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

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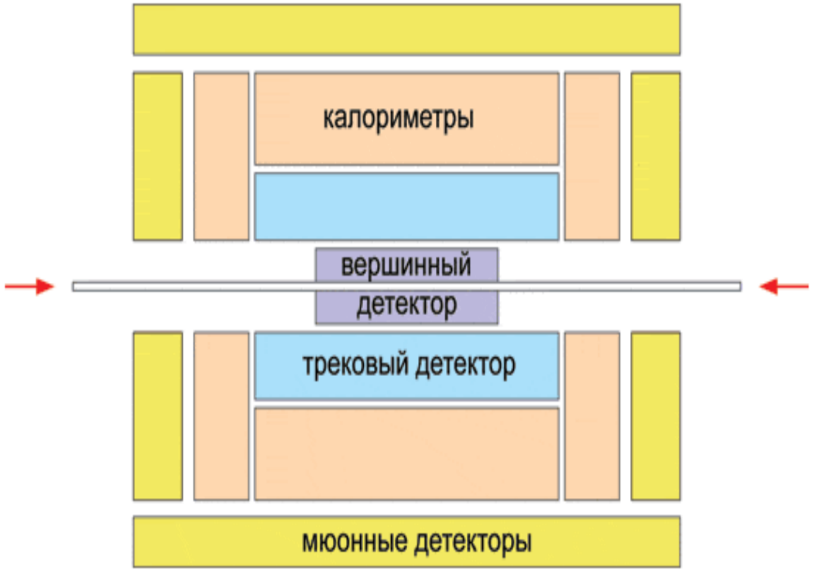
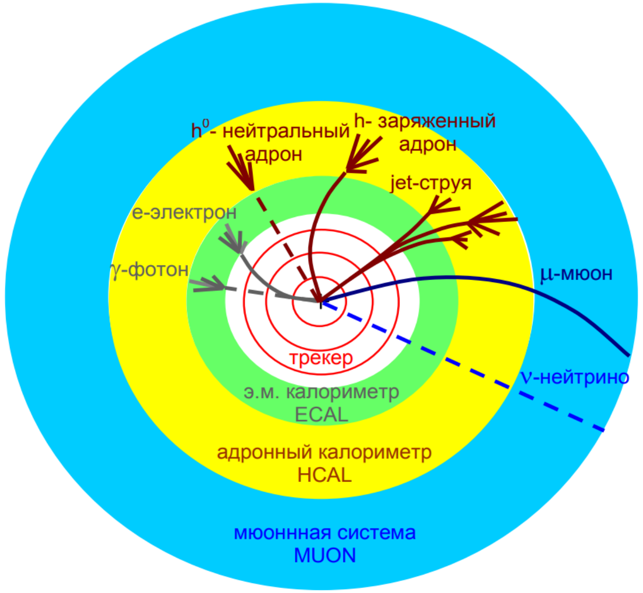
Outline

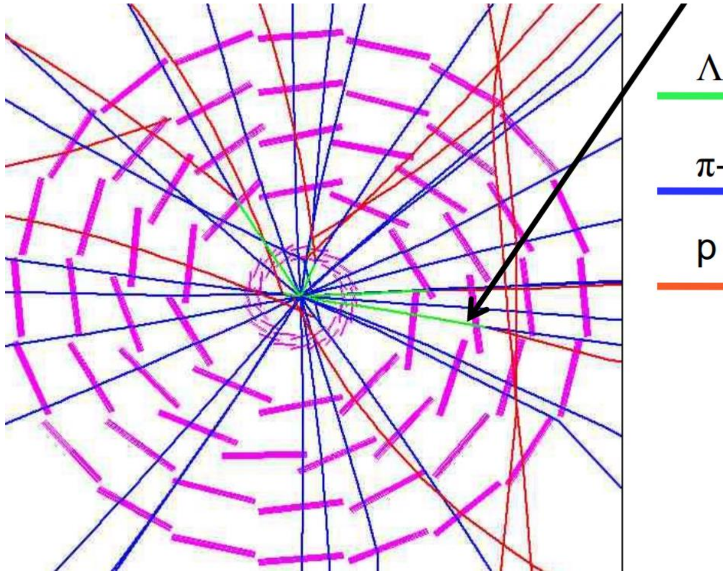
- Demands for sensors produced in Russia
- Designs of MAPS (monolithic active pixel sensor)
- Development of Tip APD – Silicon Photomultiplier based on spherical p-n junction
- On possible development of MAPS

Pixel sensors for vertex / tracking detectors

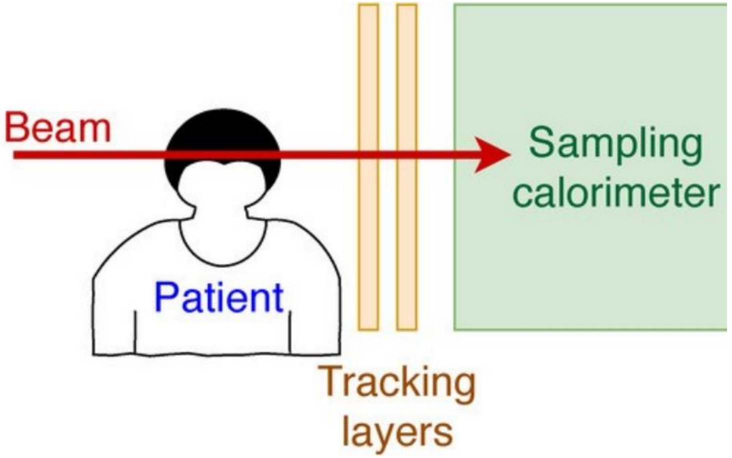
- High demands in particle detectors







- High demands in nuclear medicine

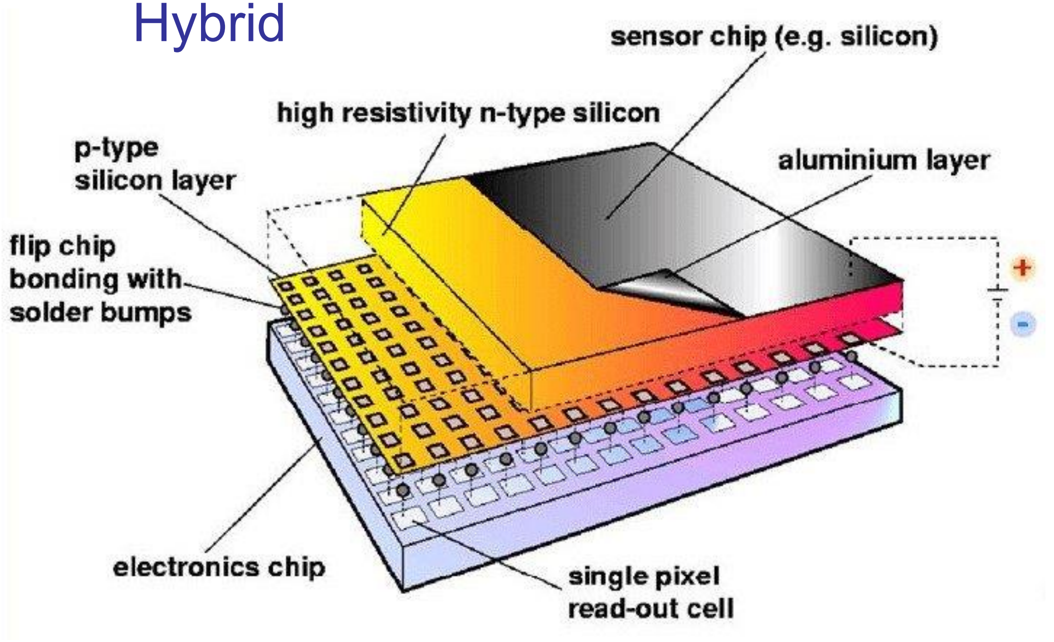


Monolithic vs Hybrid

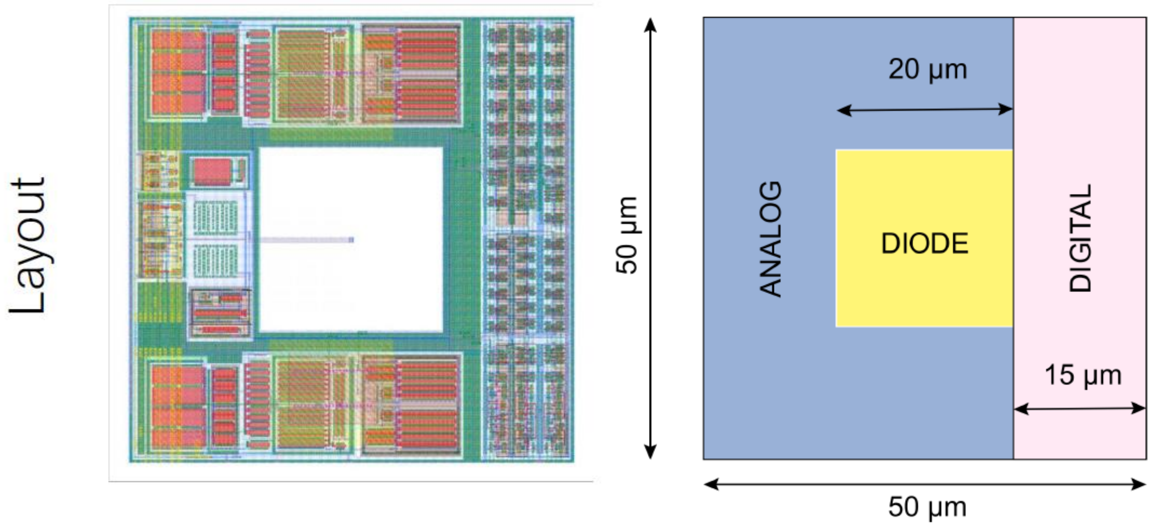
- Hybrid = sensor chip + FEE chip coupled by flip-chip integration
  - Became obsolete, large total thickness => particle scattering and resolution losses

