}$.

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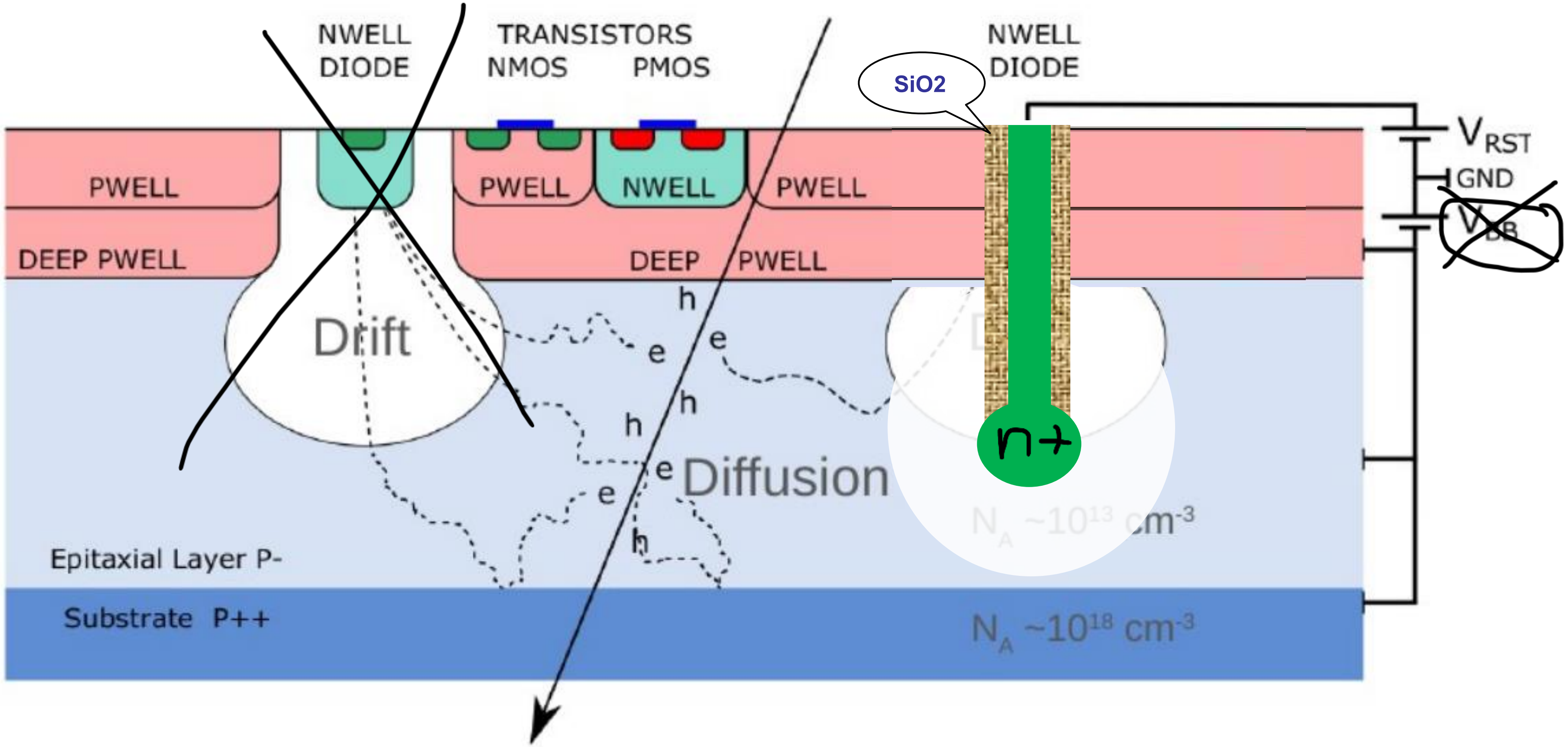
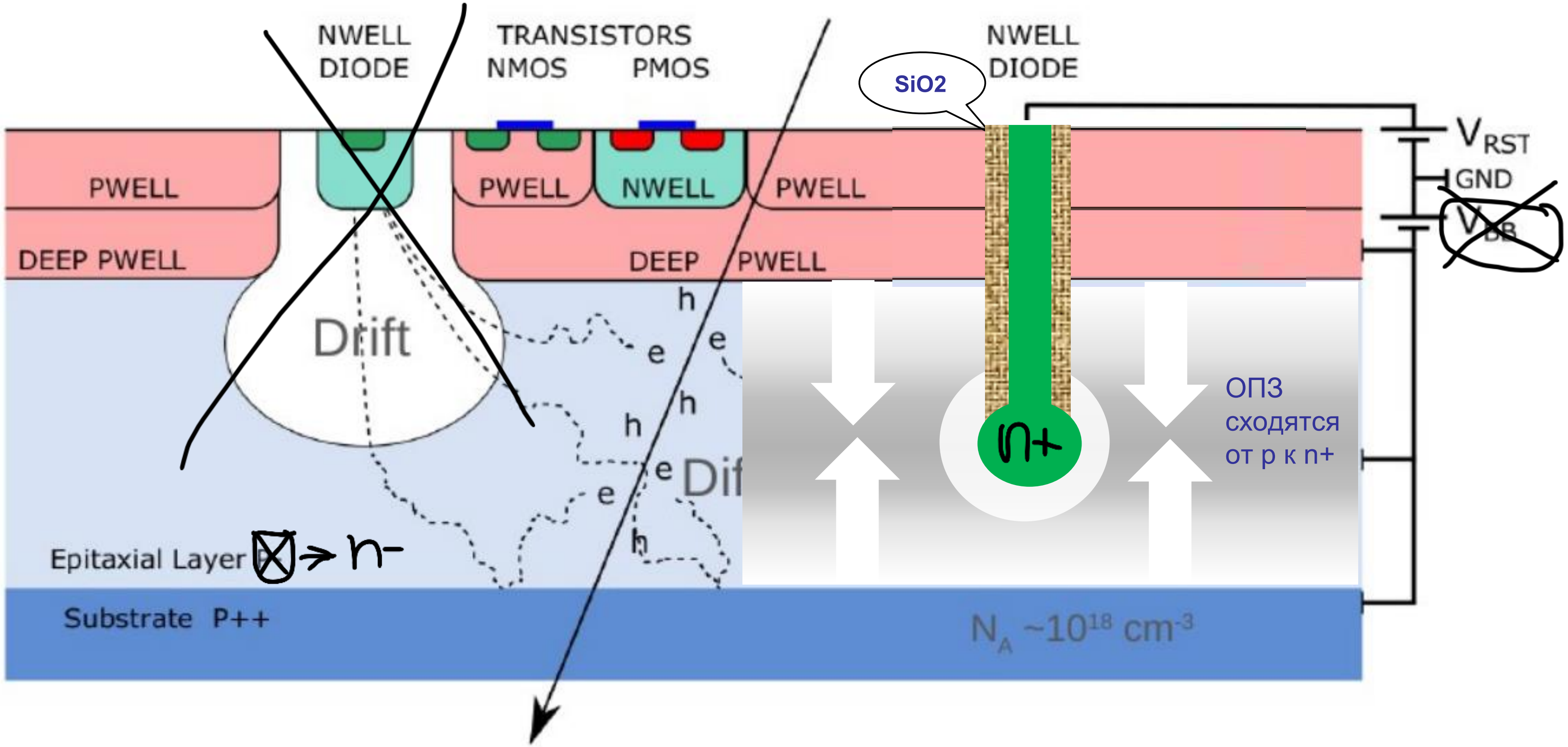
Предлагаемые конструкции пикселя MAPS:
Tip APD + MAPS-ALPIDE – 1) заглубление n+ коллектора

