# Novel Sensors for Particle Tracking

## 5 technologies

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**(part of this is derived from a contribution to the 2021 Snowmass Community Planning exercise)**


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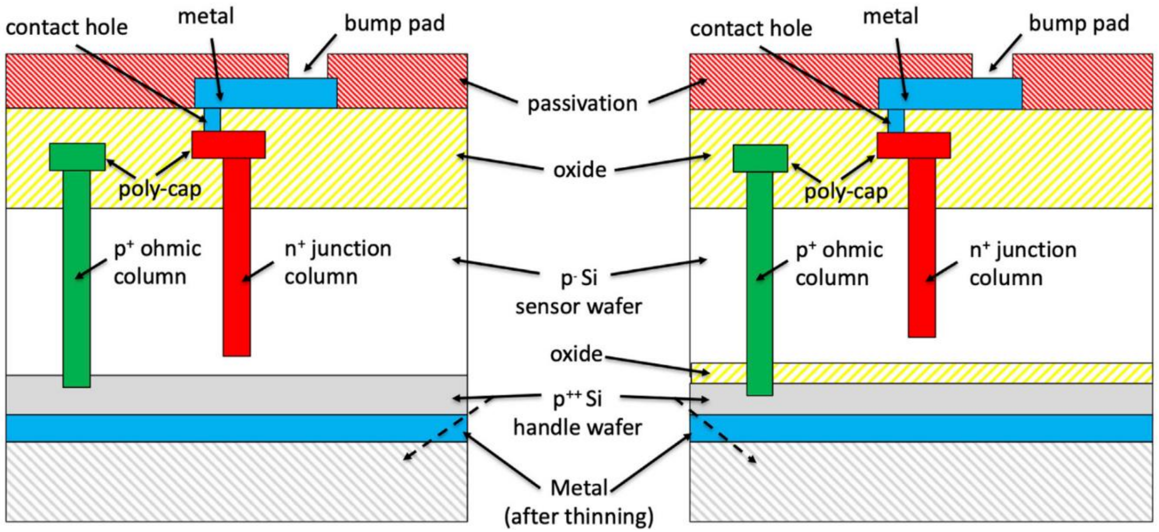
# Novel Sensors for Particle Tracking

## 3D pixels



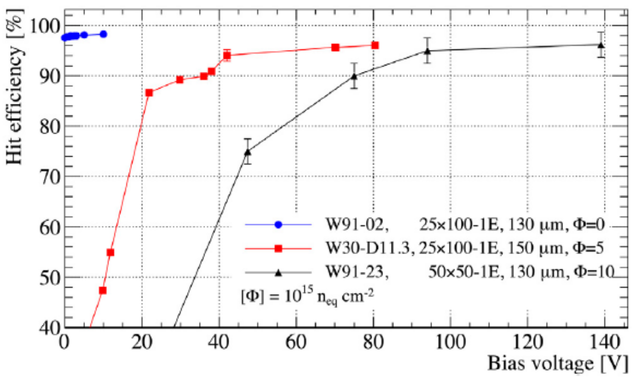




**FIGURE 10** | Hit efficiency as a function of the bias voltage for RD53A modules with FBK 3D sensors from second and third batches before and after irradiation. The modules are tuned to a mean threshold of 1 ke.

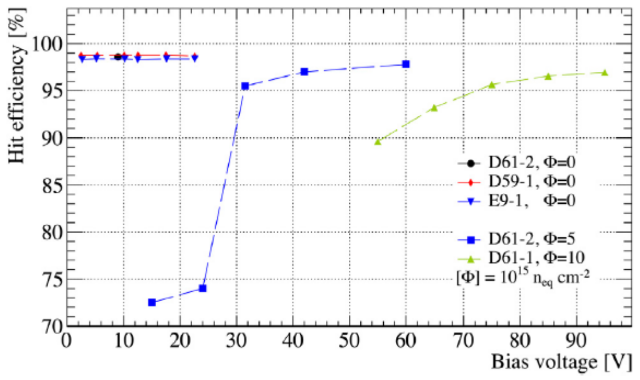



**FIGURE 11** | Hit efficiency as a function of the bias voltage for RD53A modules with SINTEF 3D sensors from run four before and after irradiation. The sensors have a 50 × 50–1E pixel geometry. For better visibility the data of D61-2 before irradiation (black circles) is shifted by −1 V.

