A look to Charge carrier properties in single-crystal diamonds using the Allpix-squared simulation framework

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Department of Physics
TU Dortmund
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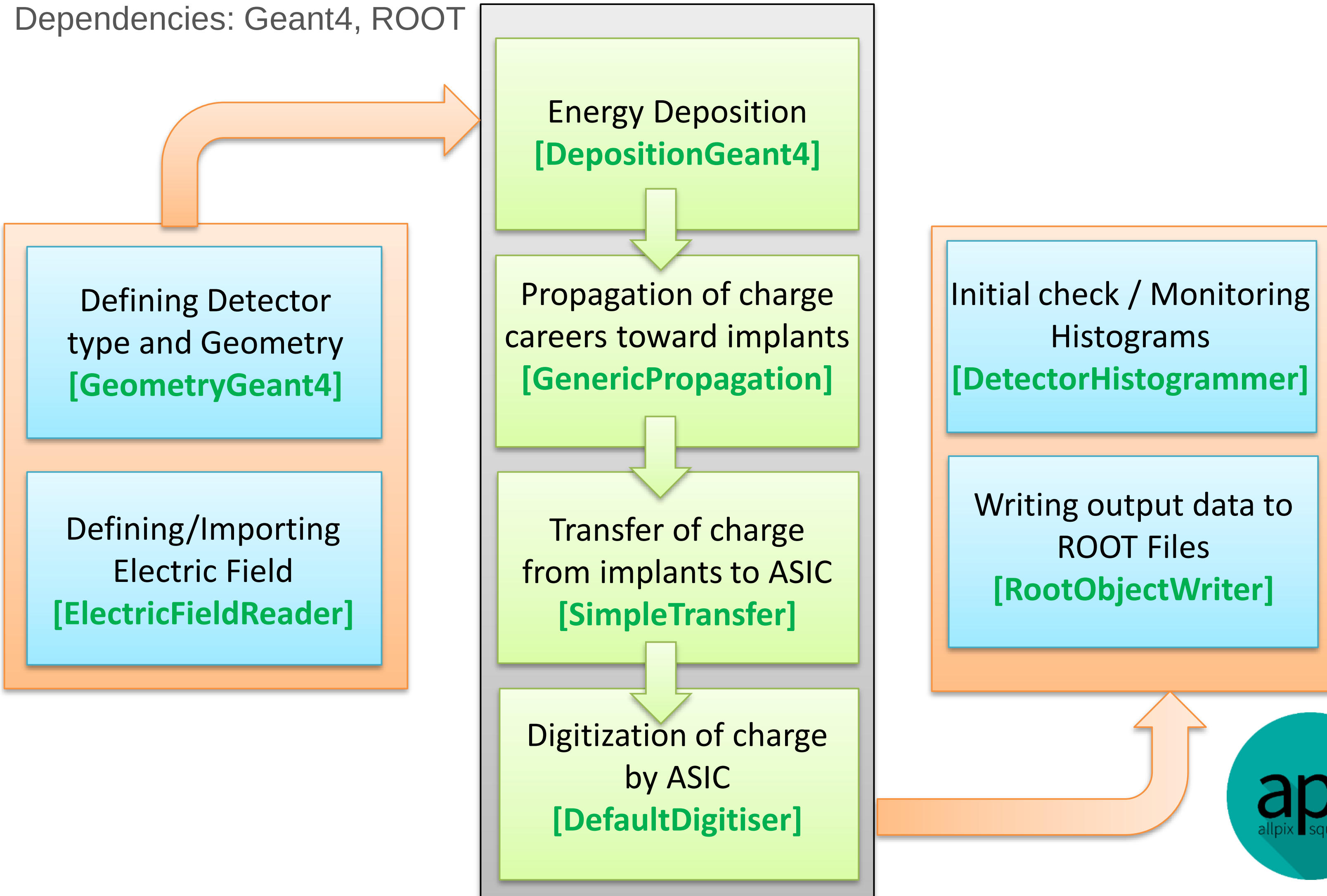
Simulation Flow

- Minimum required modules for simulation run
- Dependencies: Geant4, ROOT



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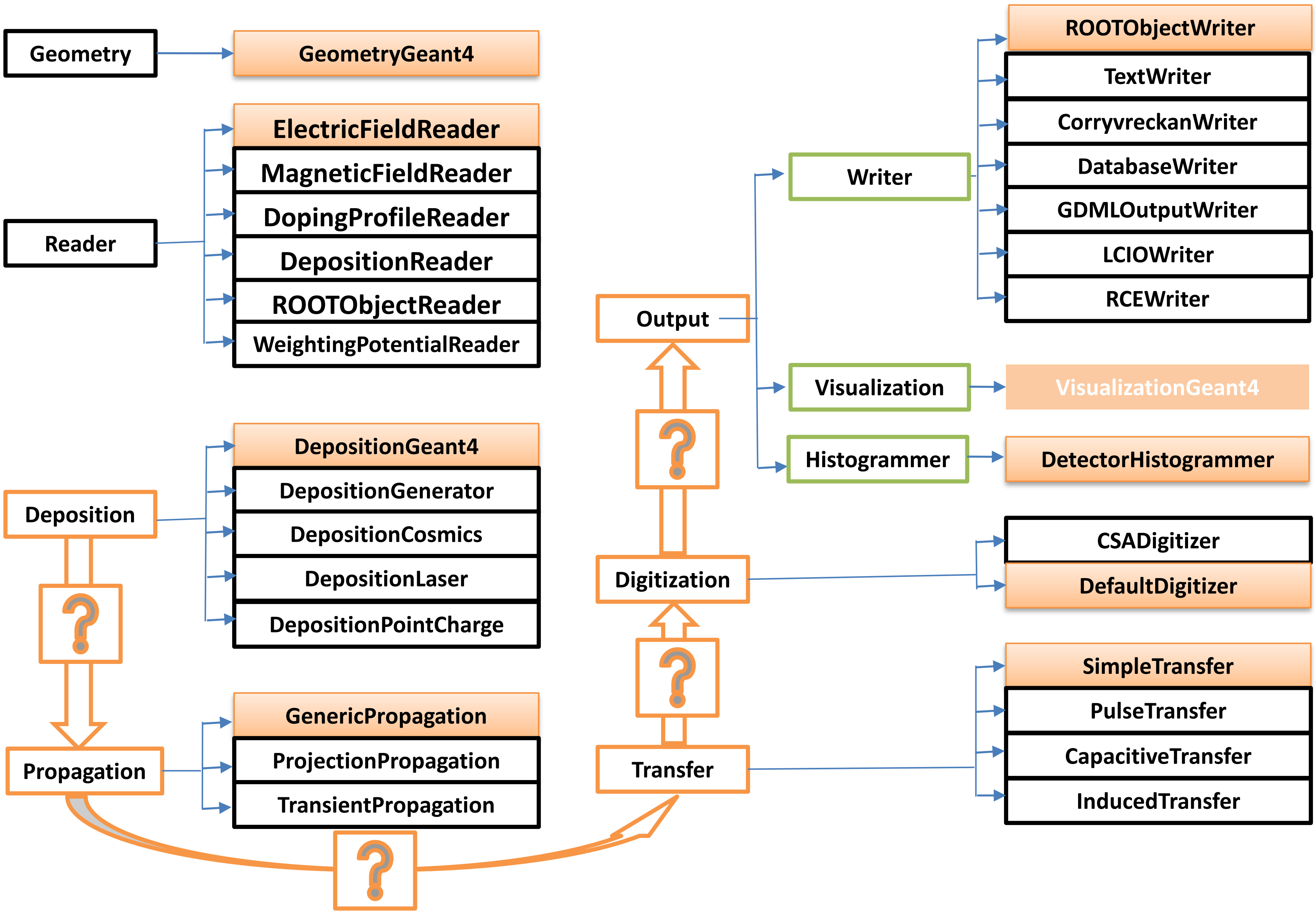
Modules