- Неполное обеднение, слой электроники изолирован от диода и может занять всю площадь
- Deep Pwell и p+ substrate могут быть заземлены, смещение +U на n+ диод



Предлагаемые конструкции пикселя MAPS:
Tip APD + FD-MAPS – 2) замена p-эпи на n-эпи

- Полное обеднение, слой электроники изолирован от диода и может занять всю площадь
- Deep Pwell и p+ substrate могут быть заземлены, смещение +U на n+ диод



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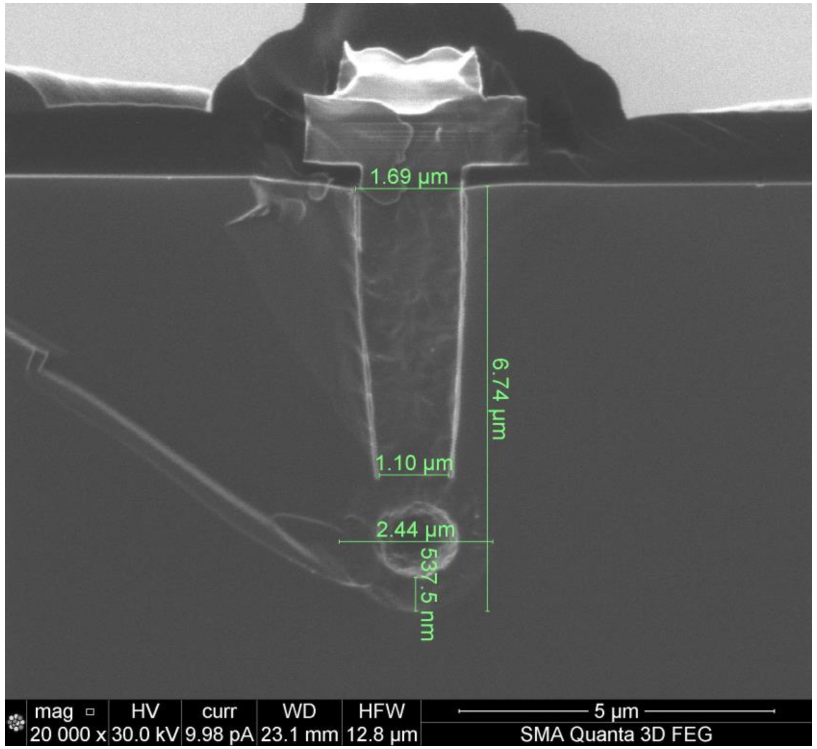
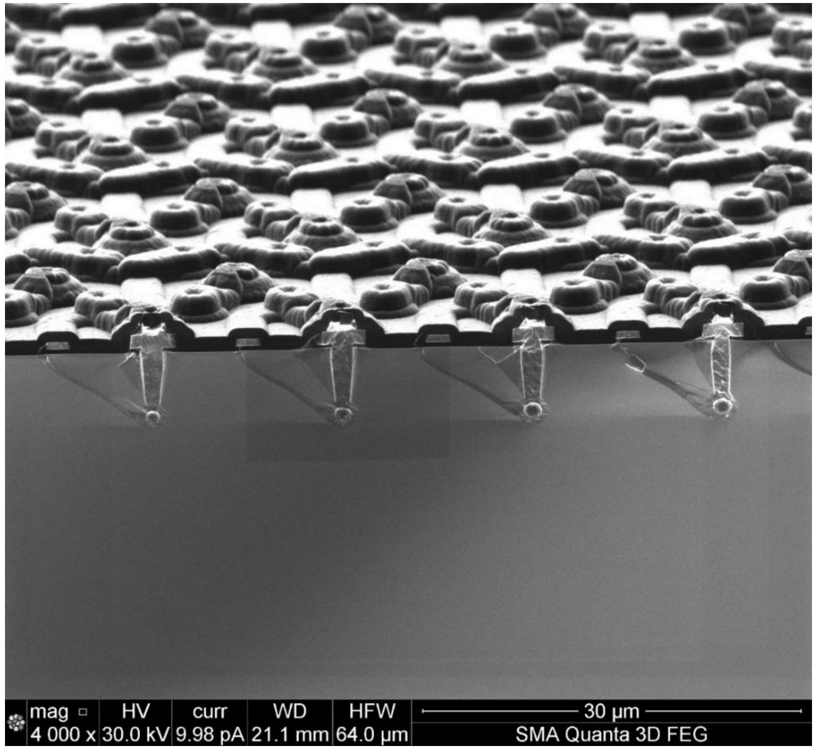
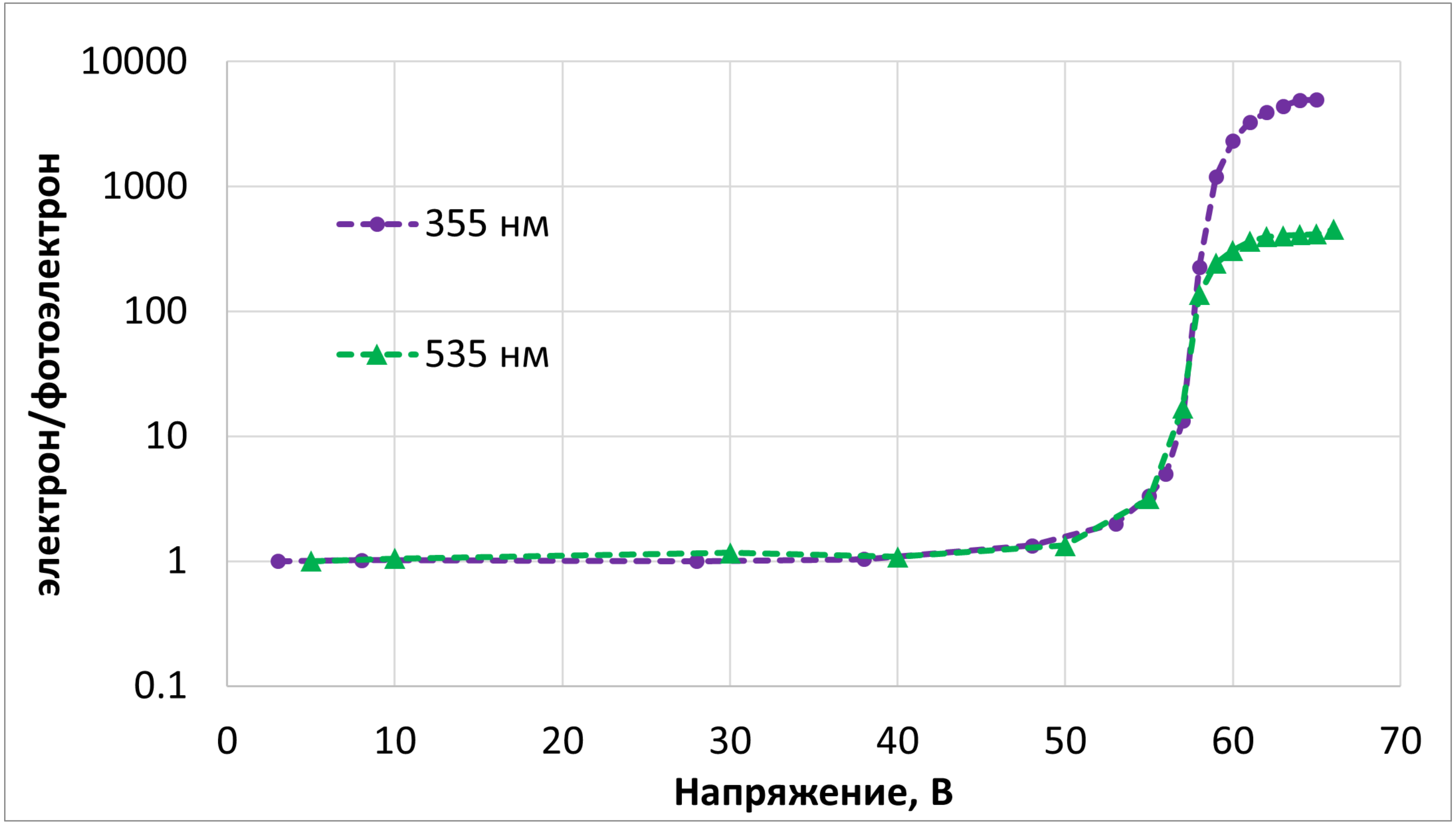
Проект по разработке TAPD с МИЭТ / НПК ТЦ, Зеленоград

