Artificial diamonds as particle detectors and radiation dosimeters

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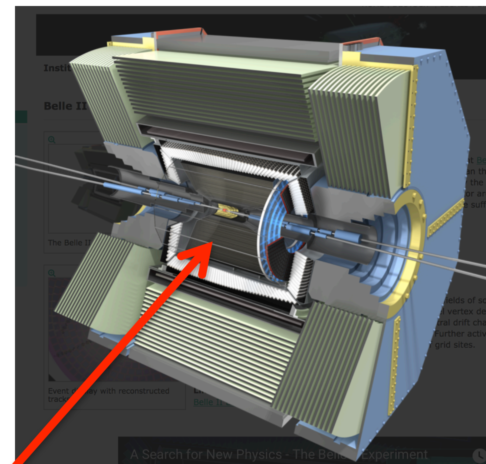
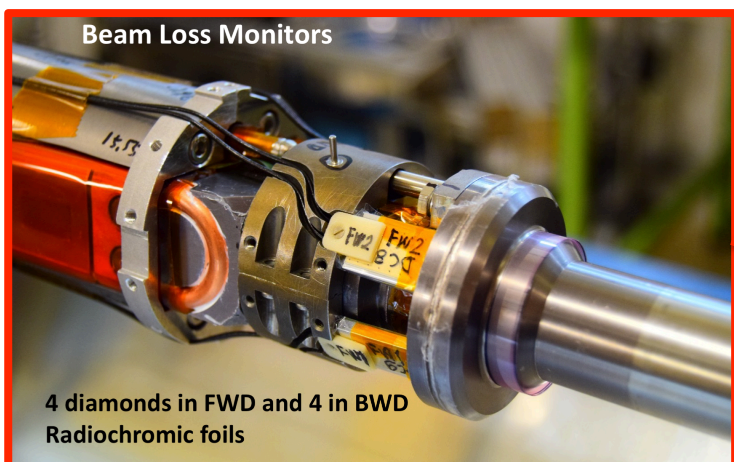
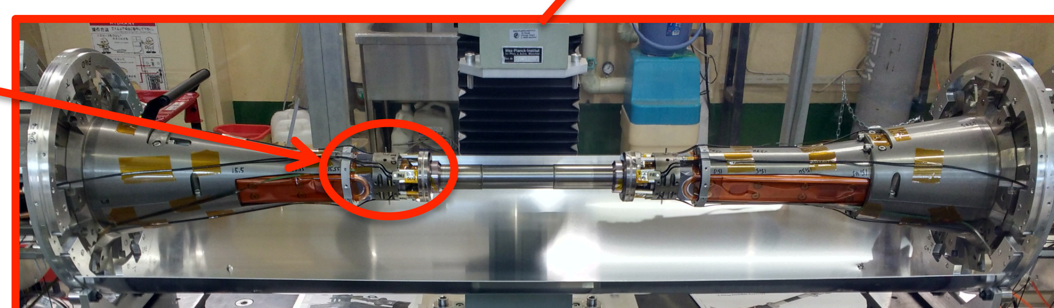
- Diamond sensors in HEP
- Detection of charged particles by ionization
- Diamonds as “solid-state ionization chambers”
- Characterization of diamond sensors with α-particles
- Experimental set-up and data collection
- Data analysis challenge

Diamonds in HEP: active research

- RD42 Collaboration & High Luminosity LHC at CERN
  - ATLAS Diamond Beam Monitor (DBM)
  - CMS Pixel Luminosity Telescope (PLT)
- Belle II experiment at the SuperKEKB collider (Japan)
  - Belle II Radiation Monitor and Beam Abort system
  - SuperKEKB bunch-by-bunch Luminosity Monitor

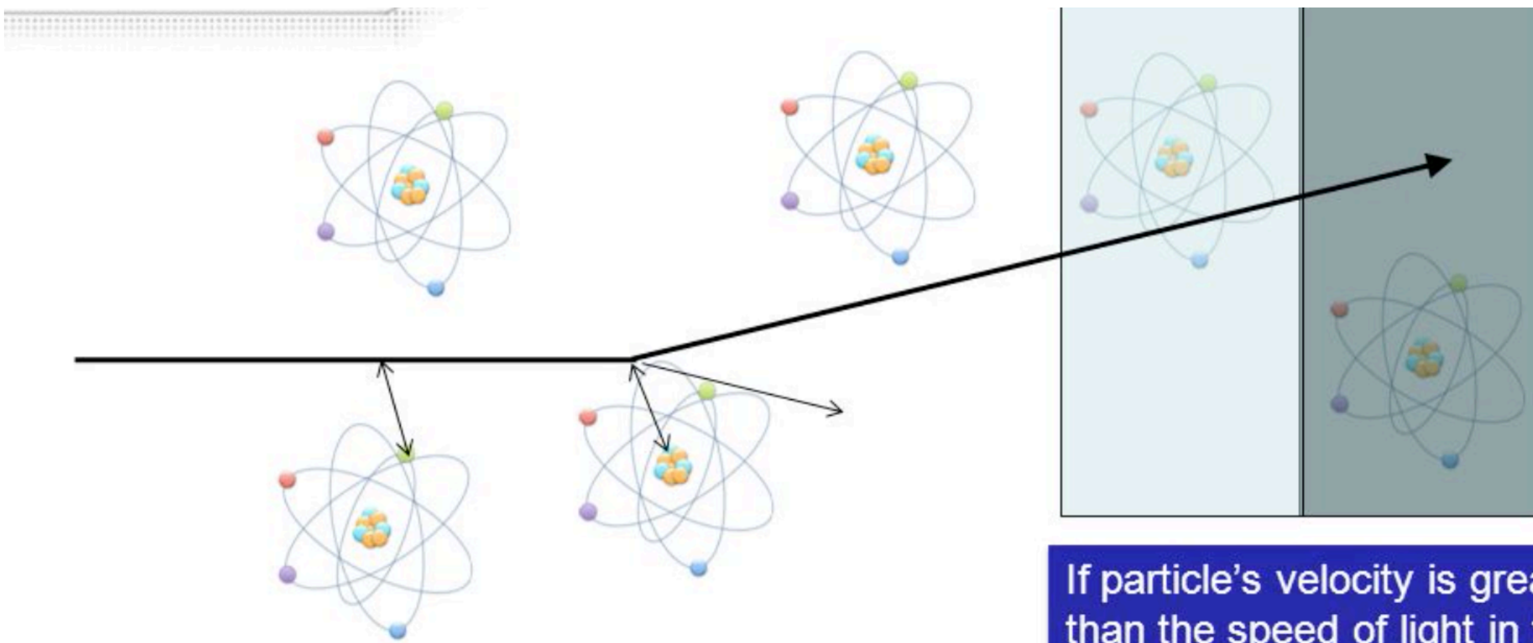






Particle detection by ionization

Energetic particles are *mainly* (not only!) detected by their energy lost in matter by ionization, directly (charged particles) or indirectly (neutral particles)