### 3D pixels : introduced by S.Y Parker in 1997

Left from : Progress in 3D Silicon Radiation Detectors , Gian-Franco Dalla Betta and Marco Povoli, Frontiers in Physics, June 2022 | Volume 10 | Article 927690

Left bottom from: «Novel 3D Pixel Sensors for the Upgrade of the ATLAS Inner Tracker », Stefano Terzo, Maurizio Boscardin et al., Frontier In Physics, April 2021, Volume 9 , Article 624668 (Silicon 3D)

**The concept can be generalized to other material systems**

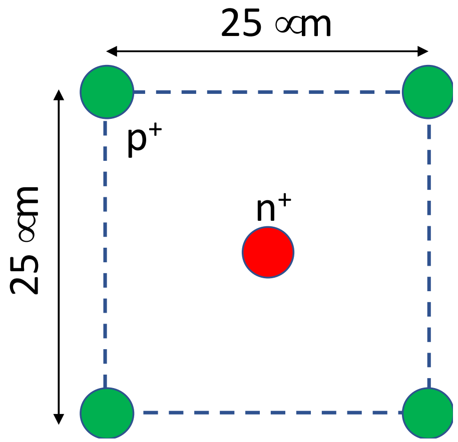
3D silicon pixels are optimized for radiation hardness with silicon process compatibility

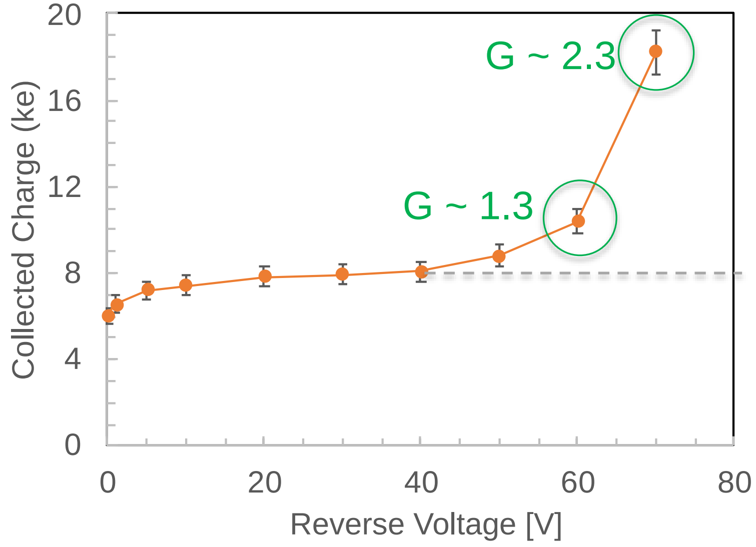
- Lc = distance between the electrodes
- Ld is the mean drift length for carriers before trapping
- $1/Ld = 1/Ld0 + K\Phi$ , with $\Phi$ the incident particle integrated flux. The degradation parameter K empirically depends on the material , the nature of the particles and other conditions , it reflects the defect introduction rate.
- K is different from holes to electrons. Nt=K' F , were Nt is the trap concentration.
- In this case Lc is much lower than the thickness of the pixels , so we have a number of generated carriers equal to : Nc ~ Thickness , we can set Lc so that Lc < Ld
- Improving CCE charge collection efficiency by acting on the aspect ratio which is not possible using a planar configuration Lc/Thickness