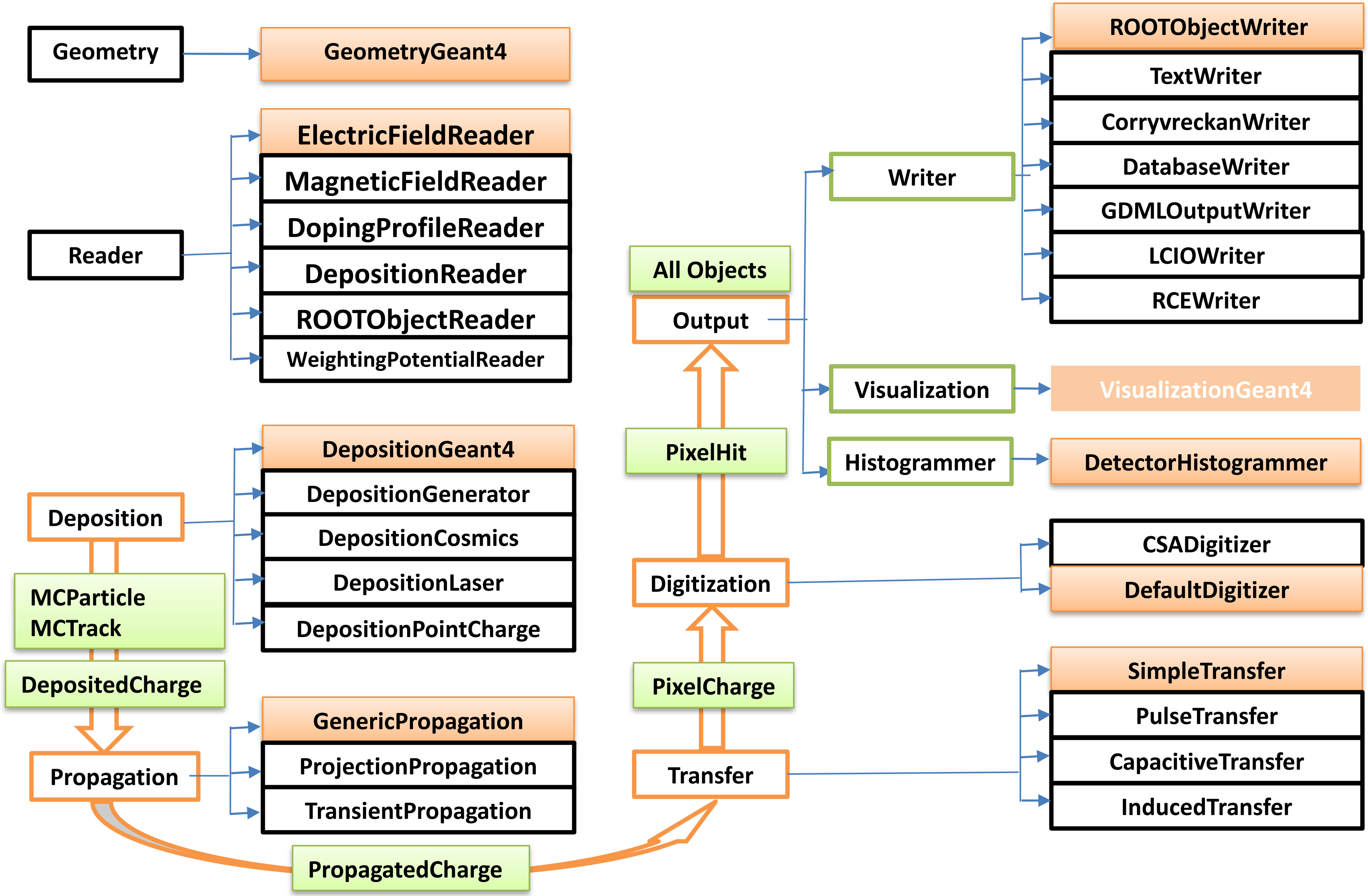


Objects

- transfer data between modules
- store the simulation results in to file

MCTrack	particle trajectory from initial to final point
MCParticle	Monte Carlo truth information about particle passage
DepositedCharge	Set of charge carriers deposited by traversing particle
PropagatedCharge	Set of charge carriers due to drift/diffusion process
SensorCharge	meta class inherited by DepositedCharge and PropagatedCharge objects
PixelCharge	The set of charge carriers collected at a single pixel
Pulse	meta class to hold the time information of a charge pulse
PixelHit	The digitised pixel hits after processing the PixelCharge in the detector's front-end electronics

Data Transfer b/t Modules



Validity of Diamond

Goal: to check the validity of diamond as sensor material

Why Diamond?

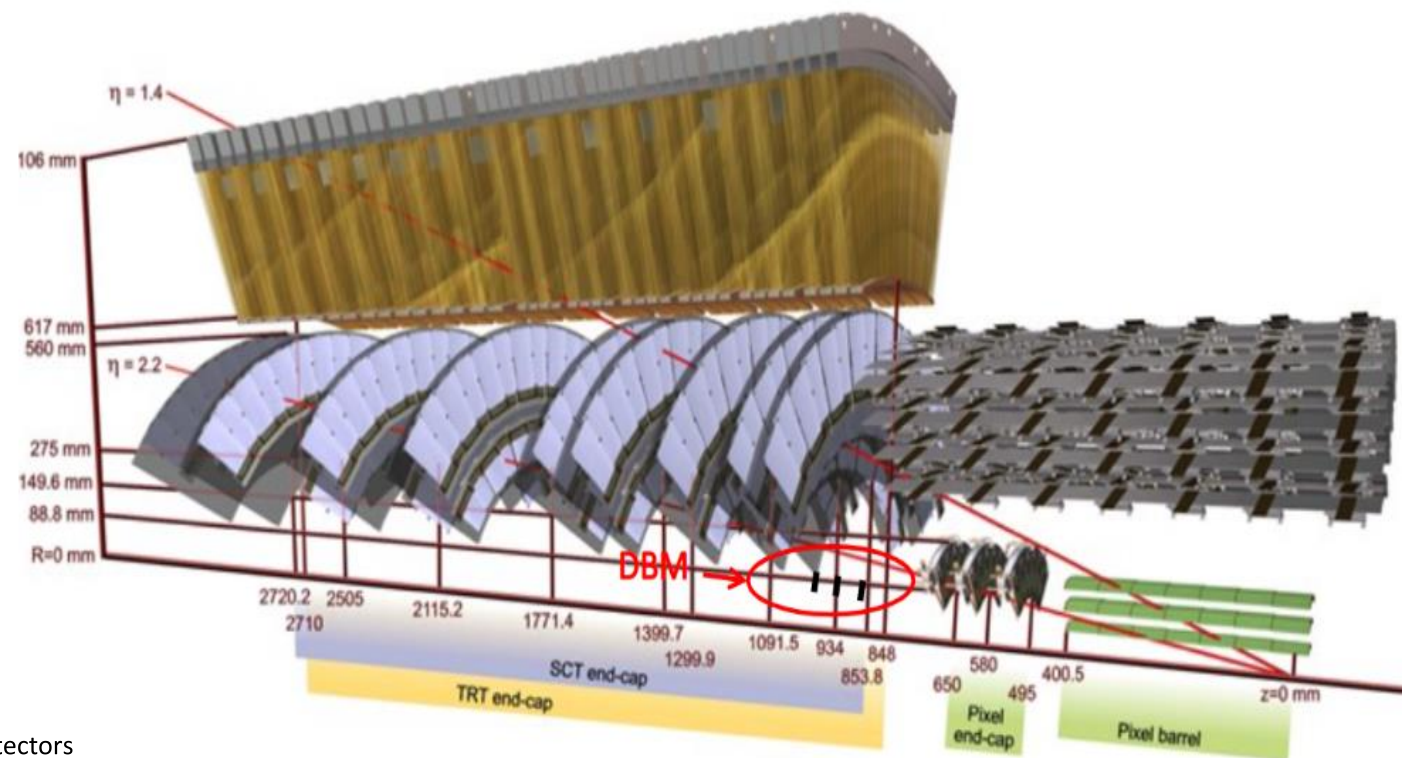
Diamond's advantages as sensor material in HEP

- Low Atomic Number – ideal for tracking detectors but low signal
- 43 eV Displacement energy – Radiation hard
- High drift velocities – Fast Signal Readout

Property	Diamond	Silicon	
Band Gap (ev)	**5.5**	1.12	**Low Noise**
Atomic Number (z)	$\mathbf{6}$	14	**Low Signal**
Displacement Energy ($ev/atom$)	$\mathbf{43}$	$13-20$	**Radiation Hard**
Mobility (cm^2/Vs)	$\mathbf{1900}(e), \mathbf{2300}(h)$	$1350(e)480(h)$	**Fast Signal**
Saturation Velocity ($10^7\ cm/s$)	$\mathbf{1.3}(e), \mathbf{1.7}(h)$	$1.1(e), 0.8(h)$	**Fast Signal**
Aver. Signal Created/100 um (e)	**3602**	8892	**Low Signal**

Applications in HEP

- LHC (CERN) [1] and CDF (Collider Detector at Fermilab) [2] use diamond sensors for beam monitoring and accident Protection. ATLAS BCM/BLM, CMS BCM/BCM-F
- LHCb BCM
- ATLAS Diamond Beam Monitor (DBM)
- Inner layer?



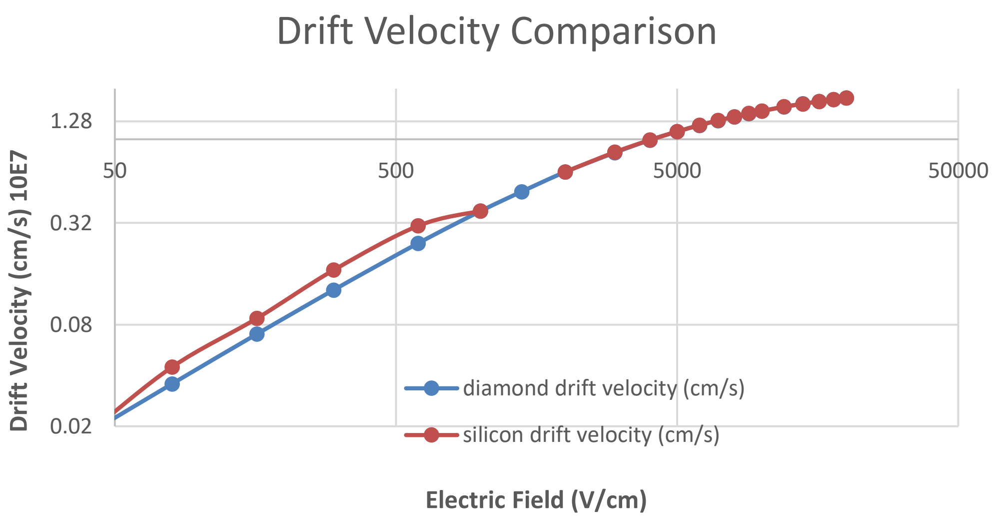
[1] F. Hugging: Diamond Detectors
[2] FERMILAB-CONF-07-112-E

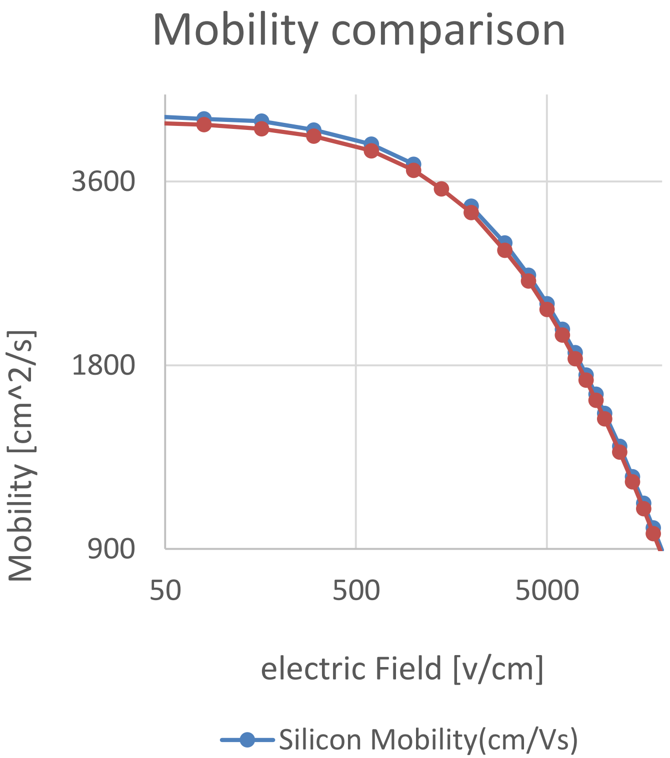
Marko Mikuz: Diamond Sensors

Diamond Validity Check

- Same drift velocity and mobility output for Diamond and silicon

Projection Propagation





ToF or TCT

- A simple single-crystal CVD sensor sandwiched between two metallic electrodes
- metal-insulator-metal (MIM) detector