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

Hybrid

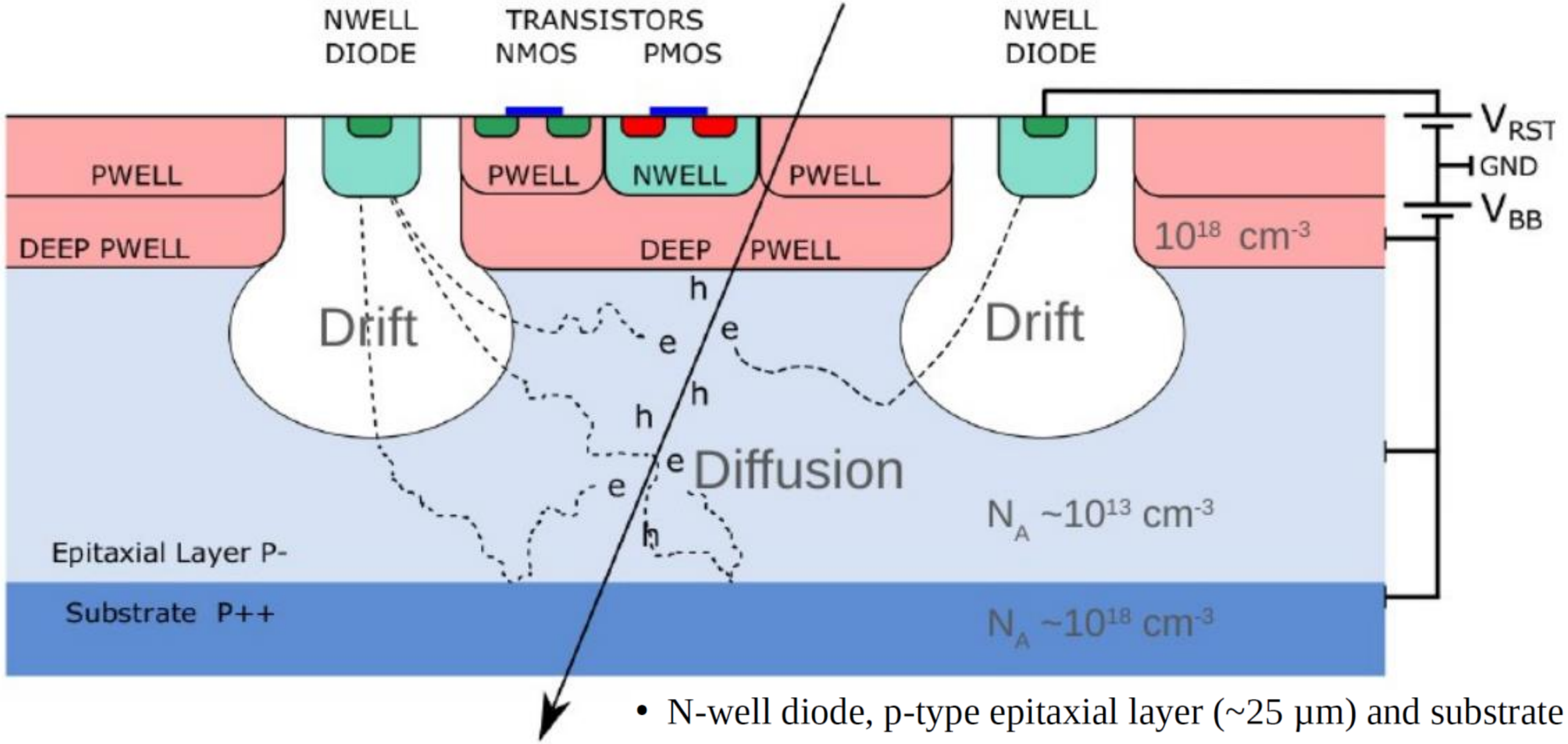


Monolithic (MAPS)



MAPS-ALPIDE – partial depletion design

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

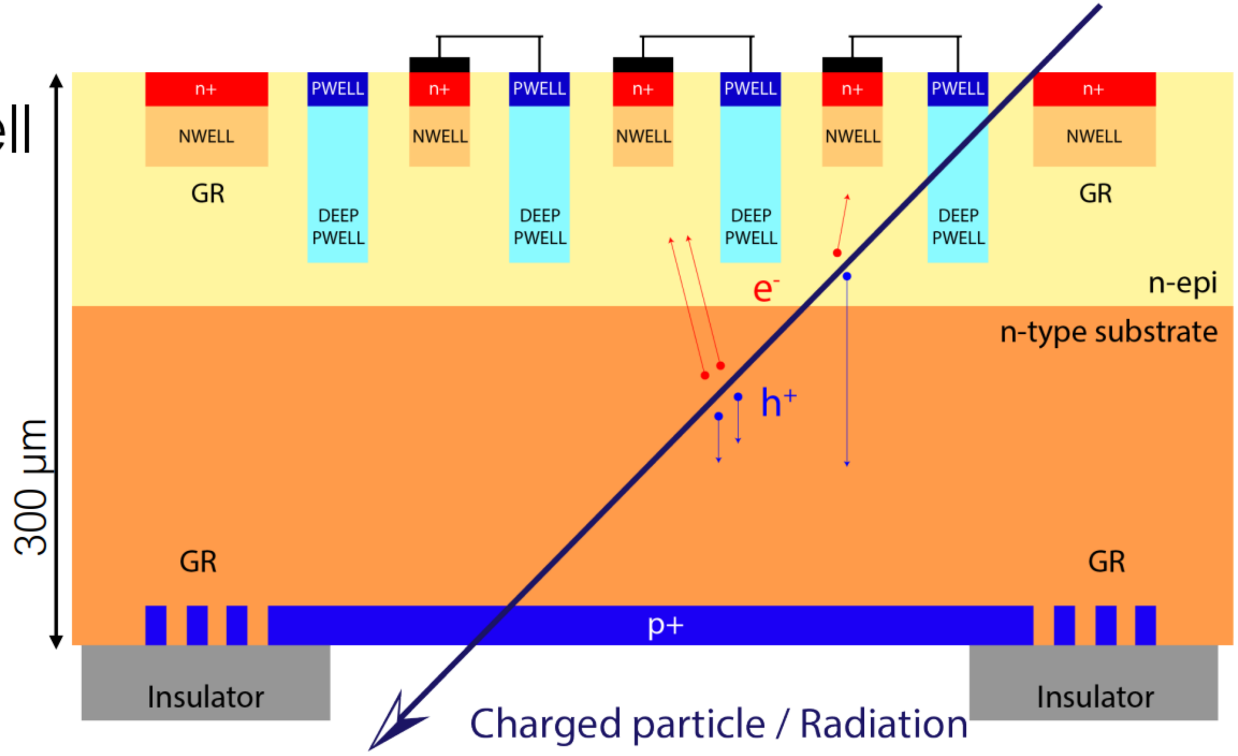


- N-well diode, p-type epitaxial layer (~25 μm) and substrate
- Diode size (2-3 μm) – very small than pixel size – low capacitance – high S/N
- Possible to reverse bias (up to -6 V)
- Drift e- reaching the collection diode induce a current signal at the input of transistors
- Deep PWELL shields NWELL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