# Novel Sensors for Particle Tracking

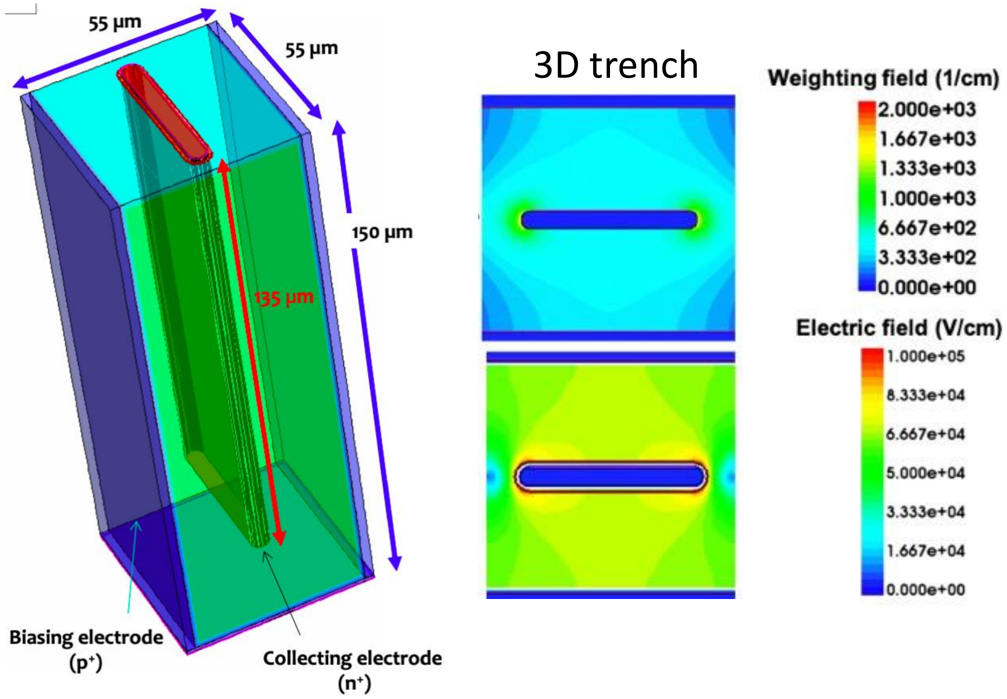
## 3D silicon sensors (credit G.F. Dalla Betta)

- 3D sensors are the most radiation-hard silicon detectors
- First installed in the ATLAS IBL, they will equip the innermost tracking layers of ATLAS and CMS detectors at HL-LHC
- They are efficient up to very large irradiation fluences at low voltage (hence low power dissipation)
- For future applications, advanced designs should be optimized




- Very small-pitch 3D sensors can effectively counteract charge trapping and yield moderate charge multiplication at relatively low voltage even before irradiation




- 3D sensors with trenched electrodes offer uniform electric and weighting field distributions for enhanced timing performance (~11 ps time resolution recently proved in samples irradiated at $2.5 \times 10^{16}$ $n_{eq}/cm^2$)

G.-F. Dalla Betta et al. , IEEE NSS 2019, N30-02



R. Mendicino et al, NIMA 927 (2019) 24

# Novel Sensors for Particle Tracking

## 3D diamond pixels

**Diamond detectors : within the framework of RD 42 (CERN) since 1994**

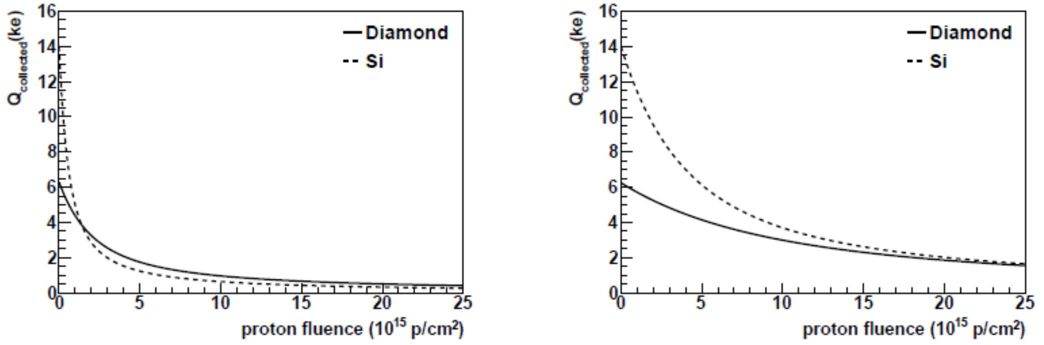
- **3D diamond pixels is the evolution**
- **Electrodes fabricated by graphisation using femtosecond lasers**
- **Conductive electrodes are obtained**
- **Optimized for Radiation Hardness , with improved time resolution**

See, Lucio Anderlini et al., Fabrication and Characterisation of 3D Diamond Pixel Detectors With Timing Capabilities, Frontiers in Physics, November 2020 | Volume 8 | Article 589844

Figures and tables: derived from : J W Tsung *et al* 2012 *JINST* **7** P09009

| | 25 MeV protons | 24 GeV protons |
|---|---|---|
| $k_{\text{diamond}}$ | $3.02^{+0.42}_{-0.36}$ | $0.69^{+0.14}_{-0.17}$ |
| $k_{Si}$ | $10.89^{+1.79}_{-1.79}$ | $1.60^{+0.38}_{-0.38}$ |

J W Tsung *et al* 2012 *JINST* **7** P09009




(a) 25 MeV proton irradiation. (b) 24 GeV proton irradiation.

