Charge Collection: Carrier Mobility & Lifetime

- Semiconductor detector signal → induced from carrier motion
    - Weighting field / potential describes coupling of charge carriers to electrodes (see previous lecture)
    - Time-profile of carrier position
        - Carrier position as function of time: *mobility*
        - Diffusion can also play a role in charge collection
            - E.g. charge cloud dispersion over long drift distances
    - Signal due to carrier **drift**
        - Trapped carriers (recombination or deep traps) remove carriers from contributing to signal induction: *lifetime*
- Resources & Literature
    - Spieler Ch. 2 (esp. Sec 2.4 & 2.6)
    - S.M. Sze - Physics of Semiconductor Devices (Ch 1)
    - Bart Van Zeghbroeck - Principles of Semiconductor Devices

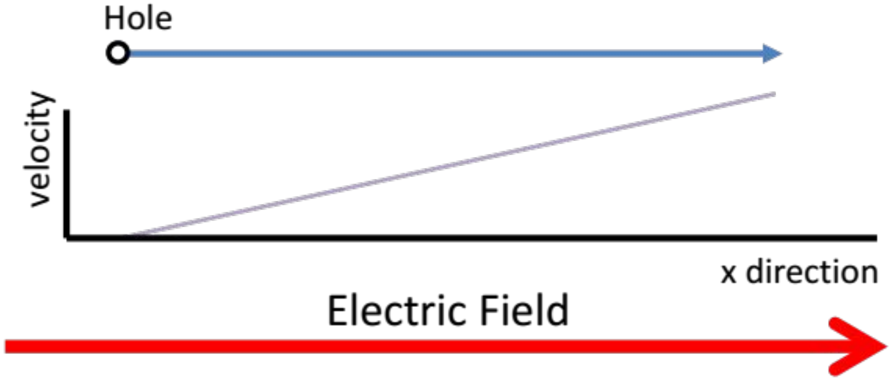
Carrier Diffusion

- Before we consider charge carrier motion under the influence of an electric field, it is important to note that the carriers are subject to thermal motion as well
  - Carrier concentration profile over time → Gaussian distributed
    - $\sigma = (D*t)^{1/2}$, where D = diffusion constant
  - Thermal velocity quite large, but direction dictated by concentration gradient
    - $v_{th} = ((3kT)/m)^{½} \sim 10^6$ cm/s for electrons in HPGe @ 77k
- Carrier diffusion is an important consideration in many circumstances
  - Under-depleted systems
    - Charge collection in low-field regions driven by diffusion
  - Extent of charge cloud on position resolution
    - $\sigma = (D*t)^{½} \sim 50$ microns for 200 ns drift time; ~ 120 micron FWHM

Definition: Charge Carrier Mobility

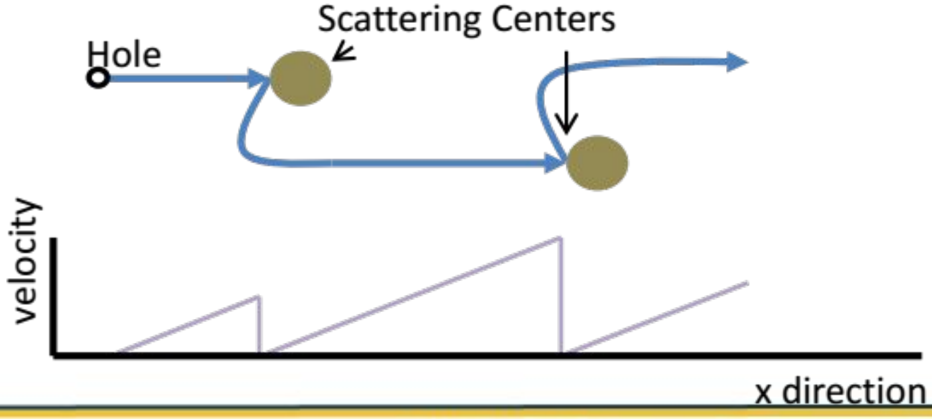
- Charge carriers in vacuum
  - Ballistic motion: $v(t) = \int a(t)dt \rightarrow$

$$v = \frac{e\vec{E}}{m^*}t$$



Slide & Images courtesy
Brian Plimley & Quinn
Looker, NE204 2013

- Charge carriers in crystal lattice - scattering along trajectory!
  - Charge carriers still accelerated || or anti-|| to E-field



$$\vec{v} = \boxed{\mu}\vec{E}$$

Mobility μ
units = [$cm^2/V*s$]

