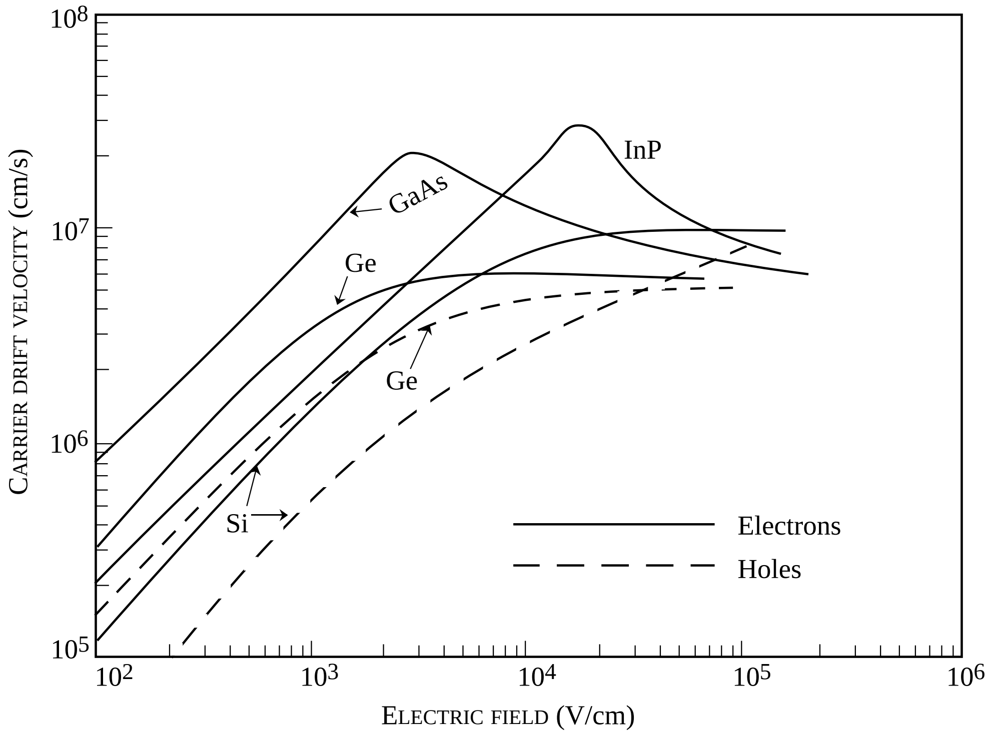
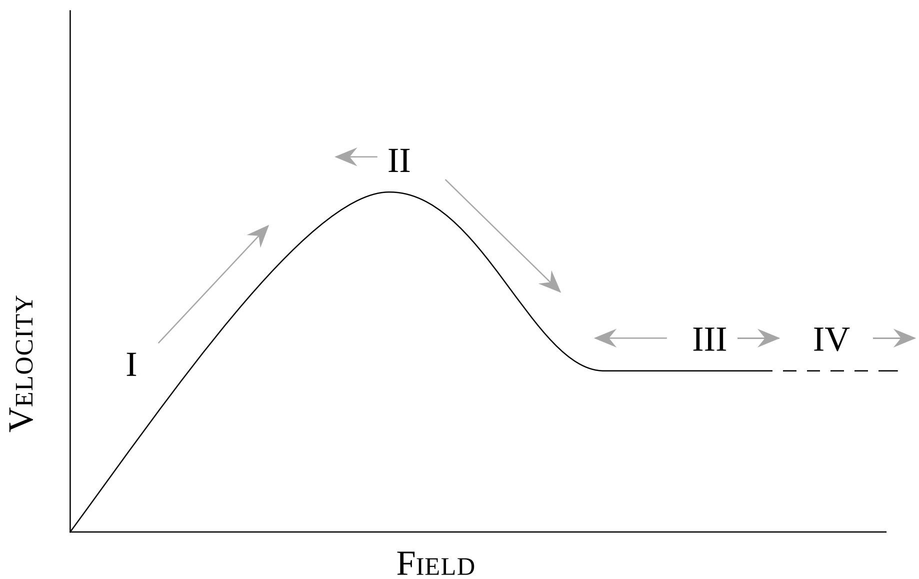
Chapter 7

VELOCITY-FIELD RELATIONS IN SEMICONDUCTORS



Velocity-field curves for several semiconductors.