$$\lambda_{e/h} = v_e \tau_e + v_h \tau_h \,,$$

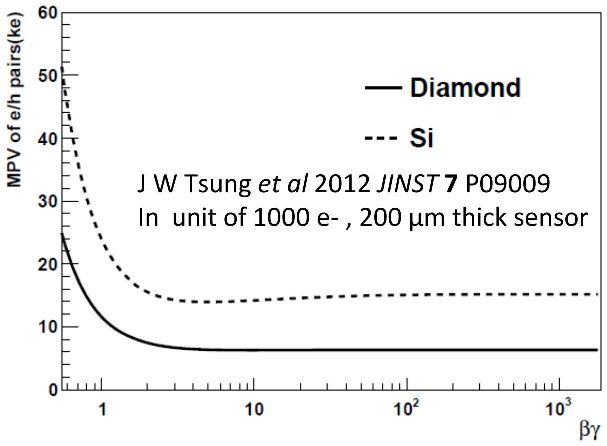
$$\frac{CCD}{d} = \frac{Q_{\text{collected}}}{Q_{\text{ionized}}} = \frac{\lambda_{e/h}}{d} \cdot \left[1 - \frac{\lambda_{e/h}}{d}\left(1 - e^{-\frac{d}{\lambda_{e/h}}}\right)\right] + (e \leftrightarrow h)\,.$$

Charge Collection Distance,
d : thickness of the detector

More generally the free drift length is defined by :
$1/\lambda = \Sigma$ Nt $\sigma$t where $\sigma$t is the capture cross section of the trap and Nt is its concentration

- Parameter : Si Diamond
- $\delta$ : 0.95 eV 1.84 eV
- I 174 eV 81 eV
- wi : 3.61 eV 13.1 eV
- Eg 1.1 eV 5.5 eV
- ni 1ᵉ10 cm-3 1ᵉ-27 cm-3
- Resistivity (I) $3.2\cdot10^5\Omega\cdot$cm $> 10^{42}\Omega\cdot$cm
- Similar effective masses.

Mot of these are extracted from: J W Tsung *et al* 2012 *JINST* **7** P09009
I and d are necessary to calculate the energy deposit in the layer
I= mean excitation energy



# Novel Sensors for Particle Tracking

## DoTPiX

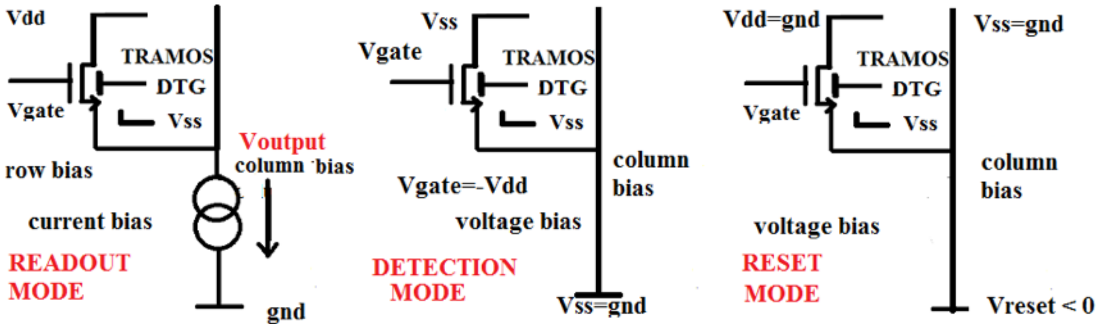



Figure 1: The operational principle of the DoTPiX structure within a pixel array (row and column); the array readout is similar to those of CMOS sensors, with detection, readout, and reset modes. The end of column is connected to a preamplifier, for digital or hit/no hit readout mode. Power dissipation occurs only during readout, due to the biasing scheme. In detection mode, Vgate < Vdrain and Vsource, to collect holes in the buried gate.