- НИОКР «Разработка нового типа кремниевых фотоумножителей непланарной конструкции»
  - Грант фонда содействия инновациям «Техностарт-1» на 2022 – 2023 гг.
  - На технологической базе НПК «Технологический Центр», гл. технолог А.А. Жуков
  - Разработана технология создания сферического перехода радиусом 1 мкм на глубине 7 мкм с шагом 15 мкм
  - Выпуск 1-й партии - лето 2023; 2-й партии – весна 2024



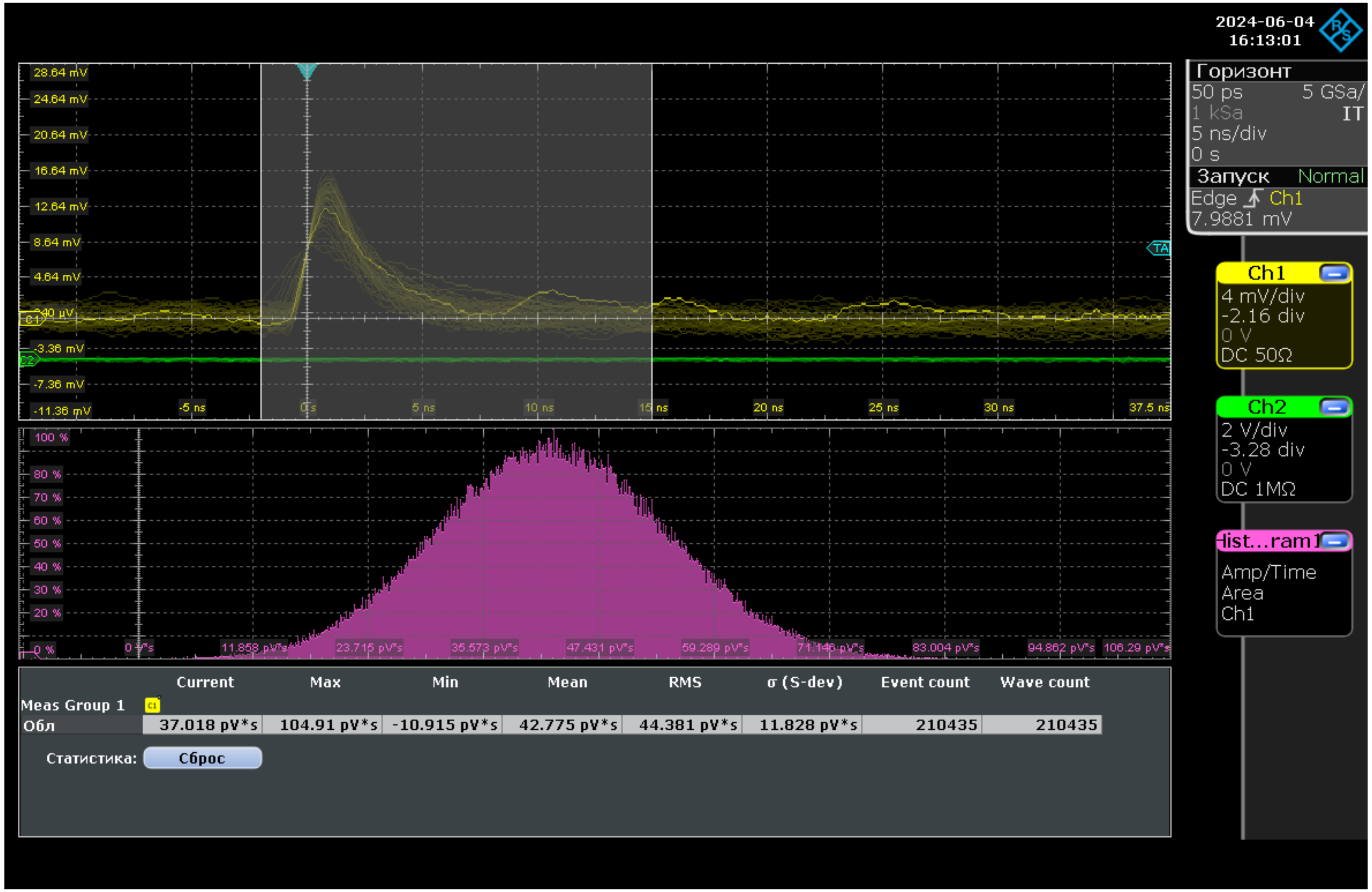


Результаты 2023 (1-я партия)
Gain ~ 5 K, photoresponse ~ ns

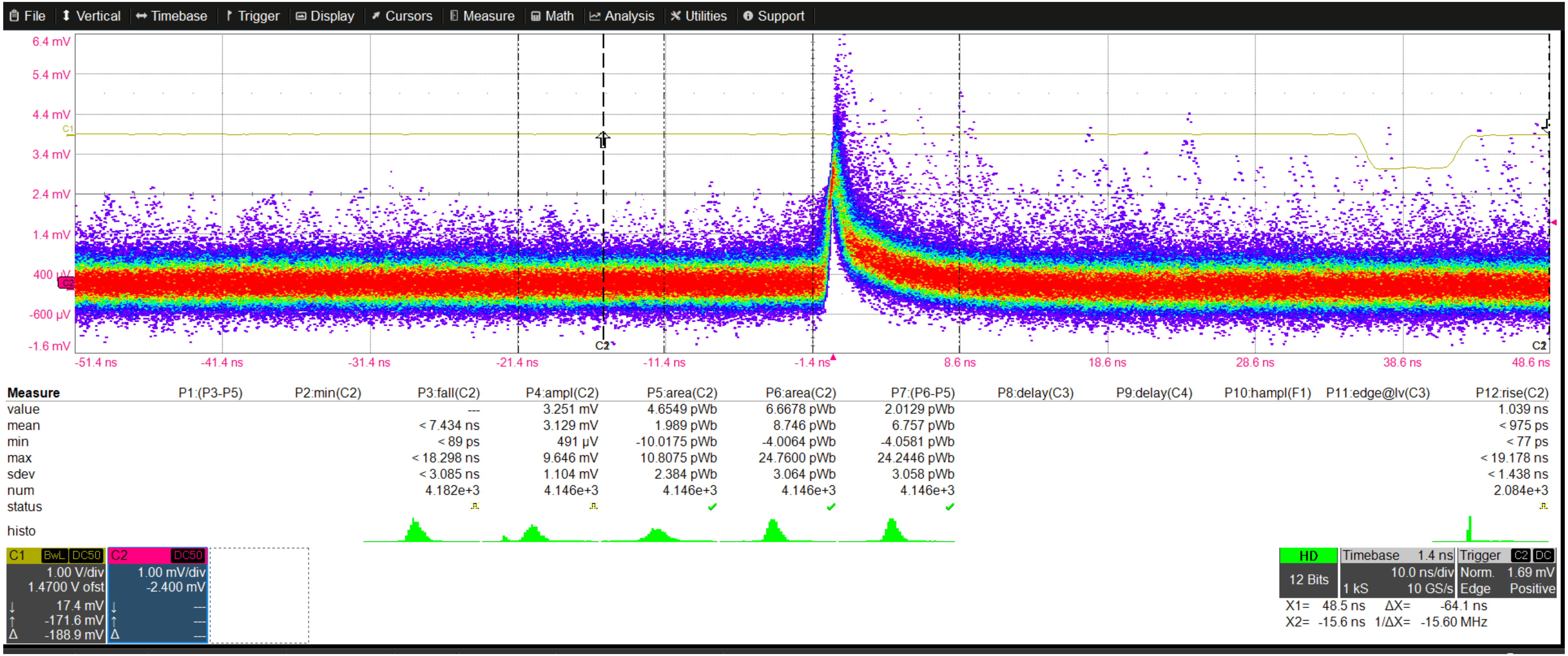


Результаты 2024 (1-я партия)
Детектирование альфа-частиц ^{241}Am (5.486 MeV)

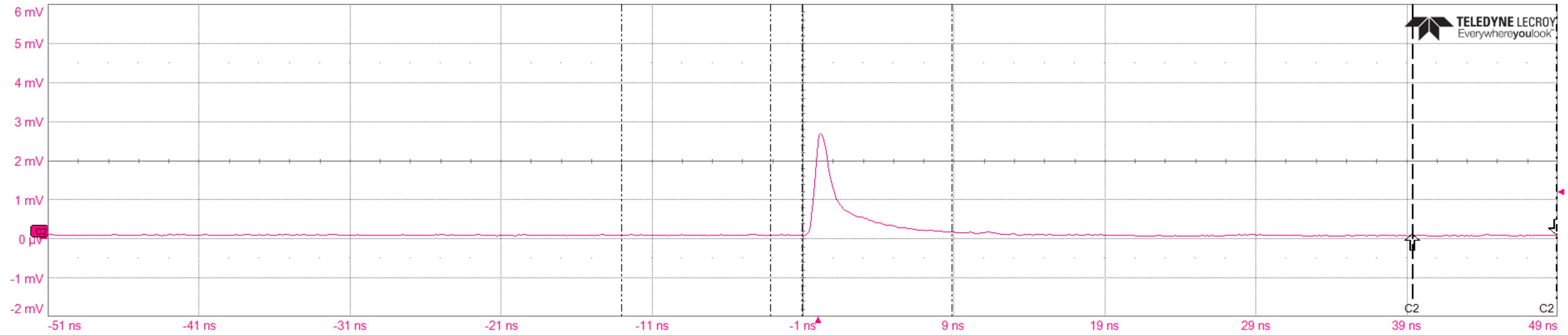
- Амплитуда ~ 13 мВ, разрешение σ/μ ~ 27%, ширина импульса ~ 5 нс