Mobility: Characteristics & Relationships

- Note that electrons and holes have **different** mobilities

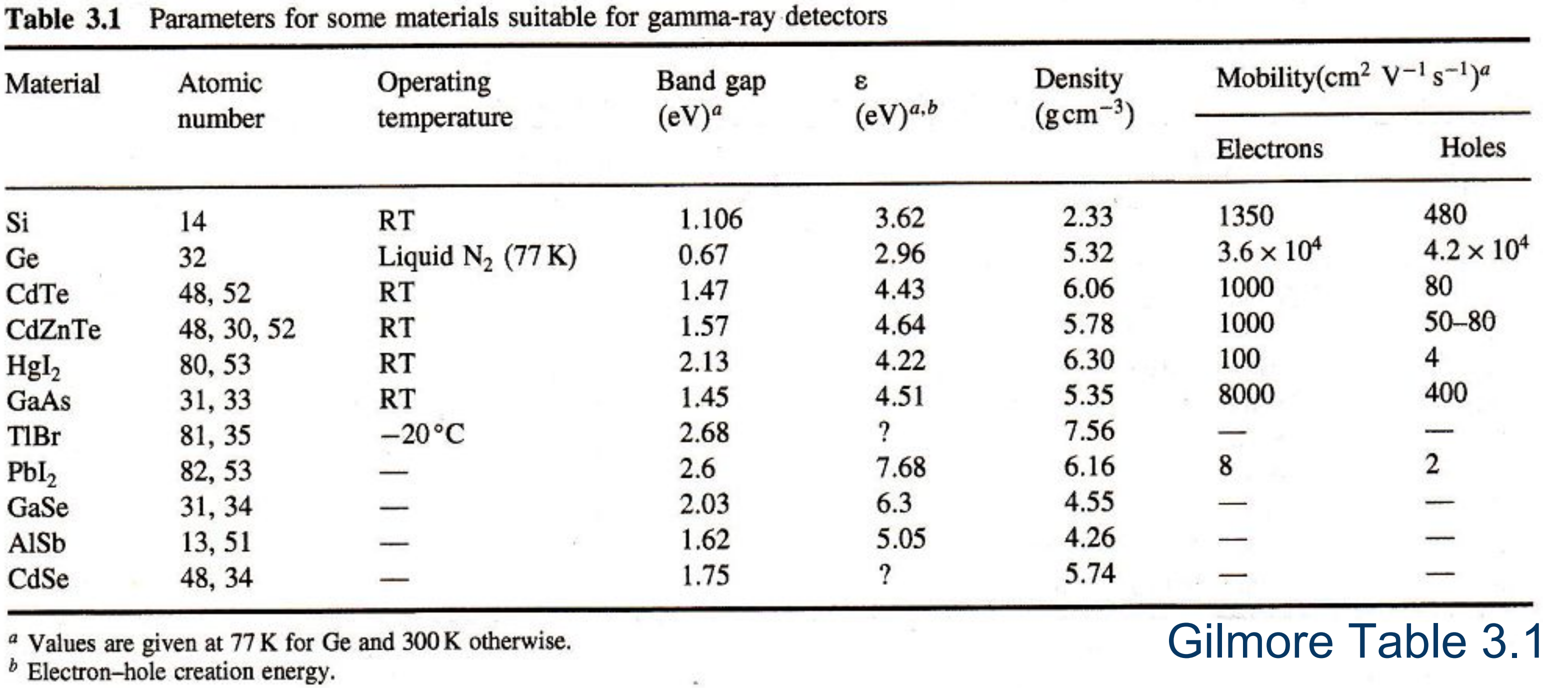


Table 3.1 Parameters for some materials suitable for gamma-ray detectors

Material	Atomic number	Operating temperature	Band gap (eV)[a]	ε (eV)[a,b]	Density ($g\,cm^{-3}$)	Mobility ($cm^2\,V^{-1}\,s^{-1}$)[a]	
						Electrons	Holes
Si	14	RT	1.106	3.62	2.33	1350	480
Ge	32	Liquid N_2 (77 K)	0.67	2.96	5.32	3.6×10^4	4.2×10^4
CdTe	48, 52	RT	1.47	4.43	6.06	1000	80
CdZnTe	48, 30, 52	RT	1.57	4.64	5.78	1000	50–80
HgI_2	80, 53	RT	2.13	4.22	6.30	100	4
GaAs	31, 33	RT	1.45	4.51	5.35	8000	400
TlBr	81, 35	−20 °C	2.68	?	7.56	—	—
PbI_2	82, 53	—	2.6	7.68	6.16	8	2
GaSe	31, 34	—	2.03	6.3	4.55	—	—
AlSb	13, 51	—	1.62	5.05	4.26	—	—
CdSe	48, 34	—	1.75	?	5.74	—	—

[a] Values are given at 77 K for Ge and 300 K otherwise.
[b] Electron–hole creation energy.

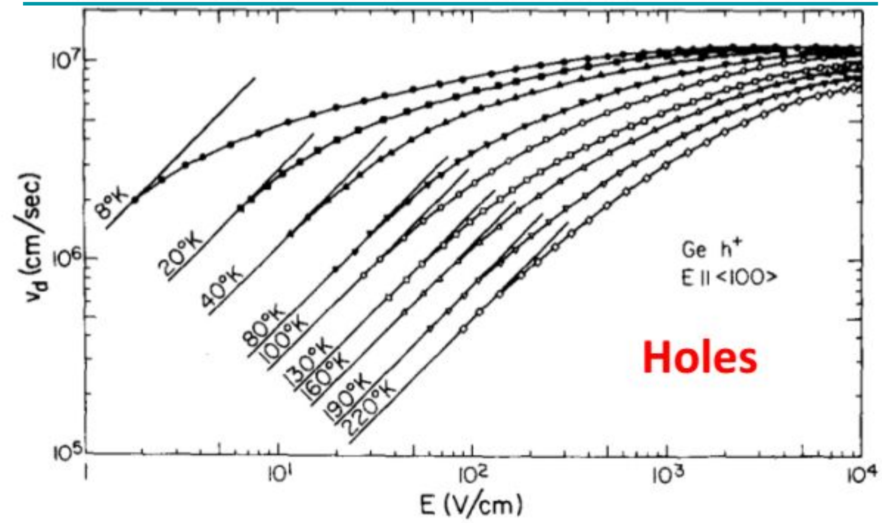
Gilmore Table 3.1

- Carrier mobility depends on:
  - Material, E-field strength, Temperature, Orientation of crystal lattice
- Mobility often **treated as** property of the material
  - Resitivity of doped semiconductor: $\boldsymbol{\rho = (eN_{Dopant}\mu)}$
  - Diffusion coefficient: $\boldsymbol{\mu = e(kT)^{-1}D}$

