In-depth characterization of semiconductor particle detectors: silicon diodes and microstrips

Theory:
- Silicon
- n-p doping
- pn junction
- Silicon detectors

Exp. 1:
Electrical characterization of Silicon Diodes:
IV, CV characteristics

Theory:
Signal formation in any system with electrodes

Experiments:
Laser Transients Induced currents (TCT)

Marcos Fernandez Garcia - Santander, 7th January 2019

A bit of theory: Si, p n doping

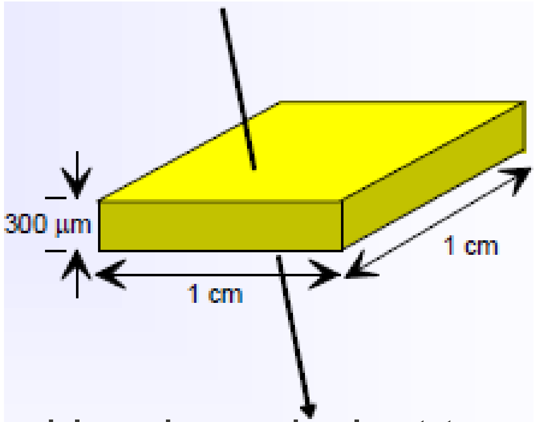
The problem: getting rid of free carriers in Si

- We want to detect ionization due to a crossing particle.
- Si atomic density is ~10^{22} cm$^{-3.}$ Intrinsic carrier concentration n_i~10^{10} cm^{-3}

→ 1 in 10^{12} atoms loose an electron at RT

- In the volume shown to the right, we have **4.5·10^{8}** free carriers.

About **32000** eh would be produced by a crossing particle (MIP) Finding these 32000 charges in 10^8 is not possible. We need to remove these free charges.



More complex problem than finding a needle in a haystack. This problem is equivalent to finding 33 cl of your glass of water in a swimming pool.

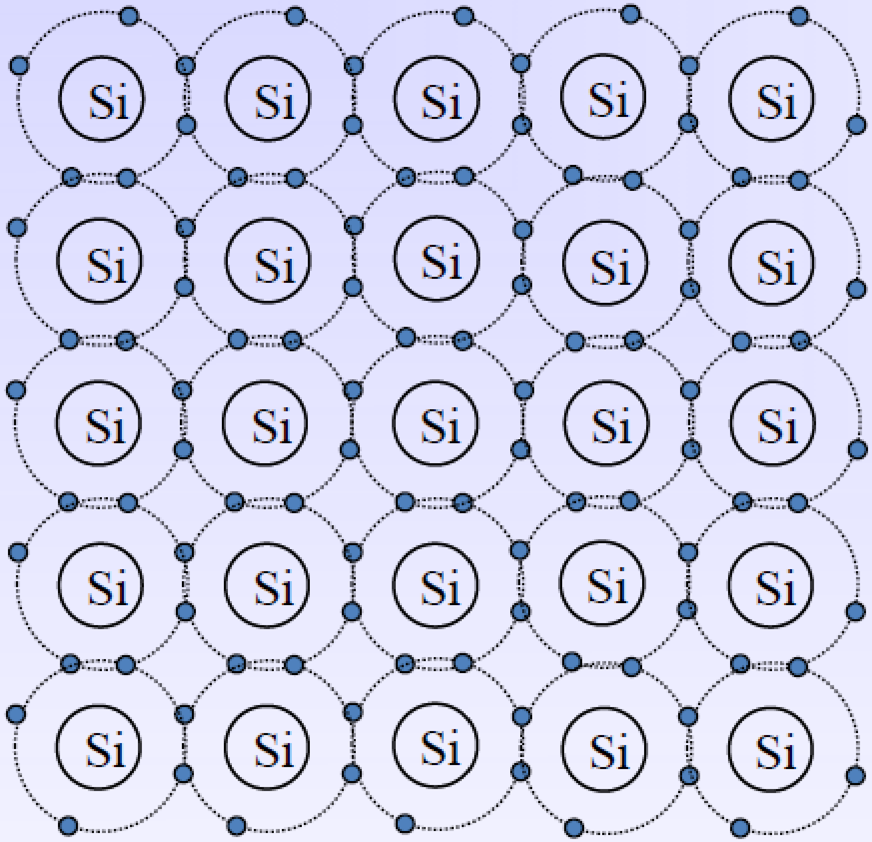
dayala0001c fotosearch.com

The problem: getting rid of free carriers in Si

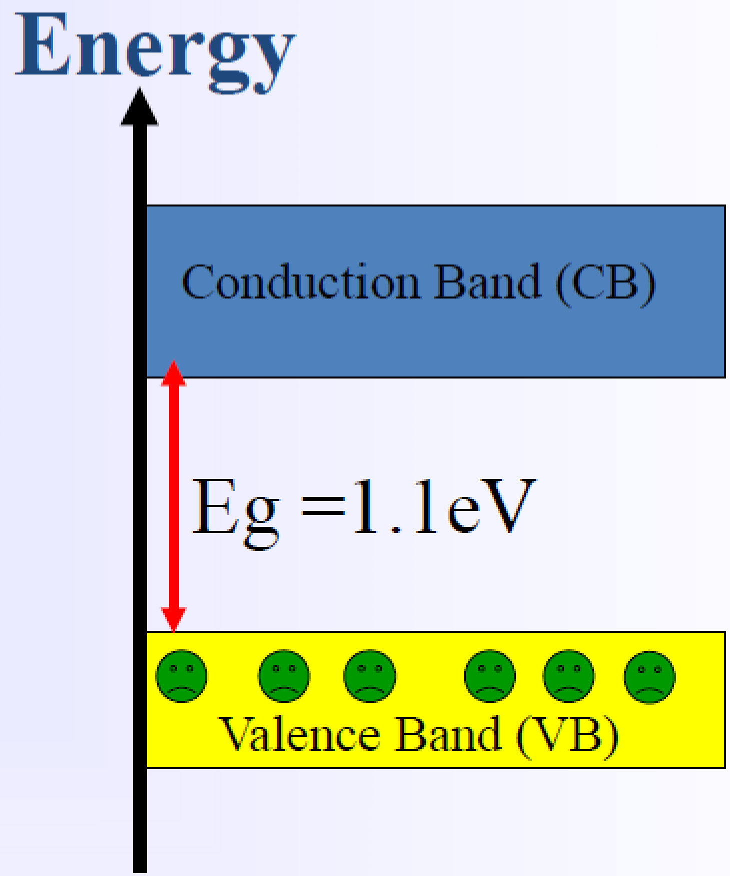
- If you apply a potential difference to a Si slab, you will get a continuous current due to the thermally generated carriers, and you will still not distinguish the small contribution from ionizing particle.

- Depleting **intrinsic** Si of charge carriers is not possible. However a bulk of **doped Si can be depleted**. Trick is realized using a junction of ***n*** and p***-doped*** Si.

Covalent Bonding of Pure Silicon



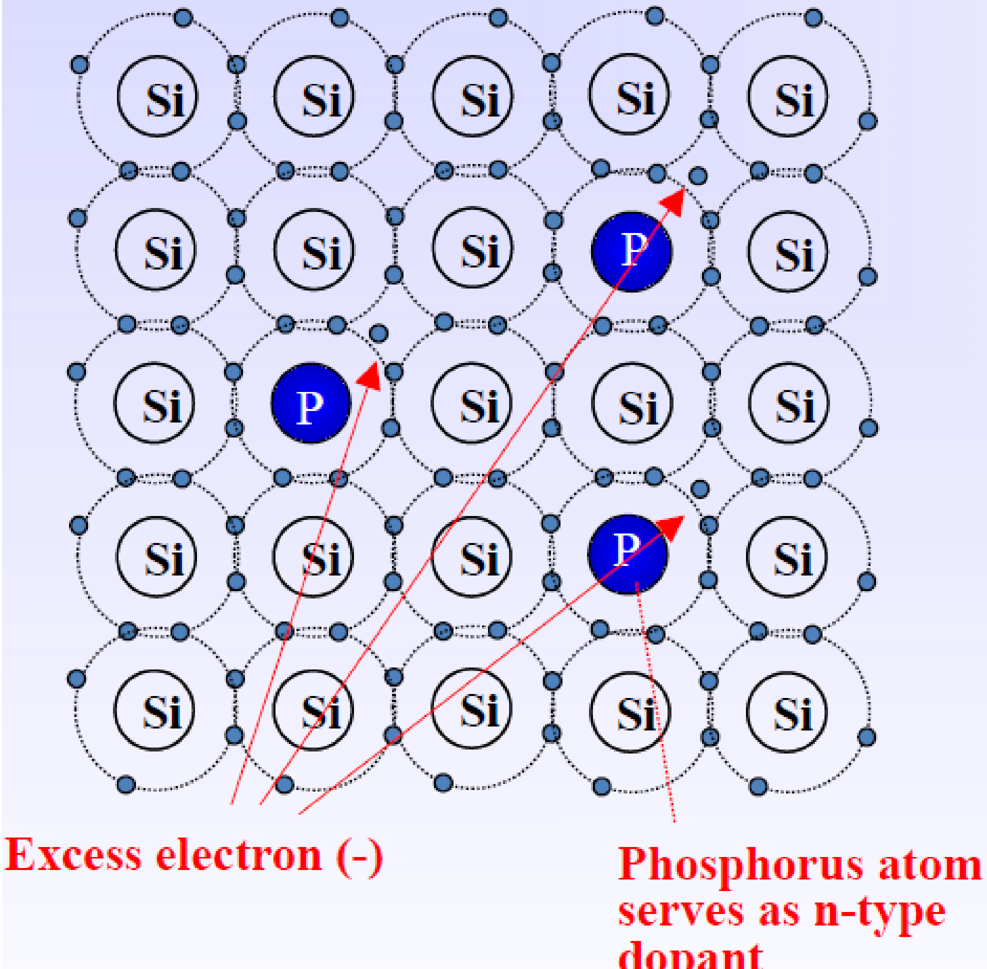
Silicon atoms share valence electrons
to form insulator-like bonds.