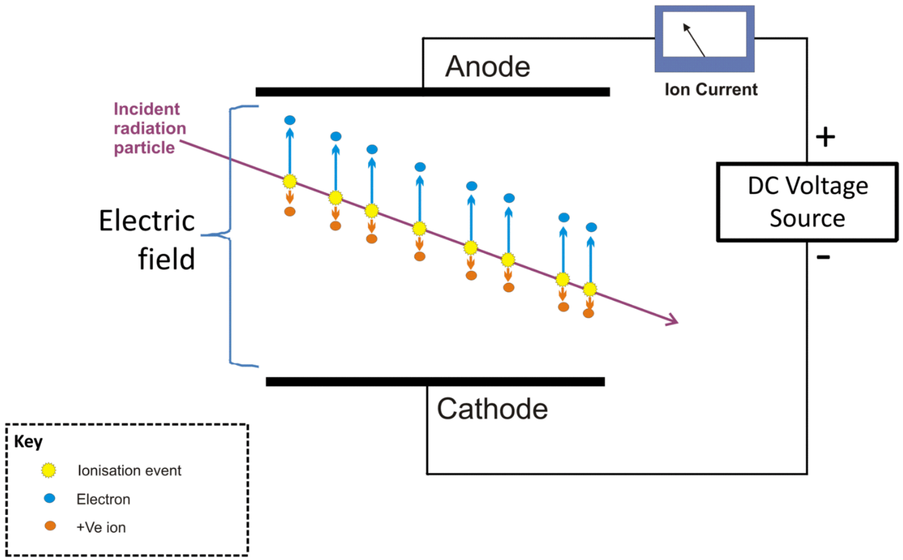
Interaction with atomic electrons. Particle loses energy; atoms are excited or ionized.

Interaction with atomic nucleus. Particle undergoes multiple scattering. Could emit a bremsstrahlung photon.

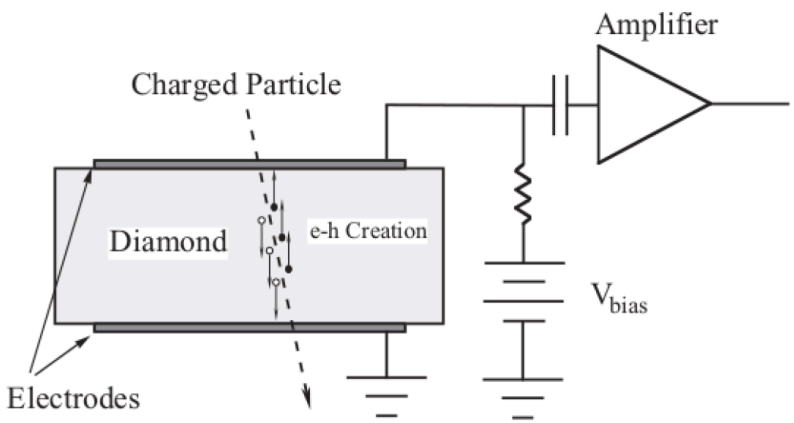
If particle's velocity is greater than the speed of light in the medium -> Cherenkov Radiation. When crossing the boundary between median, ~1% probability of producing a Transition Radiation X-ray.

Diamonds: solid state ionization chambers

Parallel-plate ion chamber
filled with gas



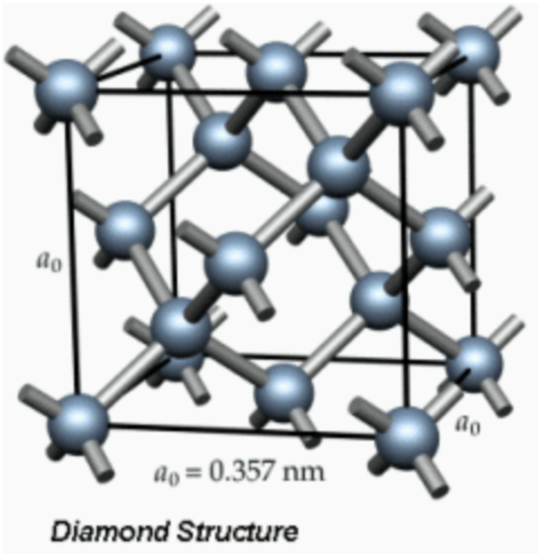
Artificial diamond,
single- or poly-crystal,
with deposited metal electrodes



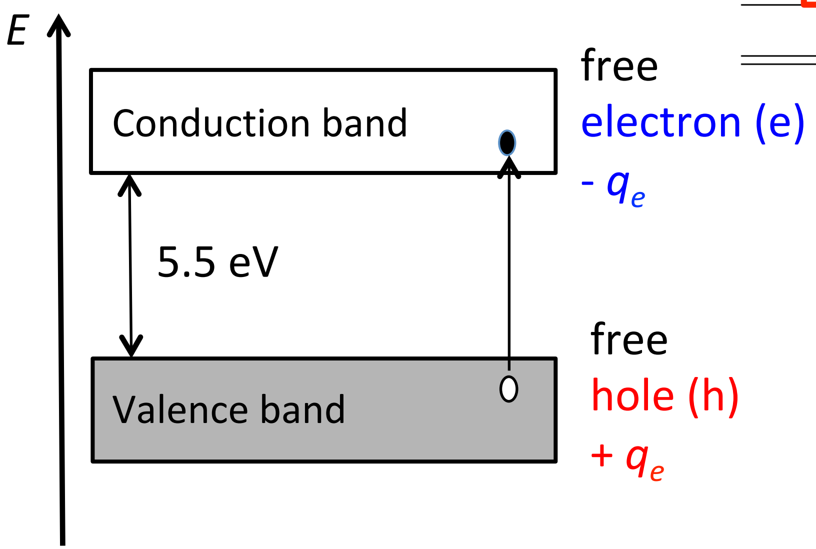
electrons and ions drift towards opposite electrodes, and diffuse (electrons 1000 times faster than ions)

electrons and holes drift towards opposite electrodes, and diffuse (electrons and holes, similar speed)

