DEVICES BASED ON 2D MATERIALS FOR ON-CHIP AMPLIFICATION OF IONIZATION CHARGES

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ABSTRACT

The aim of this work is to explore the applications of 2D materials to high energy particles detectors.

- Many detectors based on 2D materials have been proposed in the past years, due to intriguing electrical and optical properties.
- Typically direct absorption of radiation by the thin film to detect low-energy radiation (IR-UV).

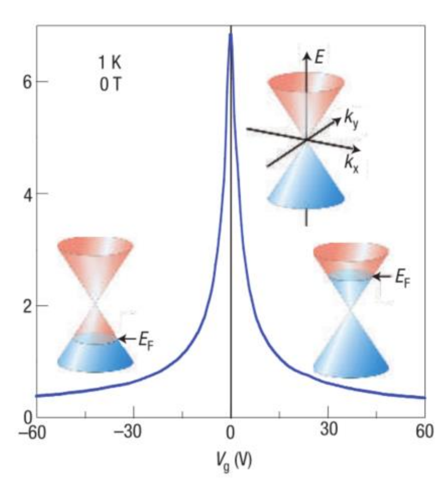
Another application could be in the fabrication of charged-particles pixel detectors. Possible advantages include:

- **Simpler fabrication** process if compared to semi-monolithic devices like DEPFETs.
- **Built-in pre-amplification** of the pixel signal, thus achieving better detection performance in terms of **higher SNR**

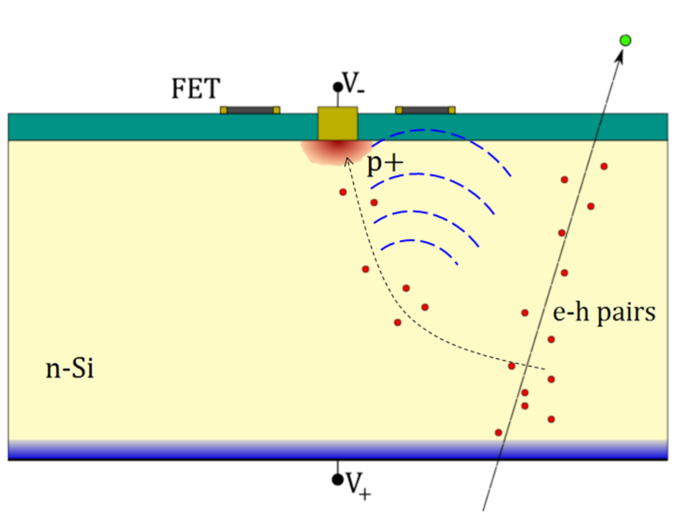
DETECTION PRINCIPLE

The detector is based on the electrical **resistivity modulation** due to the **field-effect in a 2D material channel**.
The device is composed of a reverse-biased high-resistivity Si substrate with a thin SiO_2 layer on top. On the oxide there is a 2D-material based, which constitutes the sensing element.

When a particle hits the device, e-h drift towards the ends of the sensor. The field generated by the ionization charges causes a shift in the Fermi level of the 2D channel, leading to a variation of its conductivity. Keeping a constant source-drain bias, this results in a **modulation of the output current of the device**.



DETECTOR SIMULATIONS

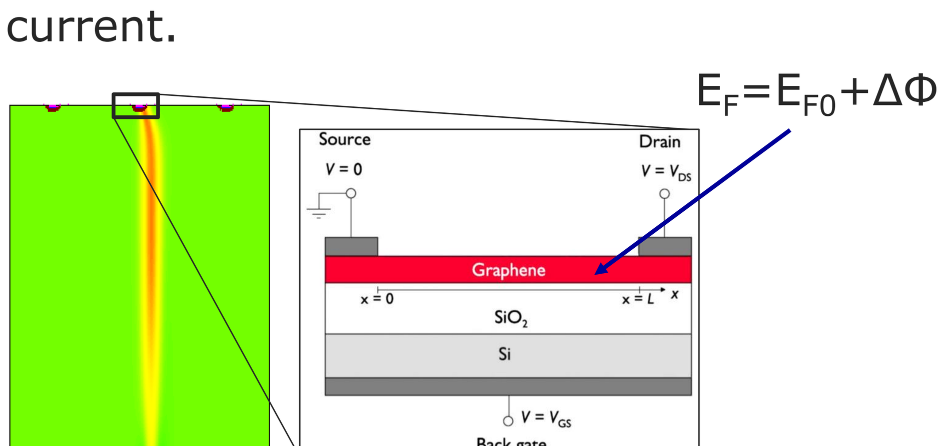


Several architectures were explored, highlighting important design issues:

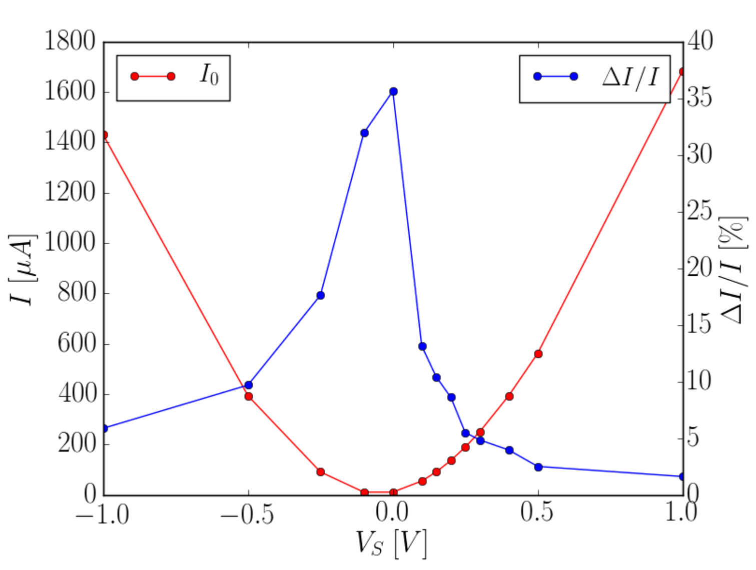
- Need for depleted/insulating substrate to have strong signal and fast response
- Polarization electrodes must be far from the sensing element to avoid field screening
- Importance of the initial Fermi level position, to be set using source, drain, top-gate voltages

Possible performance of the proposed devices was evaluated using **Synopsys Sentaurus** and **NanoTCAD ViDES**.

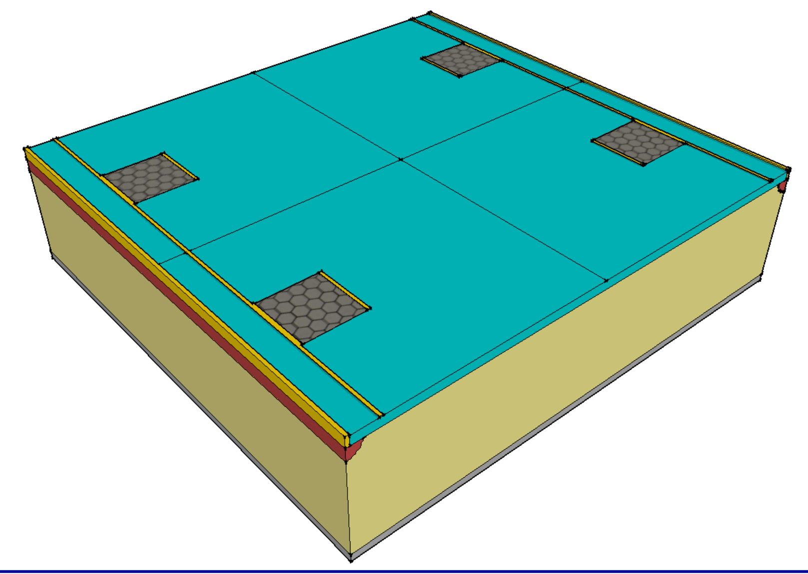
Relevant material properties were replicated with **ad-hoc models** to simulate the electrostatics inside a device hit by a MIP. The field produced by the ionization charges acts as a gate voltage in a MOS, controlling the drain-source current.



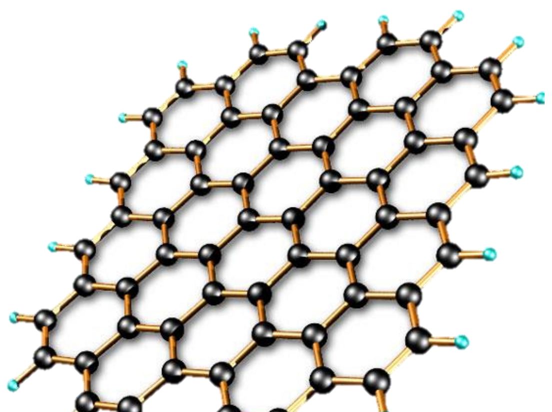
$$I(x) = q\mu W \frac{\int_0^{V_{DS}} \rho_{sh} dV}{L - \mu \int_0^{V_{DS}} v_{sat}^{-1} dV}$$