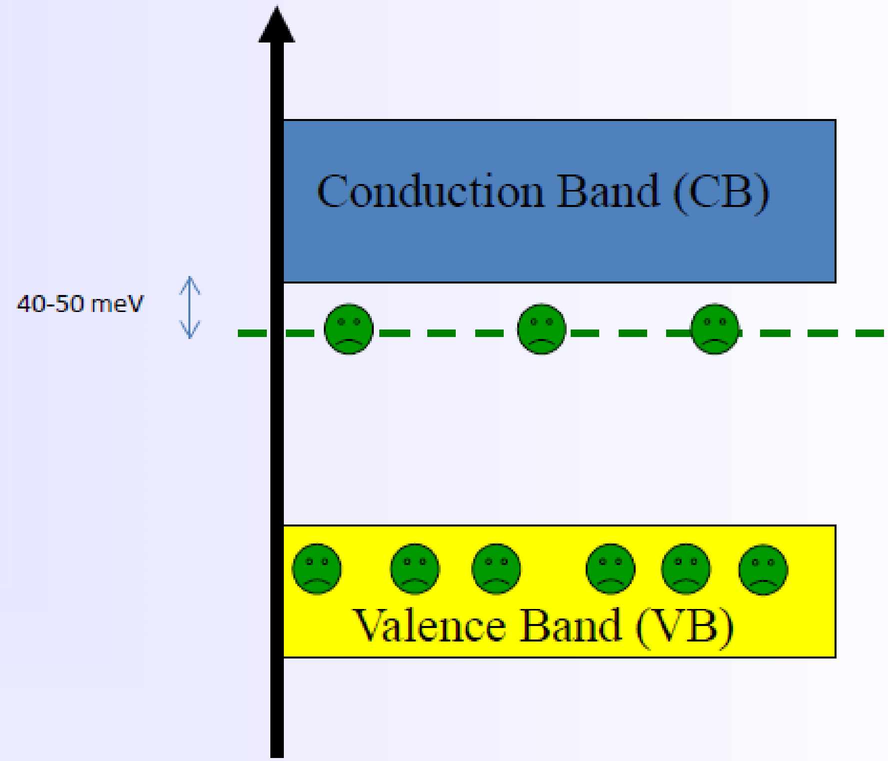


Thermal energy at RT: $\frac{3}{2}k_BT \sim 40$ meV

Electrons in N-Type Silicon with Phosphorus Dopant

Donor atoms provide excess electrons to form n-type silicon.



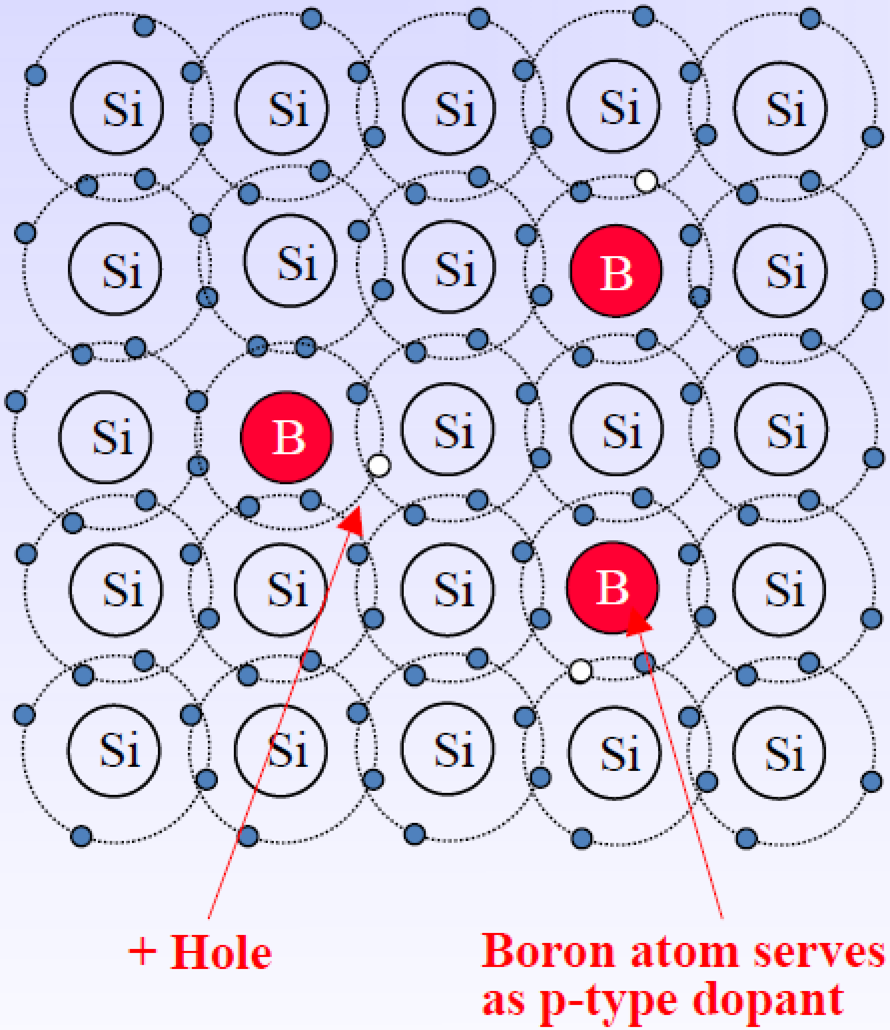


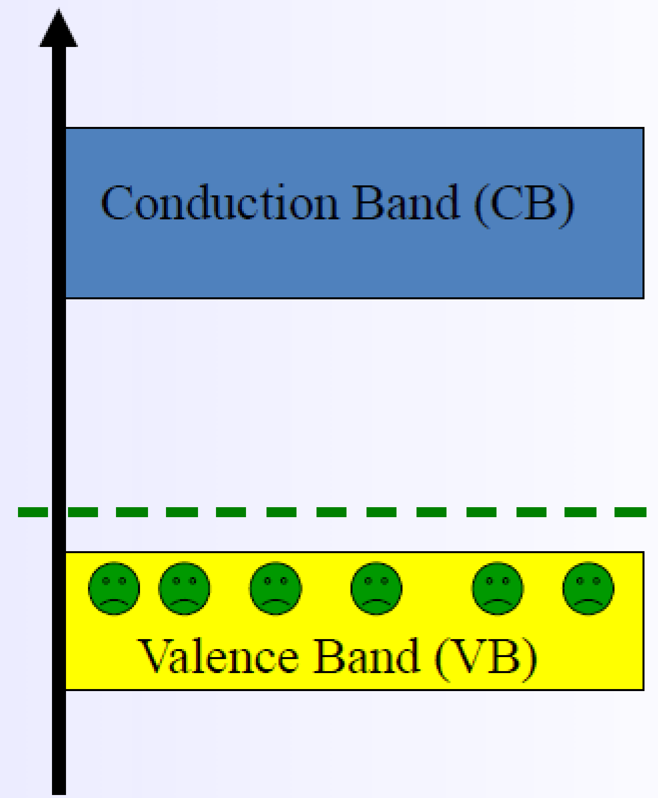
In N-type Si, electrons are the majority charge carriers. They surpass the number of holes by orders of magnitude (n_i~10^{10} cm^{-3}, N_d=10^{12}-10^{18} cm^{-3}):

$$p_n = \frac{{n_i}^2}{N_d}$$

Holes in p-Type Silicon with Boron Dopant

Acceptor atoms provide a deficiency of electrons to form p-type silicon.

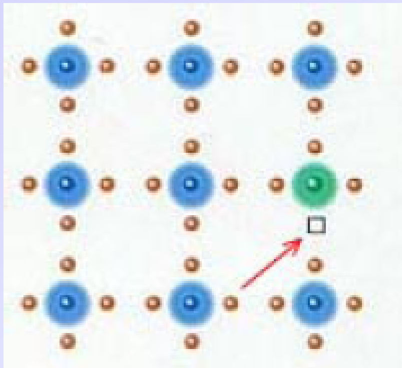




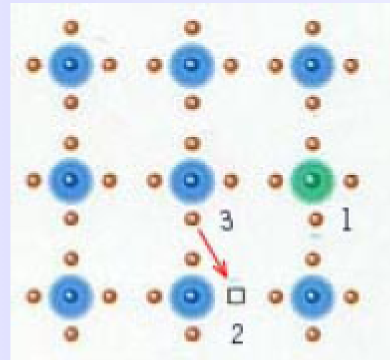
In P-type Si, holes are the majority charge carriers. They surpass the number of electrons by orders of magnitude.

- **Mass action law** (valid for doped/undoped material) relates number of charge carriers of each type in equilibrium: $n \cdot p = n_i^2$

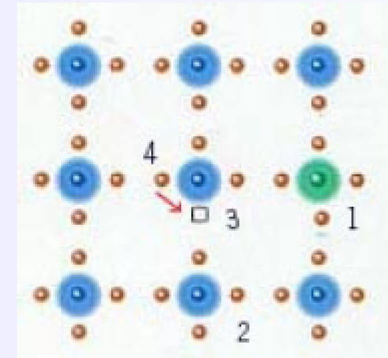
"Hole Movement in Silicon"



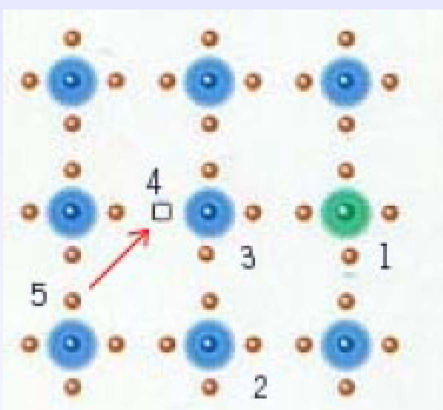
Boron is neutral, but nearby electron may jump to fill bond site.



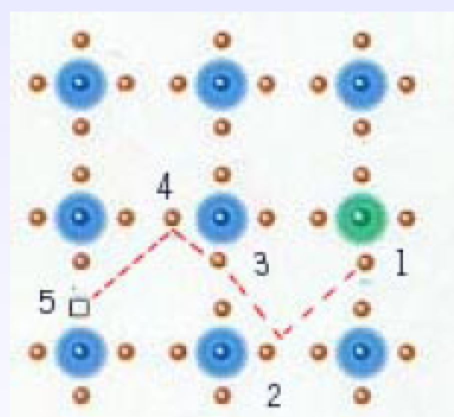
Boron is now a negative ion.