REGIONS OF STEADY STATE TRANSPORT



I: Linear region: $v = \mu F$

$$\mu = \frac{e\tau_{sc}}{m^*}$$

II: Negative resistance region (in direct gap conduction band):
velocity decreases with field due to charge transfer
from low mass valley to high mass valley

III: Velocity saturation region

IV: Breakdown region due to impact ionization

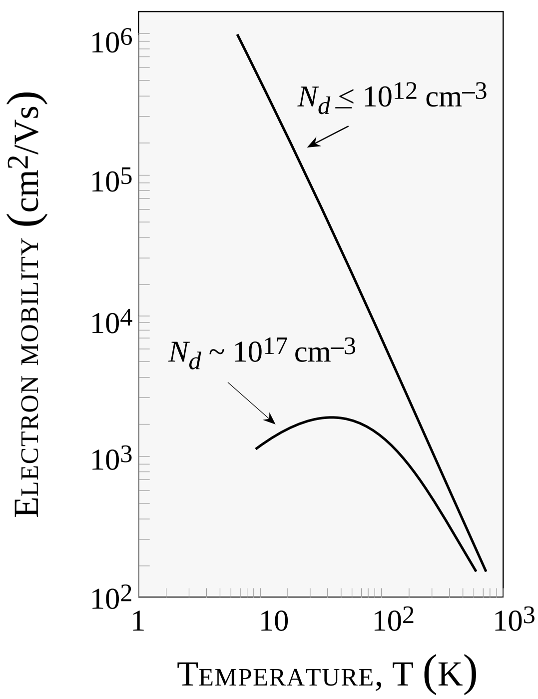
LOW FIELD TRANSPROT: MOBILITY

Mobility: $\mu = \dfrac{e\langle\langle\tau\rangle\rangle}{m^*}$

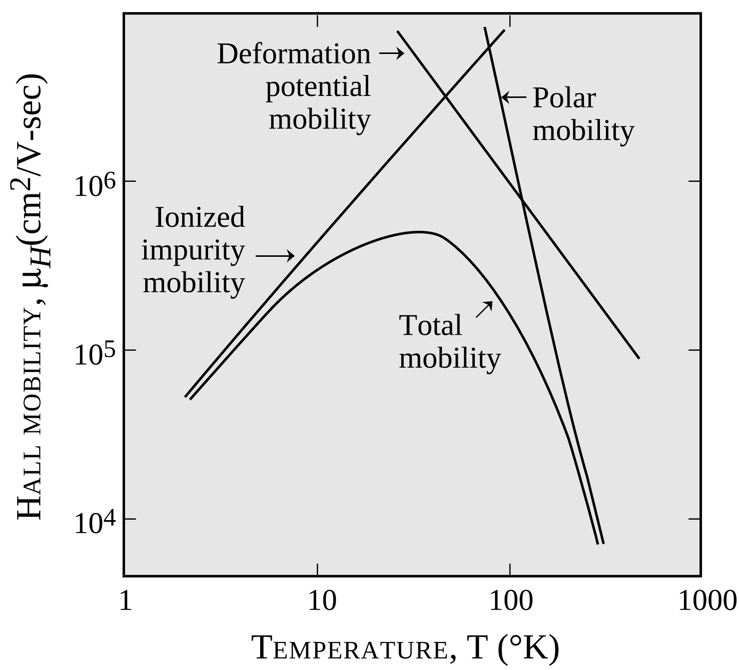
$$\langle\langle\tau\rangle\rangle = \frac{\langle E\tau\rangle}{\langle\tau\rangle}$$