FD-MAPS (ARCADIA) – full depletion design

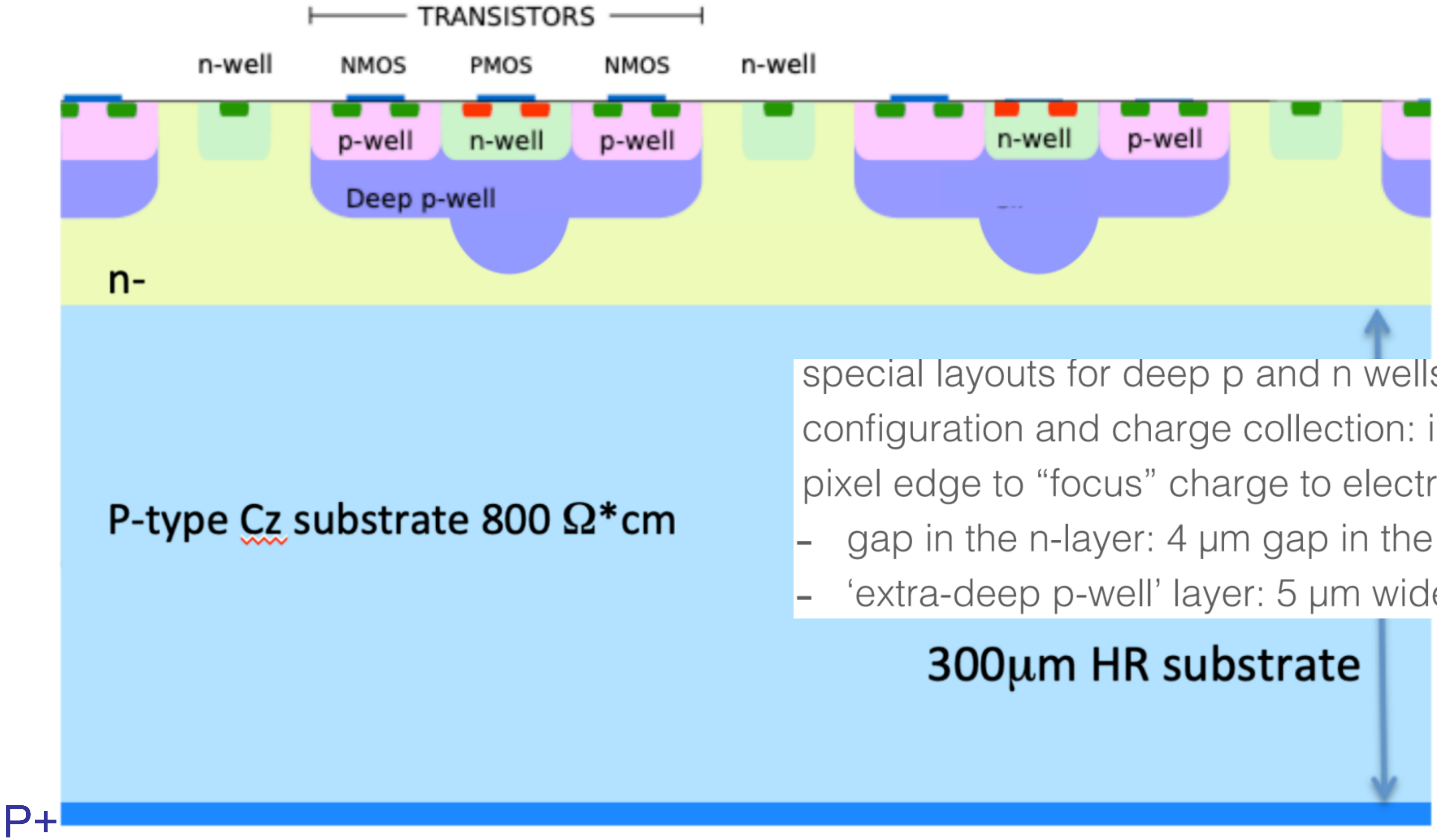
- Full depletion at -160 V @300 um Si, -40 V@100 um Si sensor thikness

  - 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

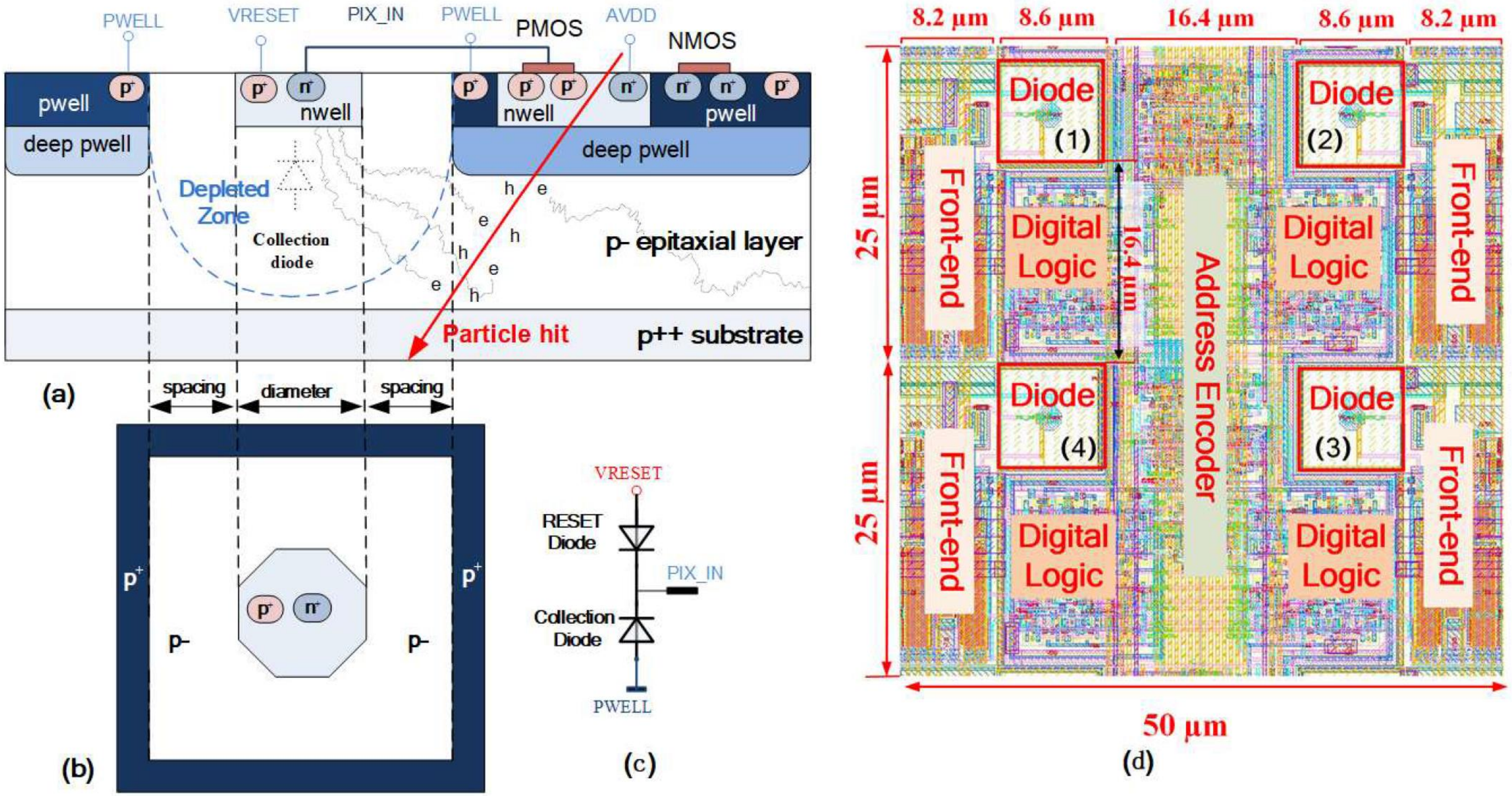


special layouts for deep p and n wells to optimize field configuration and charge collection: increase lateral field near pixel edge to “focus” charge to electrode:

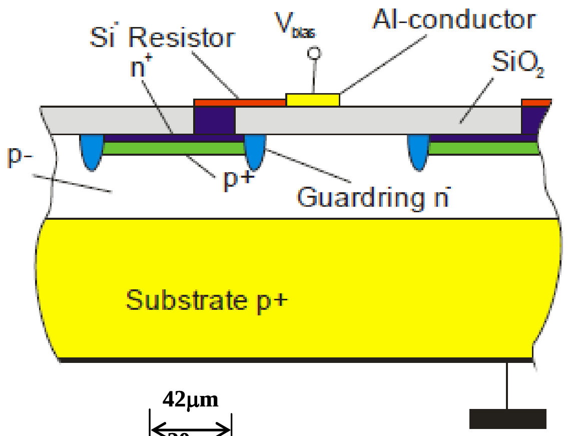
- gap in the n-layer: 4 μm gap in the low dose n-layer
- ‘extra-deep p-well’ layer: 5 μm wide additional p-well implant

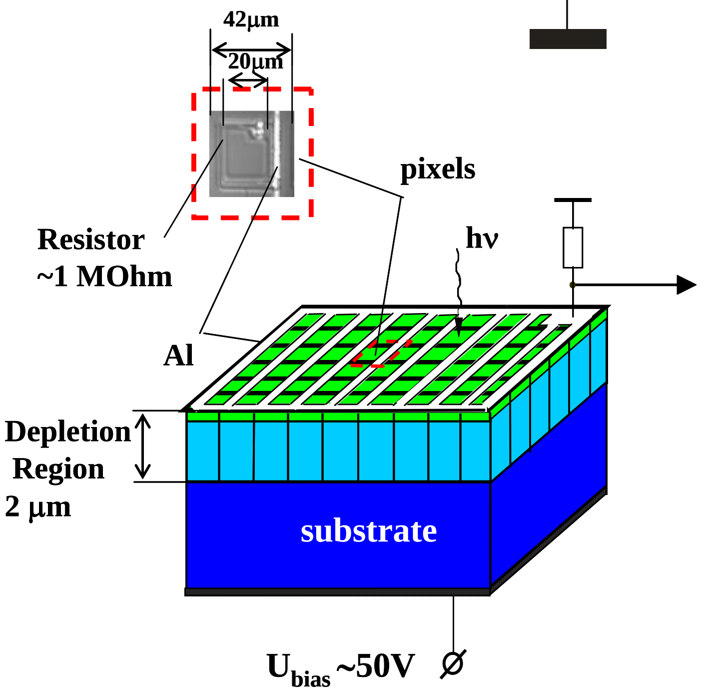
Reproduced in China: TaichuPix1 ≈ MAPS-ALPIDE

- Prototype 2022: Si-epi 25 um, pixel size 25 um, array 192×64 (~512×1024 to be in 2023)