Only thermal energy to kick electrons from atom to atom.

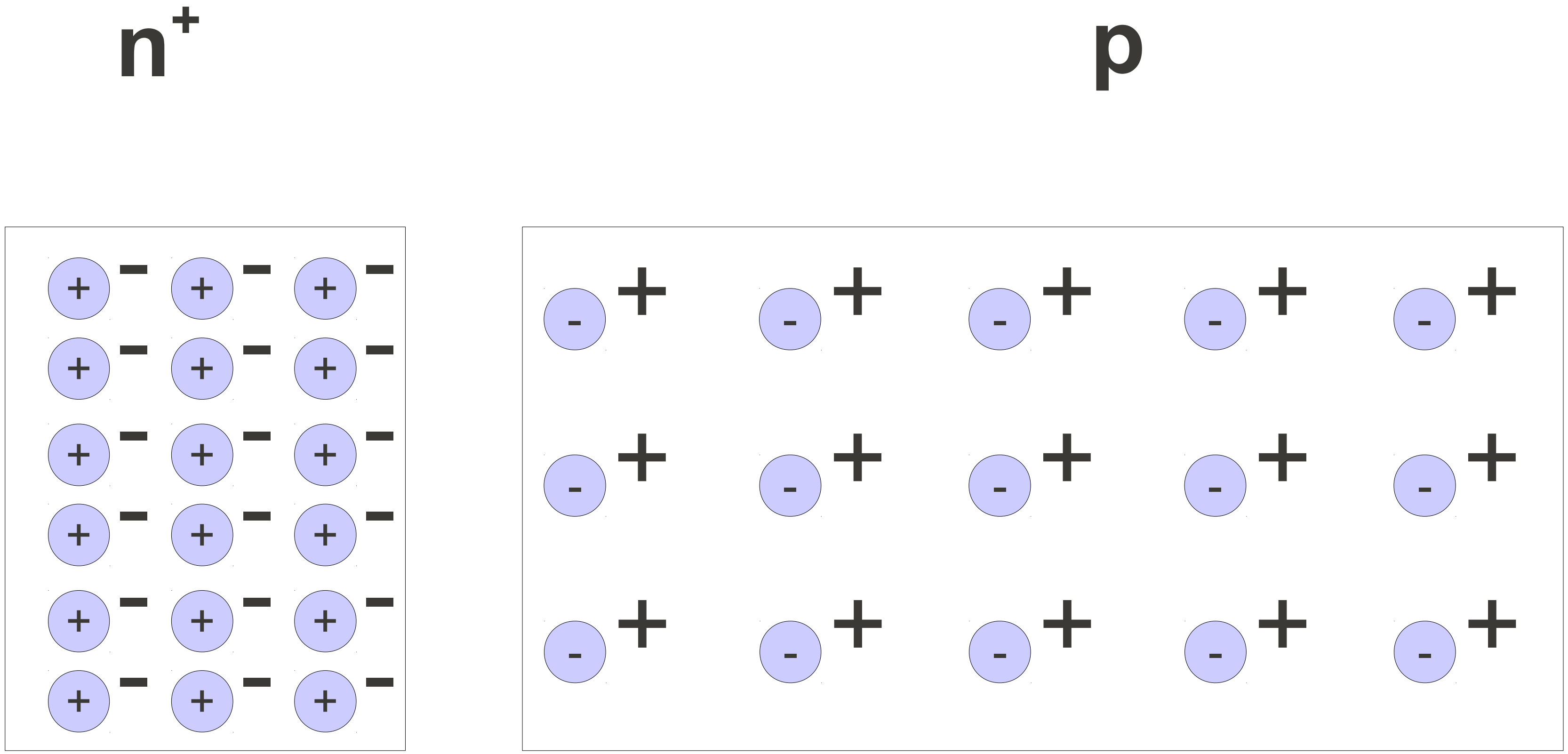


Hole moved from 2 to 3 to 4, and will move to 5.

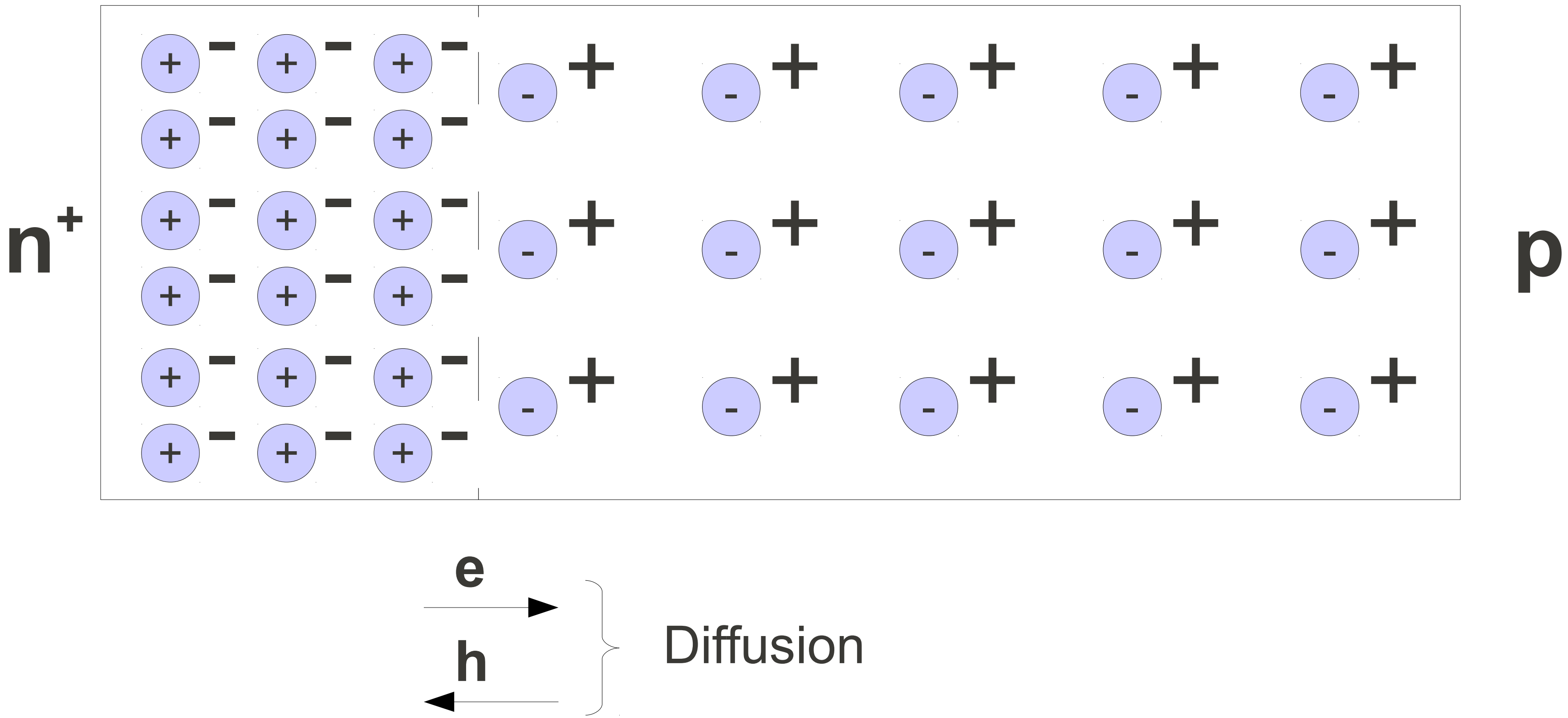


The empty silicon bond sites (holes) are thought of as being *positive*, since their presence makes that region positive.

pn junction



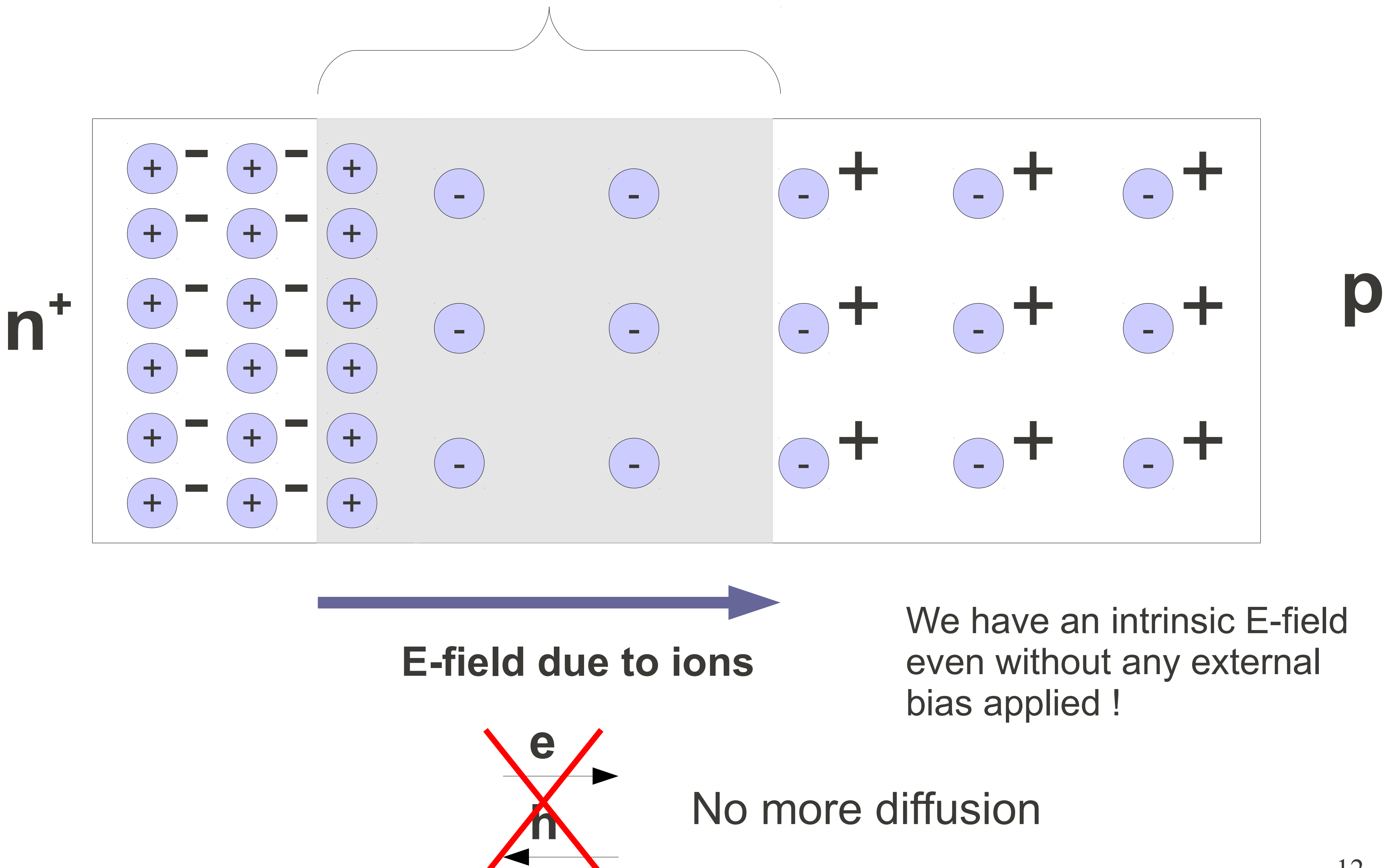
- Sketchy, not to scale
- In detectors, one element of the junction more doped than the other (here, n>>p)