Diamond: a "wide-gap semiconductor"



Property	Diamond	Silicon
Atomic number Z	6	12
Number of atoms N $[10^{22}\mathrm{cm}^{-3}]$	17.7	5.0
Mass density ρ $[g\,\mathrm{cm}^{-3}]$	3.53	2.33
Band gap E_g [eV]	5.47	1.12
Resistivity ρ_c $[\Omega\,\mathrm{cm}]$	$> 10^{12}$	2.3×10^{5}
Electron mobility μ_e $[\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}]$	1800	1350
Hole mobility μ_h $[\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}]$	1200	480
Electron saturation velocity v_e^s $[10^6\mathrm{cm\,s}^{-1}]$	26	10
Hole saturation velocity v_h^s $[10^6\mathrm{cm\,s}^{-1}]$	16	7
Thermal conductivity k $[\mathrm{W\,cm}^{-1}\mathrm{K}^{-1}]$	21.9	1.5
Energy to create e-h pair E_{eh} [eV]	13	3.6
Displacement energy E_d [eV/atom]	42	15



Forbidden band gap:

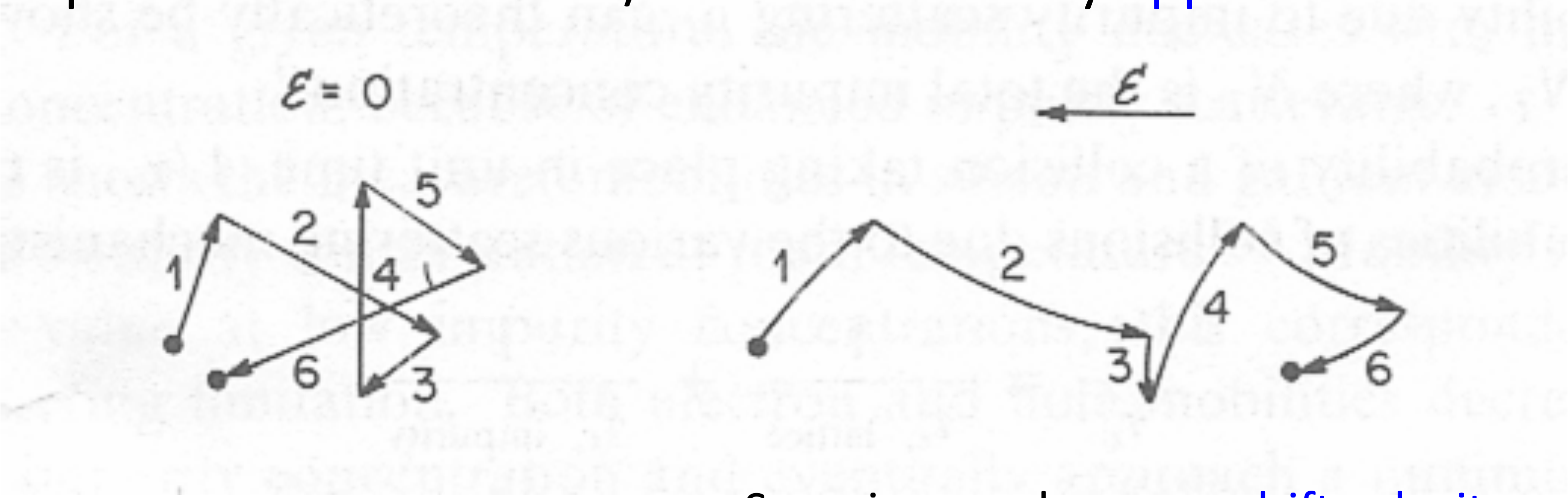
≈ 5.5 eV

Average energy to create an e-h pair:

≈ 13 eV

Applied E-field: drift of electrons, holes

Example: electrons without/with an externally applied electric field



Random thermal motion: diffusion only

Superimposed average drift velocity due to E-field (similar for holes)