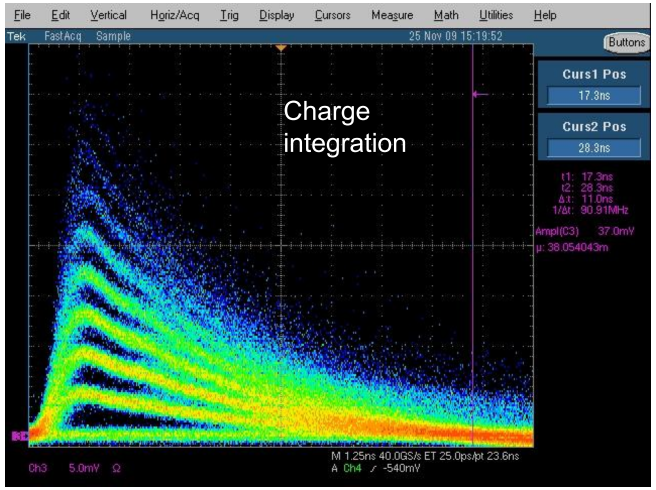


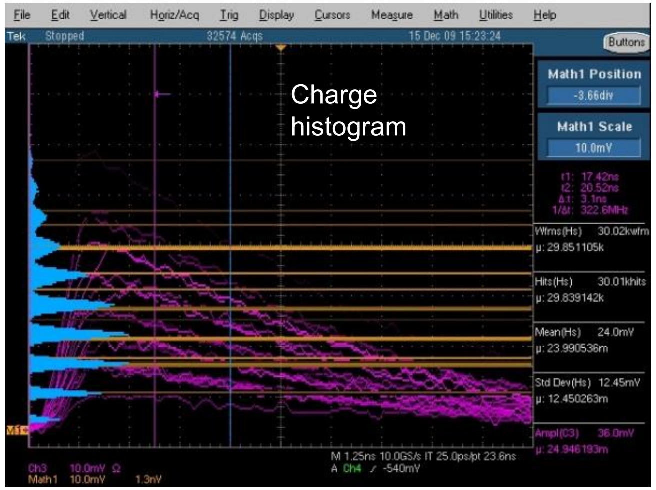
R&D on Silicon Photomultiplier (SiPM): basic studies (1980s, LPI), MRS APD (1990s, CPTA), SiPM (2000s, MEPhI)