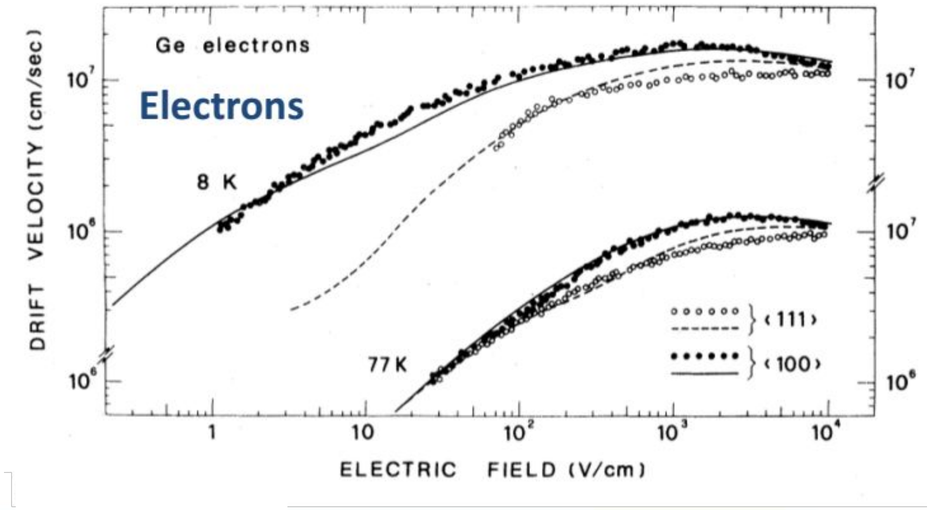
Mobility Dependence on Electric Field

- Linear relationship between *v* and *E* is valid for low E-field
    - Carriers @ therm. equilib. with lattice
- At higher E-fields, carriers are no longer at equilibrium with lattice
    - v_d relationship modulated by "effective temperature" of carriers:
- Very high fields
    - Optical phonon scattering
    - v_d independent of E

Ottaviani 1973 - Hole drift in HPGe from 8K to 220K

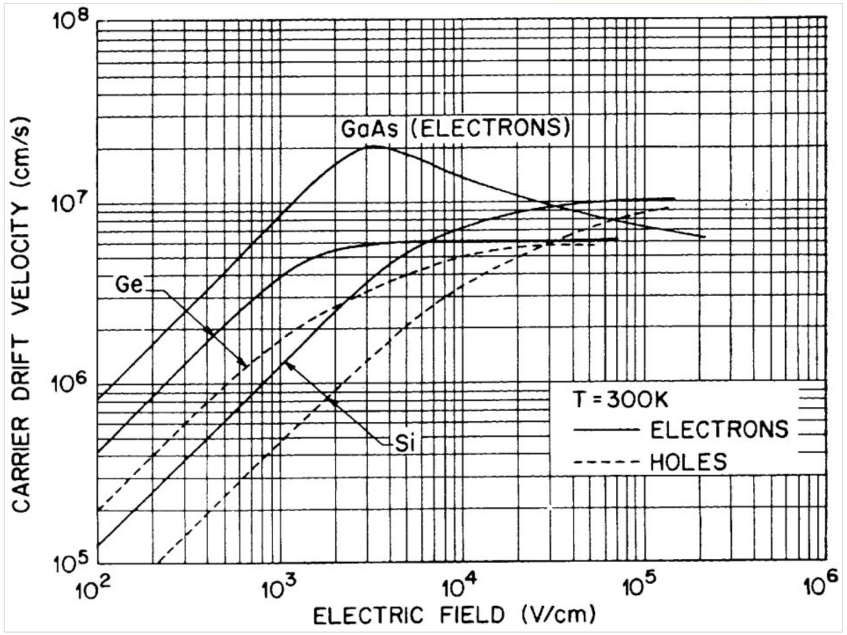


Jacoboni 1981 - Electron drift velocity and diffusivity in germanium



Mobility Dependence on Electric Field

- Linear relationship between *v* and *E* is valid for low E-field
  - Carriers @ therm. equilib. with lattice
- At higher E-fields, carriers are no longer at equilibrium with lattice
  - v_d relationship modulated by "effective temperature" of carriers:
- In practice, use single empirical equation:
  - C_2 ~ 2 for e^-, ~ 1 for holes
  - C_2 depends on temperature