$$v_{e,x} = -\mu_e E_x$$

$$v_{h,x} = \mu_h E_x$$

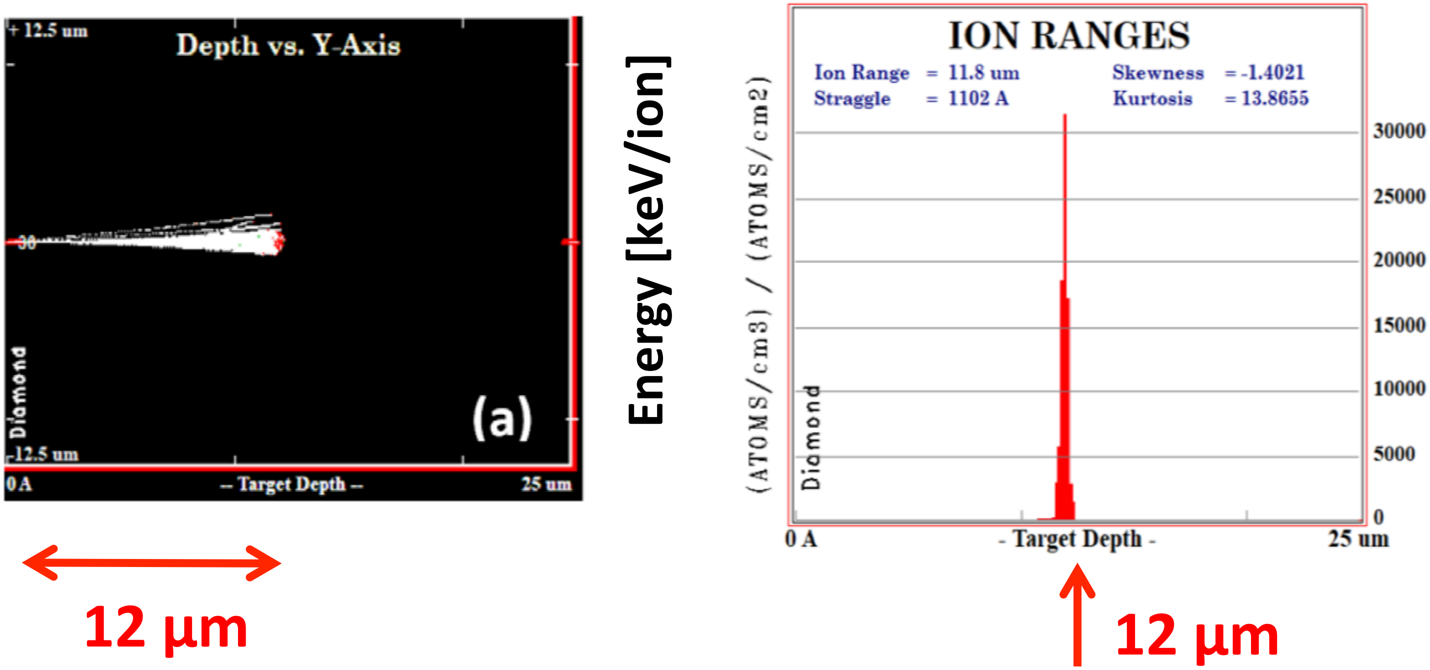
μ_e, μ_h : mobility

NB: *not so simple*…

Free electrons and holes may be captured by “traps” => space charge, distorted E_x

Charge carriers may be injected at the metallic electrode − diamond interface

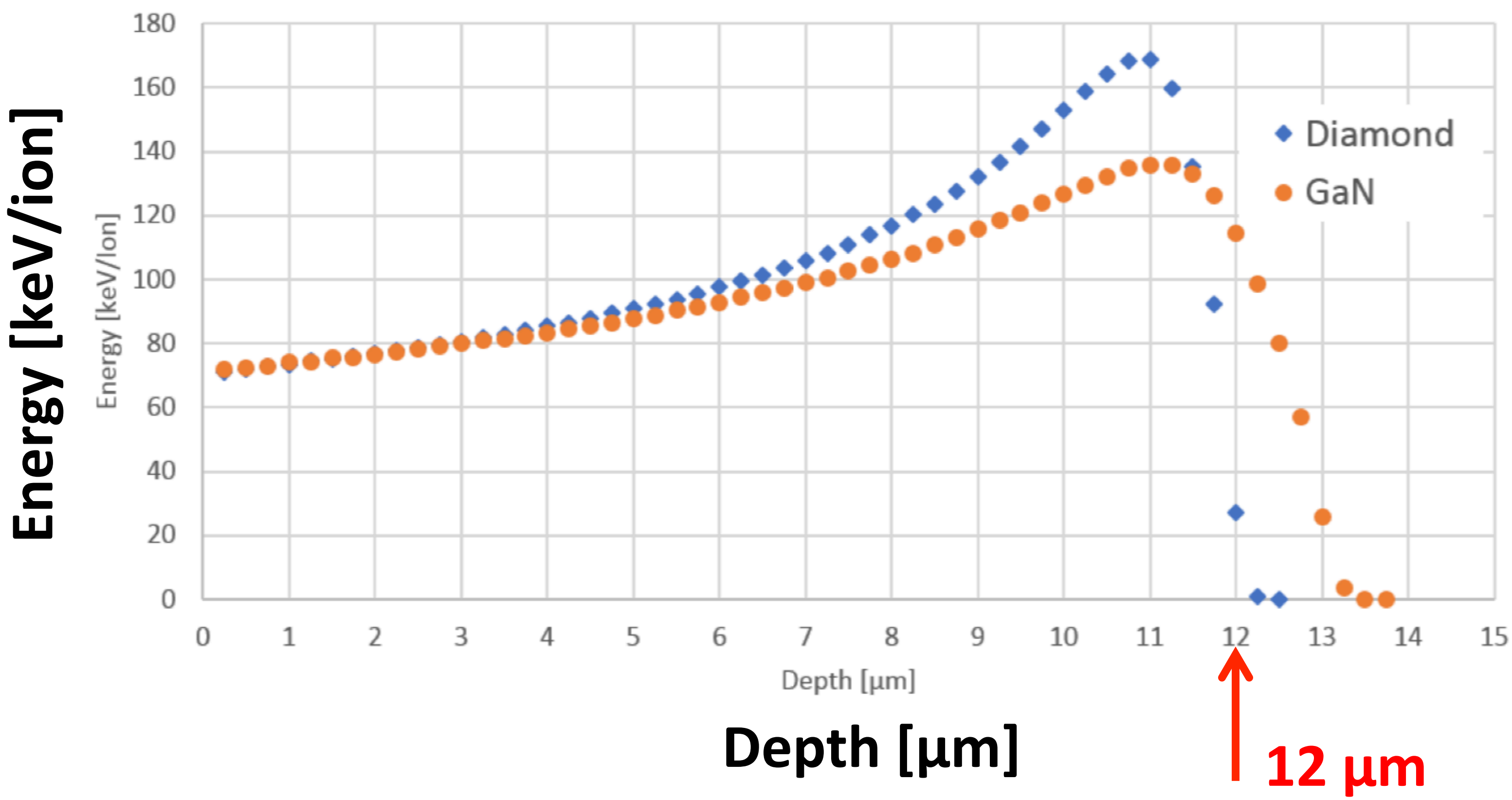
α-particles to test diamond sensors



Simulation of 5.5 MeV α-particles from ^{241}Am radioactive source:

their *range* (penetration depth) is ≈ 11 ÷ 12 µm in diamond

Energy deposit of α-particles in diamond



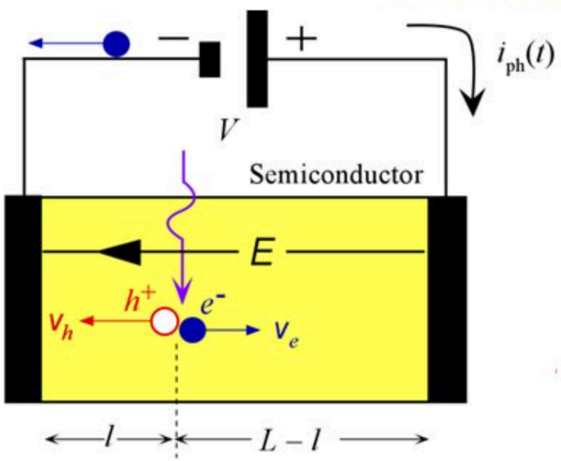
5.5 MeV α-particles from ^{241}Am source