Результаты 2024 (2-я партия)
одноэлектронный импульс: Gain ~ 75 K



Результаты 2024 (2-я партия)
одноэлектронный импульс: *Trise* = 0.45 ns, *Tfall* = 4.45 ns



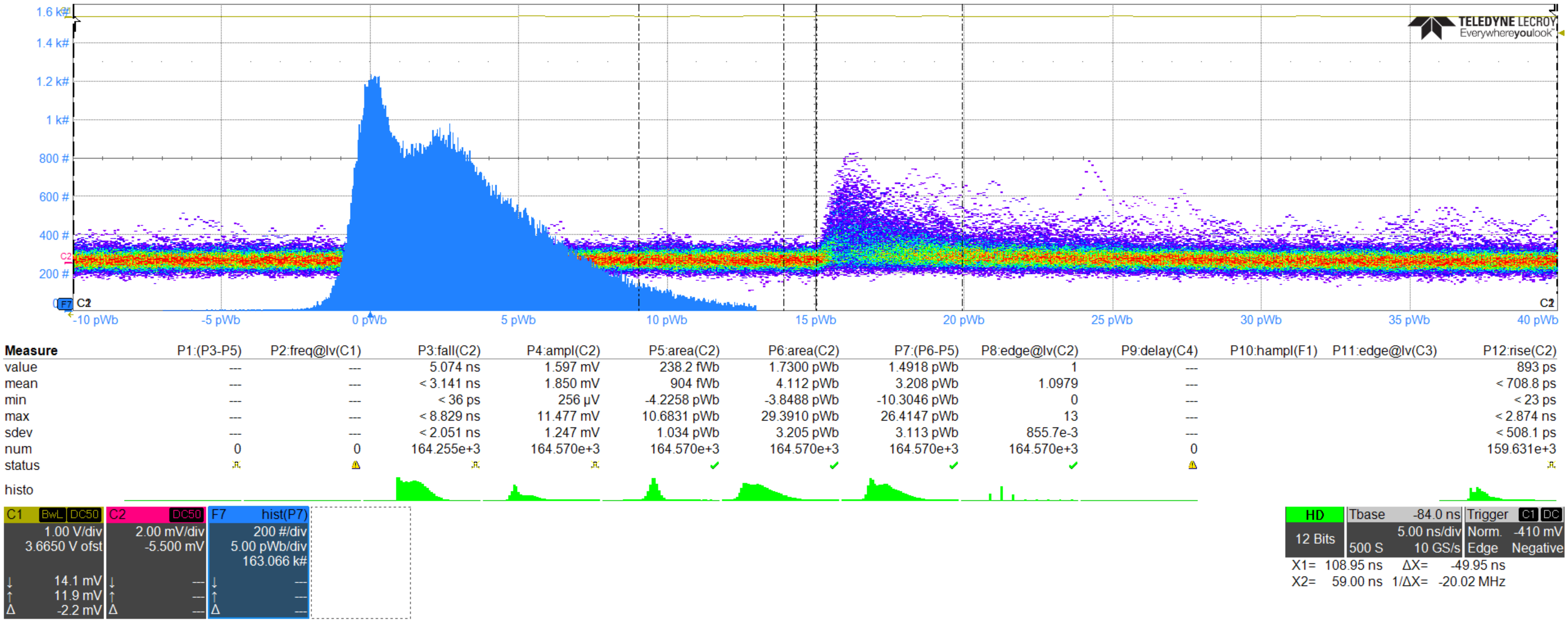
Measure	P1:(P3-P5)	P2:min(C2)	P3:fall(C2)	P4:ampl(C2)	P5:area(C2)	P6:area(C2)	P7:(P6-P5)	P8:delay(C3)	P9:delay(C4)	P10:hampl(F1)	P11:edge@lv(C3)	P12:rise(C2)
value			4.456 ns	2.617 mV	815.687 fWb	6.014480 pWb	5.198793 pWb					491 ps
mean			4.456 ns	2.617 mV	815.687 fWb	6.014480 pWb	5.198793 pWb					491 ps
min			4.456 ns	2.617 mV	815.687 fWb	6.014480 pWb	5.198793 pWb					491 ps
max			4.456 ns	2.617 mV	815.687 fWb	6.014480 pWb	5.198793 pWb					491 ps
sdev			---	---	---	---	---					---
num			1	1	1	1	1					1
status					✓	✓	✓					
histo												