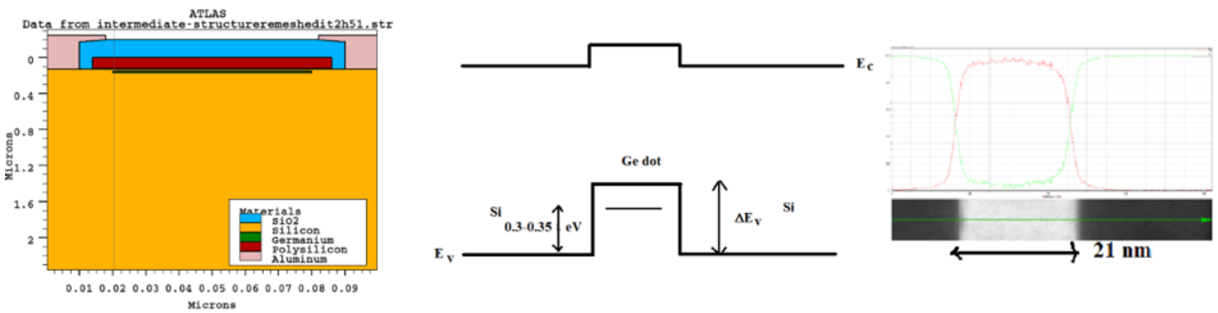
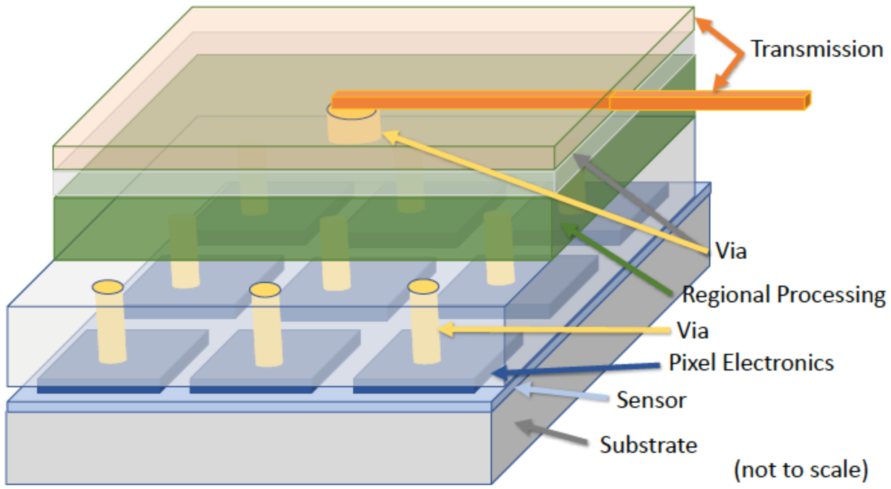


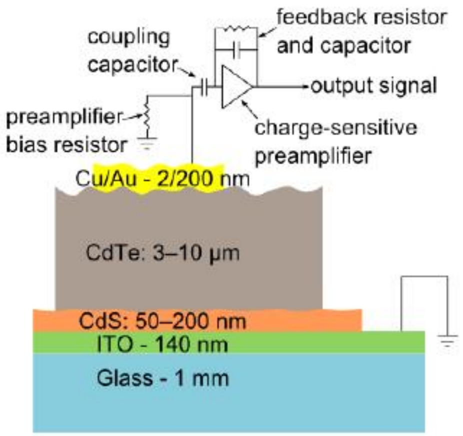

Figure 2: For the DoTPiX project: (left) the TCAD simulation structure; (center) Ge hole quantum well, and (right) results of the processing (on a full wafer), the deposition of a thin Ge layer. This results from electron microscopy, STEM Energy Dispersive X Spectrometry (STEM-EDX).The Ge concentration reaches 95 percent in the 21 nm thick buried layer.The wafer prepared this way should be CMOS compatible with some mitigation of the thermal budget of the process.

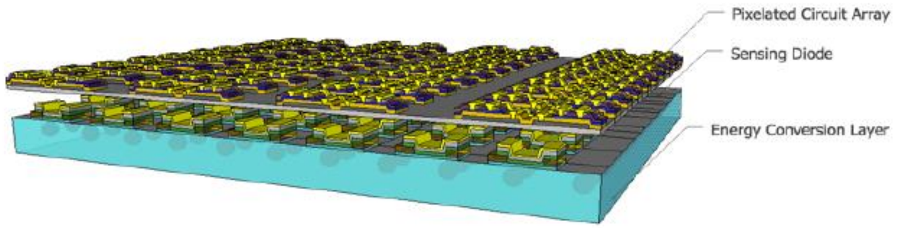
- **Proposed in 2017**, derived from another structure (TRAMOS 2010) : goal ultimate point to point spatial resolution ( ~ 1µm)
- See : N. T. Fourches, "Ultimate Pixel Based on a Single Transistor With Deep Trapping Gate", IEEE Trans. on Electron Devices 64, pp. 1619-1623 (2017). https://doi.org-98/10.1109/TED.2017.2670681.
- Accumulation of holes in the buried Ge layer , modulation of the source-drain current in read mode. No power dissipated in detection mode
- Up to now , simulations (TCAD) have shown the operational capabilities of the device. UHV-CVD growth (C2N) is now under way to obtain a Si/Ge On Silicon structure , and with some CMOS similar processing a testable device. Thermal budget is one of the key parameter.
- GEANT4 simulations have shown that for thin devices one micron squared pixels are close to the optimum.