5.5 MeV lost within 11-12 µm
=> small cloud of *e*-*h* pairs
close to the entrance surface

Current induced by the motion of charges

Moving electrons induce a current pulse in the external circuit (*sign changes for* holes)

Shockley-Ramo Theorem



External photocurrent due to the motion of this photogenerated electron is $i_e(t)$.

The electron is acted on by the force eE of the electric field.

When it moves a distance dx, work must be done by the external circuit. In time dt, the electron drifts a distance dx and does an amount of work $eEdx$

Work done $eEdx$ is provided by the battery in time dt

Electrical energy provided by the battery in time $dt = Vi_e(t)dt$

Thus, $eEdx = Vi_e(t)dt$. In time dt, the electron drift a distance $dx = v_e dt$

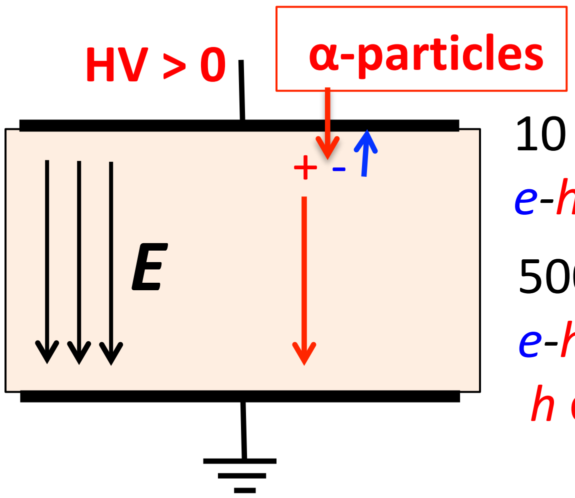
$$eEdx = Vi_e(t)dt \Rightarrow e(V/L)(v_e dt) = Vi_e(t)dt \Rightarrow i_e(t) = \frac{ev_e}{L}$$

i_e flows **while the electron is drifting**, for a time $t_e = (L - l)/v_e$

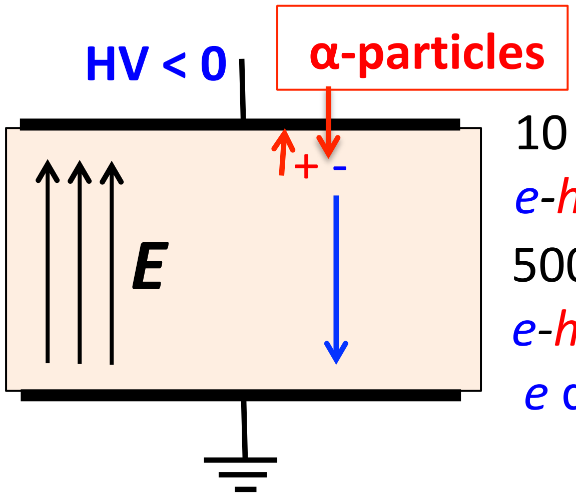
Expected signals from α-particles (1)

Parallel plane electrode configuration

e, *h* drift in uniform *E*-field (neglect trapping & space charge)



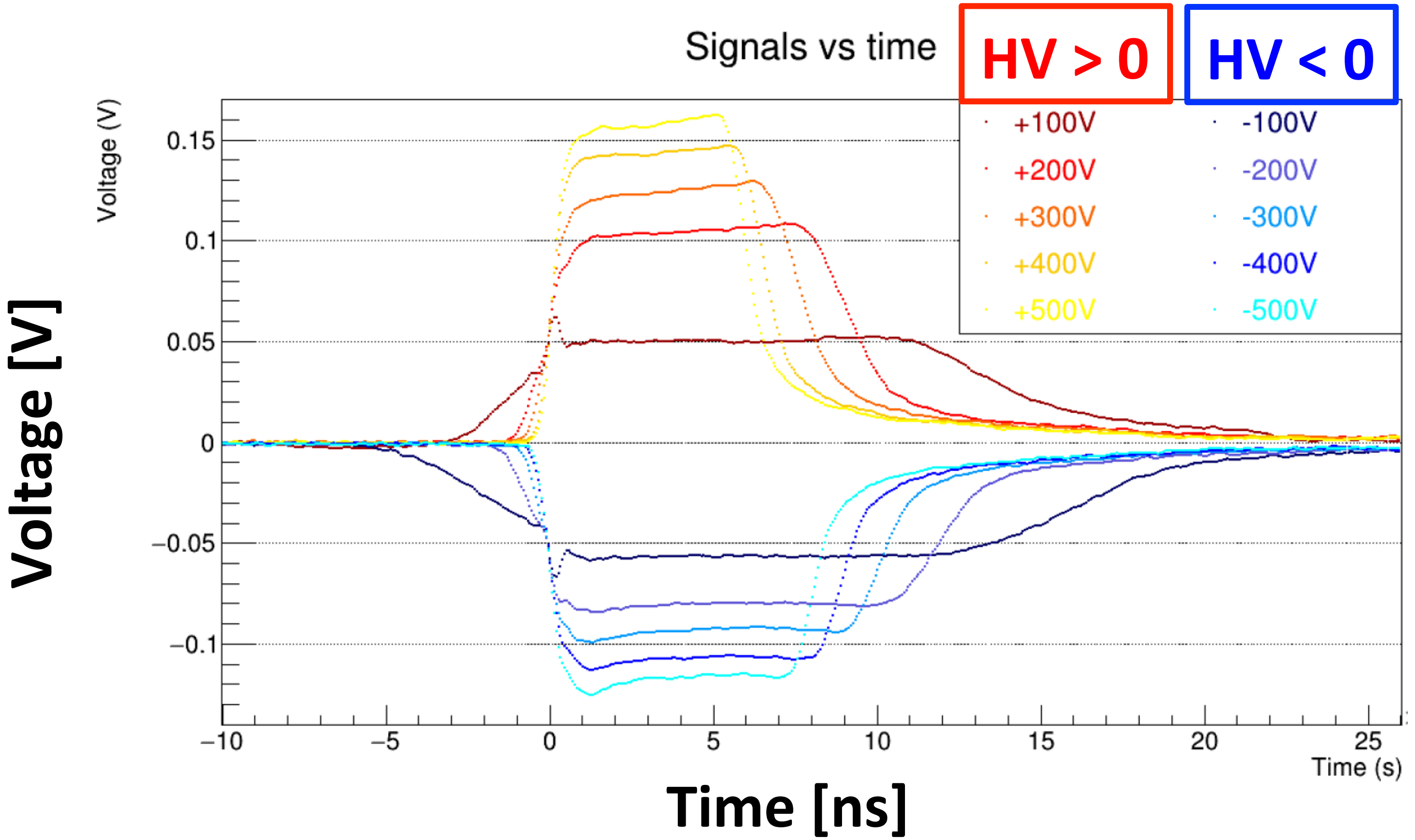
10 µm
e-*h* creation
500 µm
e-*h* separation
h drift