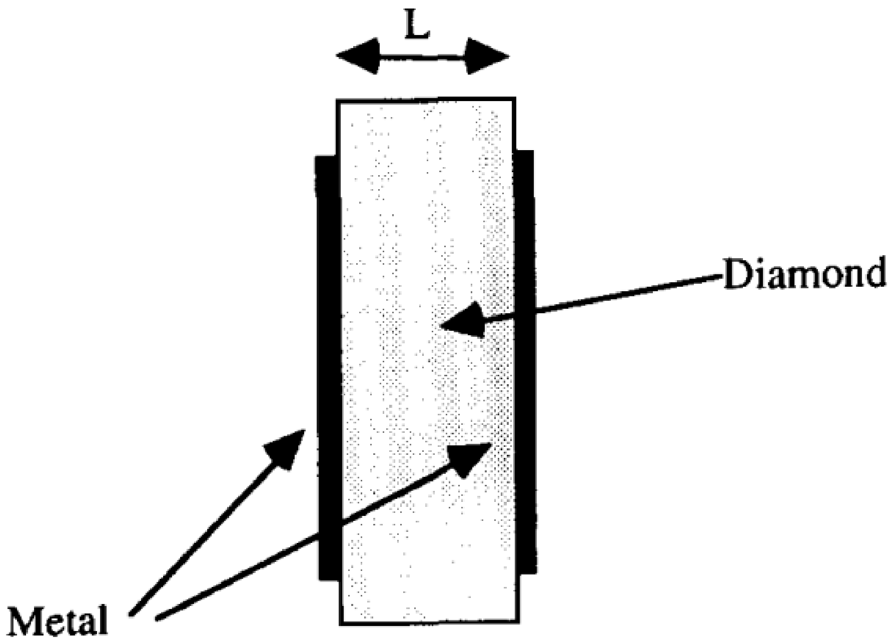
$$V_{drift} = \frac{d}{t} = \frac{L}{\tau}$$

$$V_{drift} = \mu(E)E$$

$$L = \mu E \tau$$

- the important parameters

$$\mu, \tau \text{ and } \mu\tau$$



Schematic diagram of a MIM

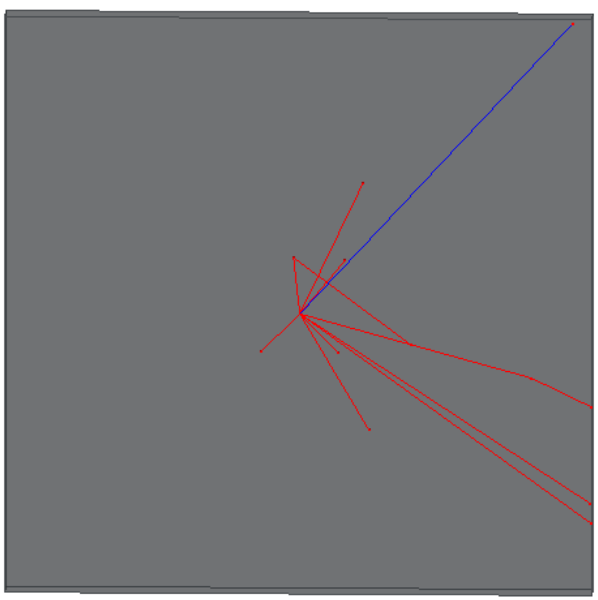
doi.org/10.1016/0925-9635(93)90266-5

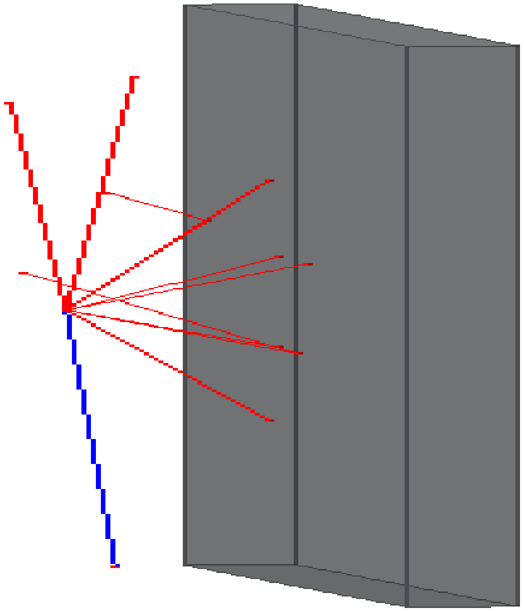
Simulation Code

- Detector Type: Monolithic pixel scCVD
- Detector Size: (3mm × 3mm) × 400um
- Mobility Model: Jacobani Canali
- Energy Source: Am-241 Alpha source
- Energy Deposited: 5.486 MeV