C2 AVG DC50
1.00 mV/div
-2.00000 mV
1.745 k#
↓ 69.92 µV
↑ 58.02 µV
Δ -11.90 µV

HD 12 Bits | Timebase 1.0 ns, 10.0 ns/div, 1 kS, 10 GS/s | Trigger C2 DC, Norm. 1.20 mV, Edge Positive

X1= 48.9 ns ΔX= -9.5 ns
X2= 39.4 ns 1/ΔX= -105 MHz

Результаты 2024 (2-я партия)
спектр фотоэлектронов от лазера 535 нм 40 пс



Summary

- Advantages to combine MAPS and spherical junction TAPD designs:
  - Sensor and FEE are isolated and independent
  - All front-side area is available for FEE
  - Spherical p-n-junction in depth of epi-layer is efficient collector with lowest capacitance
  - High radiation hardness is expected

- Good progress in R&D and application studies of TAPD

- Possibility of development and production in Zelenograd (MIET, ZNTC) - TBD

СПАСИБО ЗА ВНИМАНИЕ!

Вопросы?
Замечания?
Предложения?

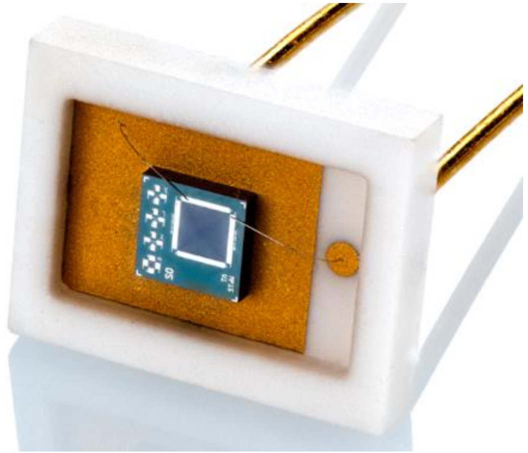
Виноградов Сергей Леонидович

vinogradovsl@lebedev.ru

Разработка TAPD SiPM

- НИОКР в сотрудничестве с компанией КЕТЕК, Германия (2017-2020)
  - На технологической базе КЕТЕК, X-Fab, Fraunhofer EMFT
- Образцы TAPD 1x1 мм^2, шаг ячеек 10 – 15 мкм, радиус 0.6 – 1 мкм

Structure Name	Nominal Radius (r_j)	Breakdown Voltage
S06	0.6 µm	43.4 V
S08	0.8 µm	50.7 V
S10	1.0 µm	53.9 V



- Измерения образцов в КЕТЕК и МИФИ
  - Подтверждение рекордных параметров в лаборатории SiPM компании Broadcom
- Публикации (2020 - 2022)

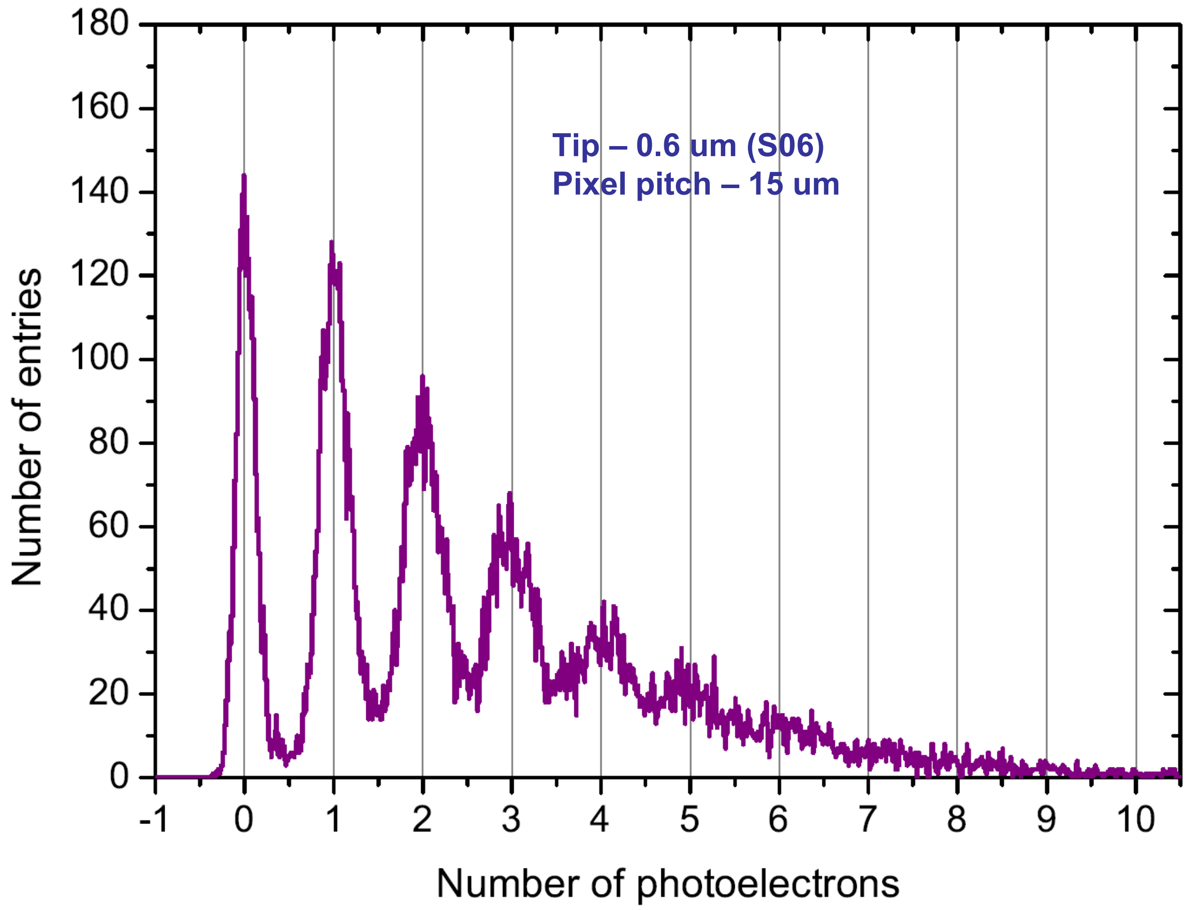
[1] E. Engelmann, W. Schmailzl, P. Iskra, F. Wiest, E. Popova, S. Vinogradov, “Tip Avalanche Photodiode - a new generation Silicon Photomultiplier based on non-planar technology”, *IEEE Sensors J.* (2020) Vol 21, No 5, 6024-6034