10 µm
e-*h* creation
500 µm
e-*h* separation
e drift

Reversing *HV polarity* and *E-field*:
select the charge carrier that drifts in ≈ 500 µm
⇒ Measure the transport properties
of electrons and holes *separately*

Expected signals from α-particles (2)



Current pulse in the external circuit: $i(t) = Q(t)\, v(t)/d$

Voltage pulse after amplification with voltage gain G:

$$V(t) = G \cdot V_{in}(t) = G \cdot Z_{in} \cdot i(t)$$

Measurements with α-particles

Measure $V(t)$ for several HV values (positive and negative)

Average over 1000 pulses to filter background noise

Extract $i(t) = V(t)/(G \cdot Z_{in})$ where:

- G is the amplifier voltage gain
- Z_{in} is the amplifier input impedance

Qualitative interpretation:

if $i(t)$ flat, rectangular pulse => uniform E-field, no trapping

Quantitative results:

Total charge: $Q = \int_{t_i}^{t_f} i(t)\,dt$ => charge collection efficiency

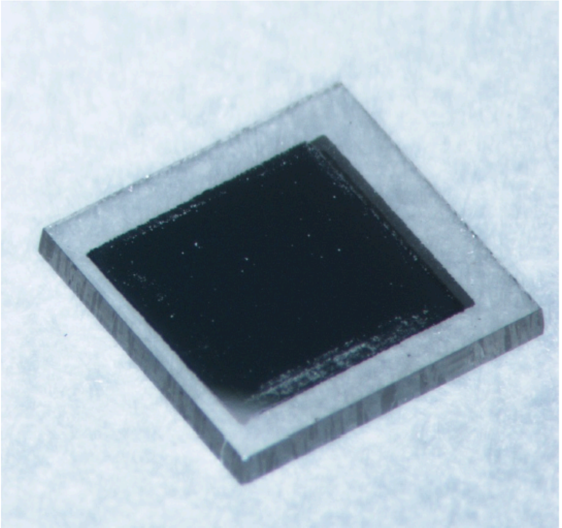
=> energy required per *e*-*h* pair

Drift time: $\Delta t = t_f - t_i$ => drift velocity for *e*, *h*

=> mobility for *e*, *h*

EXPERIMENTAL SET-UP
DATA COLLECTION AND ANALYSIS

Our diamond sensors

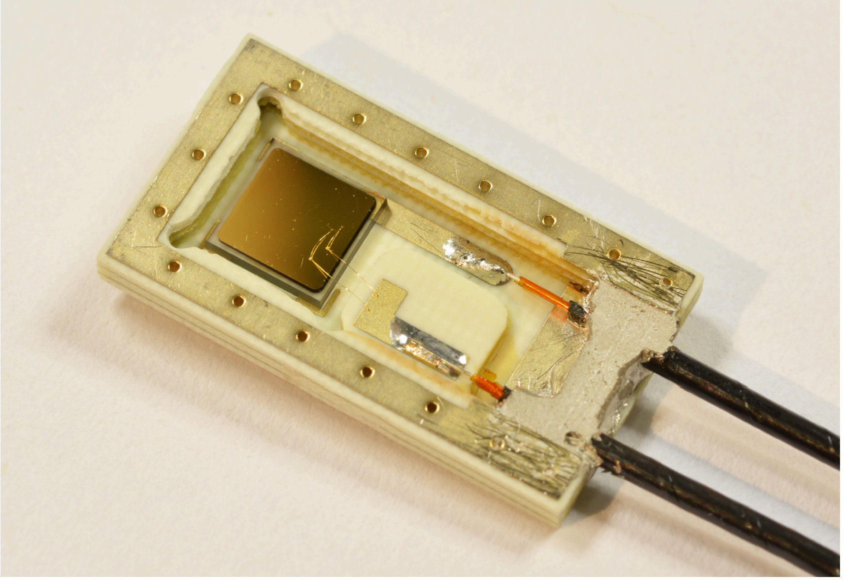


Single crystals, grown by
Chemical Vapour Deposition (s-CVD)