Detector Simulation:
Left: top view, Right side view

DOI: 10.1002/pssa.201532230



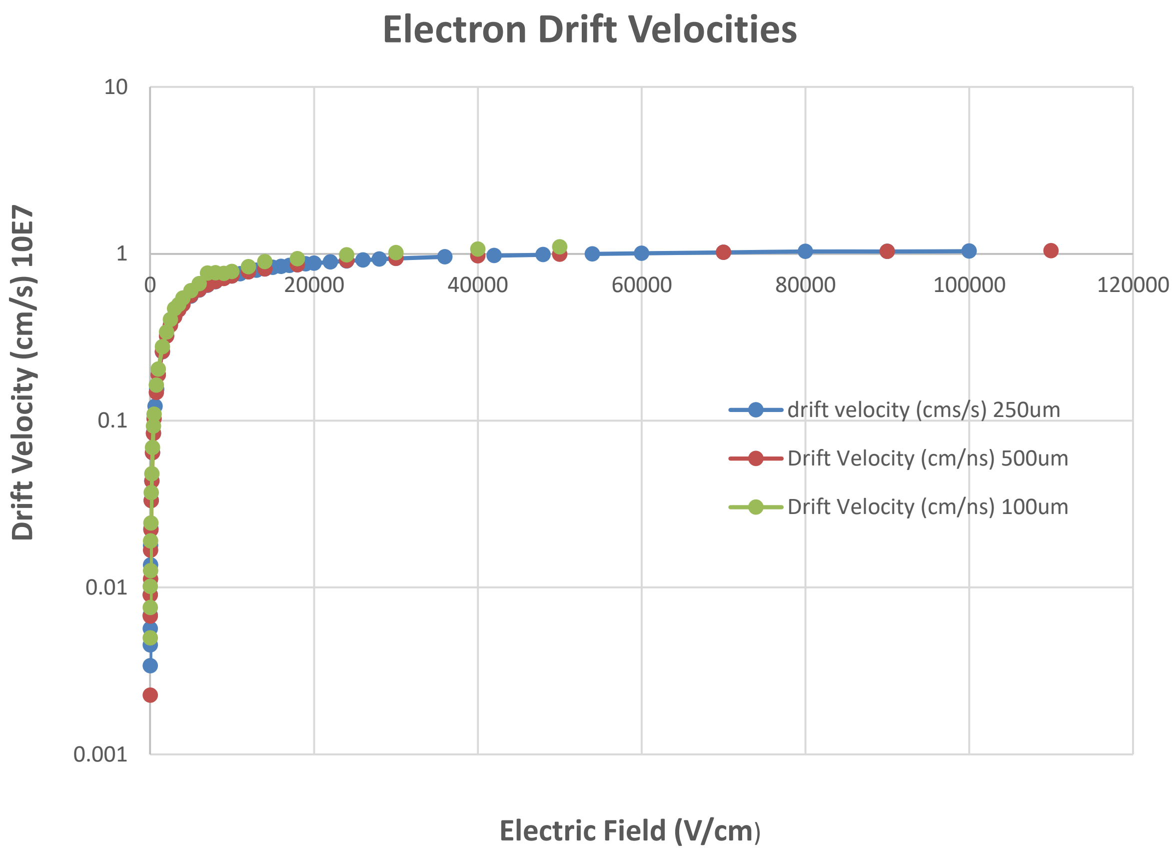


Silicon Drift Velocity

- Get saturates at around 10E7 cm/s after 30000 V/cm

Projection Propagation

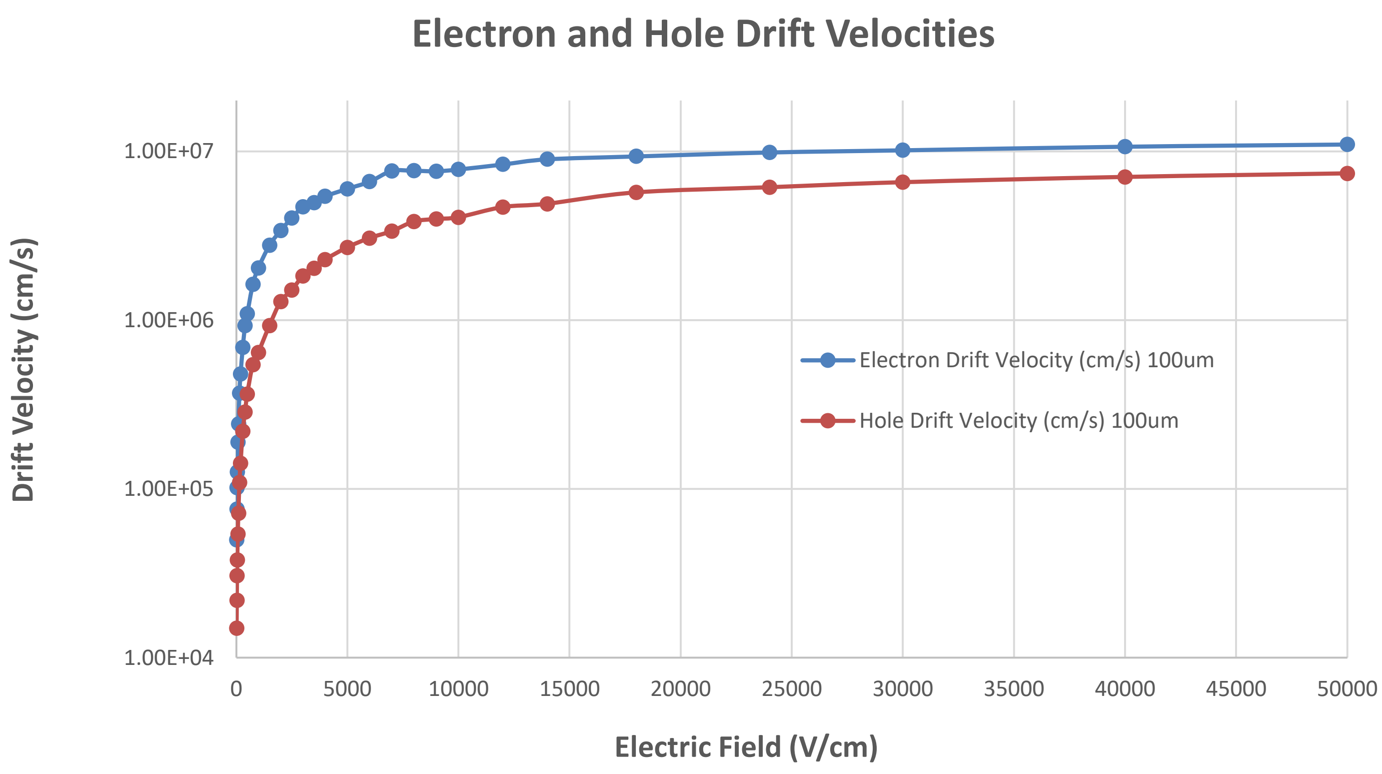
- No customization possible



Silicon Drift Velocity

- Electrons: 7000 V/cm, 0.766 cm/s
- Holes: 12000 V/cm, 0.467 cm/s

Projection Propagation

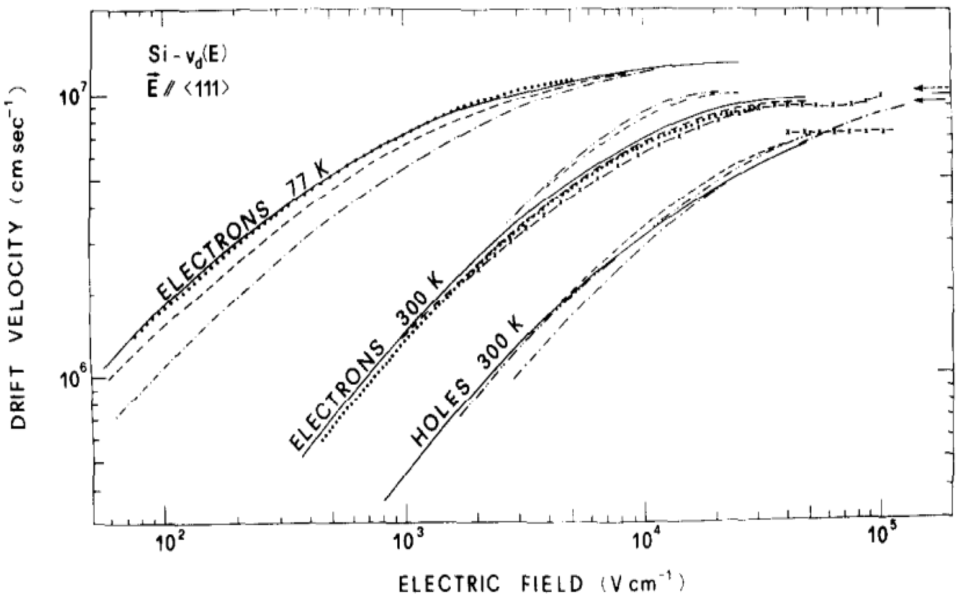


Silicon e & h Drift Velocity

- Electrons: 7000 V/cm, 0.766 cm/s
- Holes: 12000 V/cm, 0.467 cm/s

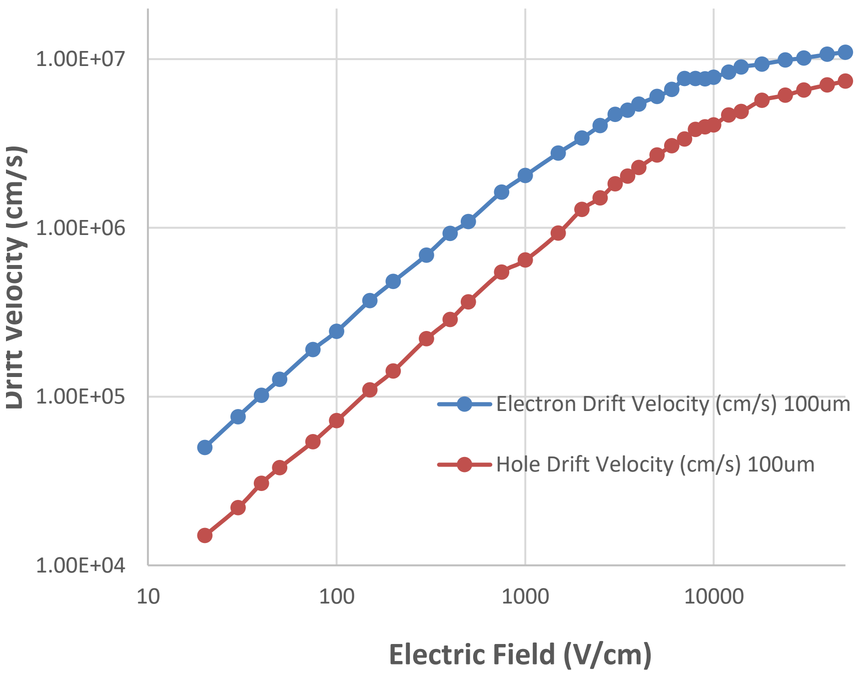
Projection Propagation

Experimental Results



doi.org/10.1016/0038-1101(77)90054-5

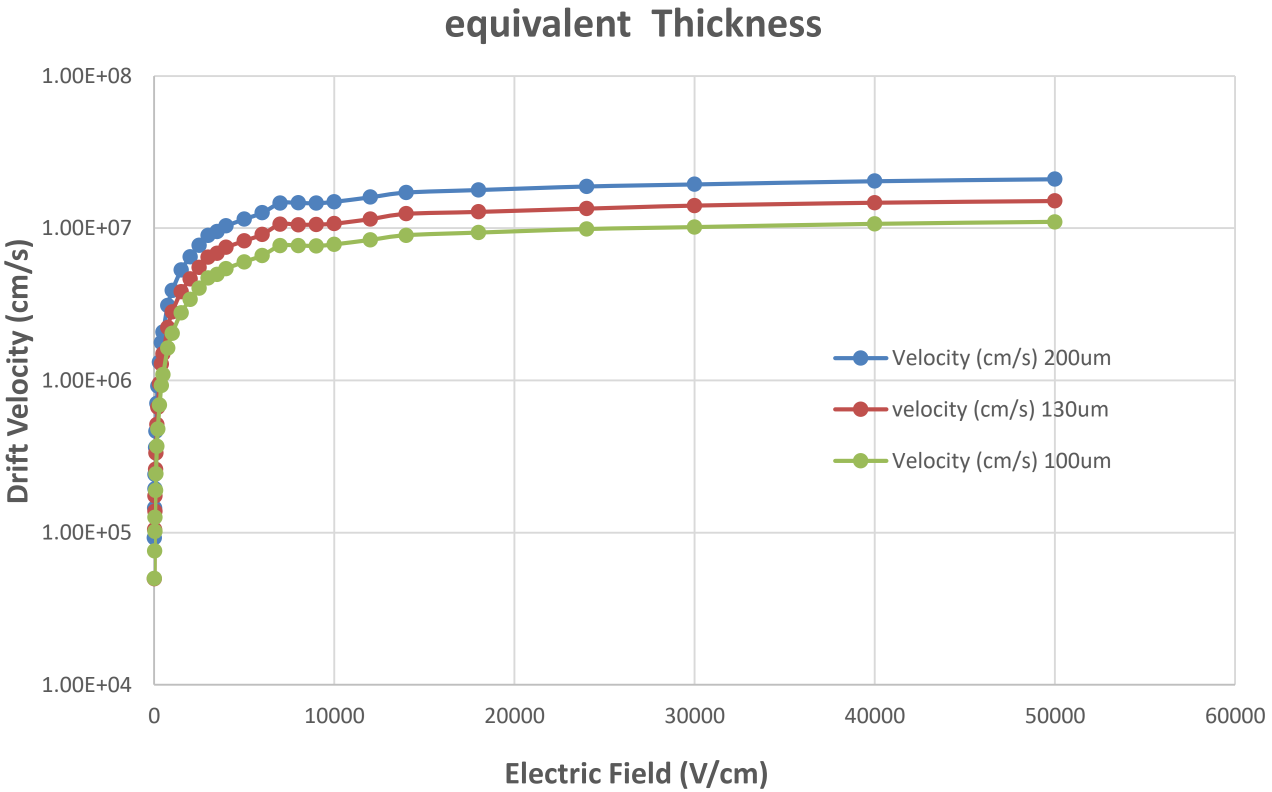
Simulation results



Silicon Drift Velocity

- Look for an ad-hoc thickness in agreement with experimental data
- 200um, 7000 V/cm, 1.46 cm/s
- 130um, 7000 V/cm, 1.06 cm/s
- 100um, 7000 V/cm, 0.766 cm/s