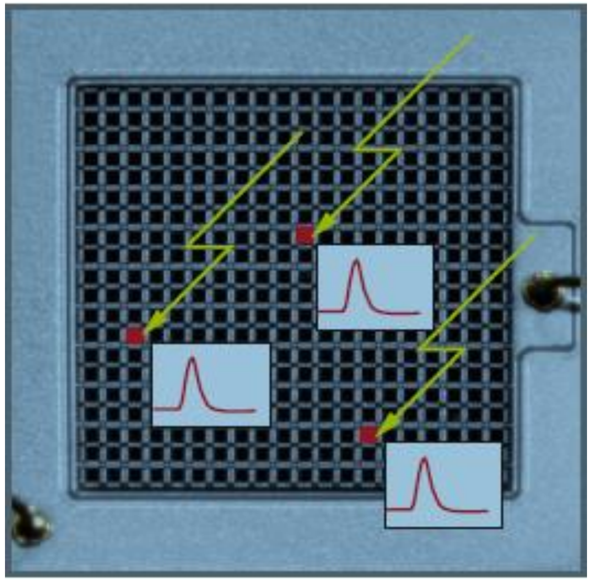


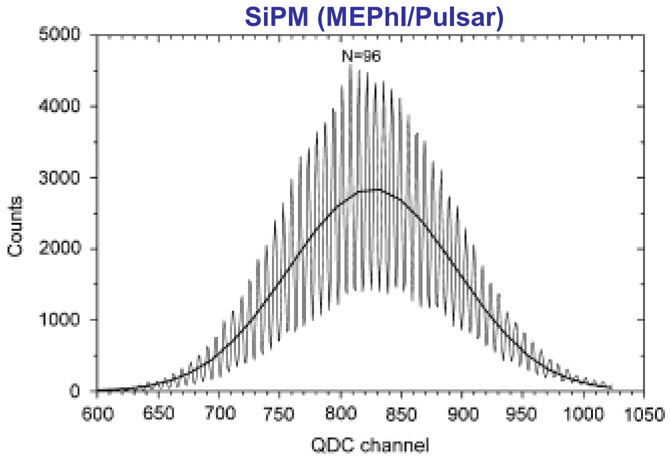


P. Buzhan, B. Dolgoshein et al, ICFA Instrum. Bull., 2001



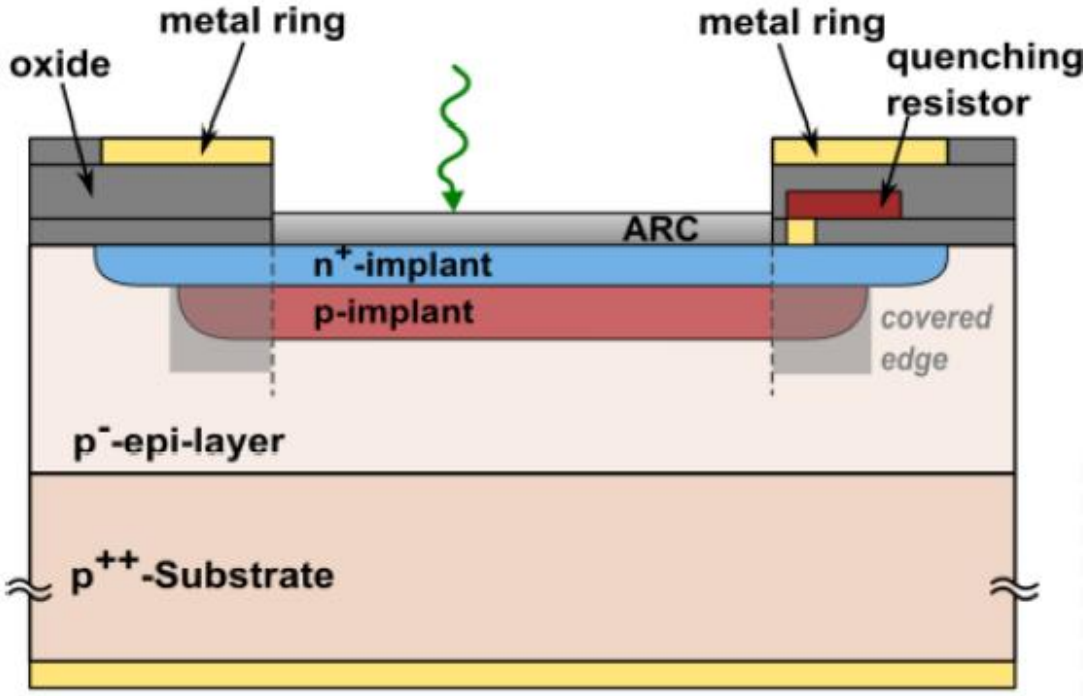




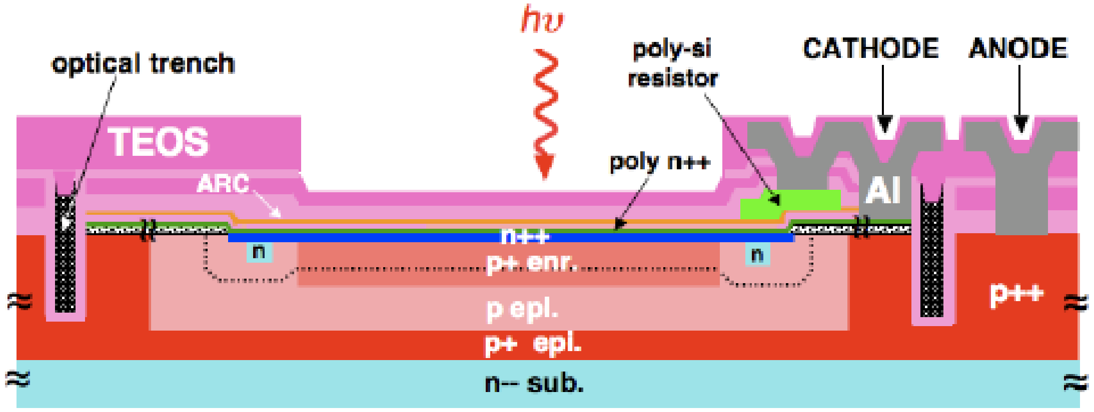


R. Mirzoyan et al., NDIP, 2008

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

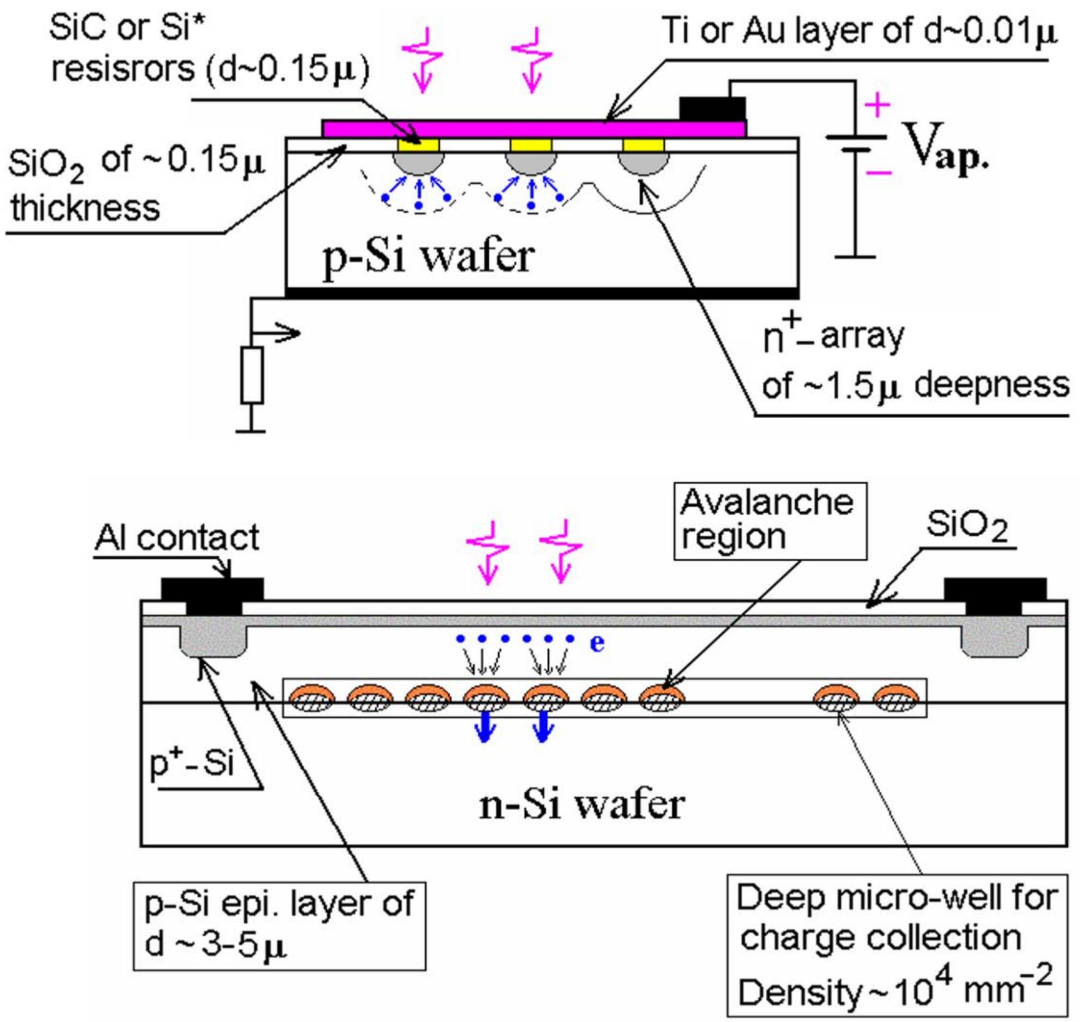


FBK

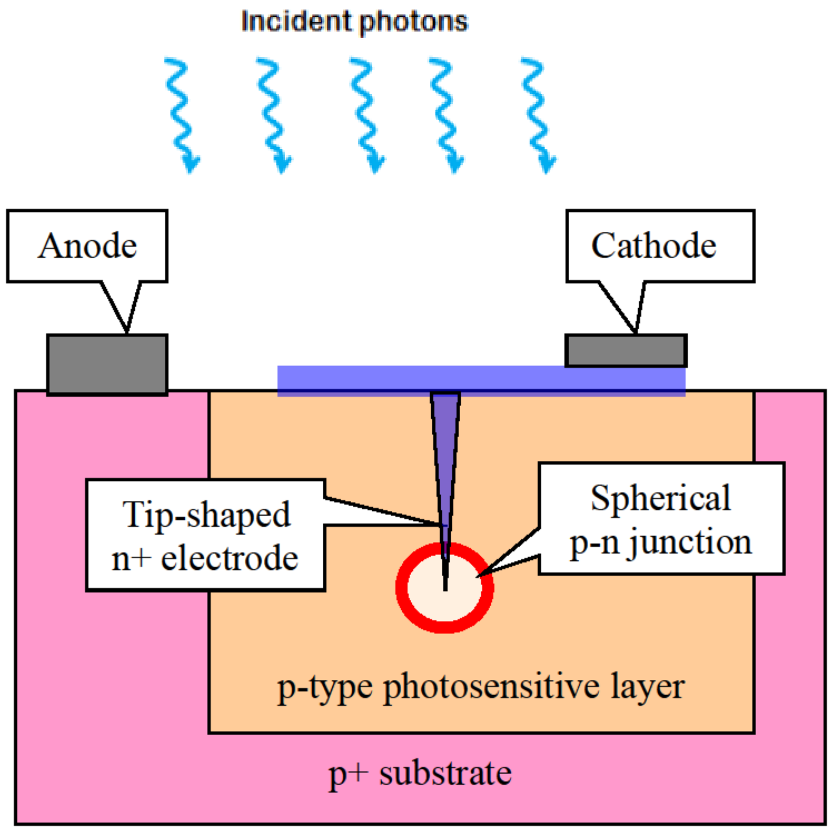


ST Microelectronics

Non-planar SiPM designs based on quasi-spherical p-n junctions: Metal-Resistor-Semiconductor APD, Micro-well APD, Tip APD



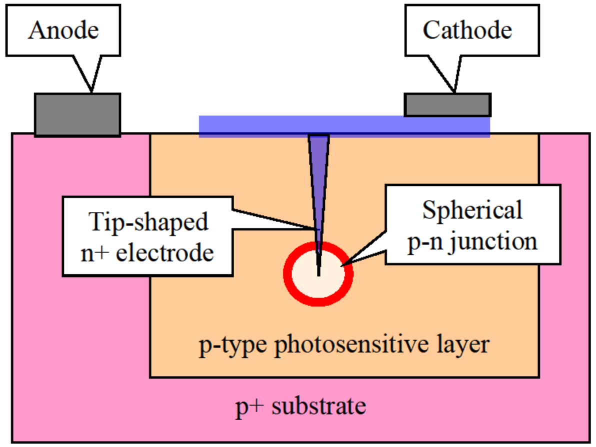
Sadygov, Z. Three Advanced Designs of Avalanche Micro-Pixel Photodiodes (NDIP 2005)

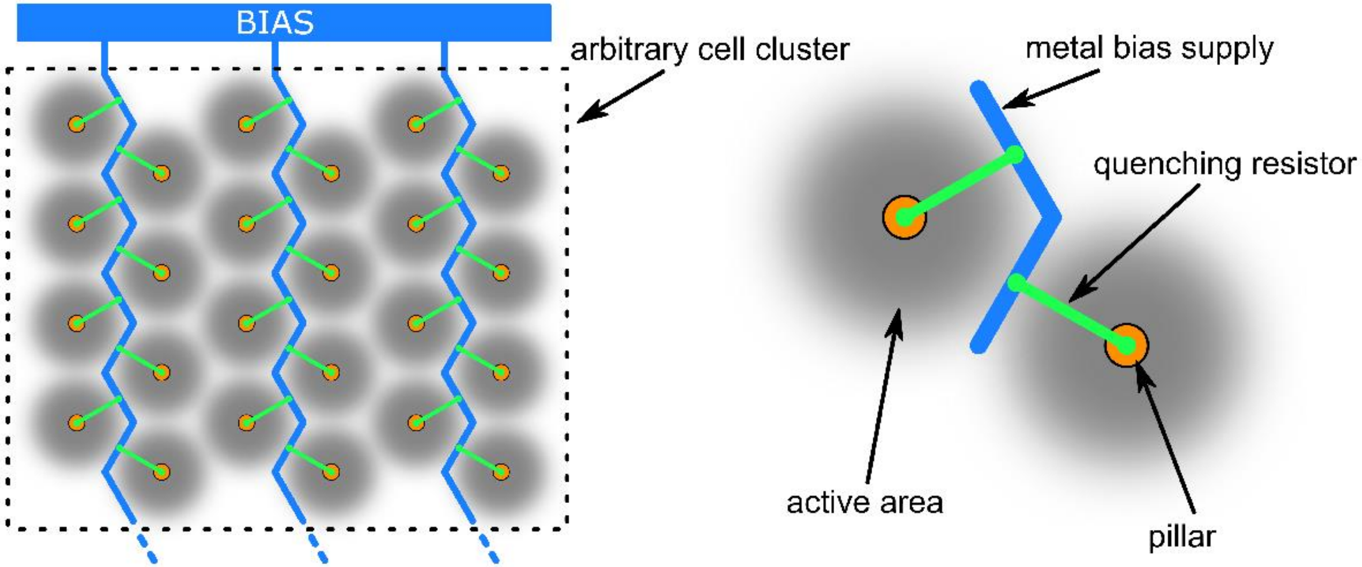


Vinogradov, S. Tip Avalanche Photodiode—A Spherical-Junction SiPM Concept (NIMA 2023)

Advantages and drawbacks of TAPD

- **Advantages**
  - High efficiency (no cell boundaries) => high PDE;
  - Low capacitance =>
    - — fast timing response, fast recovery ~ RC,
    - — low readout noise ~ kTC;
  - High Dynamic Range (small cells)
  - Low breakdown voltage =>
    - — low power consumption,
  - Low size of high electric field region =>
    - — low DCR by SHR (TBD)
    - — radiation hardness (TBD);
- **Drawbacks**
  - High sensitivity of Vbd to the tip radius
  - High risk of tunneling near the tip
  - Questionable reproducibility of the tips