(4.5 x 4.5 x 0.5) mm^3

Ti + Pt + Au electrodes

(100 + 120 + 250) nm



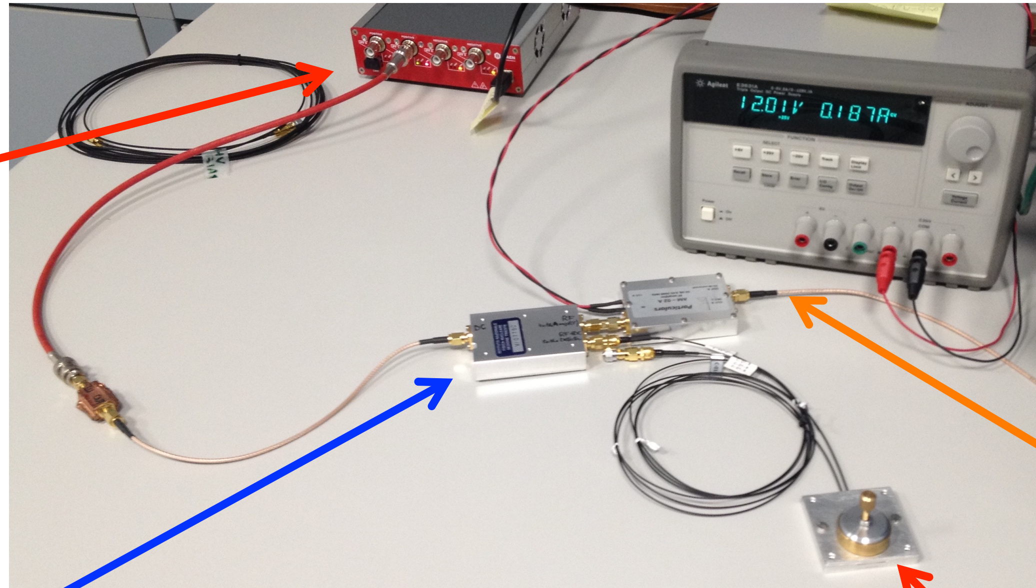
Diamond sensor glued on a metallized ceramic package

electrodes connected to coax cables

enclosed in an aluminum holder (not shown)

Experimental set-up

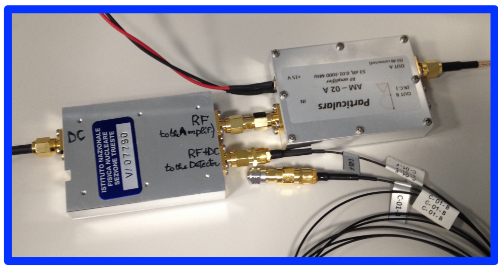
HV Power Supply
(- 800 V ÷ + 800 V)



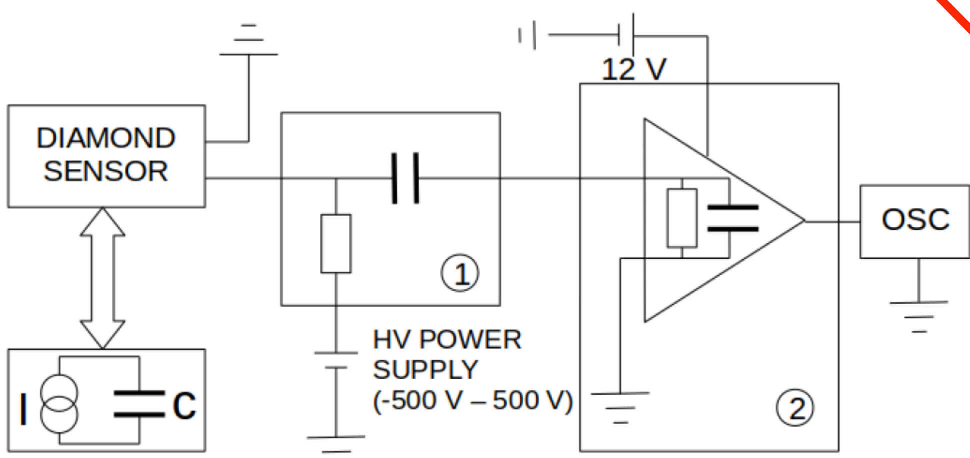
Power Supply for Amplifier (12 V)

Signal to Oscilloscope

Holder of Diamond Sensor and Alpha Source



DECOUPLER (1)
AMPLIFIER (2)



Data collection

Set HV = -200 V, take 1000 self-triggered α-events
transfer averaged data from scope to PC