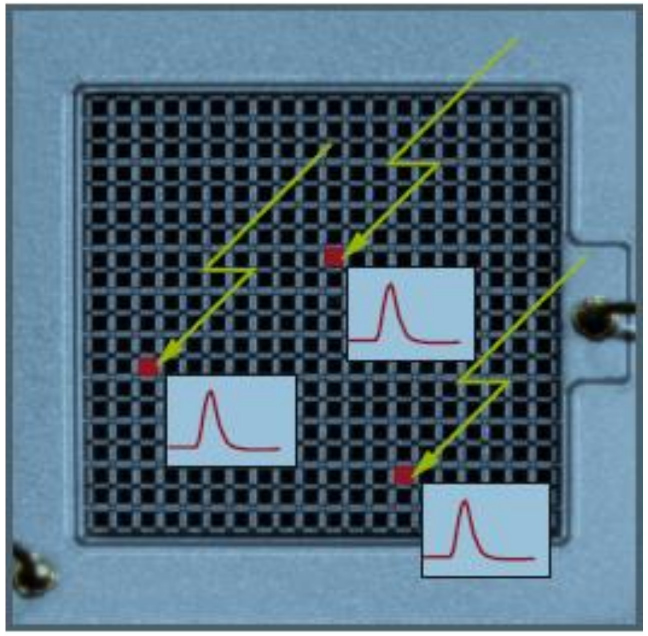
[2] S. Vinogradov, E. Popova, W. Schmailzl, E. Engelmann “Tip Avalanche Photodiode – a new wide spectral range Silicon Photomultiplier”, *“Radiation Detection Systems”,* Taylor & Francis (2021) Vol. 1, Ch. 9, 257–288

[3] S. Vinogradov, “Tip Avalanche Photodiode – a spherical-junction SiPM concept”, *9th Int. Conf. New Developments in Photodetection*, Troyes, France, 4 - 8 Jul. 2022.

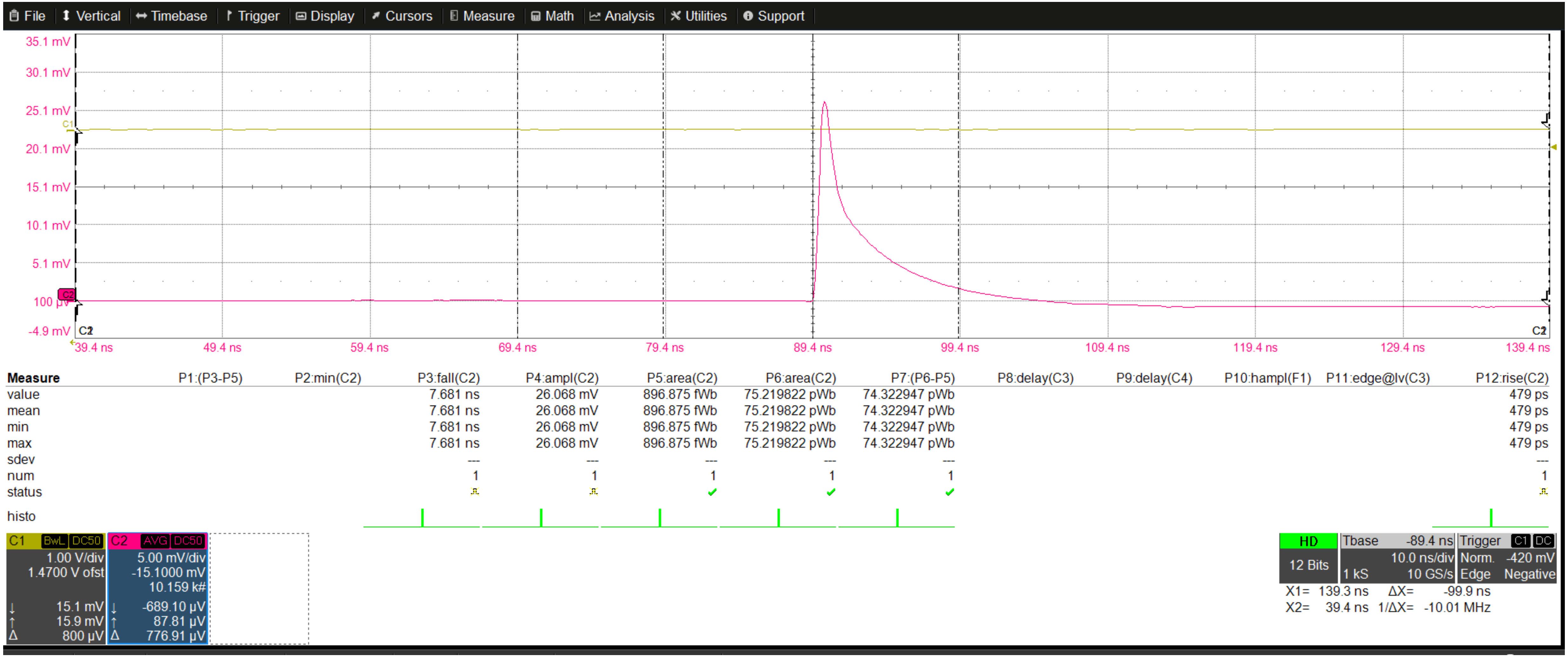
Результаты измерений TAPD: разрешение числа фотоэлектронов

- Функциональность SiPM – разрешение числа фотонов - подтверждена
  - Возможно, есть разброс радиуса сферических p-n переходов
  - Характеризация по пикам по стандартным методикам SiPM