# Novel Sensors for Particle Tracking

## Thin Film detectors




**From : Potential of Thin Films for use in Charged Particle Tracking Detectors, J. Metcalfe et al.**
**https://doi.org/10.48550/arXiv.1411.1794**

- Optimized for cost effective large area, and material choice
- Flexible substrate is one of the objectives
- Use material deposition techniques and growth with a large choice of materials

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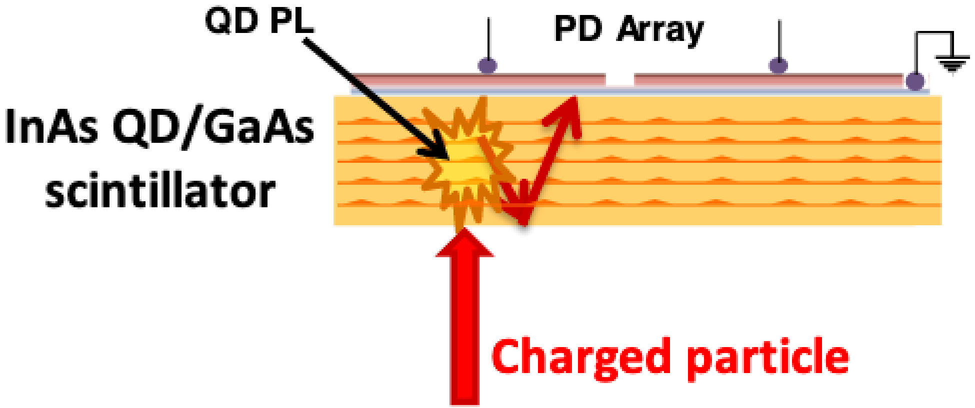
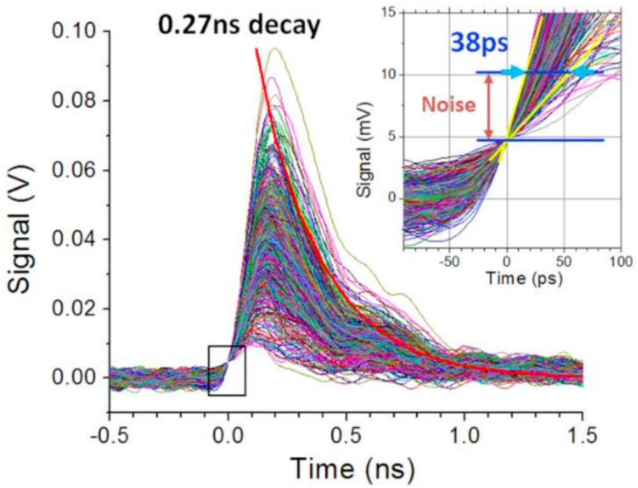
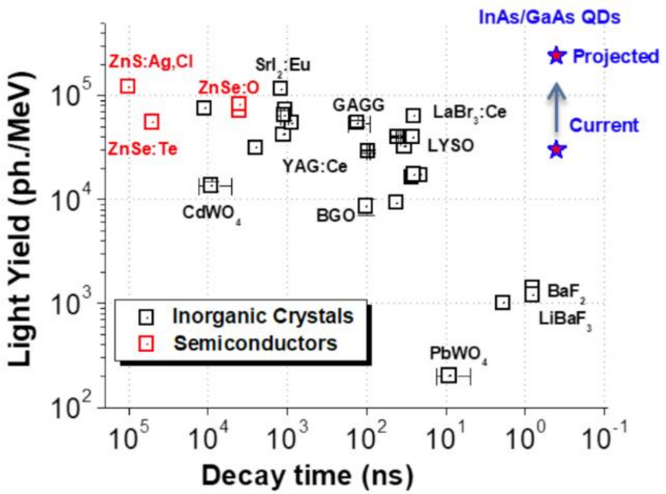
## Scintillating Quantum Dots in GaAs for Charged Particle Detection




- Optimized for timing measurements
- High granularity
- Use of GaAs electronic on the same substrate
- See : S. Oktyabrsky et al., Integrated semiconductor quantum dot scintillation detector: Ultimate limit for speed and light yield," IEEE Trans. Nucl. Sci. 63 (2016) 656-663.