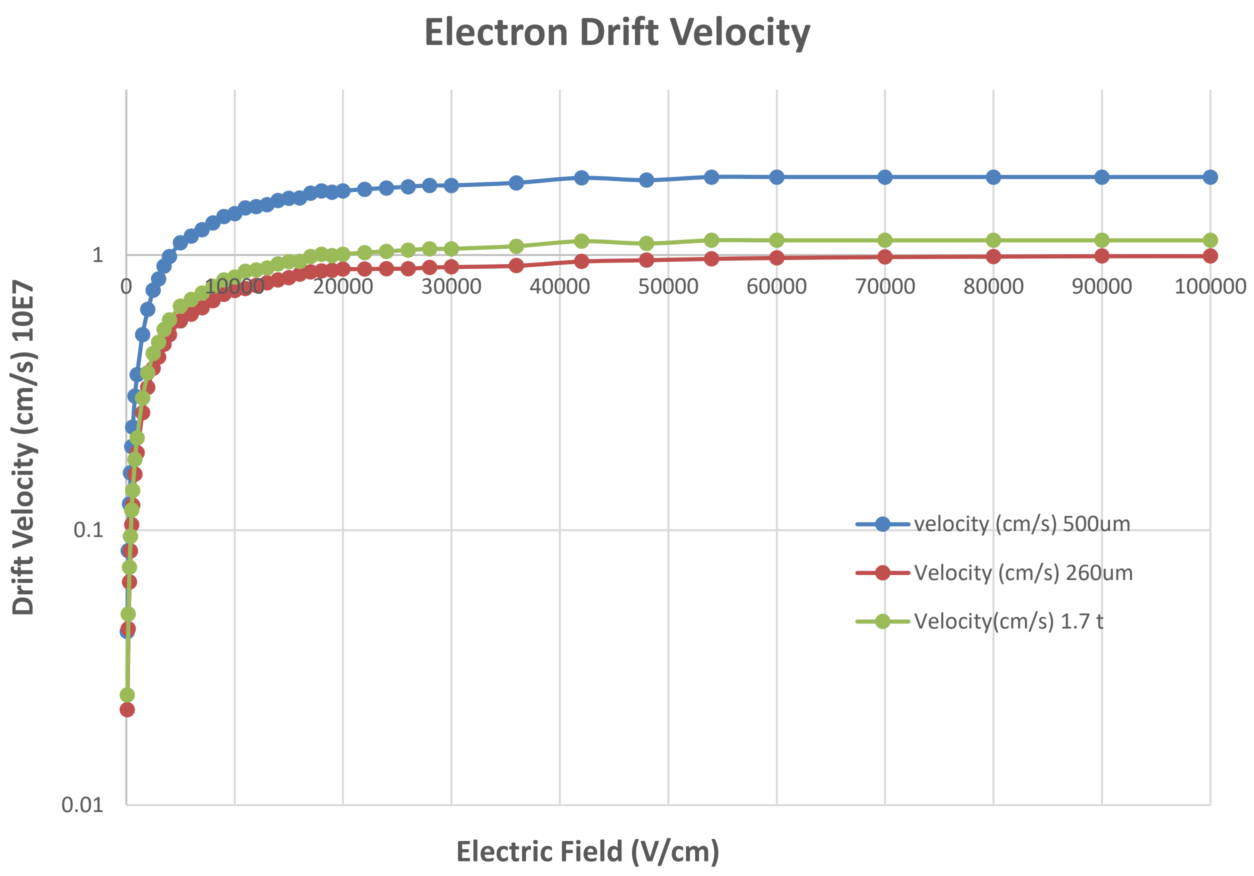
Projection Propagation



Silicon Drift Velocity

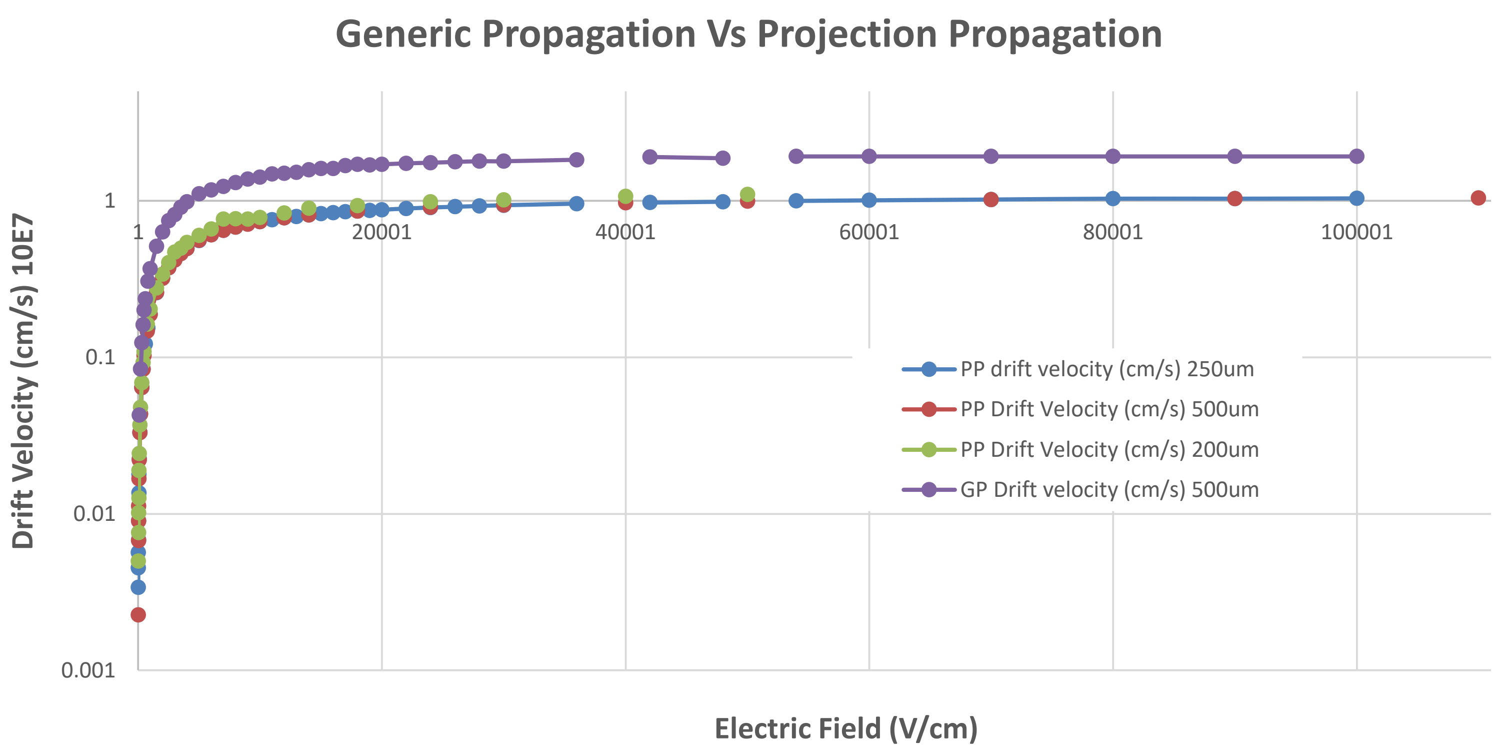
- 500um thickness with very high saturation velocity
- After scaling the thickness and time

Generic Propagation



Silicon Drift Velocity

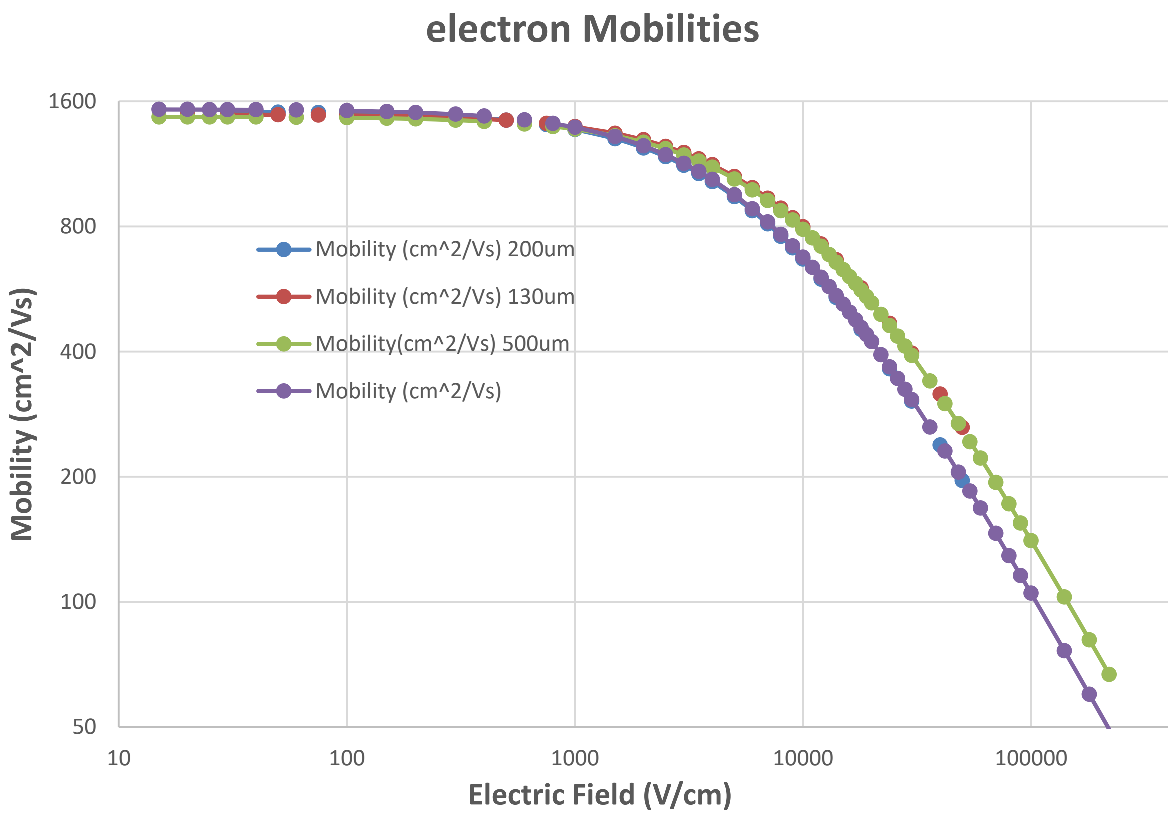
- Generic propagation gives higher drift velocity values but allows customised models