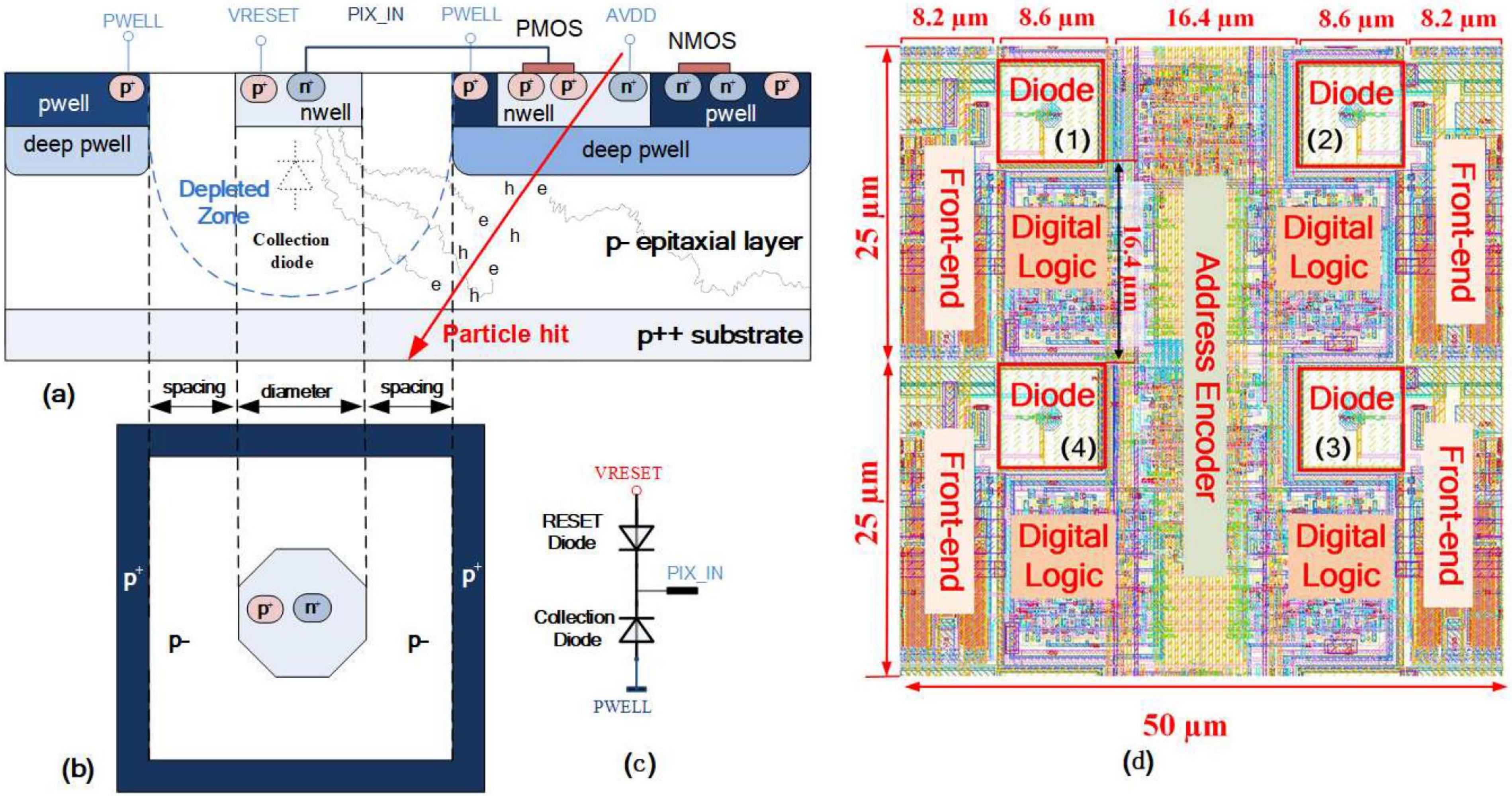


Результаты 2024 (2-я партия)
Фотоотклик на лазерный импульс 40 пс: *Trise* = 0.48 ns, *Tfall* = 7.68 ns



MAPS - TaichuPix1

- Si-epi 25 um, pixel size 25 um, 512×1024 array



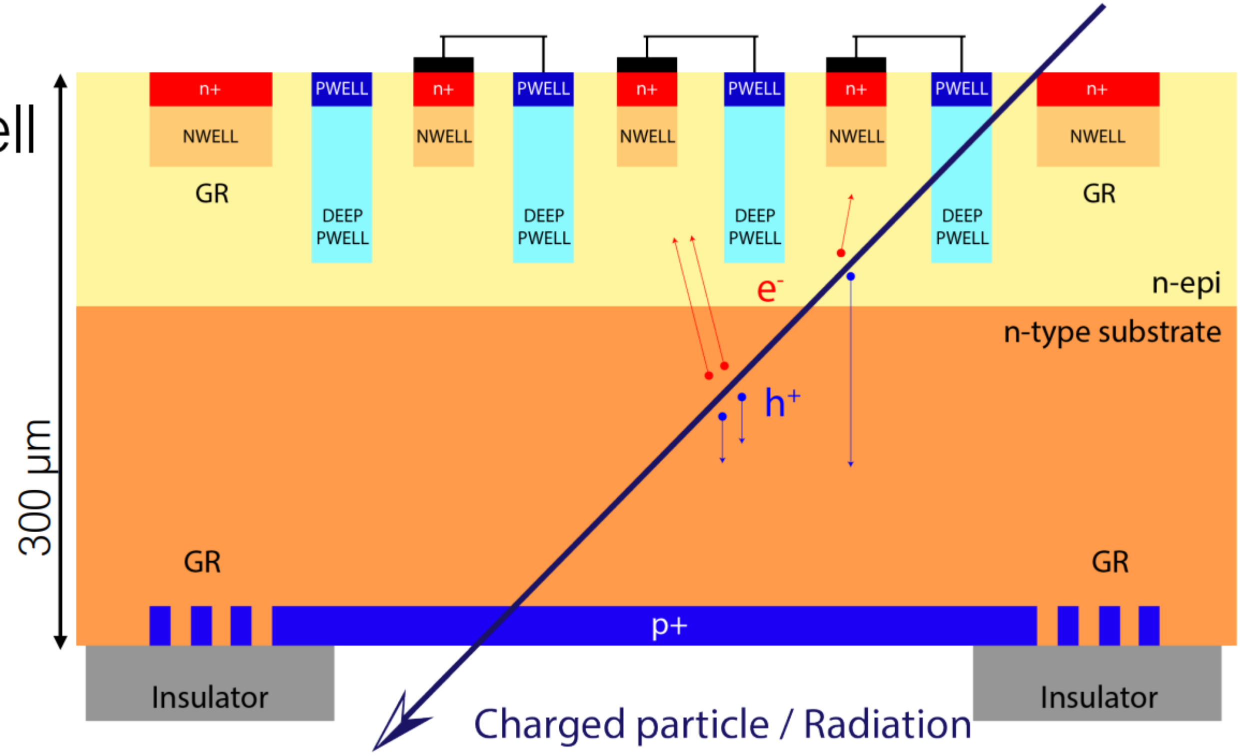
FD-MAPS (ARCADIA) – full depletion design

- Full depletion at -160 V @300 um Si, -40 V@100 um Si sensor thikness

  - Standard CMOS process
  - Electronics buried in deep p-well
  - n-type high ρ substrate
  - Back-side standard CMOS process
  - Fully depleted substrate