Spieler fig. 2.26

$$v_d = \mu_0 \mathscr{E} \sqrt{\frac{T}{T_e}}$$

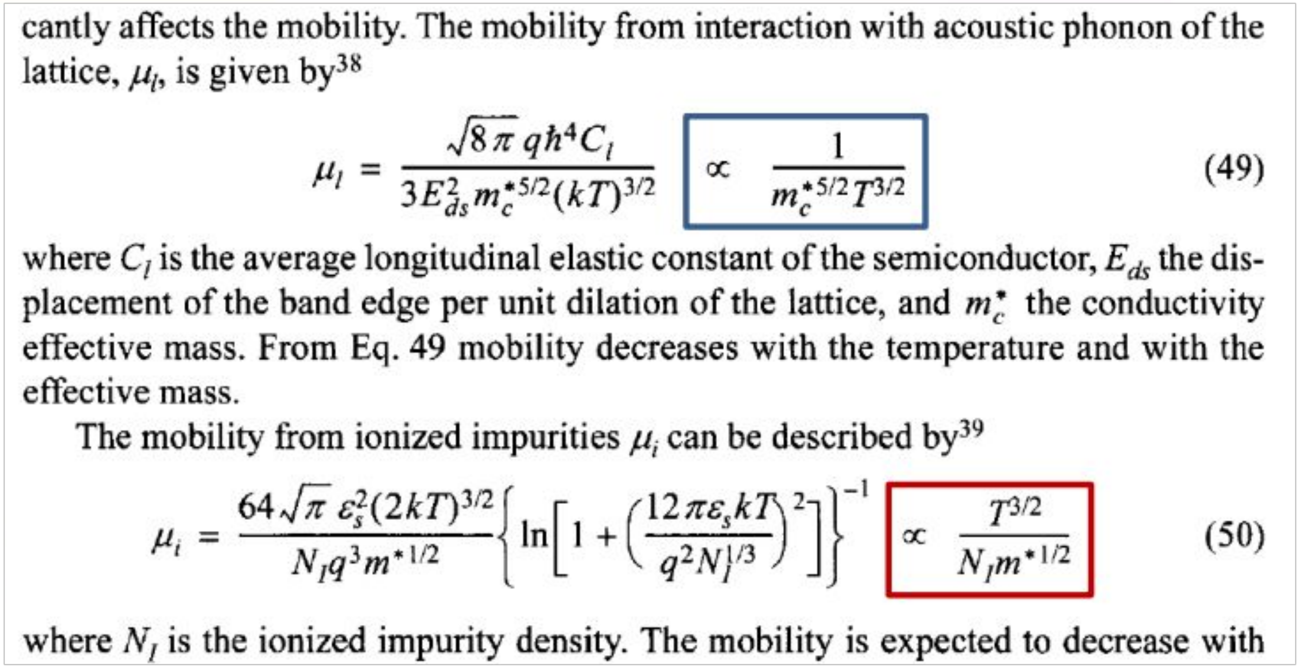
Sze Ch. 1

$$v_d = \frac{\mu_0 \mathscr{E}}{[1 + (\mu_0 \mathscr{E}/v_s)^{C_2}]^{1/C_2}}$$

Sze Ch. 1

Mobility: Physical Mechanisms

- **Phonon scattering** (warmer is worse)
- **Impurity scattering** (colder is worse)



cantly affects the mobility. The mobility from interaction with acoustic phonon of the lattice, μ_l, is given by[38]

$$\mu_l = \frac{\sqrt{8\pi}\, q\hbar^4 C_l}{3E_{ds}^2 m_c^{*5/2}(kT)^{3/2}} \quad \boxed{\propto \frac{1}{m_c^{*5/2}T^{3/2}}} \qquad (49)$$

where C_l is the average longitudinal elastic constant of the semiconductor, E_{ds} the displacement of the band edge per unit dilation of the lattice, and m_c^* the conductivity effective mass. From Eq. 49 mobility decreases with the temperature and with the effective mass.

The mobility from ionized impurities μ_i can be described by[39]

$$\mu_i = \frac{64\sqrt{\pi}\,\varepsilon_s^2(2kT)^{3/2}}{N_I q^3 m^{*1/2}}\left\{\ln\left[1+\left(\frac{12\pi\varepsilon_s kT}{q^2 N_I^{1/3}}\right)^2\right]\right\}^{-1} \quad \boxed{\propto \frac{T^{3/2}}{N_I m^{*1/2}}} \qquad (50)$$

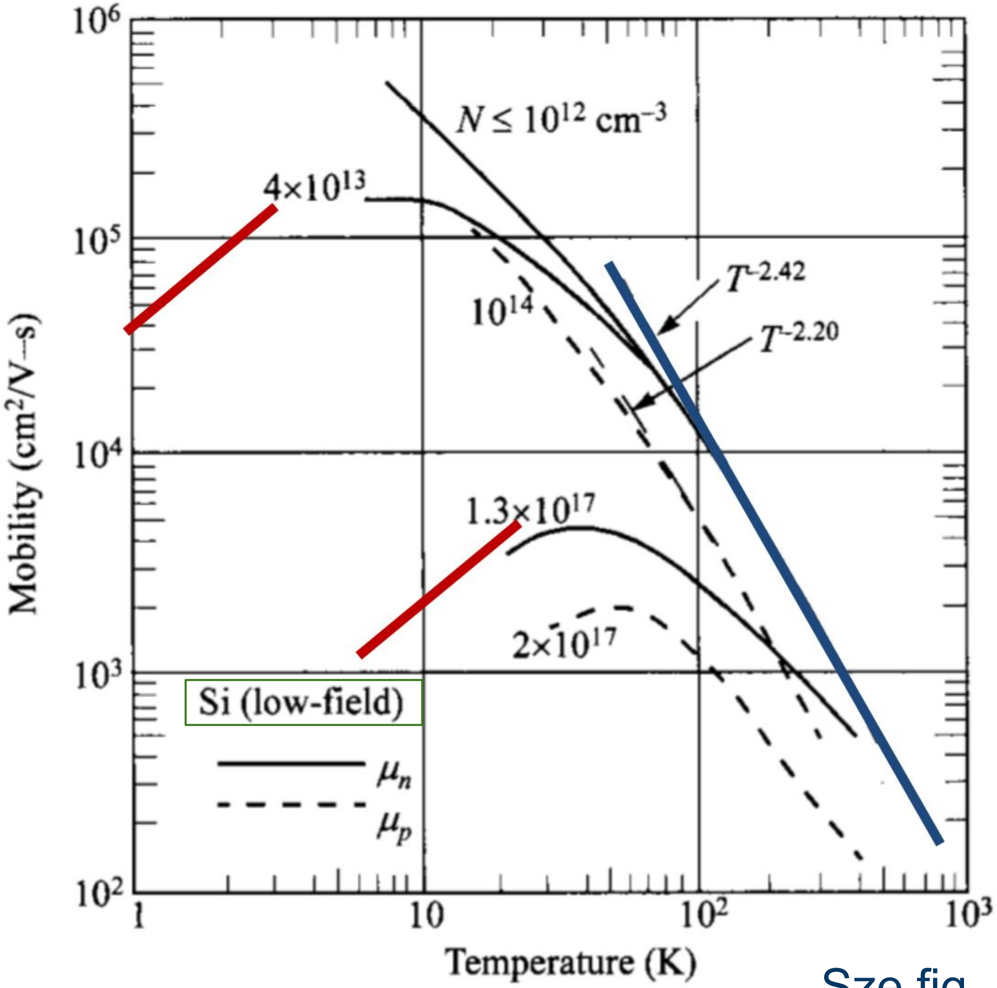
where N_I is the ionized impurity density. The mobility is expected to decrease with