Silicon Mobilities

- Constant low field mobilities below 1000 V/cm round about 1500 cm^2/Vs

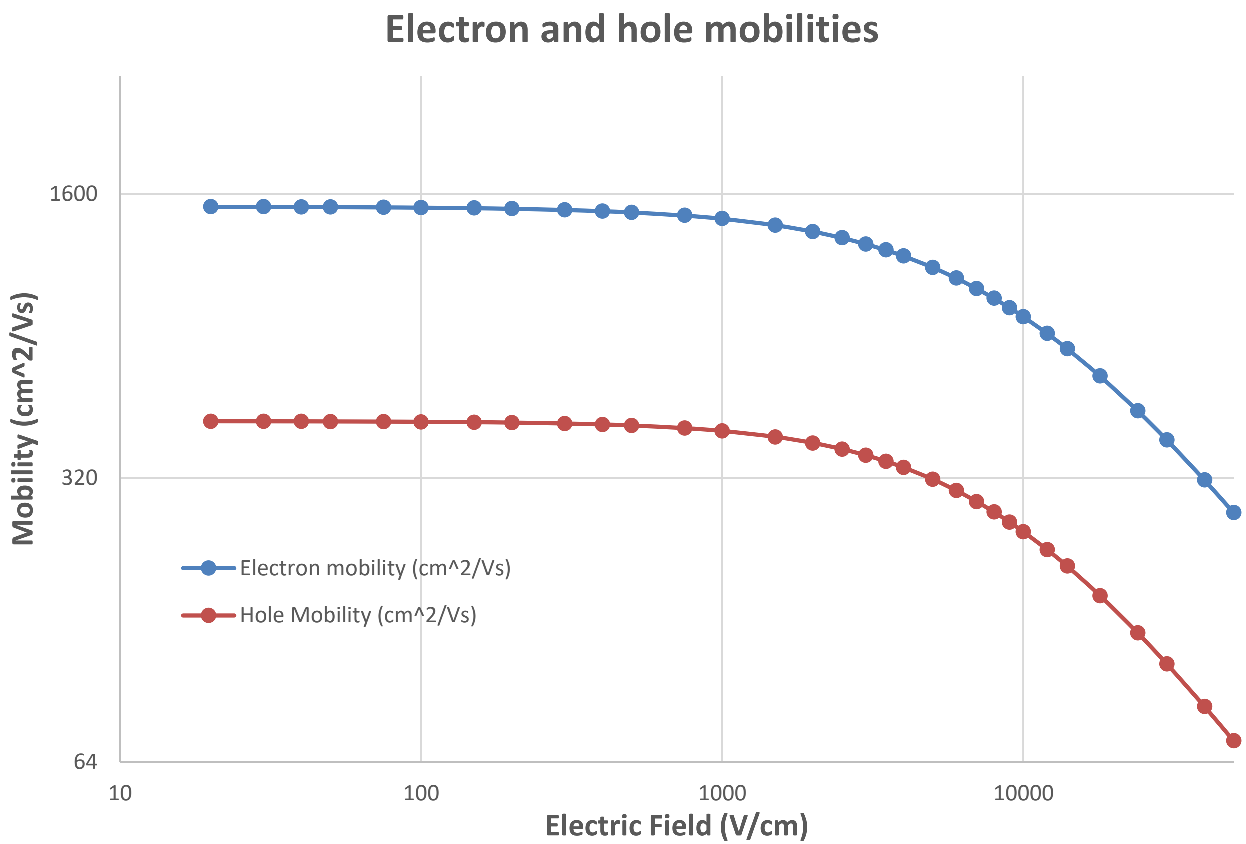
Projection Propagation



Silicon Mobilities

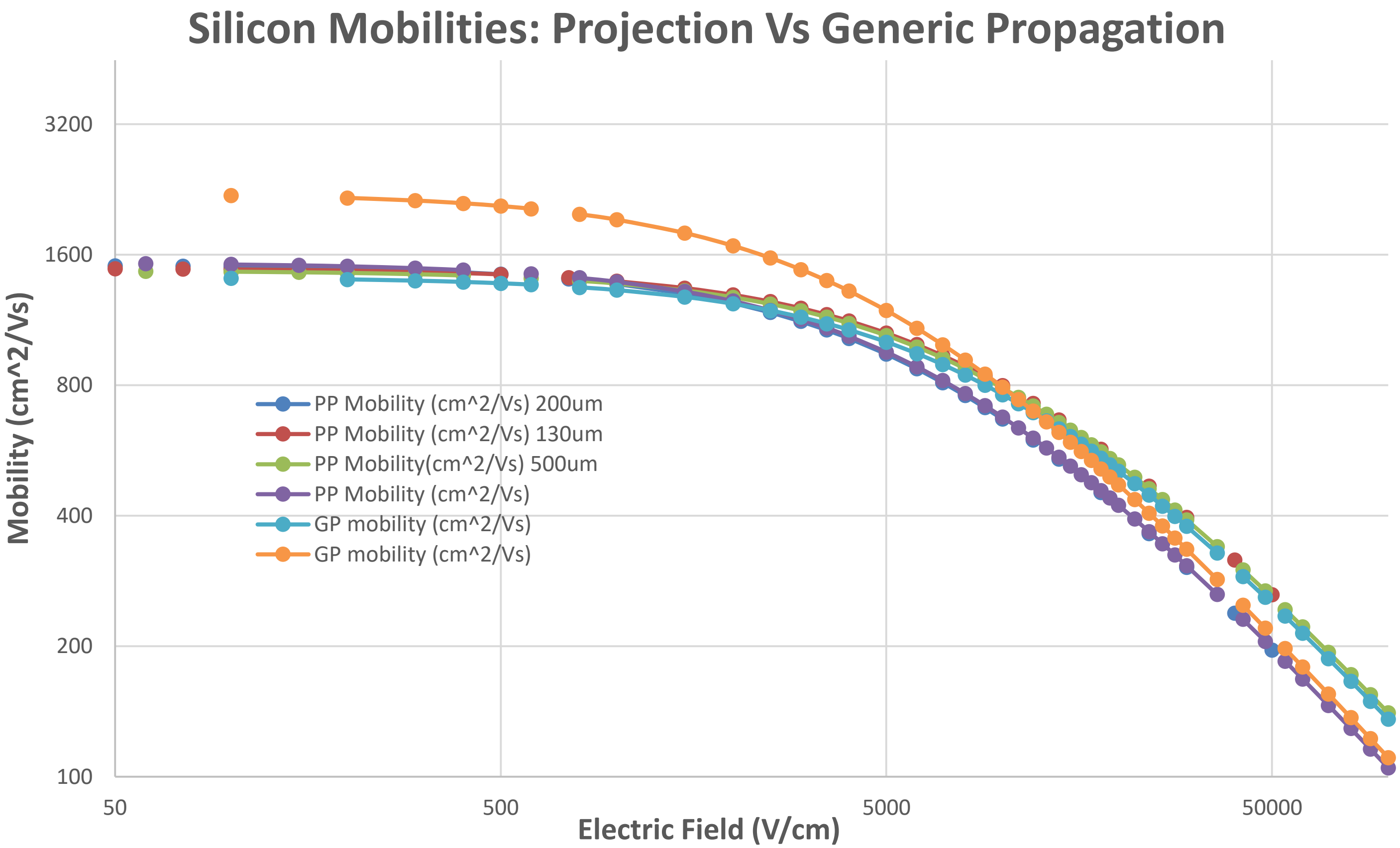
- Electrons: 1488 cm^2/Vs
- Holes: 441 cm^2/Vs

Projection Propagation



Silicon Mobilities

- Generic Propagation predicts higher values



Caughey Model for Diamond

- Huge variation of parameters for diamond

Generic Propagation

$$v_{\text{drift}} = v_{\text{sat}} \frac{E/E_c}{(1 + (E/E_c)^{\beta})^{1/\beta}}$$