Sensor matrix using graphene-based pixels

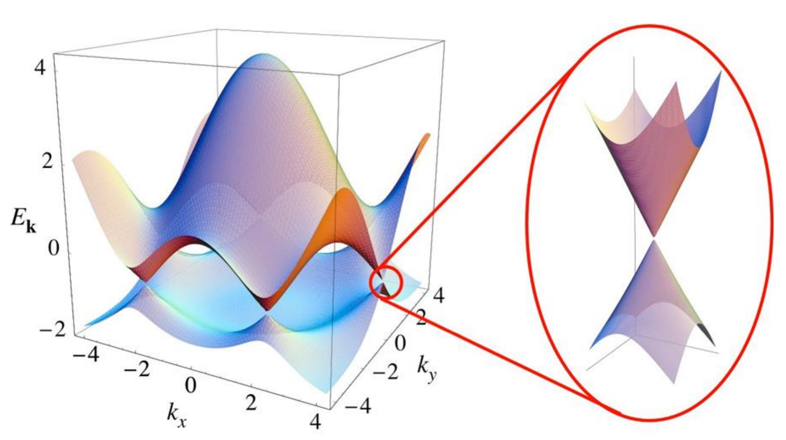


2D MATERIALS



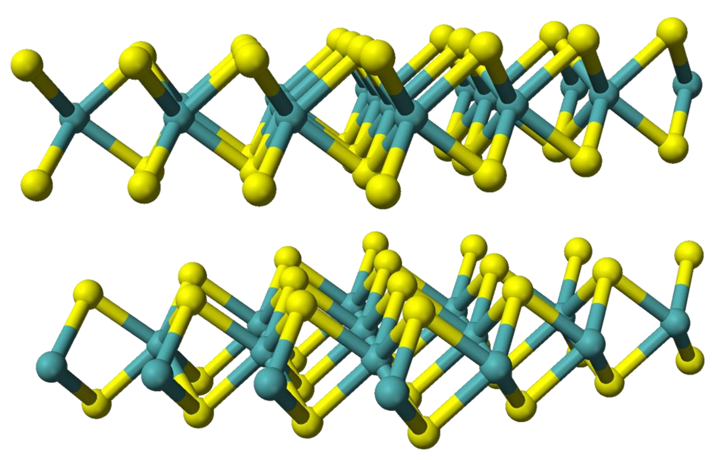
GRAPHENE

- Gapless (ML), linear dispersion
- **Electronic** properties: ballistic transport @RT, record mobility (up to 200.000cm²/Vs), ambipolar field-effect
- **Mechanical** properties: High breaking strength and Young modulus, Stretchable
- **Optical** properties: Transparency, Flat absorption (2500-300nm)



MX_2 LAYERED MAT: WSe_2, MoS_2, $MoTe_2$...

- **Physical properties depend on layer number**
- **Gap**: 1 to 2 eV, tunable (E field, compounds, stress)
- Flexible and resistant
- Good mobility
- Photoluminescence



2D Mat. Growth techniques:

- Mechanical exfoliation
- SiC
- CVD
- Liquid-phase exfoliation
- Graphene oxide reduction

PERFORMANCE AND PERSPECTIVES

Simulations show promising results for graphene-based pixel detectors, due to the built-in pre-amplification.

A standard readout chain was considered, based on a charge-sensitive pre-amplifer. This way the charge input signal is the integral of the current modulation. This approach allows a **20x amplification factor**.

The effective ENC (at readout input) is higher than usual values for pixel det. (~1700), but the final signal-to-noise ratio is very good due to the built-in signal amplification.

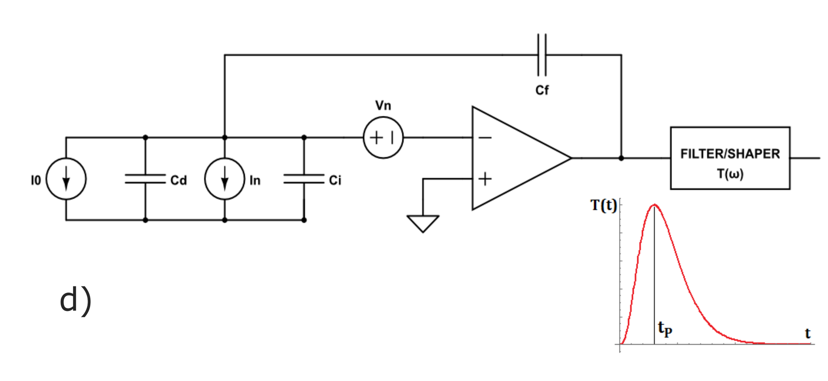
$$Q_{IN} = \int \Delta I\, dt \approx 4.9 \cdot 10^5\, e^-$$