Sze Ch. 1 - pg. 28

- N.B. Temperature dependence of different mechanisms
- Other types of scattering (see Sze or other semicon. physics text)
  - Dominant at high field

Mobility: Physical Mechanisms

- Temperature Dependence
  - **Phonon scattering** (warmer is worse)
  - **Impurity scattering** (colder is worse)

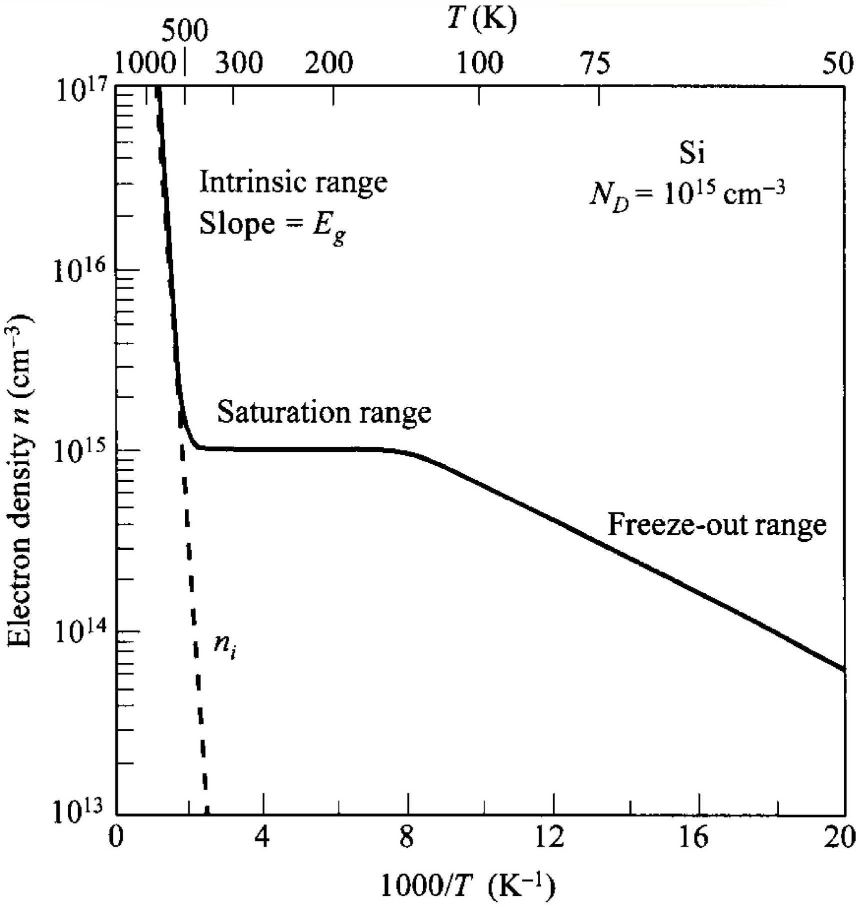


Sze fig. 16

Slide courtesy Brian Plimley NE204 2013

Aside: Carrier Freeze-out

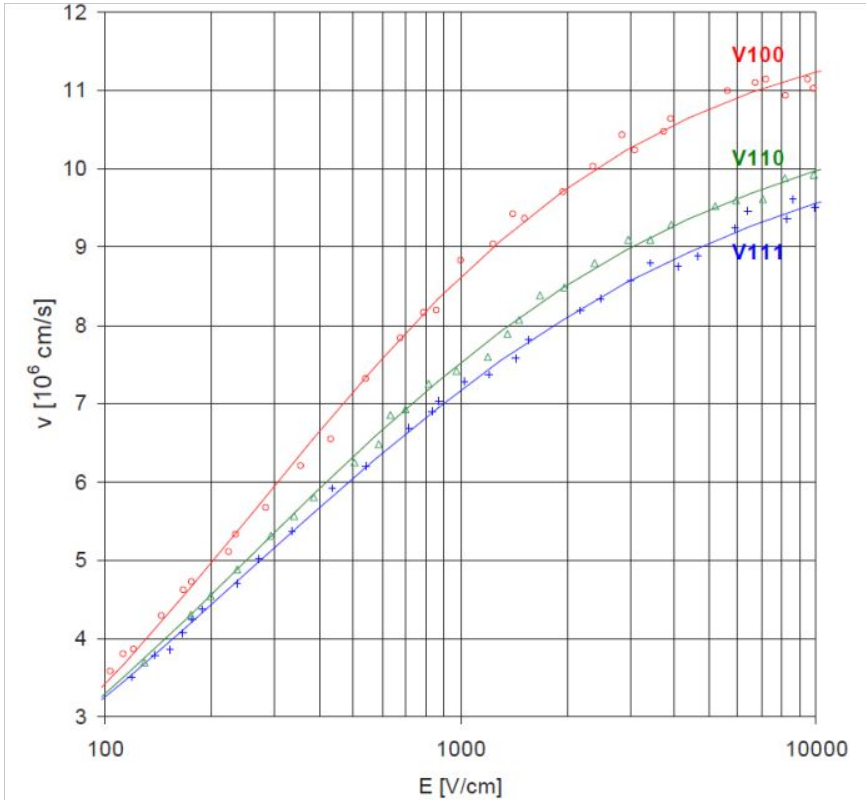
- A consideration for detector operation at very low (sub LN_2) temperature
- Low carrier density due to incomplete dopant ionization
  - Depends on
    - Dopant concentration
    - Compensated material
- For more info, see
  - Sze
  - Principles of Semiconductor Devices



Sze fig. 13

Mobility Anisotropy

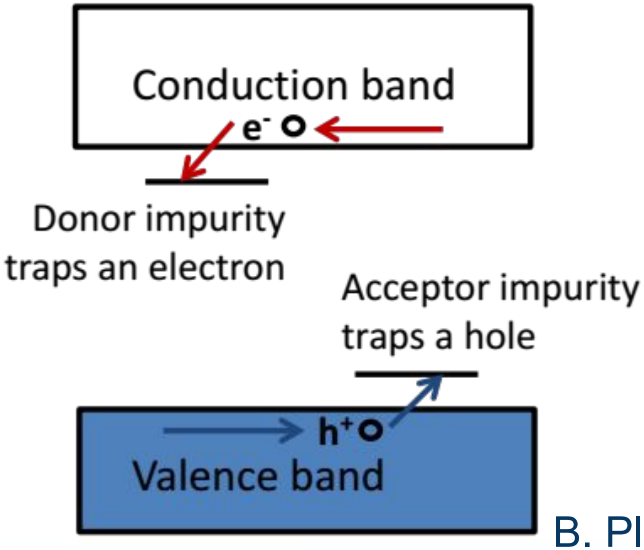
- Mobility depends on crystallographic direction
- E.g. in Ge
    - Electrons slower along [111]
    - Holes faster near along [100]
- For further info:
    - L. Mihailescu NIMA 447(2000)
    - B. Bruyneel NIMA 569 (2006)

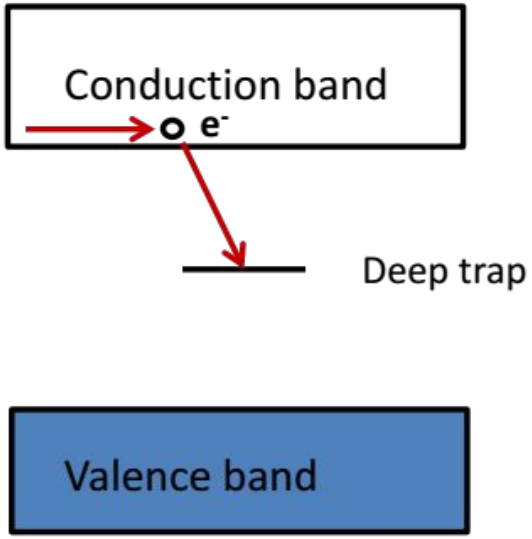


B. Bruyneel NIMA 569 (2006)

Carrier Lifetime

- **Carrier lifetime** represents mean time that a charge carrier will exist in conduction band