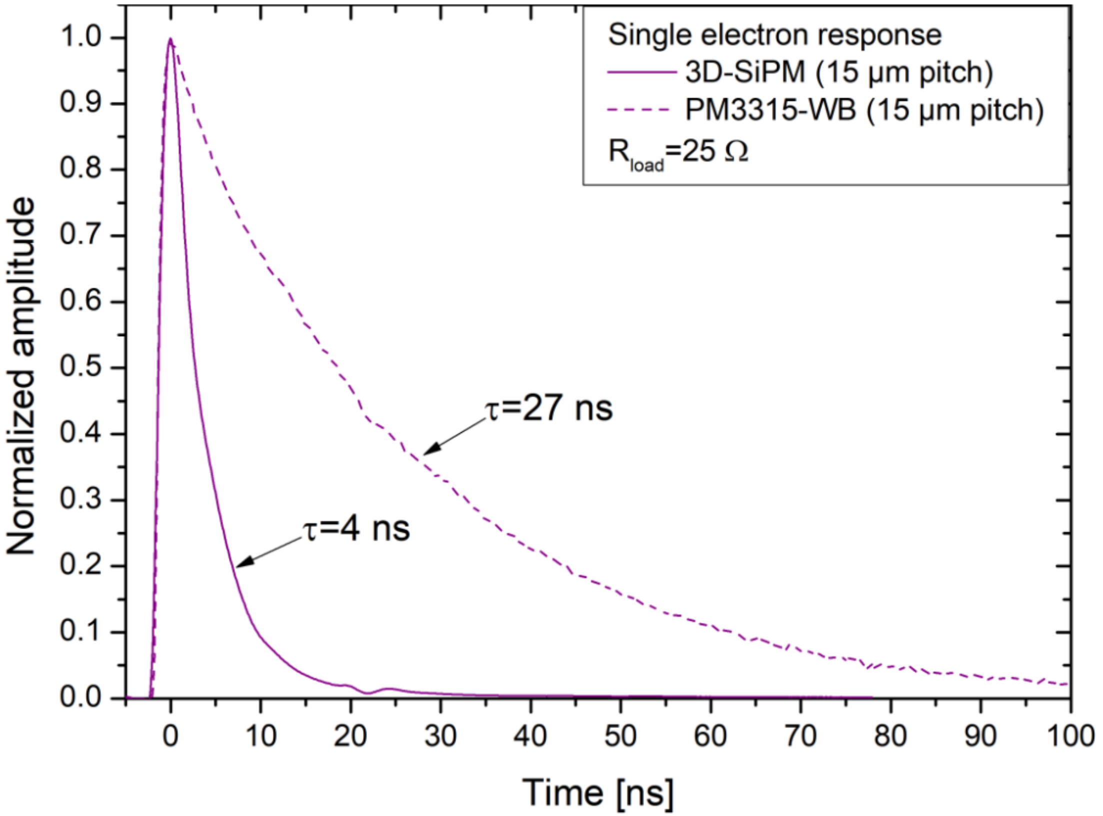


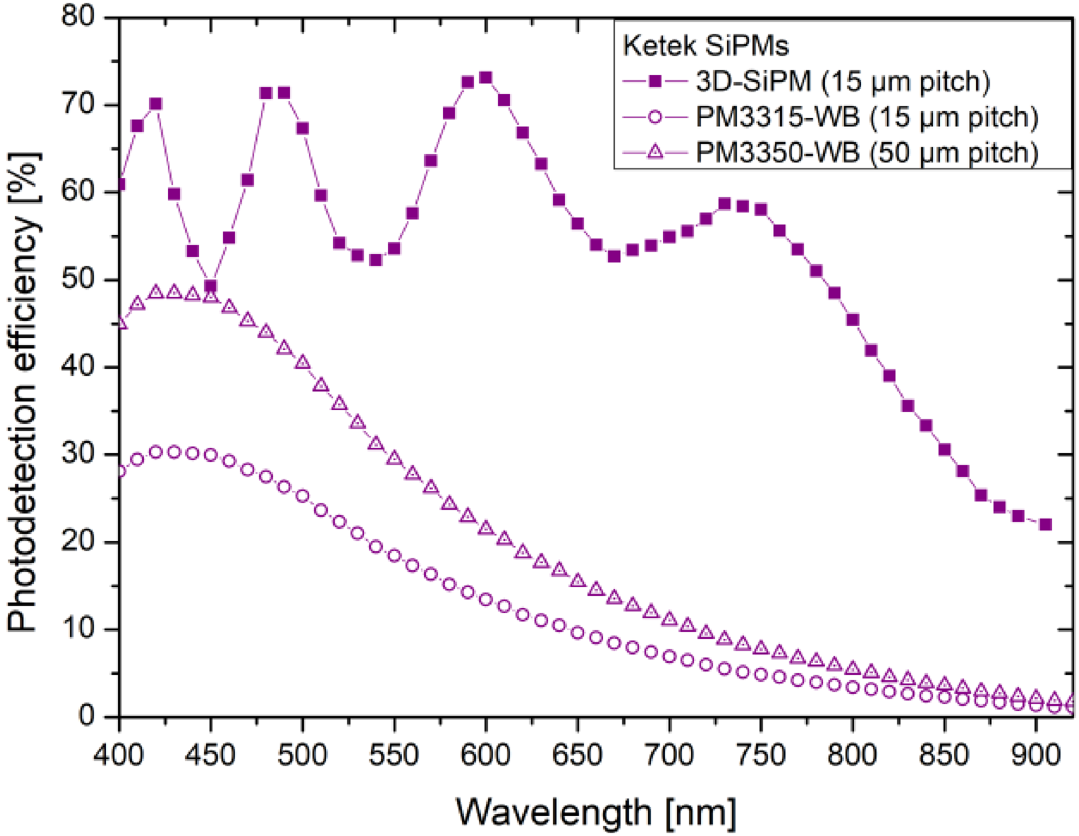


TAPD developed in collaboration with KETEK (2017 – 2020): record performance

- Single electron response time = **4 ns**
- Single cell recovery time = **4 ns**

- Max PDE = **73%** (608 nm)
- NIR PDE = **22%** (905 нм)
- Wide spectral range: PDE ≥ 50% (400 – 800 nm)