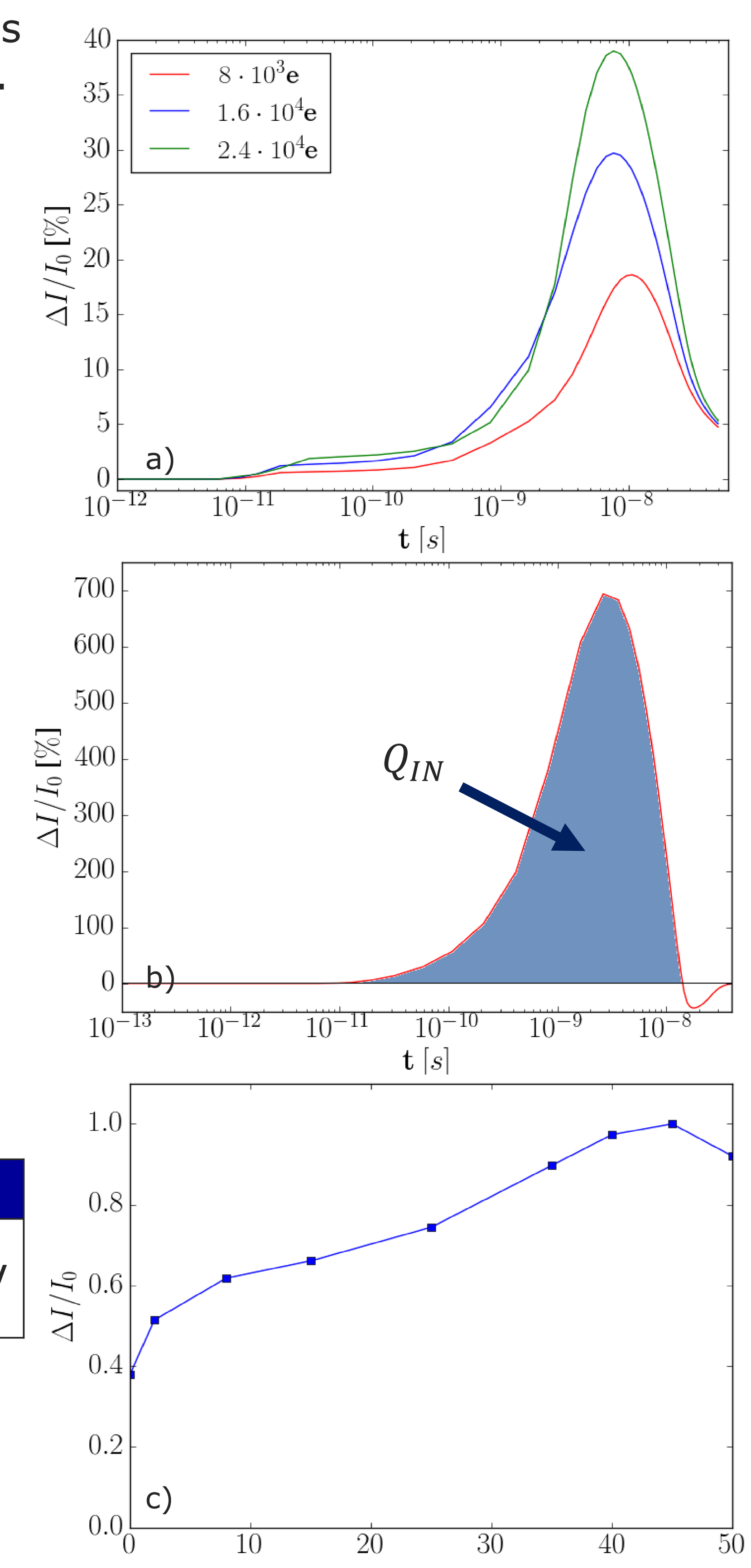
$$\mathrm{SNR} = \frac{Q_{IN}}{\mathrm{ENC}} = \frac{4.9 \cdot 10^5}{1700} \approx \mathbf{290}$$

An **MoS_2-based sensor** could offer even better performance, due the presence of a (tunable) bandgap, which would greatly further improve the signal-to-noise ratio.

- Pixel sensitivity shows a 60% variation according to the hit point
- Always well above the noise threshold
- Active area covers the entire 50μmx50μm pixel

Material	t_{PEAK}	ΔR/R	d	V_B
Graphene	~7ns	~0.3	300μm	150V
MoS2		~7		





Source-drain current variation for a graphene- (a) or MoS_2- (b) based device, pixel position sensitivity (c) and example readout chain (d).

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