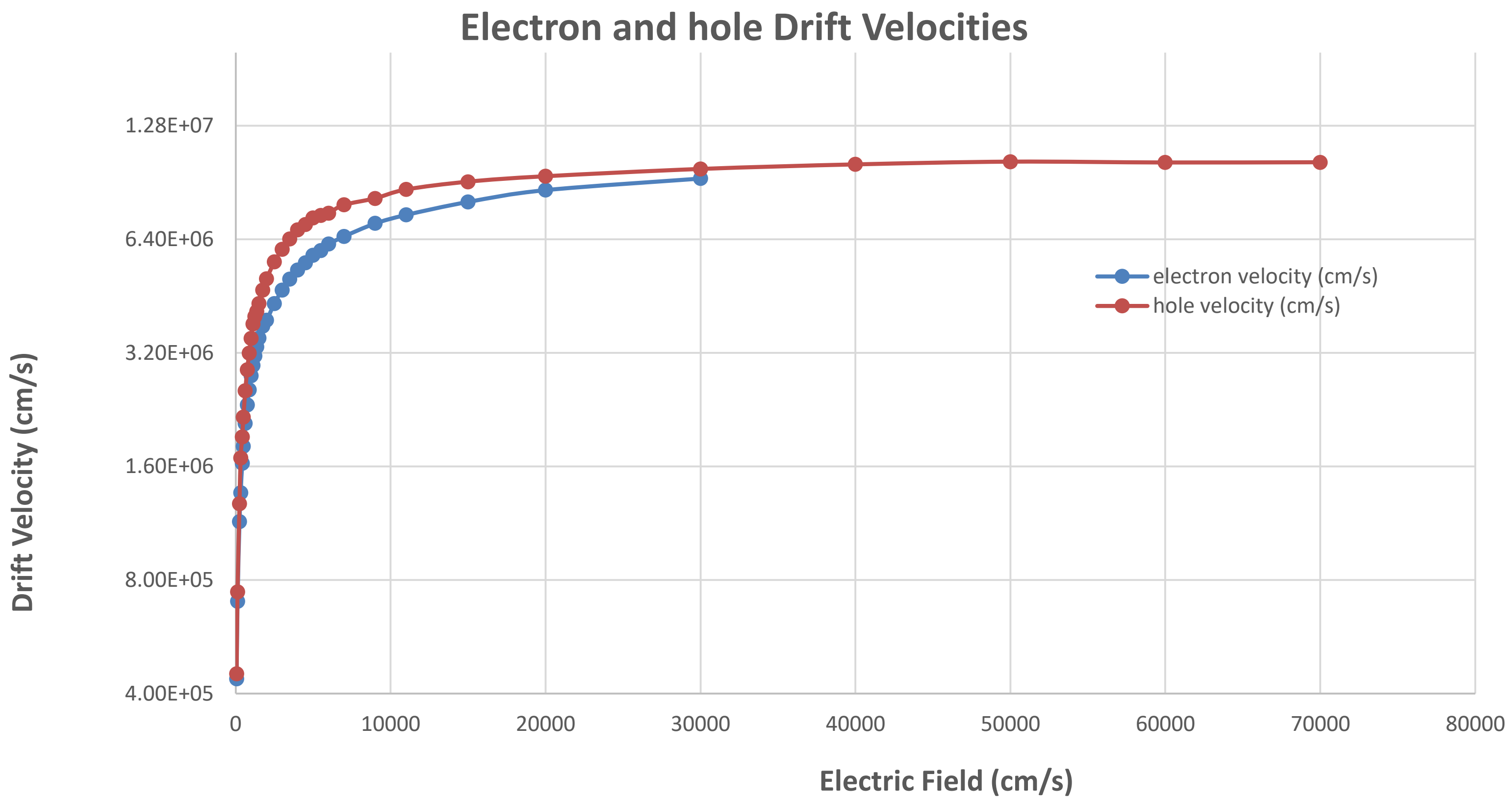
Parameters	E_c (kV/cm)	μ_0 (cm^2/Vs)	β
e_{exp}	4.325 ± 0.731	14948 ± 8303	0.26 ± 0.06
h_{exp}	5.836 ± 0.251	2615 ± 148	0.90 ± 0.09
e_{lit}	5.779 ± 0.772	4551 ± 500	0.42 ± 0.01
h_{lit}	5.697 ± 0.529	2750 ± 70	0.81 ± 0.01

IEKP-KA/2017-19

Diamond Drift Velocity

- Much lower than predicted **1.3 -2.63(e) ,1.57-1.7(h)**
- Choice of right parameters

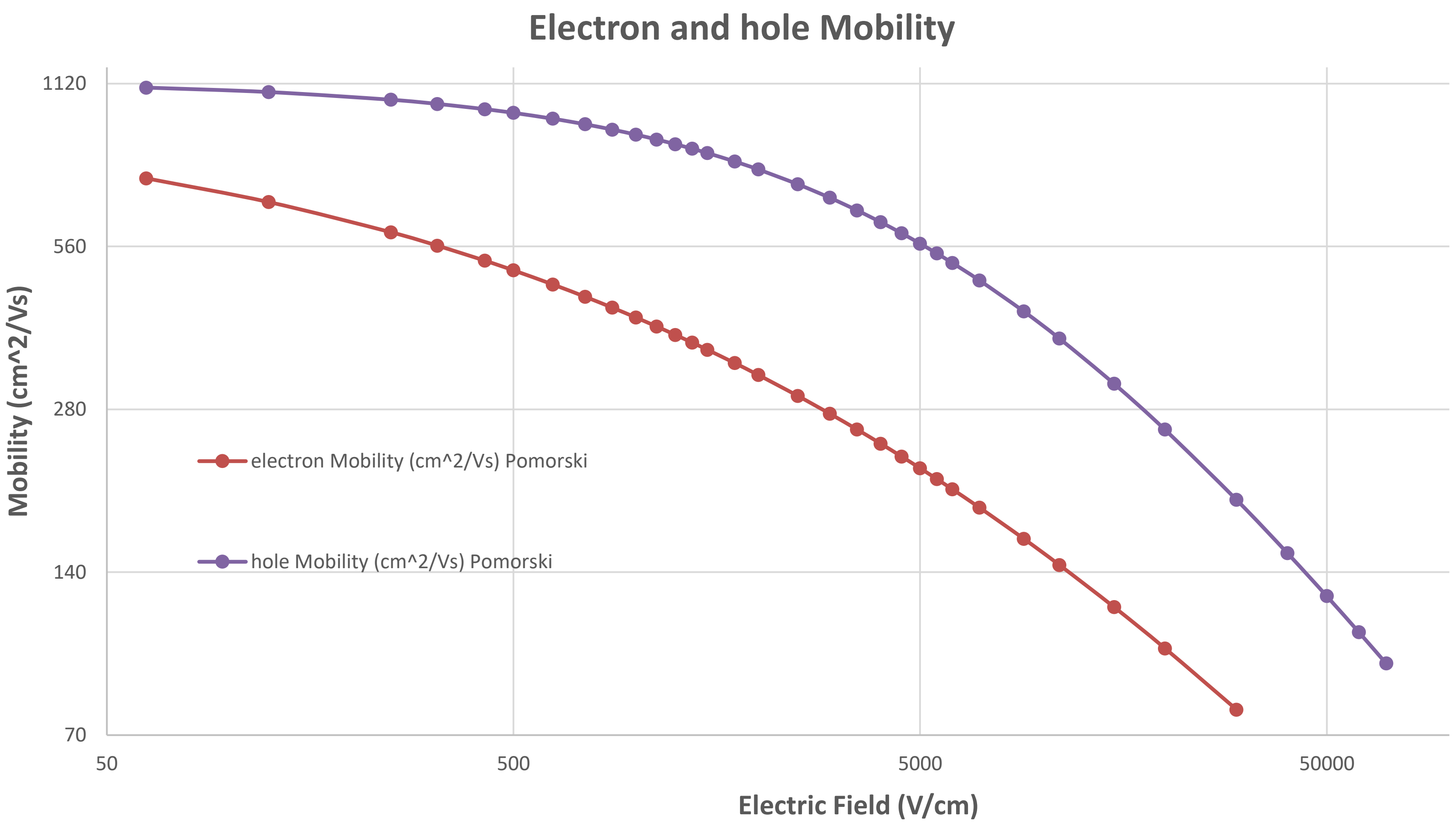
Generic Propagation



Diamond Mobility

- Prediction of lower mobilities
- Needs more work

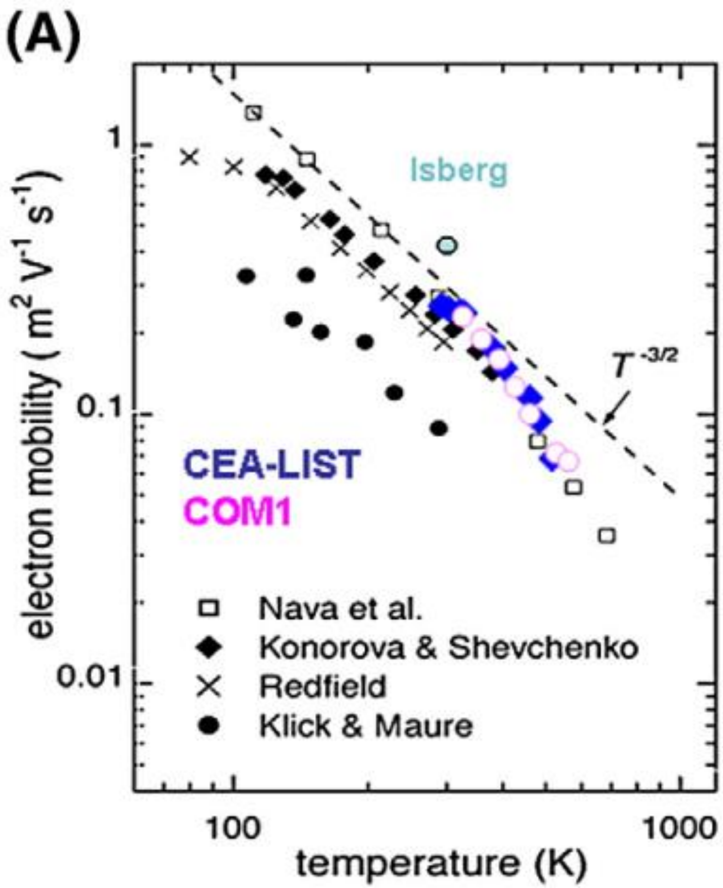
Generic Propagation

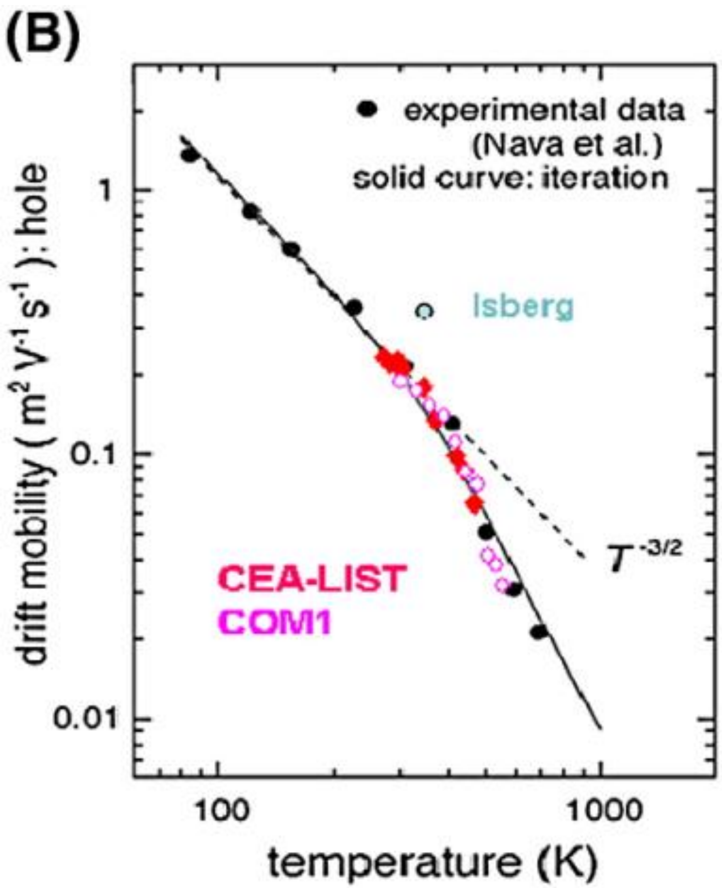


Diamond Mobility Vs T(k)