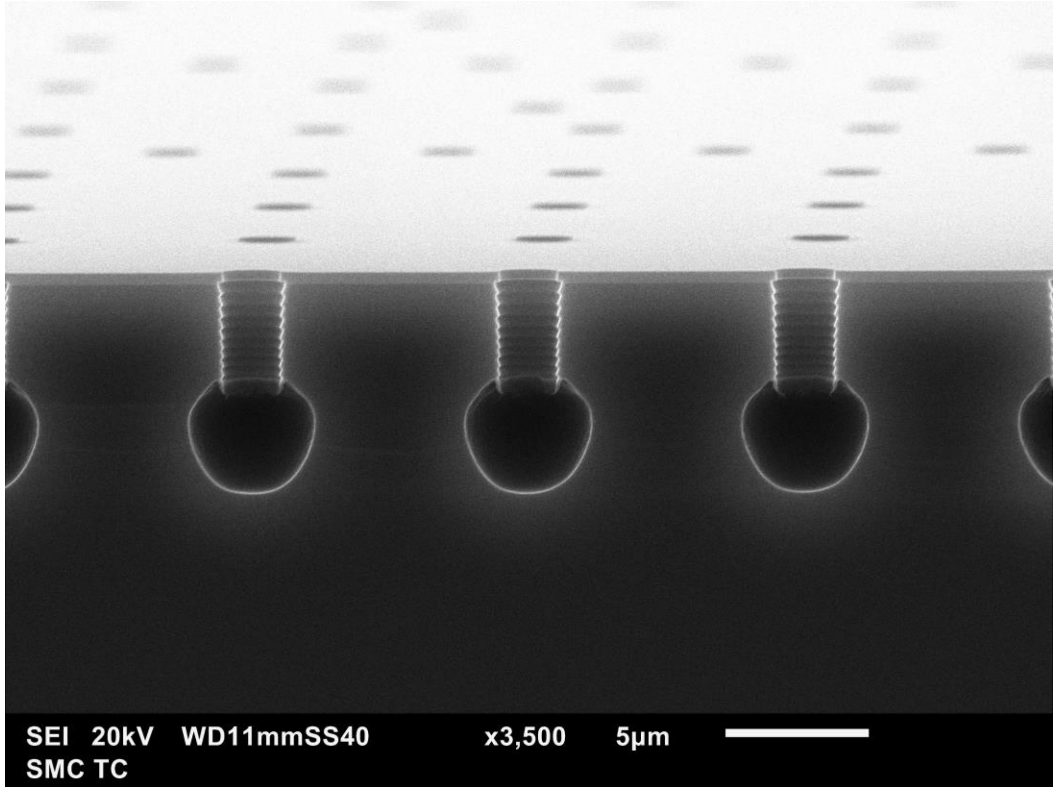


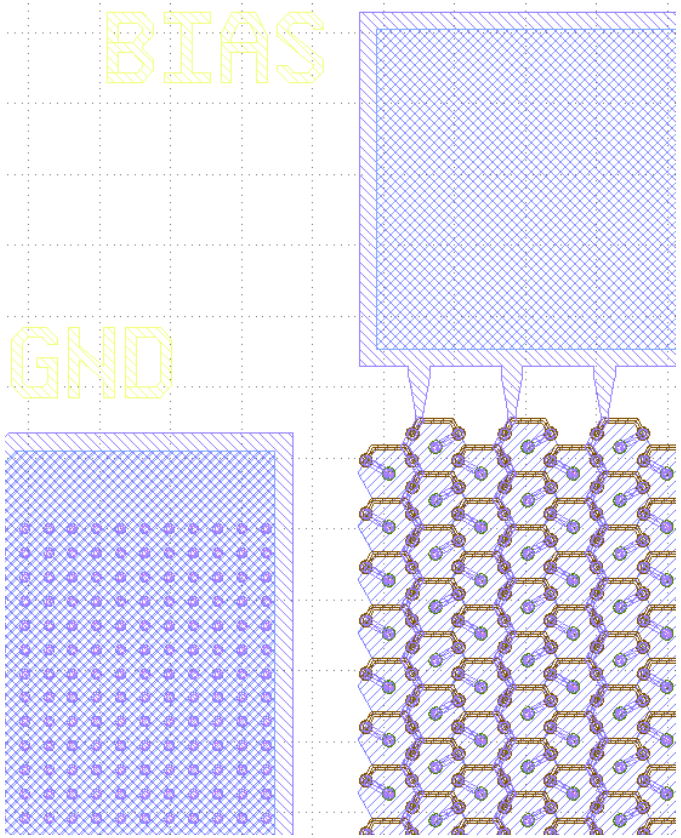


Engelmann, E.; Schmailzl, W.; Iskra, P.; Wiest, F.; Popova, E.; Vinogradov, S. Tip Avalanche Photodiode—A New Generation Silicon Photomultiplier Based on Non-Planar Technology. *IEEE Sens. J.* **2021**, *21*, 6024–6034, doi:10.1109/JSEN.2020.3041556.

Проект по разработке SiPM непланарной конструкции с МИЭТ

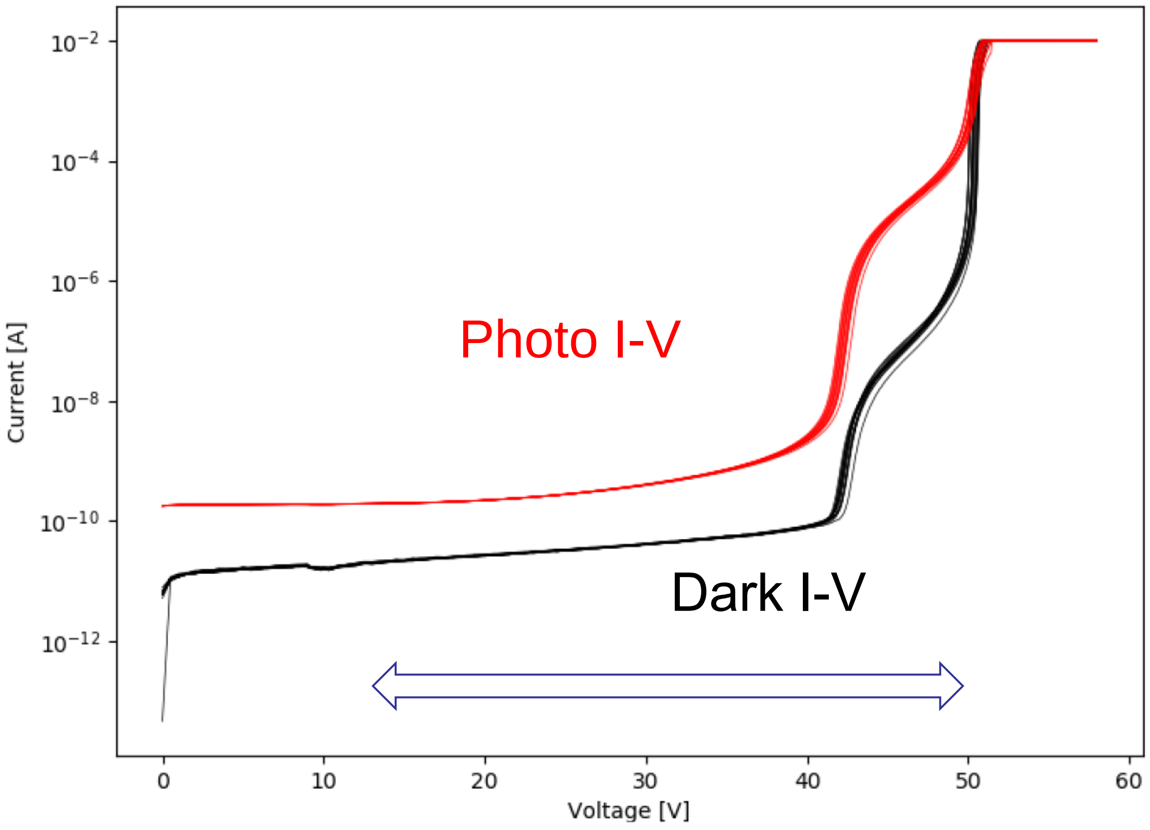
- Ведется НИОКР «Разработка нового типа кремниевых фотоумножителей непланарной конструкции»
  - Грант фонда содействия инновациям «Техностарт-1» на 2022 – 2023 гг.
  - На технологической базе ЦКП и ТЦ МИЭТ, гл. технолог А.А. Жуков
  - Разработаны ключевые элементы технологии, техпроцесс, фотошаблоны
  - Выпуск 1-й партии планируется летом 2023

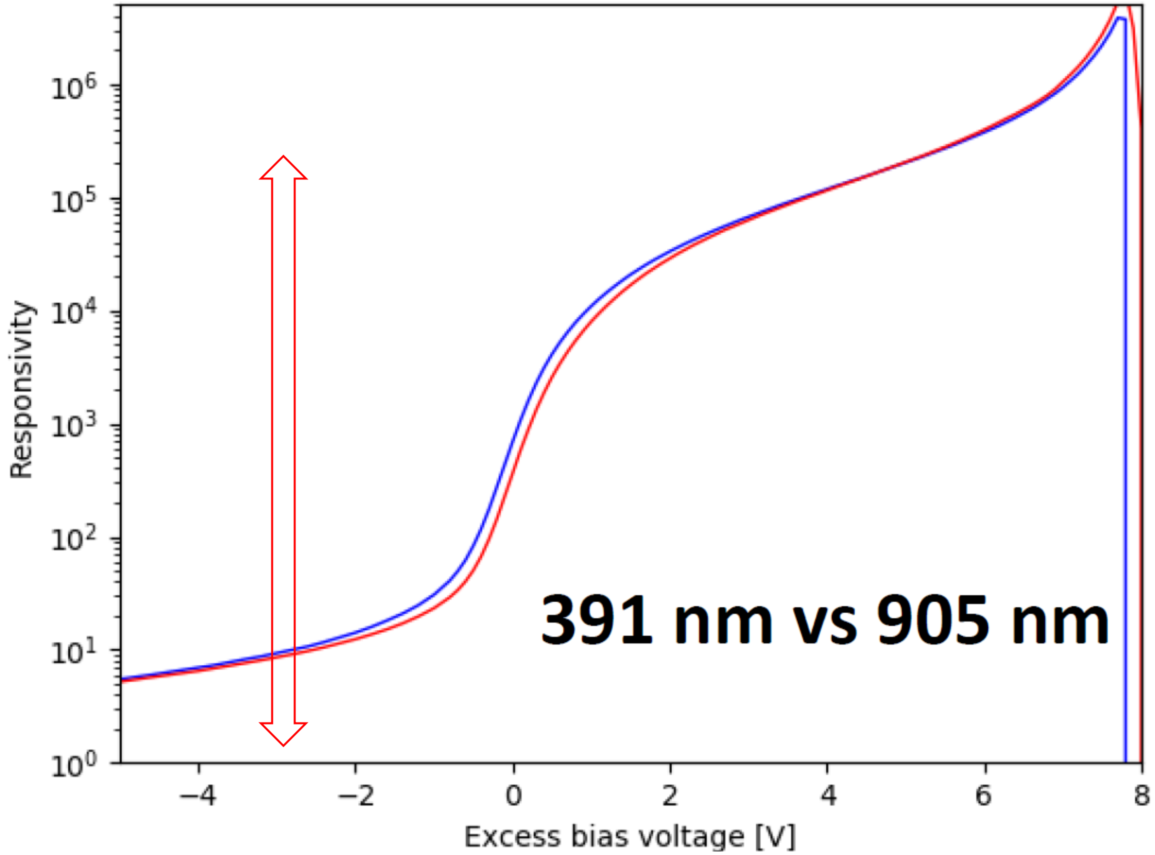




Адаптивный коэффициент умножения: 10 … 10^6 @ ΔU = 10 V

Gain ~ 10 @ U ~ 40 V, Idark ~ 40 pA/mm² .... Gain ~ 10^6 @ U ~ 50 V, I dark ~ 0.5 mA/mm²





Заключение

- Возможные конструкции непланарных SiPM + MAPS:
  - SiPM + MAPS-ALPIDE
  - SiPM + FD-MAPS
- Возможные преимущества конструкций:
  - Сенсор и активная электроника изолированы и независимы
  - Сенсор имеет минимальную ёмкость (сфера) и адаптивную чувствительность (лавина)
    — упрощение электроники (без усиления)
    — уменьшение толщины сенсора (меньше рассеяние)
- Возможность разработки и выпуска в Зеленограде - рассматривается
  - Сергей Викторович Змеев, МИЭТ
- Возможность заинтересованности BM@N – предполагается
  - Михаил Моисеевич Меркин, НИЯФ МГУ

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СПАСИБО ЗА ВНИМАНИЕ!