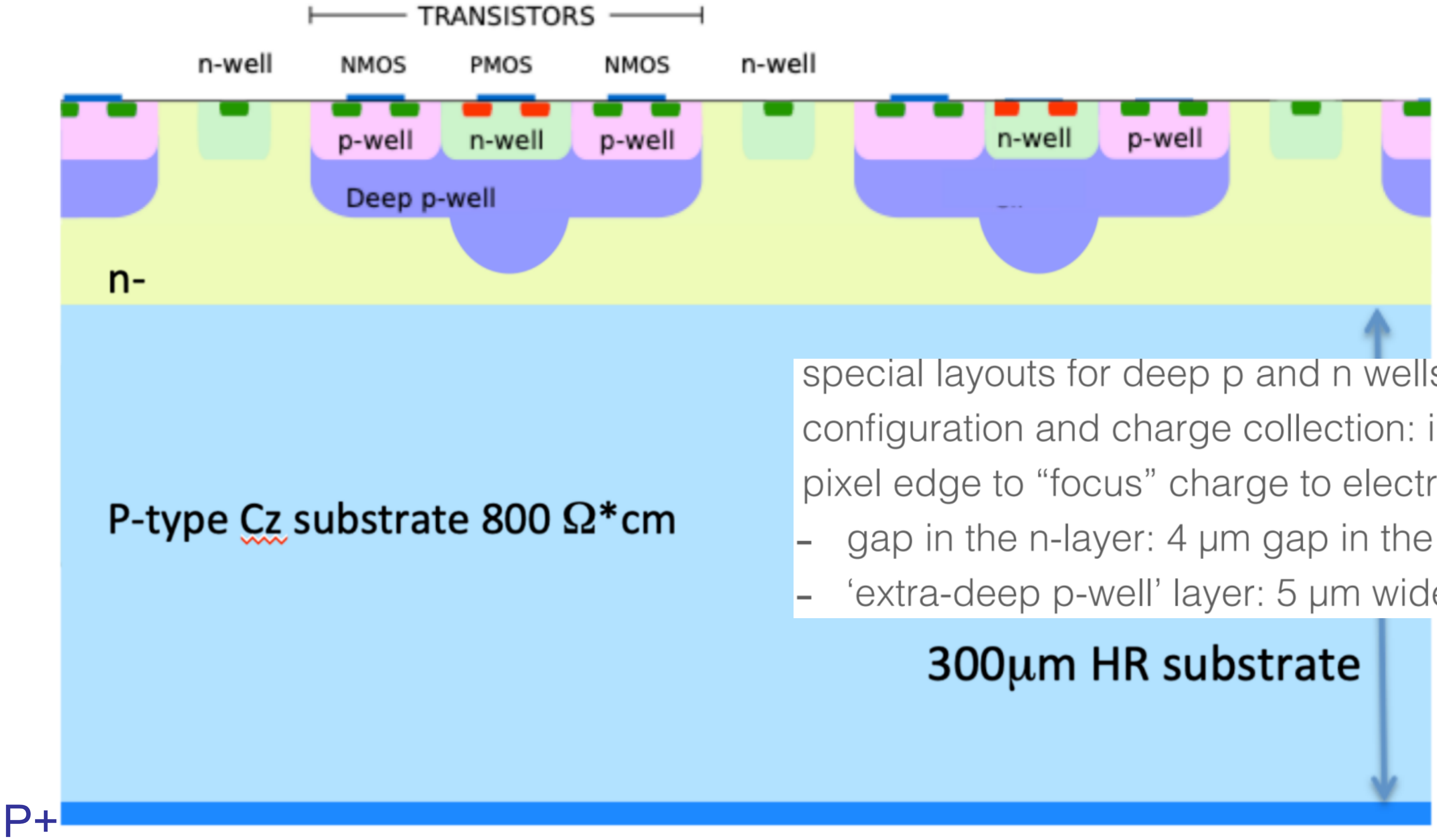
  ⇓

  - Drift charge collection
  - Bulk rad hardness



MALTA – full depletion + charge focusing

- Prototype: 100 μm thick, 36 μm pixel, full depletion at -6 V, operating voltage ≤ -50 V

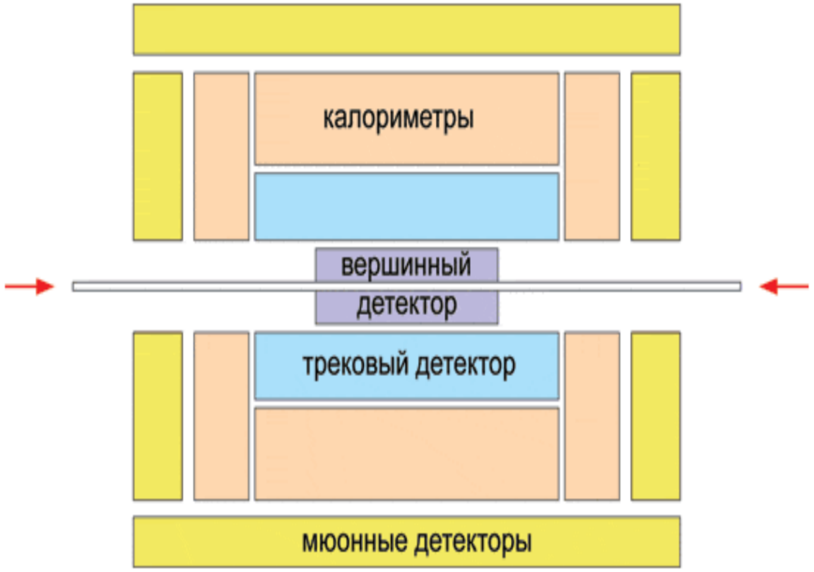


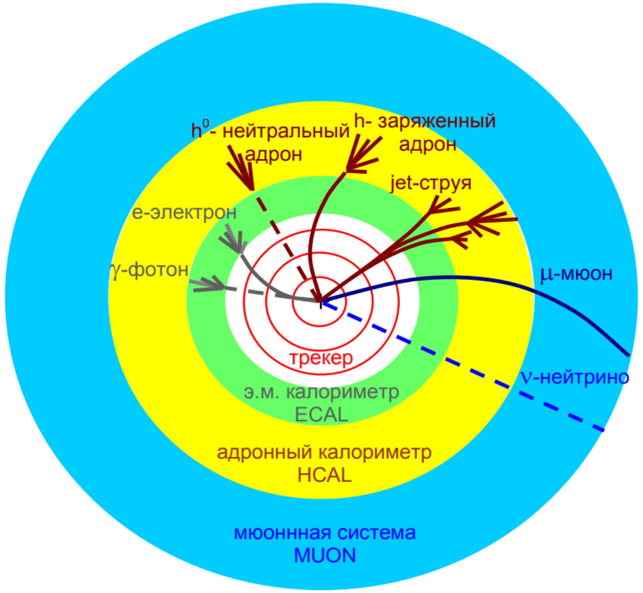
special layouts for deep p and n wells to optimize field configuration and charge collection: increase lateral field near pixel edge to "focus" charge to electrode:

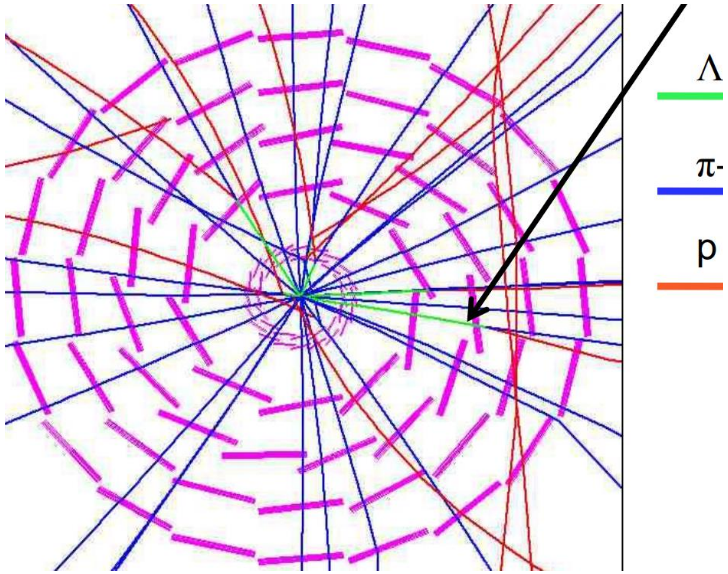
- gap in the n-layer: 4 μm gap in the low dose n-layer
- 'extra-deep p-well' layer: 5 μm wide additional p-well implant

Pixel sensors for vertex / tracking detectors

- High demands in particle detectors







- High demands in nuclear medicine