n+
p
e
h
Diffusion

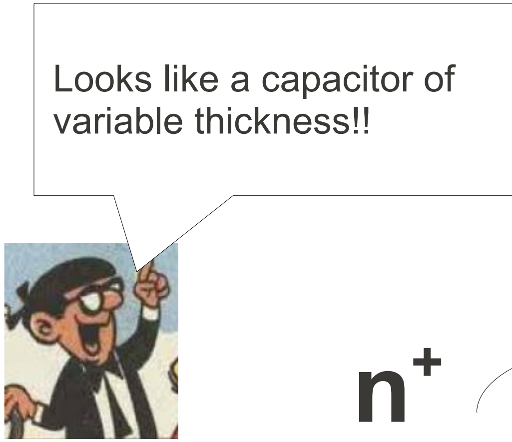
Depleted region: only fixed charges (=*space charge*), no loosely bound carriers

Note that the 1 to 1 recombination of e and h leads to deeper depletion in the less doped p side.

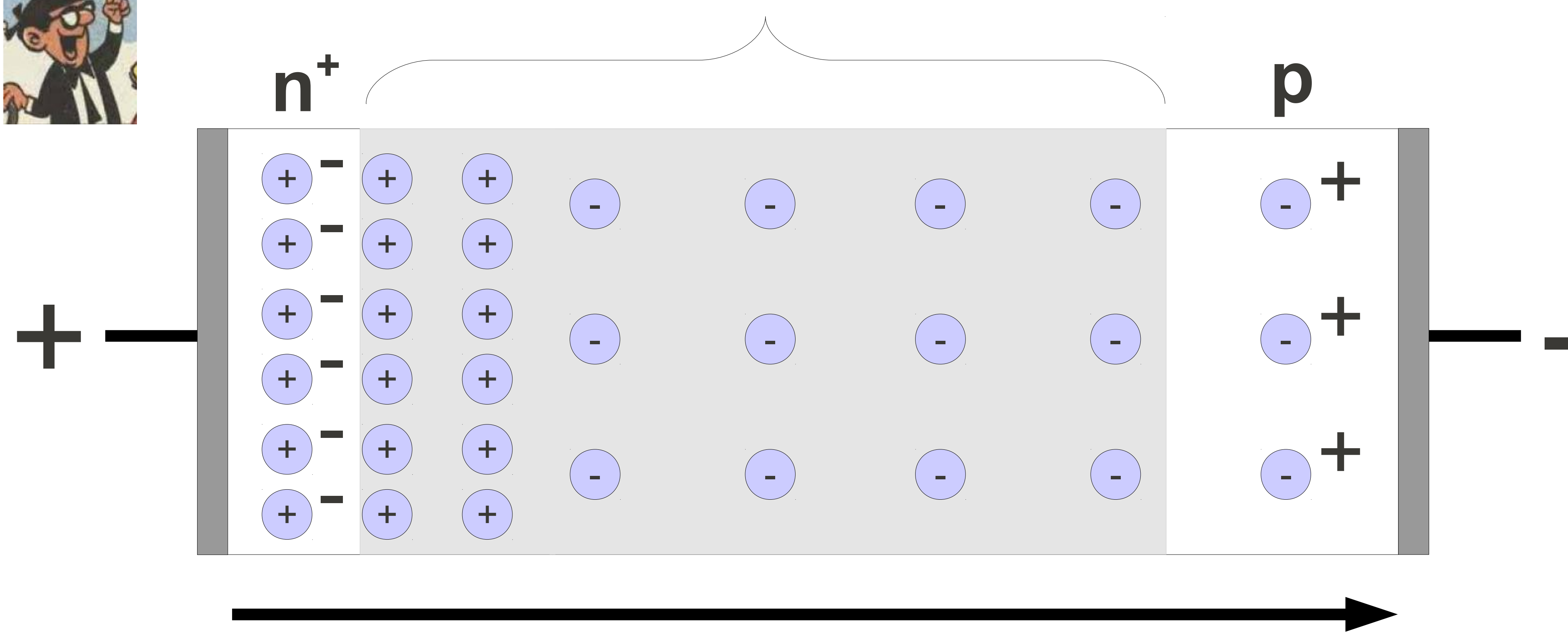


We have an intrinsic E-field even without any external bias applied !