  - Independent of drift velocity or drift distance
- Lifetime is limited by impurities, lattice defects, dislocations, etc.
  - Provide sites for **trapping** and/or **carrier recombination**
  - Deep trap - characteristic trapping time >= collection time





B. Plimley, NE204 2013

Mobility-Lifetime Product, $\mu\tau$

- Spieler sec. 2.6
- Given drift in applied field, can combine carrier mobility and lifetime to yield quantity proportional to the average drift length
    - L = $(\mu\tau)$*E
    - N.B. units of $\mu\tau \rightarrow$ [cm^2/V]
- **Hecht Relation**
    - Describes ratio of induced charge to total charge initially generated in terms of the mobility and mean carrier lifetime

$$\frac{Q_s}{Q_o} = \frac{L_e}{d}\left[1 - \exp\left(\frac{d - x_o}{L_e}\right)\right] + \frac{L_h}{d}\left[1 - \exp\left(\frac{x_o}{L_h}\right)\right]$$

- Provides means for measuring charge collection properties

Values of Mobility and Lifetime

- At 300 K (unless otherwise noted)

Material	μ_e	μ_h	$(\mu\tau)_e$	$(\mu\tau)_h$
Si	1350	450	> 1	> 1
Ge	3900	1900	> 1	> 1
Ge (77 K, 10^3 V/cm)	**~1×10^4**	**~8×10^3**	**> 10**	**> 10**
CdTe	1100	100	3×10^{-3}	2×10^{-4}
$Cd_{0.9}Zn_{0.1}Te$	**1000**	**120**	**4×10^{-3}**	**1.2×10^{-4}**
HgI_2	100	4	3×10^{-4}	4×10^{-5}