where

$\langle\ \rangle \rightarrow$ averaging over the equilibrium distribution



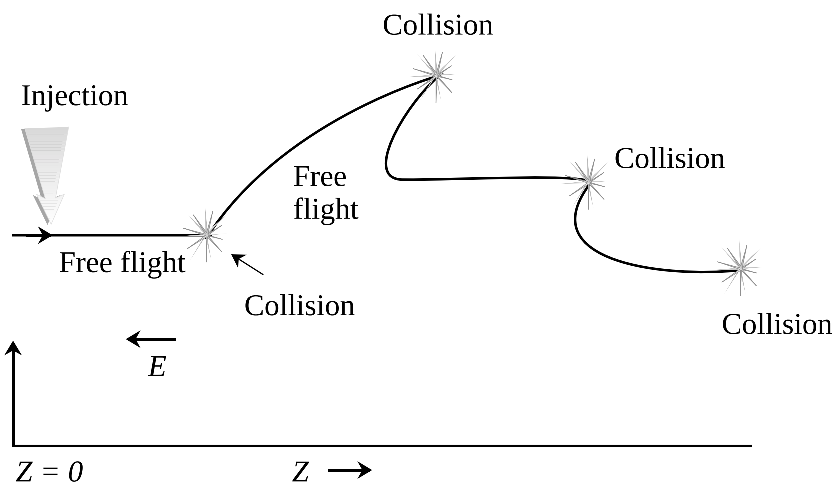
Low-field mobility of electrons in silicon as a function of temperature.



Low-field Hall mobility of electrons in GaAs as a function of temperature. The material has an ionized impurity concentration of 7×10^{13} cm^{-3}.

MONTE CARLO APPROACH TO TRANSPORT

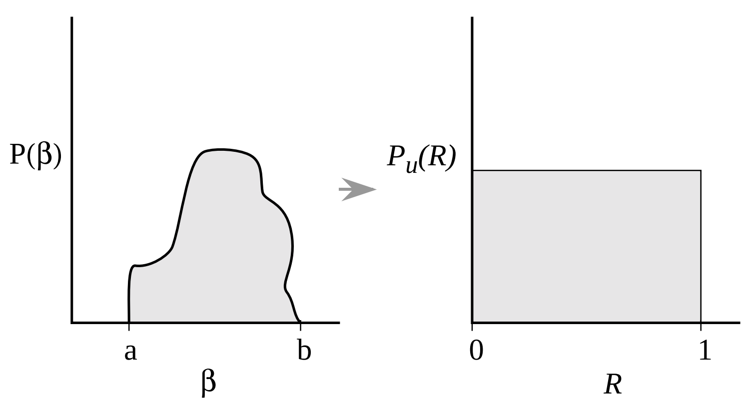
Monte Carlo is based on the computer simulations of transport events: injection, free flight, and scattering.



A schematic of processes involved in the physical picture used in Monte Carlo methods.

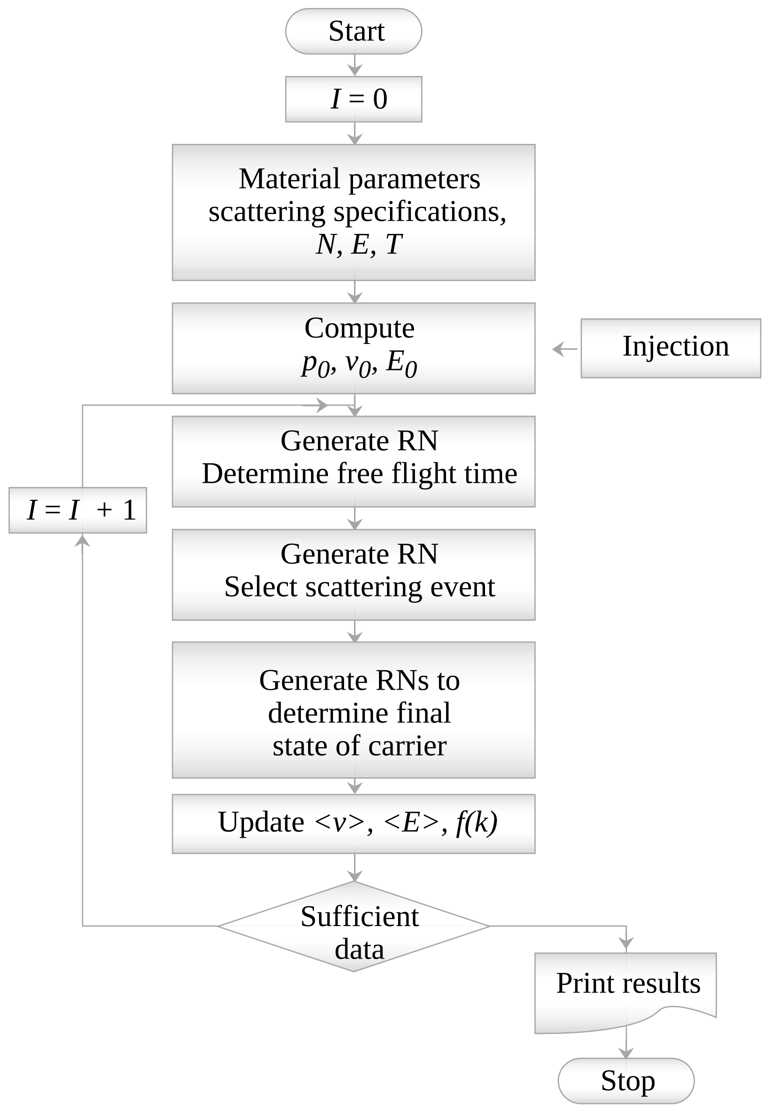
Monte Carlo depends upon using random numbers to mimick a probability function