No more diffusion



$V_{bias} < V_{full\ depletion}$



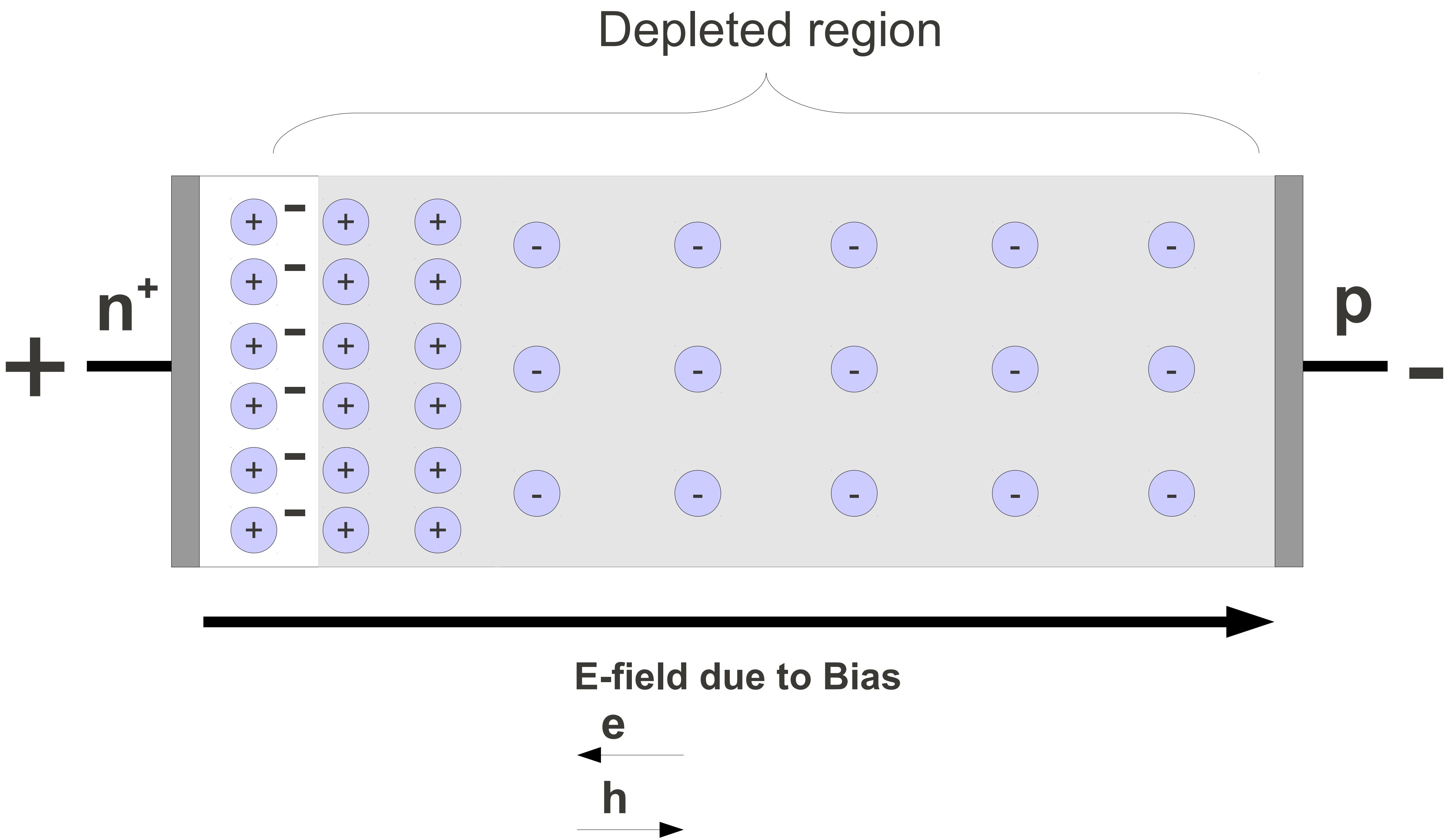
E-field due to Bias

e

h

Sense of the arrows is the opposite to the original current due to diffusion

$$V_{bias} = V_{full\ depletion}$$



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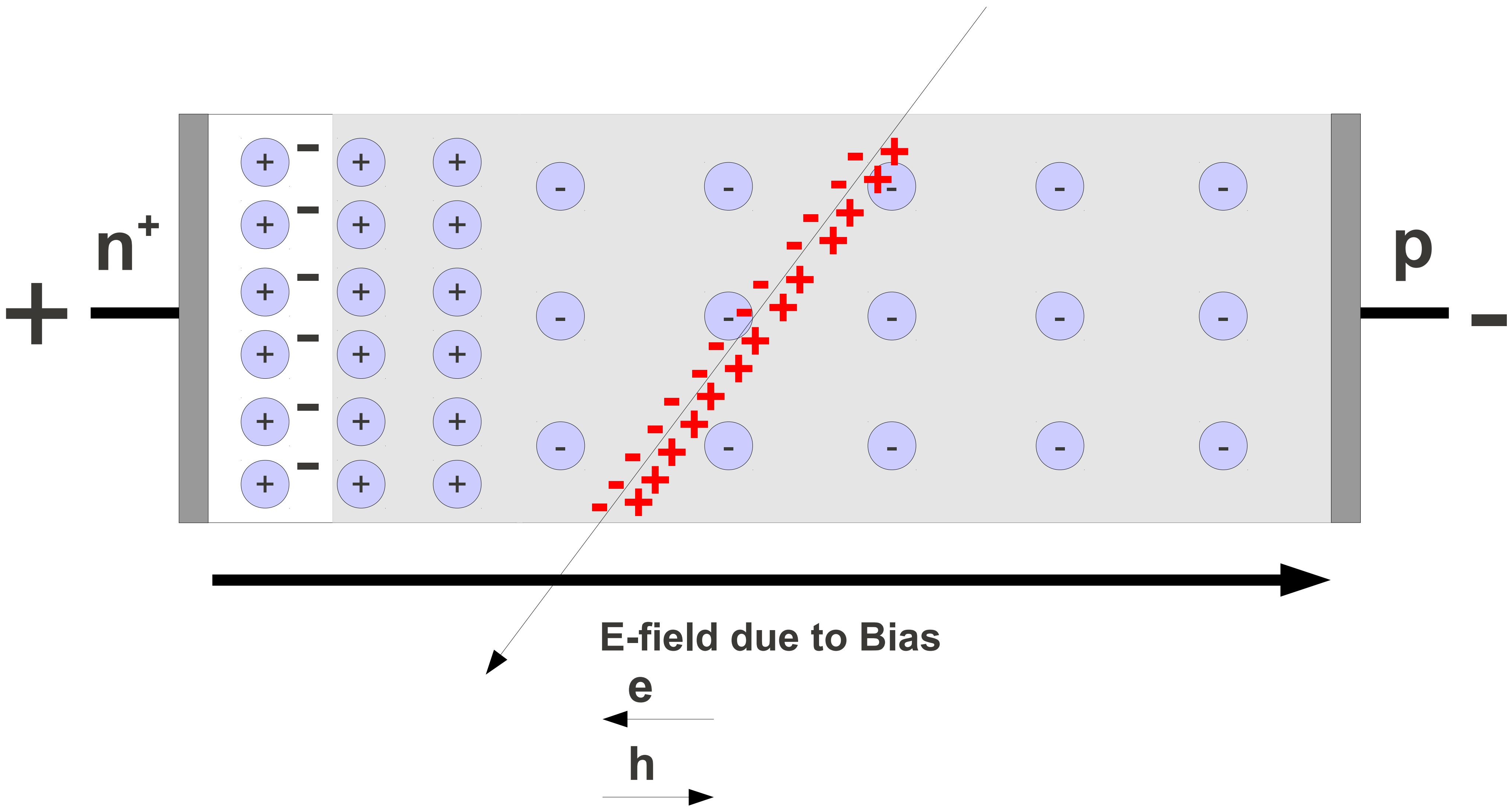
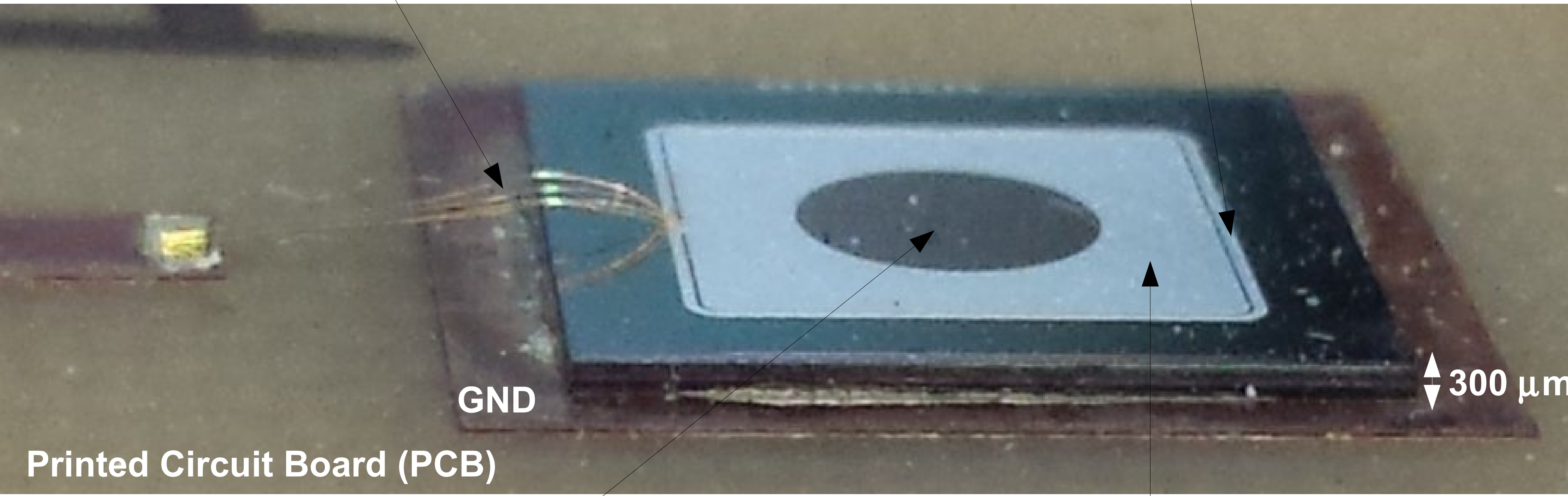


Real diode (+some dust)

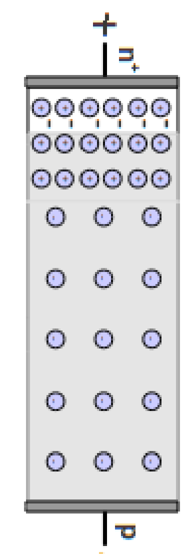
Wire bonding (Bias IN & Signal OUT)
HV applied from the top

Guard Ring



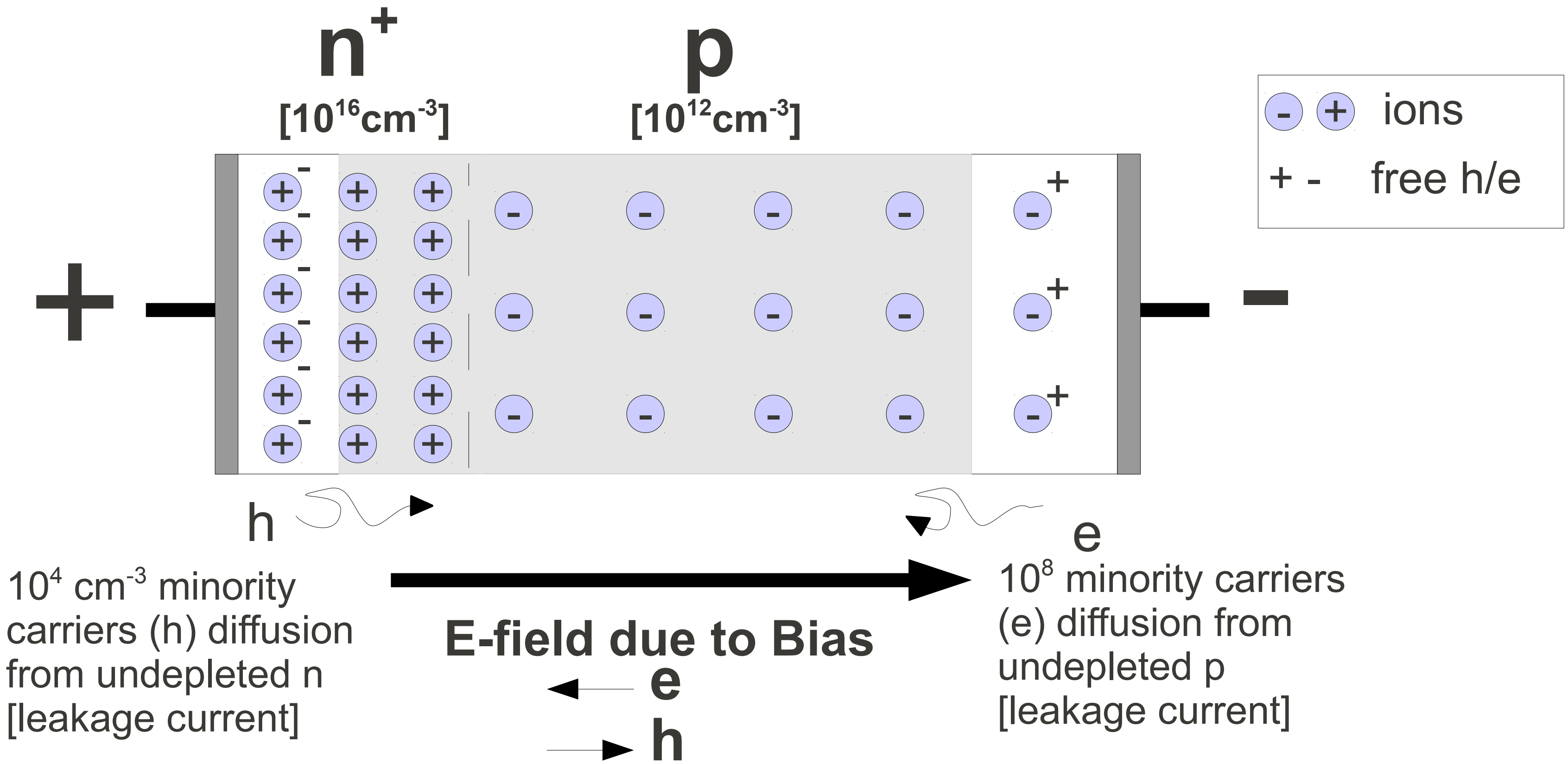
Opening for light injection
(testing purposes)

Aluminum metalization



Top and bottom (not shown) Al layers: ohmic contacts.
Guard ring: sink for “edge currents”, helps uniformity of E-field lines near the border.
Wire bonds: ultrasonic welding of wires, chip interconnection.