↓

Repeat, after setting HV = -400 V, -600 V, -800 V

↓

Change polarity to HV > 0

↓

Repeat, after setting HV = +200, +400 V, +600 V, +800 V

↓

Off-line data analysis

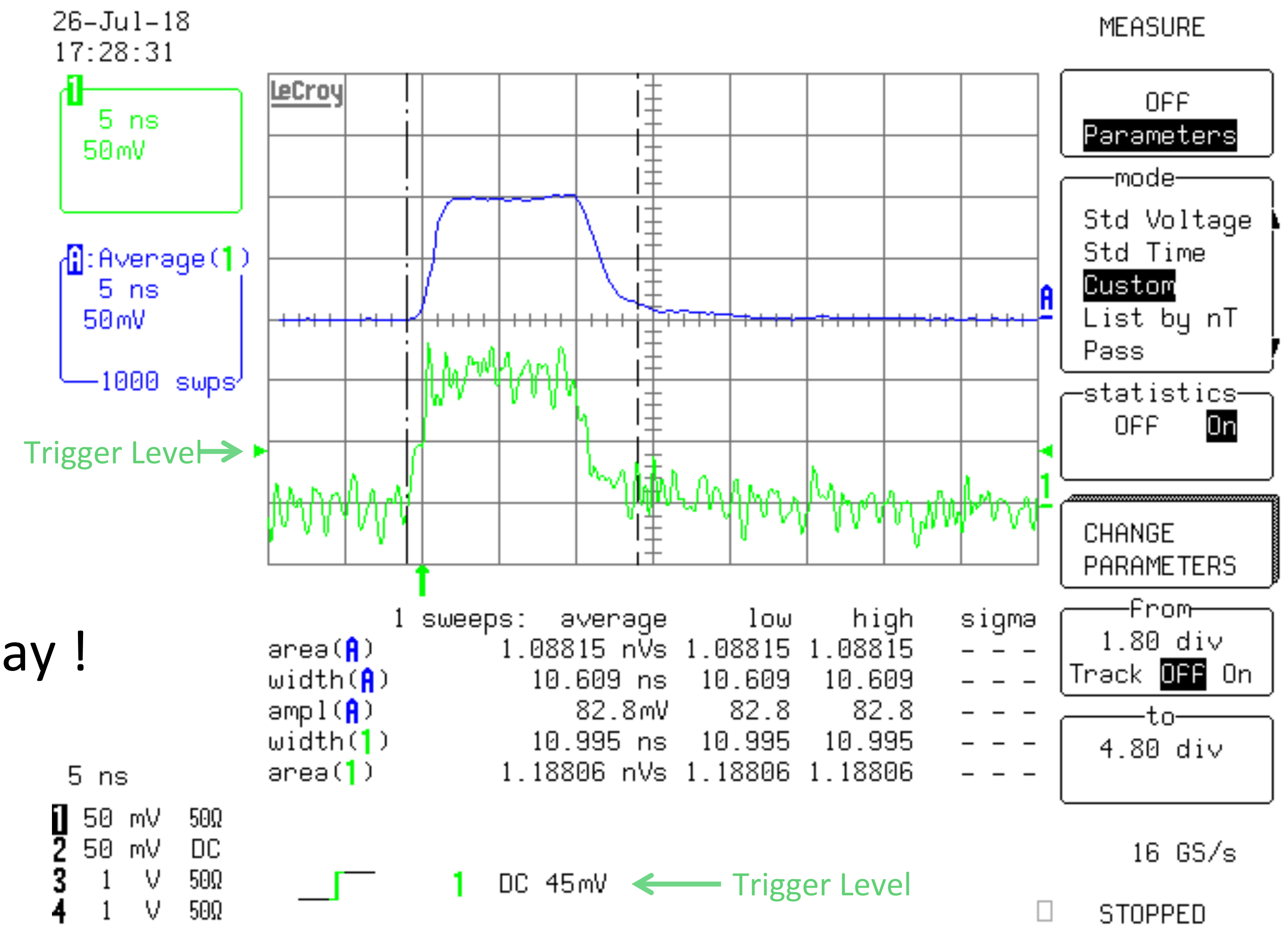
Data analysis - 1

Example of scope screenshot, after collecting 1000 events: TCT_200V_Positive.BMP

Single event

Average

The average filters noise away !



Data analysis - 2

```
LECROYWP960XL,1064
Segments,1,SegmentSize,796
Segment,TrigTime,TimeSinceSegment1
#1,26-Jul-2018 17:16:06,0
Time,Ampl
-1.003e-08,-9.76525e-05
-9.969e-09,-0.000262447
-9.906e-09,-0.000433346
-9.844e-09,-0.000500485
-9.781e-09,-0.000482174
-9.719e-09,-0.000317379
-9.656e-09,-0.000170895
-9.594e-09,-0.00012817
-9.531e-09,-0.000140377
-9.469e-09,-0.000427242
-9.406e-09,-0.000695797
-9.344e-09,-0.000939938
-9.281e-09,-0.00107422
-9.219e-09,-0.00107422
-9.156e-09,-0.000933834
```

...**etc**

header

Data format:
Text file,
can be imported
to EXCEL

Averaged data points
Time [s], Amplitude [V]

Data analysis - 3

Preliminary step:

From output voltage back to input current, using amplifier voltage gain G and input impedance Z_{in} = 50 Ω:

$$V_{in} = V_{out}/G$$

$$I_{in} = V_{in} / Z_{in}$$

Then, some quantitative results:

Total charge: $Q = \int_{t_i}^{t_f} i(t)\,dt$ => charge collection efficiency

=> energy required per *e*-*h* pair

Drift time: $\Delta t = t_f - t_i$ => drift velocity for *e*, *h*

=> mobility for *e*, *h*

Analysis program (Excel)

Screenshot from the analysis program (Excel spreadsheet): can be downloaded from the link, material for this lecture

Input constants

Diamond	Thickness *d*	Bias Voltage	Average *I*	Average *E*		Hole Mobility *μ*	Energy deposited in Diamond	Ionization Energy
DC01	[cm]	[V]	[A]	[V/cm]		[cm^2/(V·s)]	[eV]	[eV]
	5.0E-02	800	8.5E-06	1.6E+04		5.4E+02	5.17E+06	1.7E+01
Input Z	Ampl. Gain	Ampl. Gain	Baseline Current	*Qtot*				
[Ω]	[dB]	[x1]	[A]	[C]				
50.0	52	3.981E+02	-2.514E-08	4.982E-14				

Time	Output Voltage	Input Voltage	Input Current	Cumulative Charge	*Q/Qtot* = *x/d*	v_{drift}
[s]	[V]	[V]	[A]	[C]		[cm/s]
-1.003E-08	-5.859E-04	-1.472E-06	-2.944E-08	0	0.000E+00	
-9.969E-09	-5.920E-04	-1.487E-06	-2.974E-08	-2.806E-19	-5.631E-06	-3.0E+04
-9.906E-09	-5.005E-04	-1.257E-06	-2.514E-08	-2.806E-19	-5.631E-06	-2.5E+04
-9.844E-09	-4.456E-04	-1.119E-06	-2.238E-08	-1.095E-19	-2.197E-06	-2.2E+04

1.0E-(

Input oscilloscope data, imported from the text file

Analysis challenge

- Download excel spreadsheet and data files
- Understand the spreadsheet logics and formulae
- Import data from each text file (one per HV value) to the spreadsheet
- Compute the following quantities for at least one positive and one negative HV value:
  - Total collected charge Q
  - Averaged energy (in eV) used to generate an e-h pair
  - Drift time and drift velocity for electrons and holes
  - Mobility for electrons and holes
- Write a short report in your preferred format

A prize for the best report (teams of up to 5 participants)…!

BACK-UP SLIDES

Further reading

- Interactions of particles with matter:

  http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf

- Particle detectors at accelerators

  http://pdg.lbl.gov/2018/reviews/rpp2018-rev-particle-detectors-accel.pdf

- Artificial diamonds

  Satoshi Koizumi, Christoph Nebel, and Milos Nesladek. Physics and applications of CVD diamond. John Wiley & Sons, 2008.

- Diamond sensors in HEP

  https://www.sciencedirect.com/science/article/pii/S0168900216300560

… more on Ramo's theorem

Photodetectors

RAMO's Theorem and External Photocurrent

- An EHP is photogenerated at $x = l$. The electron and the hole drift in opposite directions with drift velocities v_h and v_e.
- The electron arrives at time $t_{electron} = (L-l)/v_e$ and the hole arrives at time $t_{hole} = l/v_h$.