$$\int_0^{\beta_n} P(\beta)d\beta = \int_0^{R_n} Pu\,(R)dR = R_n$$



Mapping of random probability function to a randomly generated number from a uniform random number generator.

A FLOW CHART OF THE MONTE CARLO METHOD

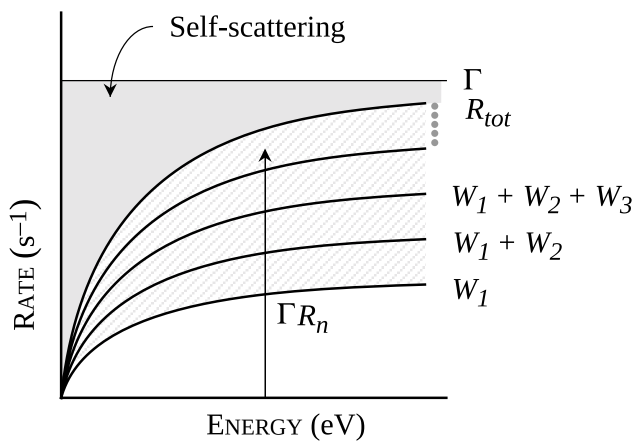


MONTE CARLO METHOD FOR TRANSPORT

Identify all important scattering processes

> $W_{\boldsymbol{k}}$ = Total scattering rate for an electron in state $\boldsymbol{k}$,
> $W(\boldsymbol{k},\boldsymbol{k}')$ = Angular dependence of scattering rate,
> W_{tot} = Total scattering rate

Random number allows one to select the scattering event.



A schematic showing how a random number allows one to determine the scatteirng mechanism responsible for scattering.

MONTE CARLO METHOD FOR TRANSPORT

Final state after scattering once the process responsible for scattering is known:

Final Energy:

Ionized impurity: $\Delta E = 0$

Alloy scattering: $\Delta E = 0$

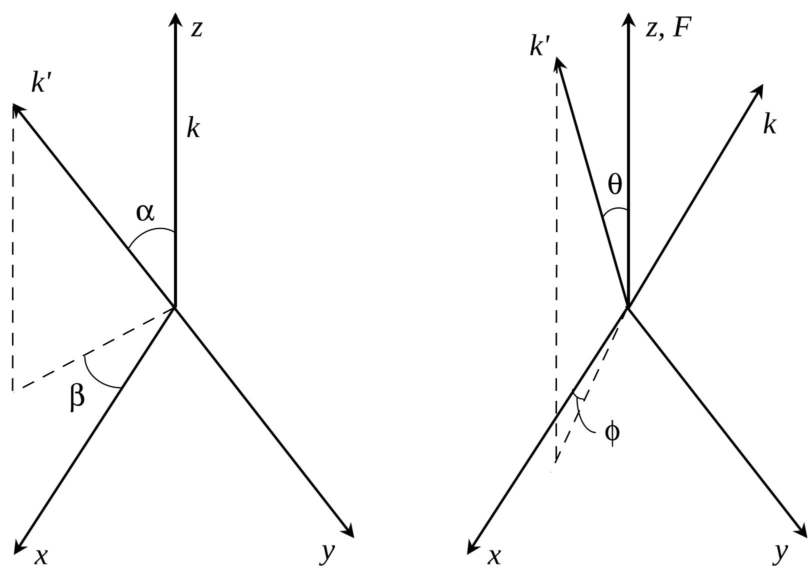
Polar optical phonon: $\Delta E = \pm \hbar\omega_0$

Acoustic phonon: $\Delta E \sim 0$

Intervalley scattering: $\Delta E = \pm \Delta E_{IV} \pm \hbar\omega$

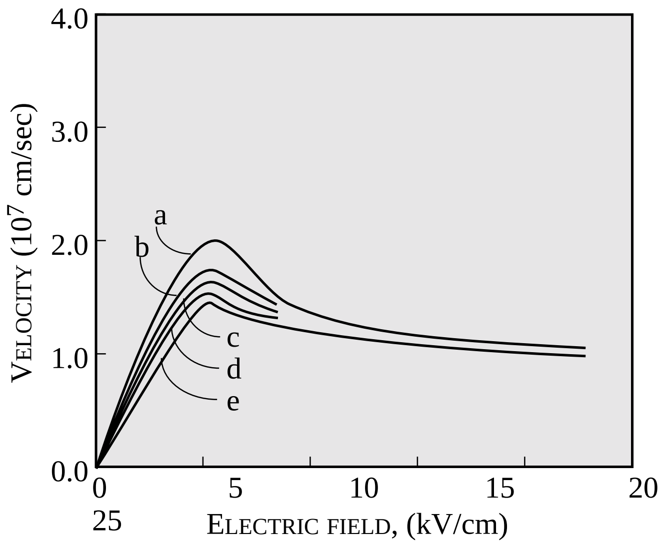
Final Angle:

Random number(s) to simulate $W(\boldsymbol{k},\boldsymbol{k}')$
+ conversion into fixed coordinate system

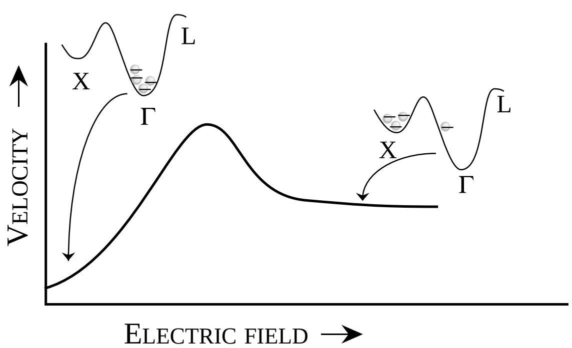


The two coordinate systems used in Monte Carlo method. One uses the system (left) where the momentum before scattering is along the *z*-axis to determine the final state after scattering. This has then to be transformed in the fixed-coordinate system (right) where the **F**-field is along the *z*-axis.

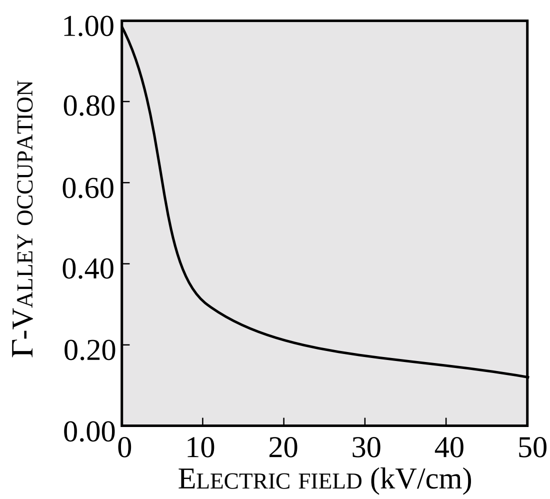
Electron transport in direct gap semiconductors: GaAs



Electron velocity as a function of electric field in a GaAs. The impurity density for the different curves is (a) $N_D = 0$; (b) $N_D = 1.0 \times 10^{17}$ cm^{-3}; (c) $N_D = 2.0 \times 10^{17}$ cm^{-3} (d) $N_D = 4.0 \times 10^{17}$ cm^{-3}; and (e) $N_D = 8.0 \times 10^{17}$ cm^{-3}.