Here you are! The most basic semiconductor detector



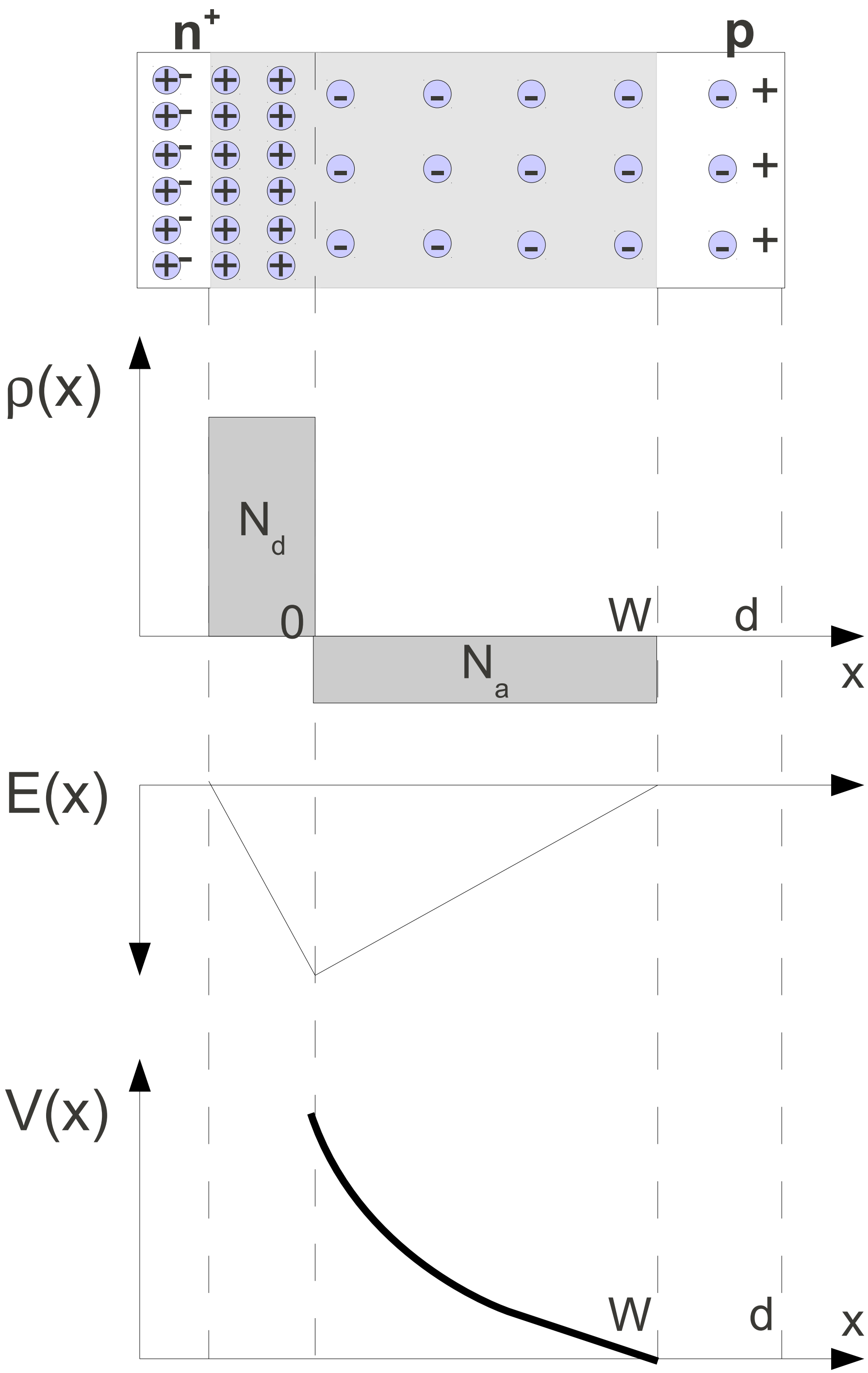
	n^+	p
Majority	$n_n \sim 10^{16}$	$p_p \sim 10^{12}$
Minority	$p_n = 10^{20}/10^{16} = 10^4 << n_n$	$n_p = 10^{20}/10^{12} = 10^8 << p_p$

Other leakage current sources:
1) edge currents from borders
[proportional to volume=AW(U)]
2) radiation induced defects

pn junctions: FUN

http://www.youtube.com/watch?v=IcrBqCFLHIY

pn-junctions: not so FUN



1D analysis, good for diodes, not for microstrips

$$-\frac{d^2\Phi(x)}{dx^2} = \frac{\rho_{el}}{\epsilon\epsilon_0} = \frac{eN_{eff}}{\epsilon\epsilon_0}$$

First integration with boundary condition $E(x=W)=-d\Phi/dx=0$ yields:

$$\frac{dE}{dx} = \frac{e}{\epsilon\epsilon_0} N_{eff} \quad \Rightarrow \quad \int_{E(x)}^{0} dE = \frac{e}{\epsilon\epsilon_0} N_{eff} \int_x^W dx$$

$$E(x) = \frac{e}{\epsilon\epsilon_0} N_{eff}(x-W) \overset{N_{eff}\approx N_a}{=} -\frac{e}{\epsilon\epsilon_0} N_a (x-W)$$

Second integration with boundary condition: $\Phi(x=W)=0$

$$\int_{\Phi(x)}^{0} d\Phi = \frac{-e}{\epsilon\epsilon_0} N_{eff} \int_x^W (x-W)\,dx$$

$$\Phi(x) = \frac{-1}{2}\frac{e}{\epsilon\epsilon_0} N_{eff}(x-W)^2 \overset{N_{eff}\approx N_a}{=} \frac{1}{2}\frac{e}{\epsilon\epsilon_0} N_a (x-W)^2$$

Built-in potential: $\Phi(x=0) = \frac{1}{2}\frac{e}{\epsilon\epsilon_0} N_a W^2 = U_{bi}$

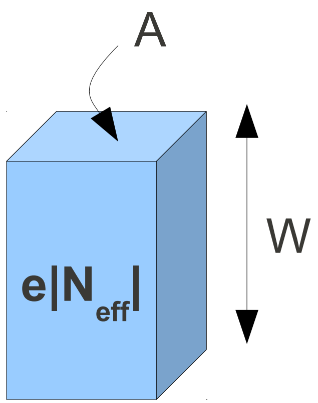
Applying a reverse bias voltage $\Phi(x=0)=U+U_{bi}$

$$W(U) = \sqrt{\frac{2\epsilon\epsilon_0}{eN_a}(U+U_{bi})} \quad ; \quad U_{dep} = \frac{eN_a}{2\epsilon\epsilon_0} d^2$$

Diode capacitance – depletion voltage calculation

Today

Depletion layer=insulator between 2 electrodes → diode acts as a capacitor
Capacitance can be used to **calculate depletion voltage**
Note: C influences the noise.



Before depletion: $$C=\frac{dQ}{dU}=e|N_{eff}|A\frac{dW}{dU}=\epsilon\epsilon_0\frac{A}{W(U)}=A\sqrt{\frac{e\epsilon\epsilon_0|N_{eff}|}{2U}}$$

After depletion: $$C=\epsilon\epsilon_0\frac{A}{d}$$

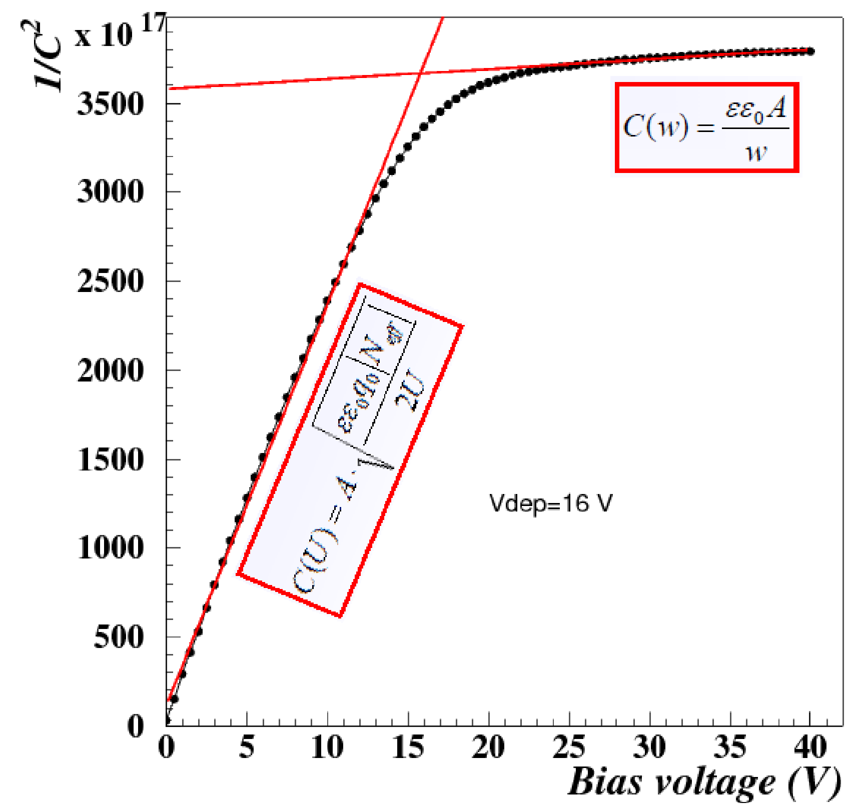
$Q=e|N_{eff}|AW$

<u>Empirical method to calculate depletion voltage:</u>

1) We plot $1/C^2$ vs Bias Voltage

2) Before depletion, $1/C^2$ is linear in V.
At depletion, this line will intercept the end capacitance of the diode.

Intercept = depletion voltage



Leakage (or reverse) current

Today

Even if the diode is reverse biased and therefore blocks current, there is a small current contribution coming from:

1) **diffusion** from non-depleted regions (small)
2) manipulation, **processing** (cutting, heat treatments during detector processing)
3) **radiation** induced defects

The last one is of most concern in particle physics. Leakage current increases linearly with radiation and degrades S/N ratio.