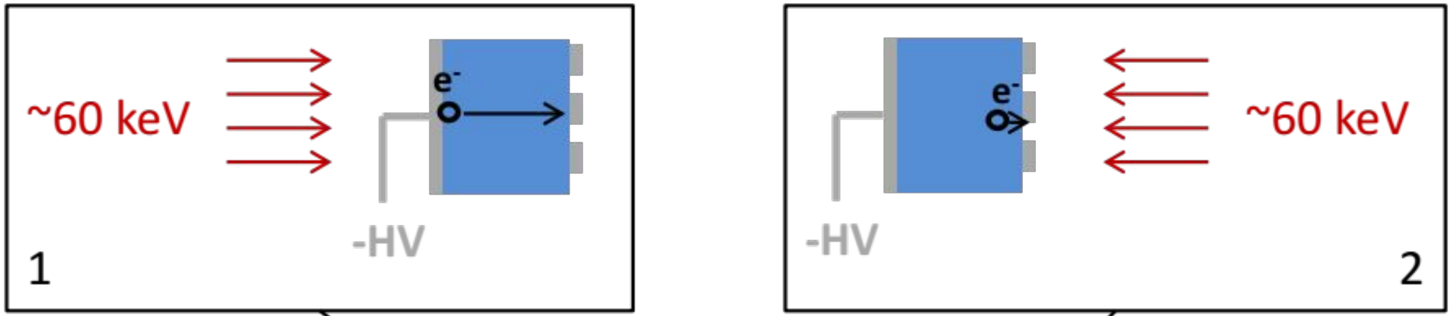
Table from B. Plimley, NE204 2013

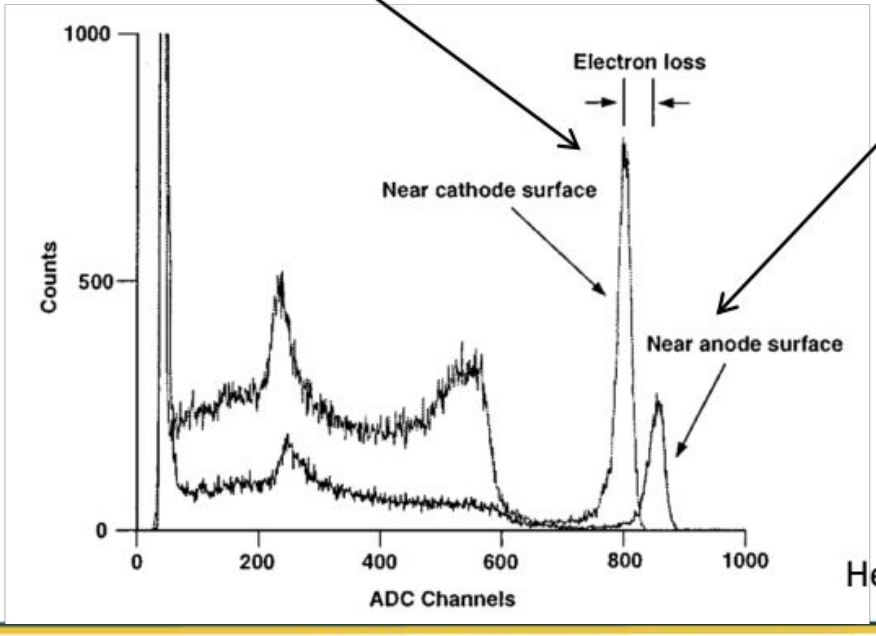
Measuring Charge Collection Properties

- Hecht relation enables indirect measurement of mobility-lifetime product, but not μ or τ individually
- For detectors with **single-polarity sensing**, possible to directly measure $\mu\tau$ as well as μ or τ individually
  - This is the basis for lab 6 (HPGe strip detector) and lab 7 (CZT w/ pixelated anode)
- Useful resources
  - Z. He, G. Knoll, D. Wehe 1998 - Direct measurement of $\mu\tau$ in SPS CZT
  - Ruzin & Nemirovsky - Evaluation of $\mu\tau$ by spectroscopy in CZT

Example: Measuring $\mu\tau$

- Pulse-height deficit vs. position
  - Use low-energy gamma-ray source to constrain interaction depth