- Mobility vs temperature for (A) electrons (B) holes
- Shows significant variations for electron mobility

doi.org/10.1016/j.diamond.2008.03.015





Conclusion

- The general trend is followed in the case of mobility and drift velocity.
- Some scaling is needed for either time, thickness, or electric field.
- The addition of Diamond specific parameters for the Caughy Model is needed

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Conclusion

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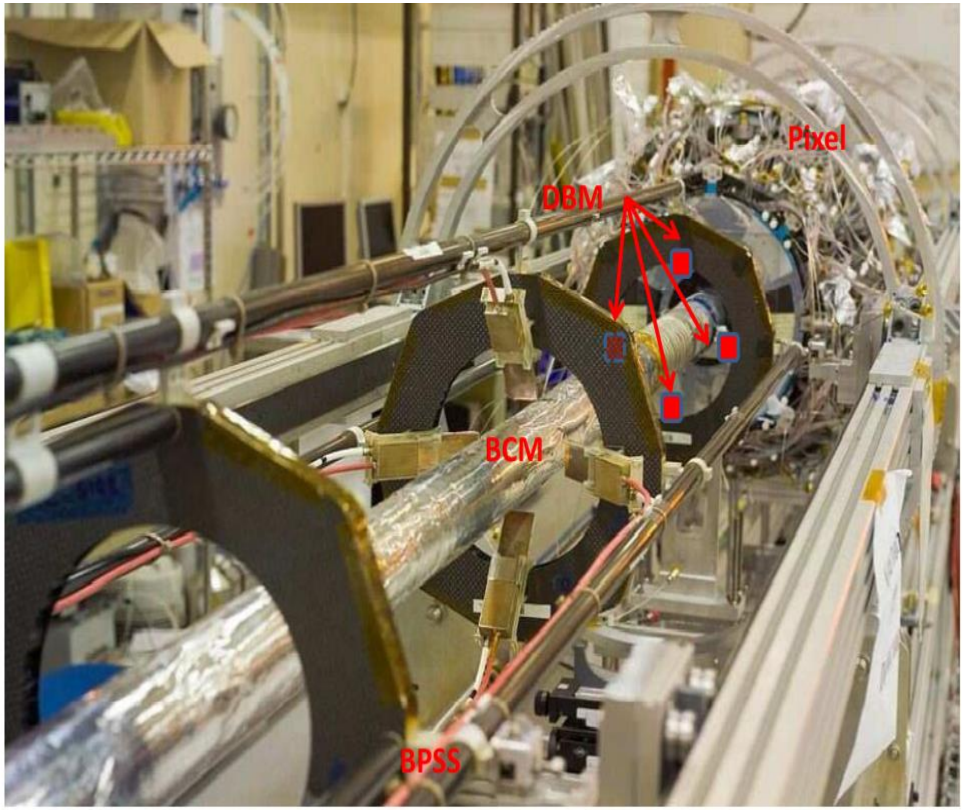
Thank You

The ATLAS Diamond Beam Monitor

Designed to measure the instantaneous luminosity, the background rates, and the beam spot position.

- **Single DBM module: 18 mm × 21 mm** pCVD diamond **500 µm thick** instrumented with an **FE-I4 pixel chip**.
- **26,880 pixels:** in 80 columns on 250 µm pitch and 336 rows on 50 µm pitch. This fine granularity provides high-precision particle tracking.
- **charge collection distance of 200-220 µm** at an applied bias voltage **of 500 V**.



CERN-LHCC-2018-015 / LHCC-SR-005 27/05/2018

Marko Mikuz: Diamond Sensors

Current Models in Allpix-Squared

Backup

- **Example:**

Charge Career Mobility
[Generic Propagation]

- **Implemented Models:**

Jacobani Canali Mobility Model for **Silicon**

Canali Model for Correction to the first one

Hamburg or Klanner-Scharf Model for high ohmic <100> **Silicon**

Masetti Model for carrier concentration in arsenic-, phosphorus-, and boron-doped **Silicon**

MasettiCanali Model (Extended Canali Model) for charge carriers in **Silicon**

Arora Model for concentration and temperature in **Silicon**

RuchKino Model for transport properties of **GaAs**

Quay Model for **Germanium**

Levinshtein Model for **GaN**

Constant Mobility Model

Custom Mobility Model

https://gitlab.cern.ch/allpix-squared/allpix-squared/-/blob/master/src/physics/Mobility.hpp

6.2.1 Jacoboni-Canali Model

From Allpix-Squared Manual

Backup

The Jacoboni-Canali model [36] is the most widely used parametrization of charge carrier mobility in Silicon as a function of the electric field E. It has originally been derived for $\langle 111 \rangle$ silicon lattice orientation, but is widely used also for the common $\langle 100 \rangle$ orientation. The mobility is parametrized as

$$\mu(E) = \frac{v_m}{E_c} \frac{1}{\left(1 + (E/E_c)^{\beta}\right)^{1/\beta}}, \tag{6.1}$$

where v_m, E_c, and β are phenomenological parameters, defined for electrons and holes respectively. The temperature dependence of these parameters is taken into account by scaling them with respect to a reference parameter value as

$$A = A_{ref} \cdot T^{\gamma} \tag{6.2}$$

where A_{ref} is the reference parameter value, T the temperature in units of K, and γ the temperature scaling factor.

The parameter values implemented in Allpix^2 are taken from Table 5 of [36] as:

$$\begin{aligned} v_{m,e} &= 1.53 \times 10^{9} \cdot T^{-0.87}\,\mathrm{cm/s} & v_{m,h} &= 1.62 \times 10^{8} \cdot T^{-0.52}\,\mathrm{cm/s} \\ E_{c,e} &= 1.01 \cdot T^{1.55}\,\mathrm{V/cm} & E_{c,h} &= 1.24 \cdot T^{1.68}\,\mathrm{V/cm} \\ \beta_e &= 2.57 \times 10^{-2} \cdot T^{0.66} & \beta_h &= 0.46 \cdot T^{0.17} \end{aligned}$$

for electrons and holes, respectively.

This model can be selected in the configuration file via the parameter `mobility_model = "jacoboni"`.

	E_c (kV/cm)	V_{sat} (cm/s)	β
electrons	5.779	2.63×10^7	0.42
	± 0.772	$\pm 0.2 \times 10^7$	± 0.01
holes	5.697	1.57×10^7	0.81
	± 0.529	$\pm 0.14 \times 10^7$	± 0.01

DOI 10.1002/pssa.201532230

Backup

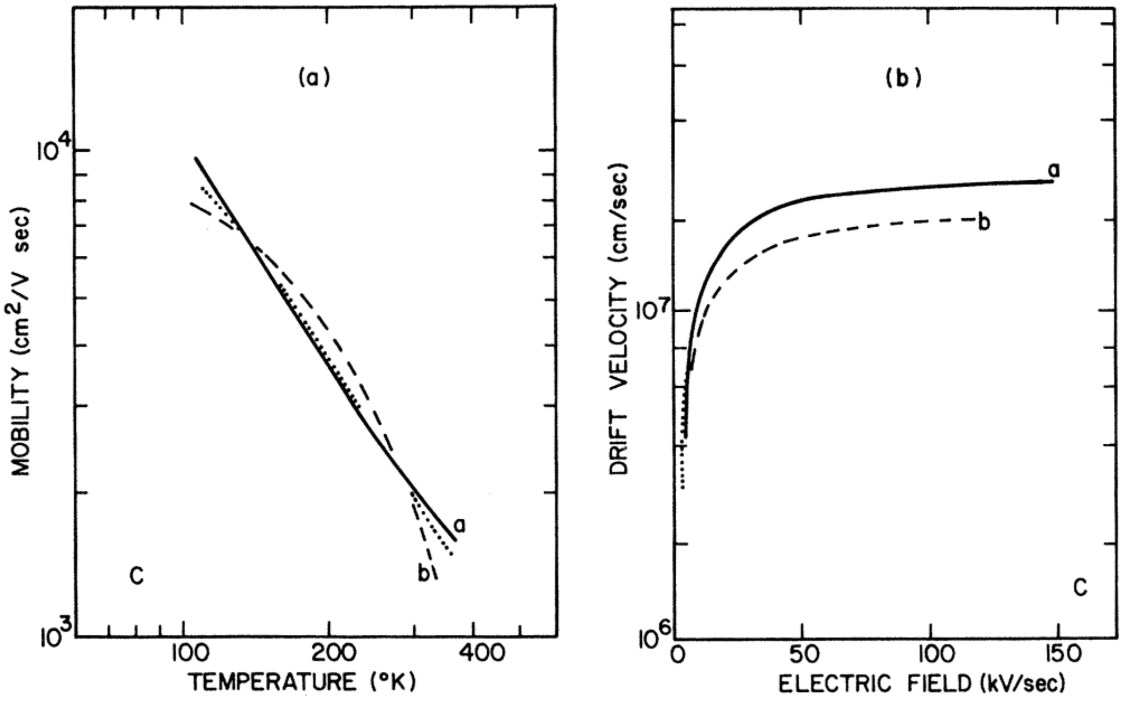


FIG. 4. (a) Calculated mobility as a function of temperature for diamond for two sets of values of coupling constants. The dotted curve is the data of Konorova and Shevchenko (Ref. 4). (b) The calculated high-field velocity is shown. The values of the constants are given in Table IV.

DOI:https://doi.org/10.1103/PhysRevB.12.2361