The more depleted volume, the more defects can contribute. Leakage current is a **bulk effect** and **increases with depleted thickness**, until it **saturates**. From there on, increasing voltage can lead to secondary ionization and then **breakdown**.

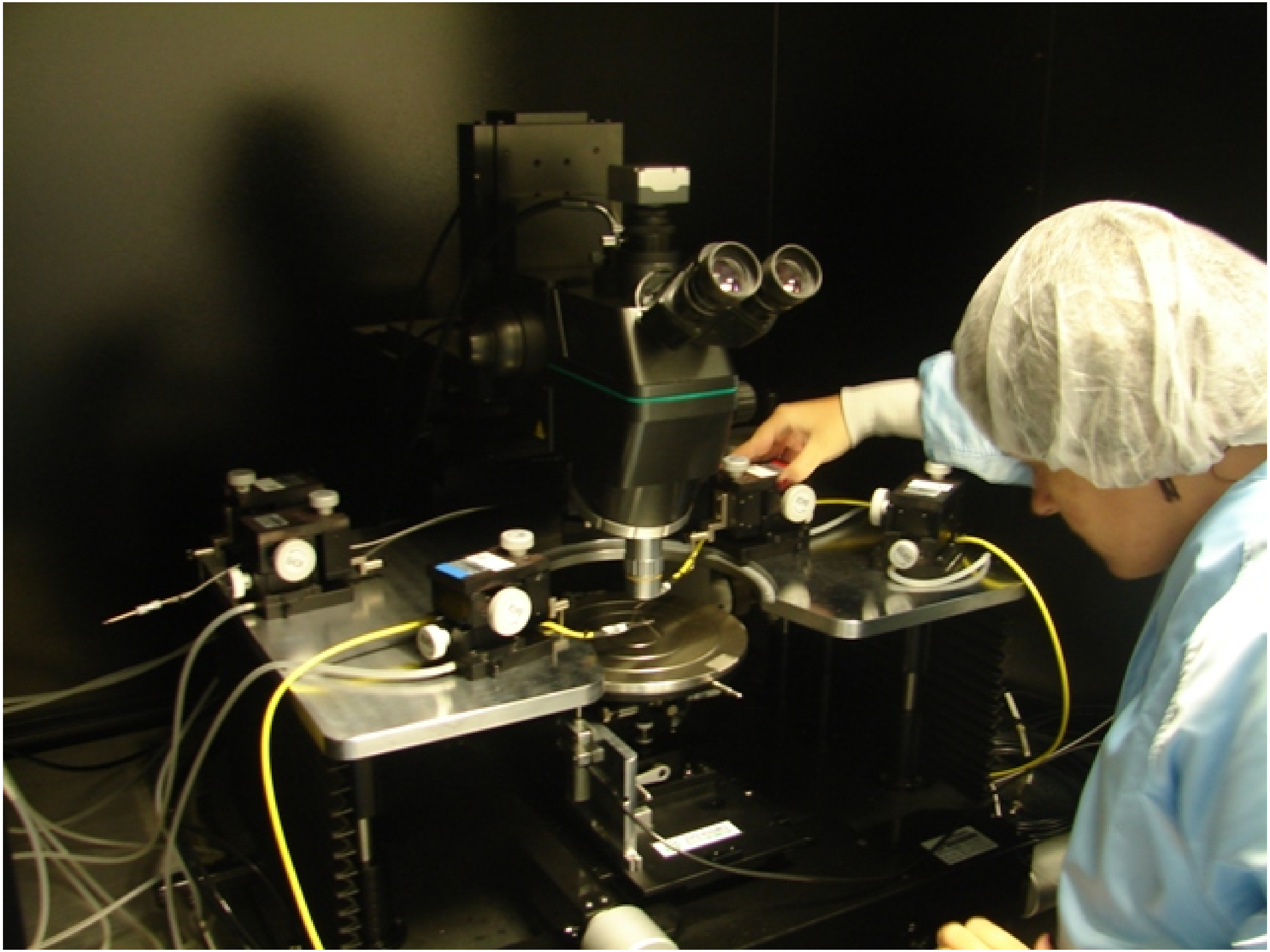
Leakage current displays a strong **temperature dependence**;

$$I_{rev}(T) = I_{rev}(T_R) \cdot \left(\frac{T}{T_R}\right)^2 \exp\left(-\frac{E_{g,eff}}{2k_B}\left[\frac{1}{T} - \frac{1}{T_R}\right]\right)$$

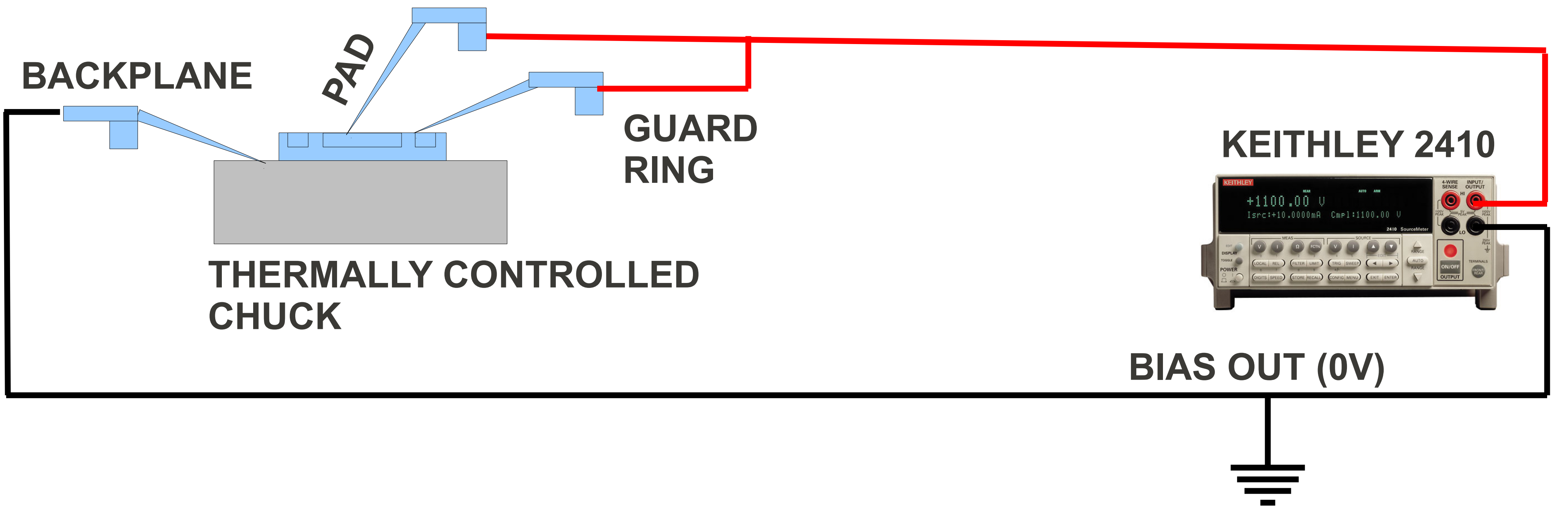
With k_B the Boltzmann constant, T_R a reference temperature, $E_{g,eff}$=1.21 eV

The rule of thumb is that I_{rev} doubles for each +7C increase
We will check this by taking measurements at different temperatures.

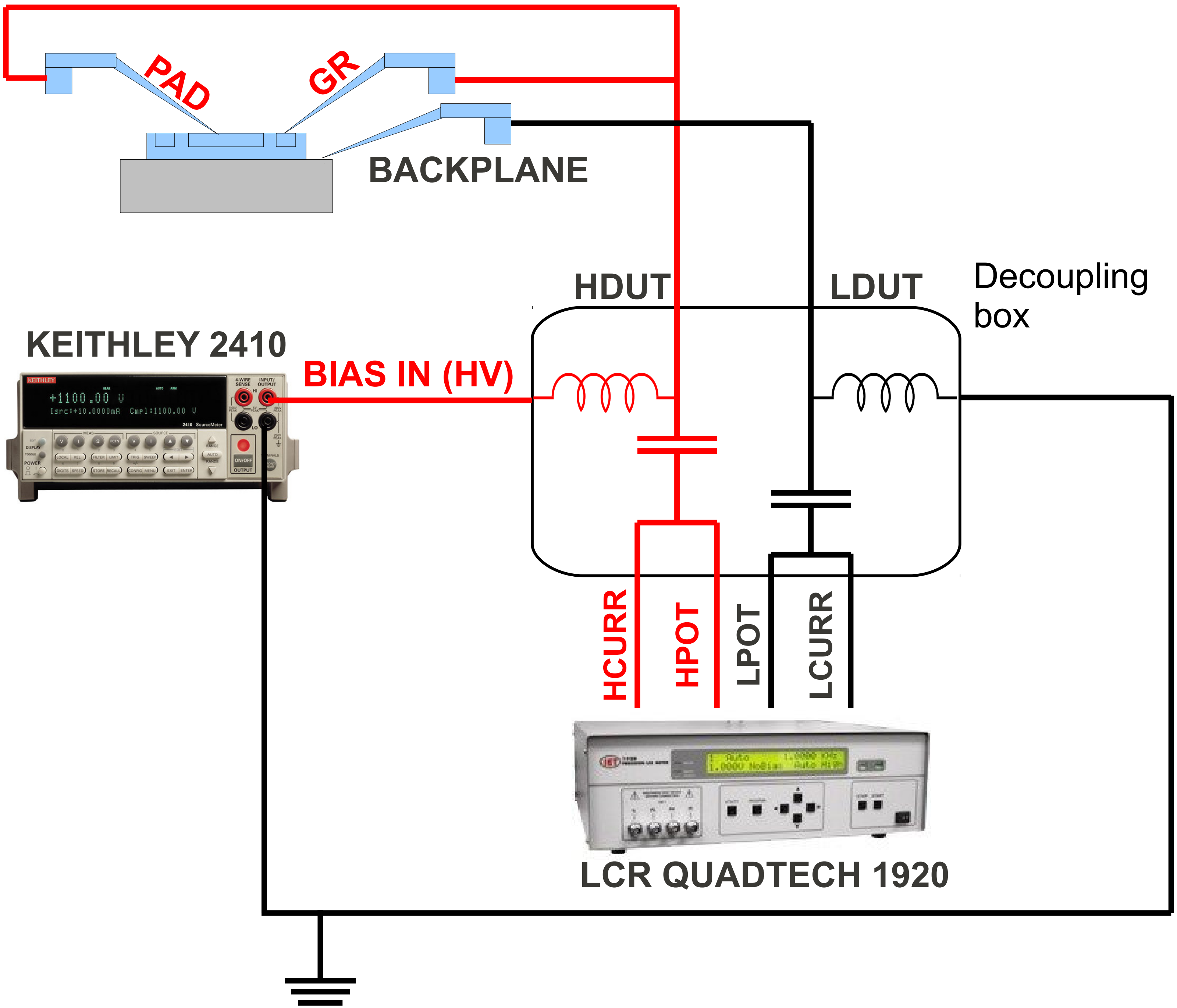
Measuring IV – CV characteristics at IFCA-Santander