Вопросы?
Замечания?
Предложения?

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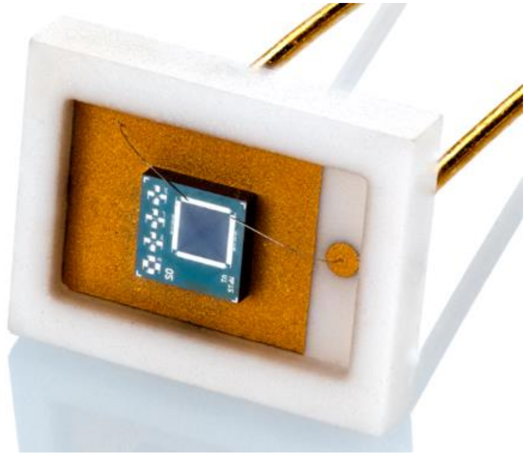
Разработка TAPD SiPM

- 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)

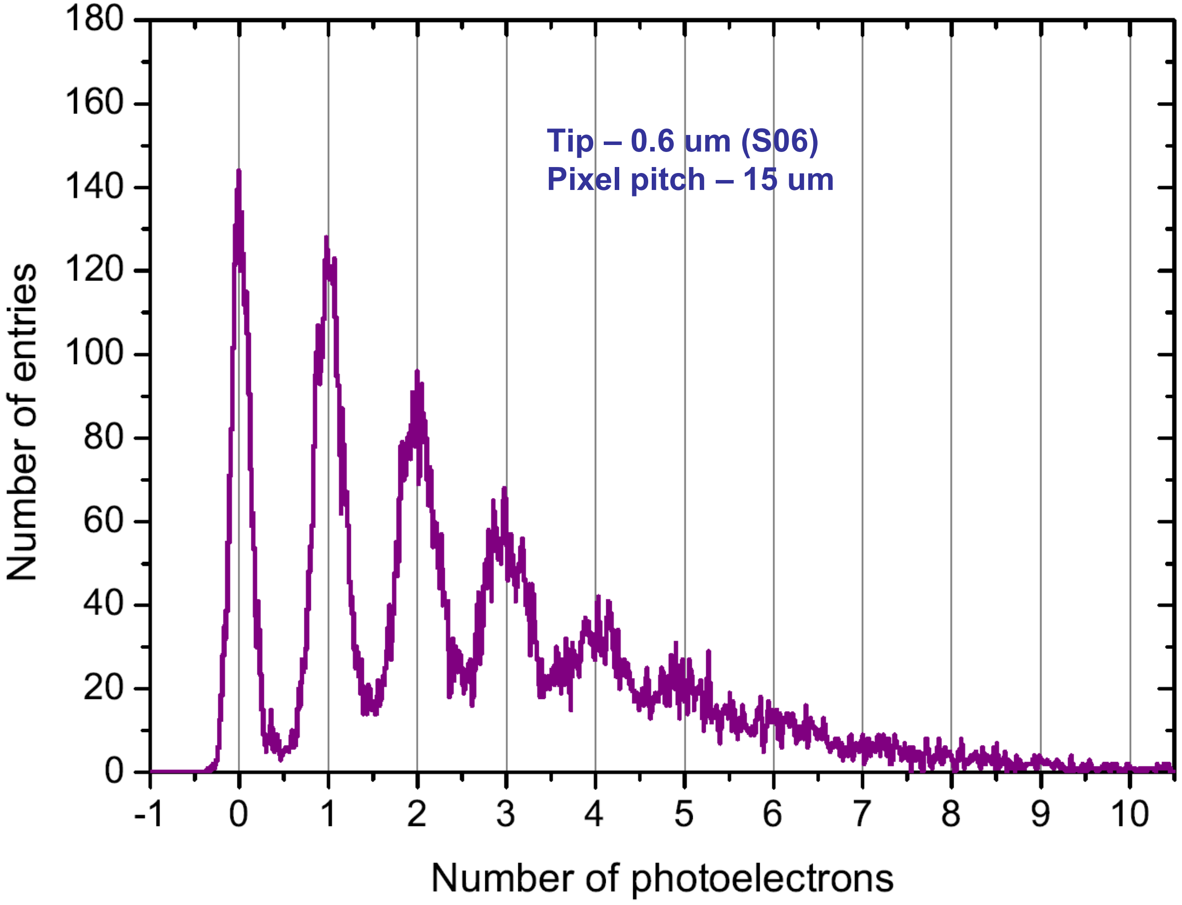
[1] E. Engelmann, W. Schmailzl, P. Iskra, F. Wiest, E. Popova, S. Vinogradov, “Tip Avalanche Photodiode - a new generation Silicon Photomultiplier based on non-planar technology”, *IEEE Sensors J.* (2020) Vol 21, No 5, 6024-6034

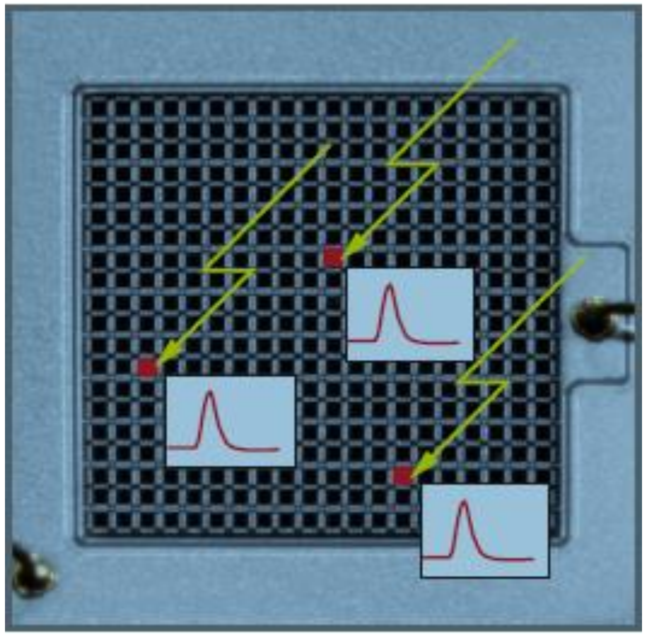
[2] S. Vinogradov, E. Popova, W. Schmailzl, E. Engelmann “Tip Avalanche Photodiode – a new wide spectral range Silicon Photomultiplier”, *“Radiation Detection Systems”,* Taylor & Francis (2021) Vol. 1, Ch. 9, 257–288

[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





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.

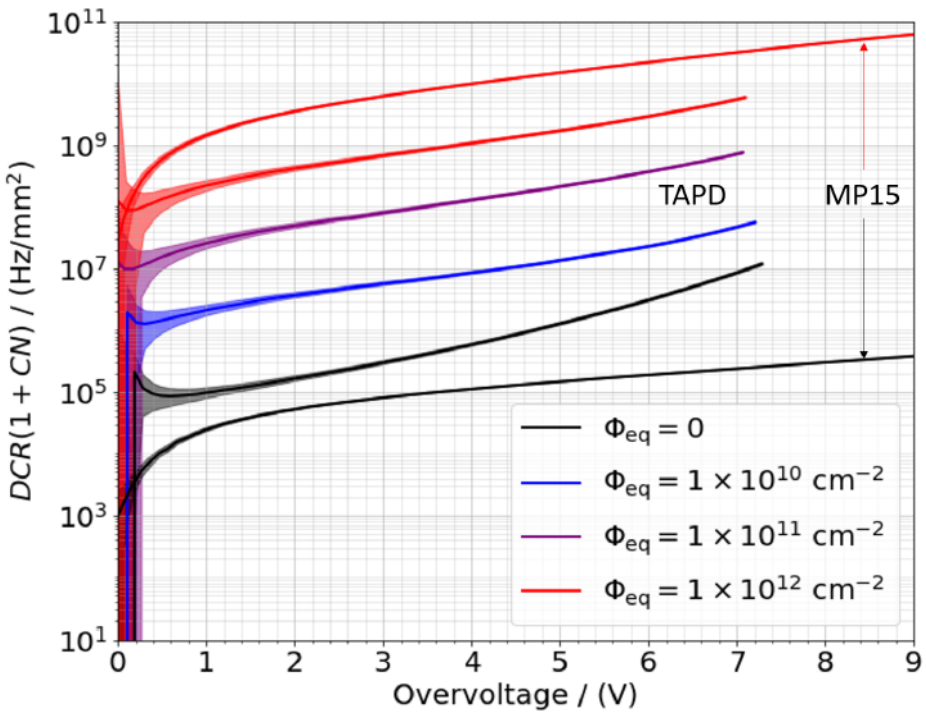


Figure 7: The dark count rate at 20 °C calculated using Eq. 7 normalized to a detector area of 1 mm^2 for the TAPD 0.6 µm and the MP15. The overvoltage is given as $V_{over} = V_{bias} - V_{BD}$.