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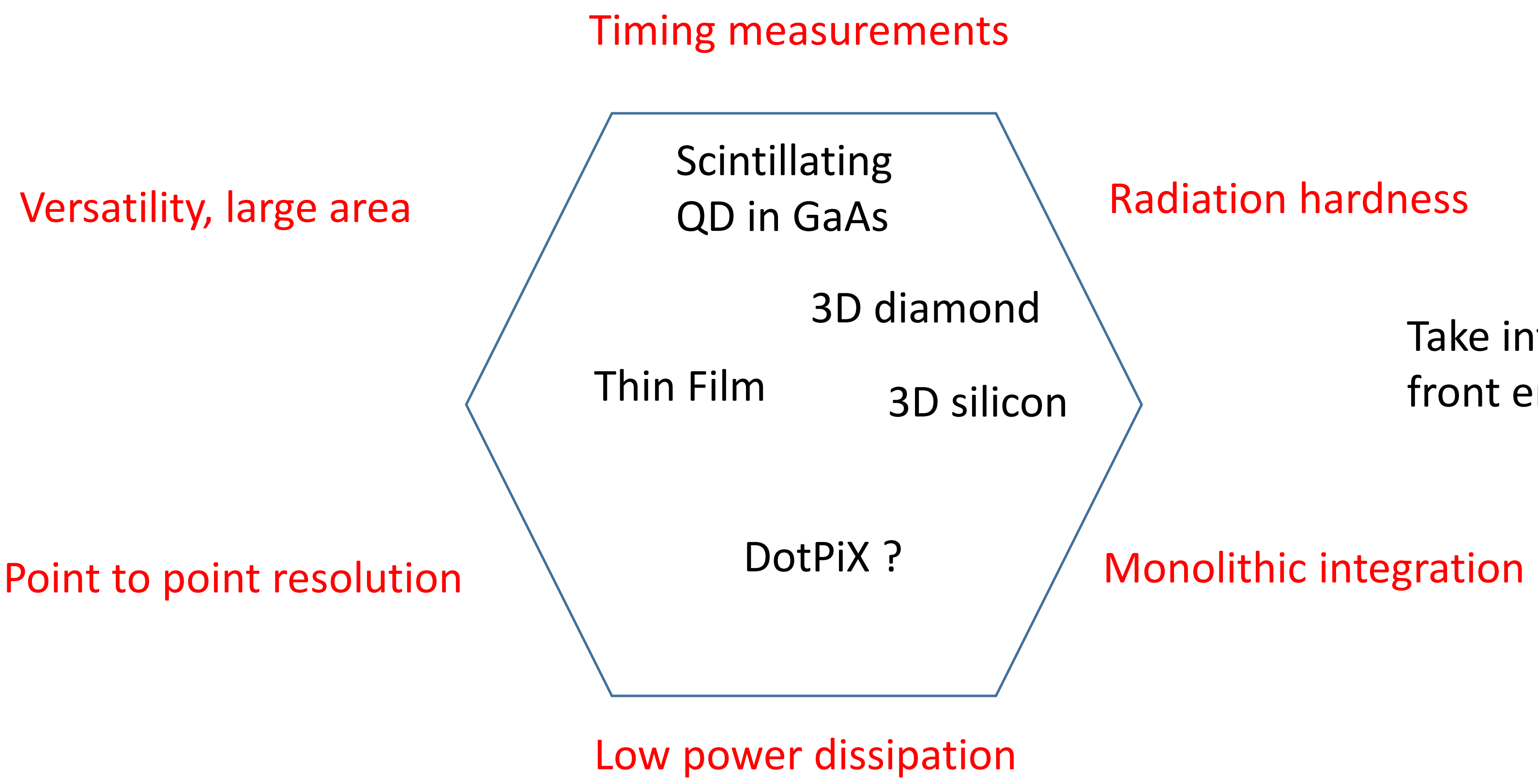
The optimisation diagram …




Take into consideration the very front end_ µelectronics readout

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Thank you for your attention