IFCA: Current vs Voltage



IFCA: Capacitance vs Voltage



Amplitude & period

Amplitude & phase shifts

Simple data analysis: CV

We will continue using ROOT

```
root -l
.L CVread.C
Cvread("yourfile.dat")
hiC2->Draw()
```

Use right mouse click over the recently drawn histogram to pop-up contextual menu
Select Fit Panel:

1) Fit raising part of the curve to pol1 (line)
2) Fit “horizontal” part of the curve to a constant or to another p1
3) Find intersection between 1 and 2 → this is your depletion voltage

Simple data analysis: IV

Use IVread.C, in the same way as you used CVread.C
Each time you run this program, an histogram hI is created.

```
root -l

//Load the function to read in data
.L IVread.C
Ivread("IV_20C.dat")

//Create a copy of the histogram we just read
TH1D *h20=hI->Clone("20C");
delete hI

//Create histogram at 15C
Ivread("IV_15C.dat")
TH1D *h15=hI->Clone("15C");
delete hI

//Divide 2 histograms, bin by bin and fill histogram hratio
TH1D *hratio20=h15->Clone("15/20");
hratio->Divide(h20)
hratio->Draw()
```

References & interesting links

BOOKS:

Gerhard Lutz,	Semiconductor Radiation Detectors
Helmuth Spieler,	Semiconductor Detector Systems
Rossi,Fischer, Rohe,Wermes	Pixel Detectors

Talks:
Michael Moll, Marcos Fernandez, Effects of Radiation on Solid State Particle Detector Performance
http://mmoll.web.cern.ch/mmoll/summer/13-07-Summi-Workshop-Silicon-Radiation%20Damage%20Intro.pptx

Video lectures
Daniela Bortoletto, Detectors for Particle Physics
http://cds.cern.ch/record/1562006

LCR Premier
http://www.componentsengineering.com/wp-content/uploads/pdfs/LCR-Measurement-Primer.pdf

PN junctions in youtube:
http://www.youtube.com/watch?v=IcrBqCFLHIY

Very educational applets on semiconductors:
http://jas.eng.buffalo.edu/index.html

Extra...

Questions:

How much Si there is in 1 cm3 of Si?

How much dopant there is in 1 cm3 of Si?

The Avogadro Project [1]

[1] The Avogadro project: redefining the kg in terms of the Avogadro constant (universal constant). Silicon single crystals may be produced today in commercial facilities with extremely high purity with few lattice defects.

Calculation of N_A uses highly polished Si spheres.

https://www.bipm.org/en/bipm/mass/avogadro/

Local vs remote sensing (2 vs 4 wire measurements)

(Sourcing I, measuring V)

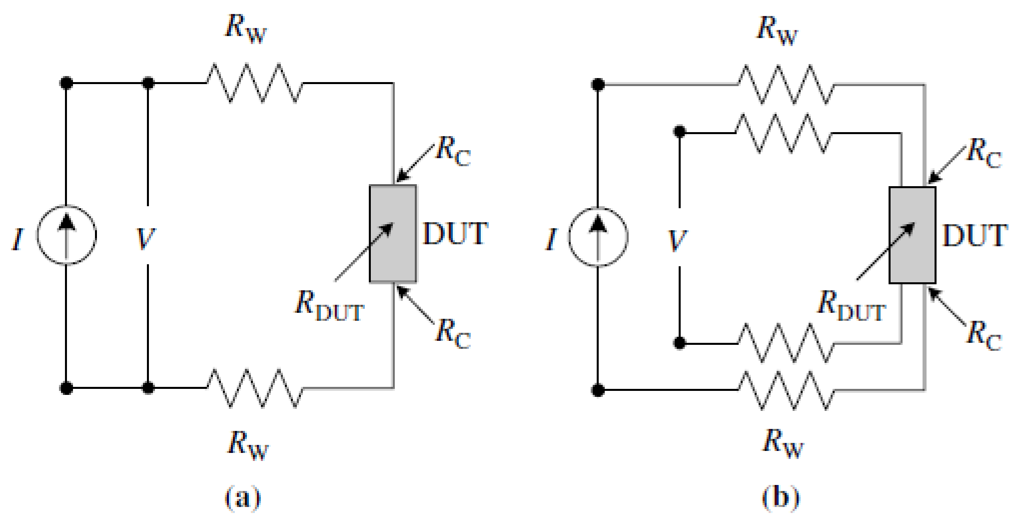


Fig. 1.1 Two-terminal and four-terminal resistance measurement arrangements.

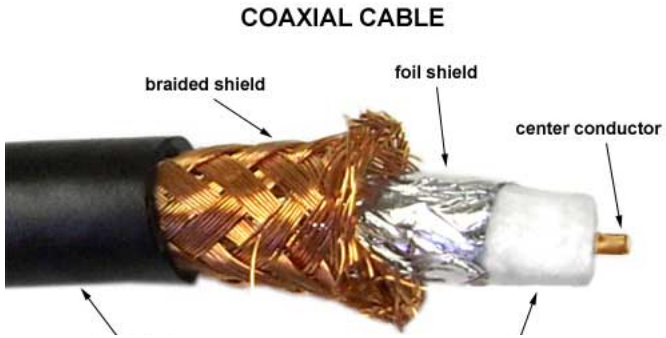
- **Two terminal (local)**: Each contact serves as a current and as a voltage probe.

$$R_T = V/I = 2R_W + 2R_C + R_{DUT}$$

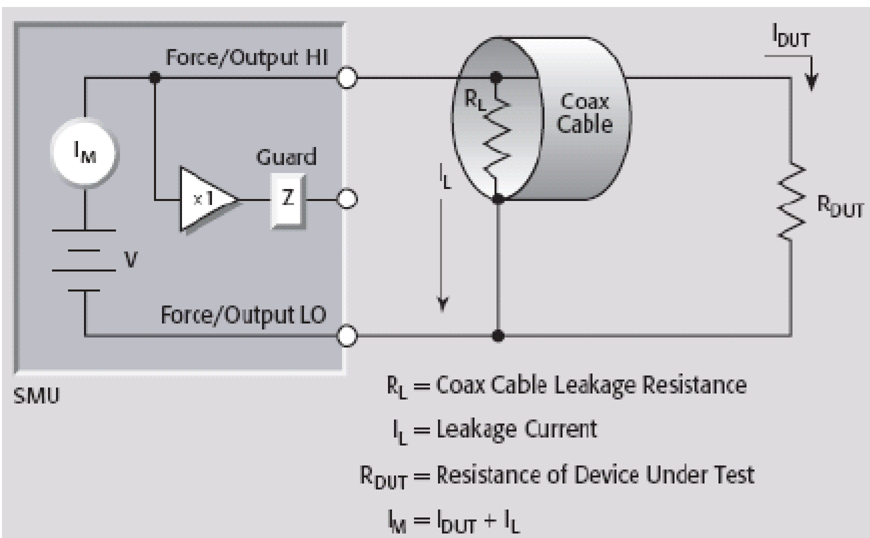
R_W is wire resistance, R_C contact resistance, R_{DUT} is what we want to measure.
If DUT=detector, then $R_{DUT}>>R_w,R_s$

- **Four terminal (remote)**: Same current path as in 2 terminal. However voltage is now measured with 2 additional contacts. Due to the high input impedance of the voltmeter the current flowing through R_w and R_C in the voltage path is very small. Voltage drop in R_W and R_C is very small and can be neglected. Measured voltage is V_{DUT}.

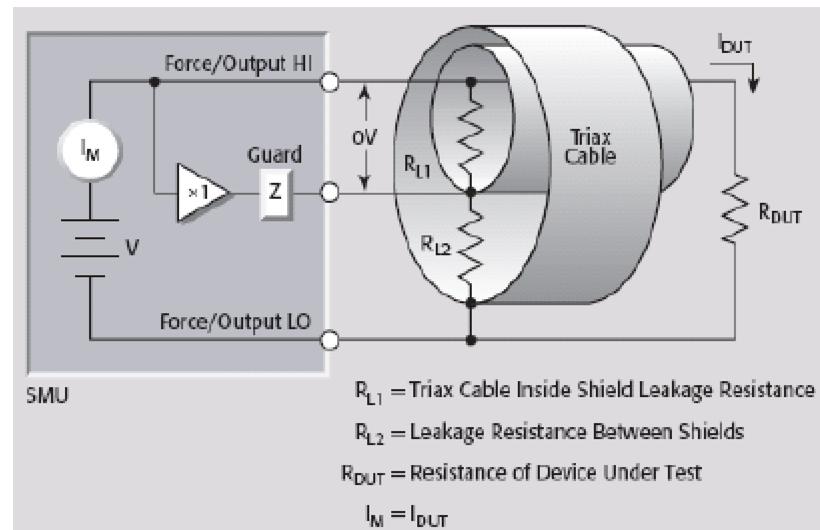
Triax vs coax (-ial) cables....



Unguarded Configuration



Guarded Configuration



Use SMU to source 10V, and measure resulting current, I_M, to determine R_{DUT}

- If R_{DUT} = 100MΩ and R_L = 10GΩ, then I_M = 101nA and measured value for R_{DUT} will be 99.01MΩ → a 0.99% Error!

Guarding eliminates leakage current in R_{L1}; measured value for R_{DUT} is 100MΩ

- Current flowing in R_{L2} is supplied by guard source and does not affect I_{DUT}

Guarding also reduces capacitance, which decreases response time of circuit.