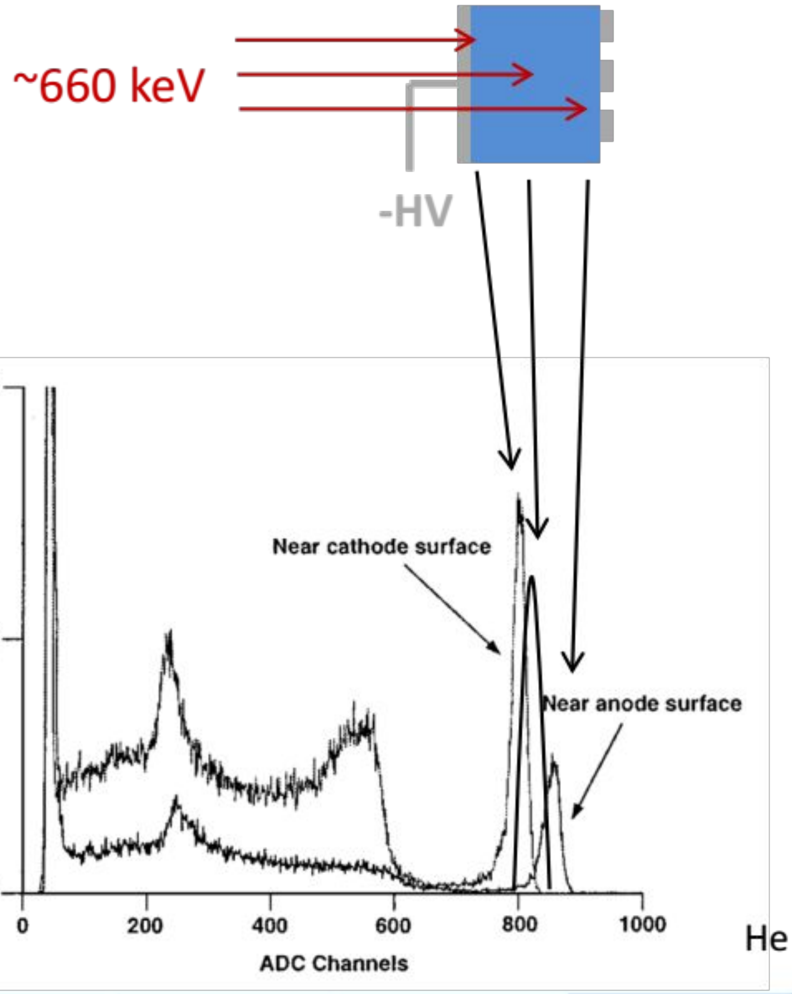


He 1998

B. Plimley, NE204 2013

Example: Measuring $\mu\tau$

- Pulse-height deficit vs. position
  - Use DOI to determine interaction position



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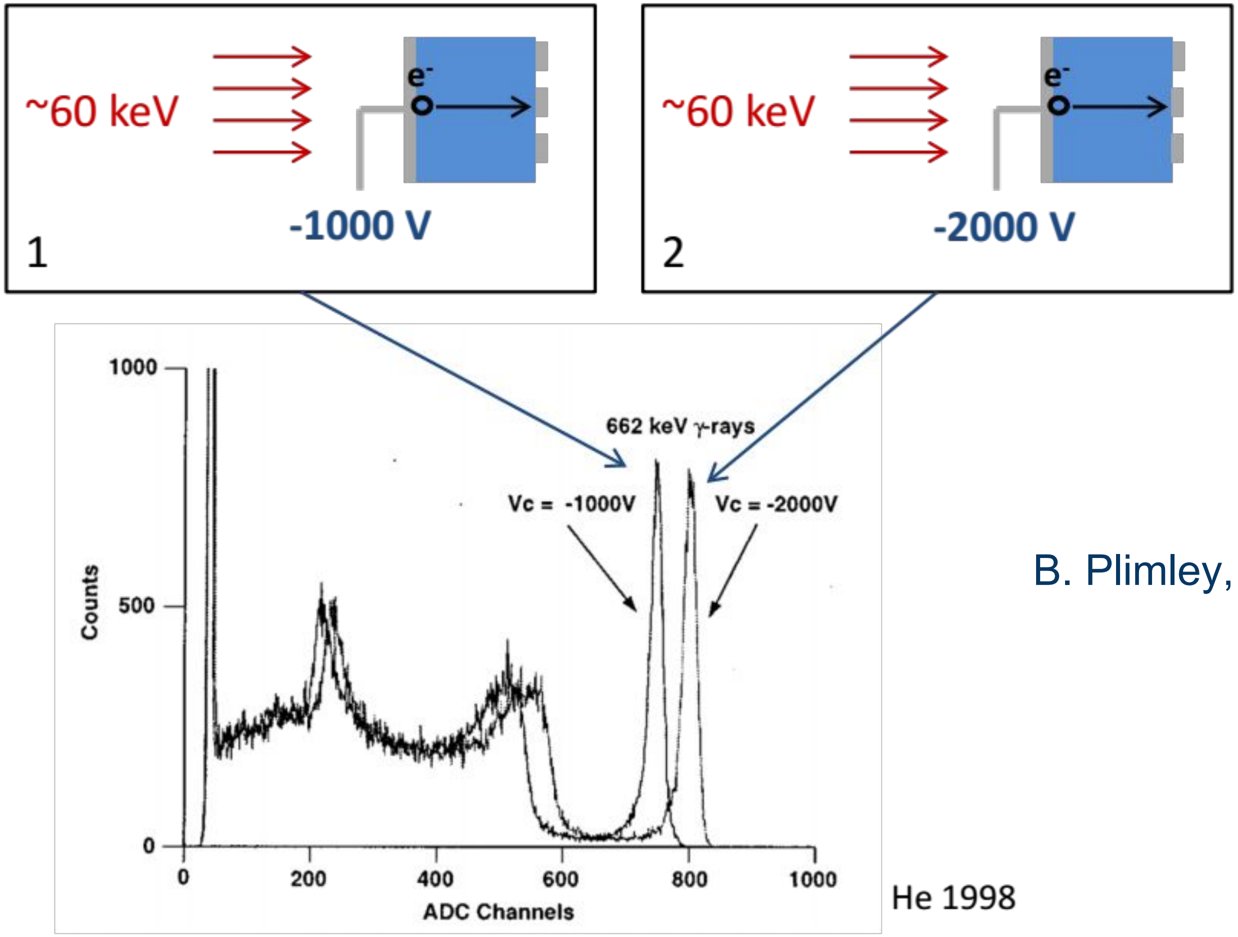
He 1998

Example: Measuring $\mu\tau$

- Pulse-height deficit vs. applied bias



He 1998

B. Plimley, NE204 2013