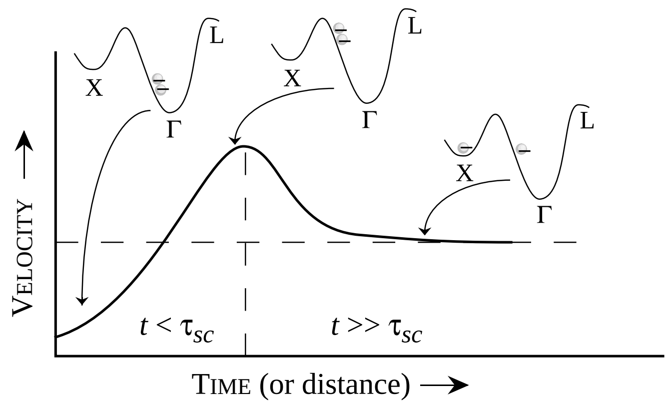
A schematic of how electrons transfer from the Γ-valley to the X-valley in GaAs as the field is increased.



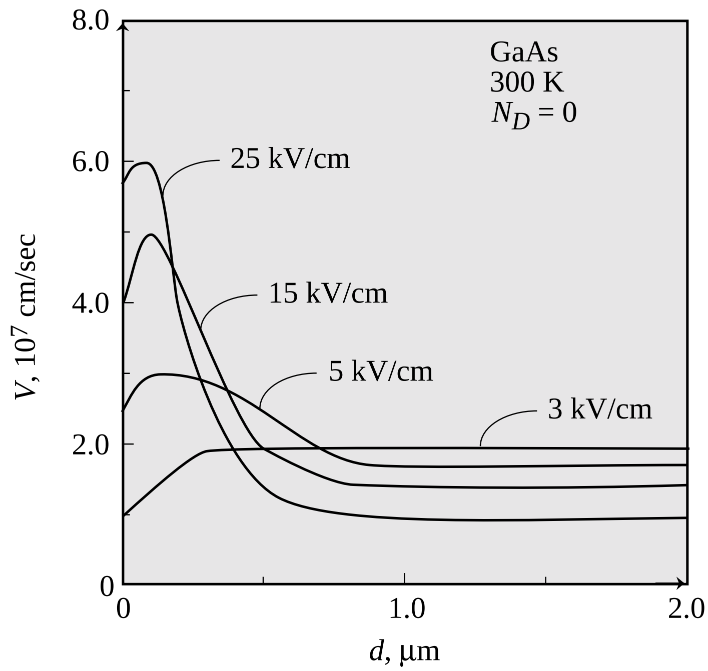
Occupation of the Γ-valley in GaAs electron transport as a function of electric field.

NON-LOCAL TRANSPORT: VELOCITY OVERSHOOT

When the electric field changes rapidly (in space or time) electrons may gain high velocities in times shorter than scattering time, thus reaching velocities higher than steady state velocities.



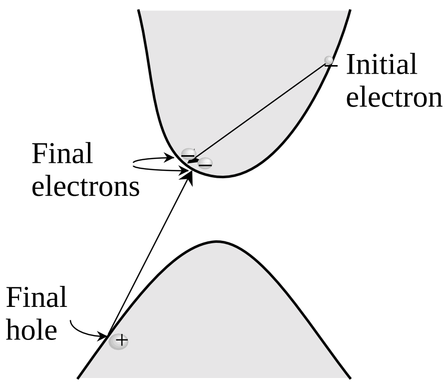
A schematic of how velocity overshoot occurs in a direct bandgap material like GaAs.



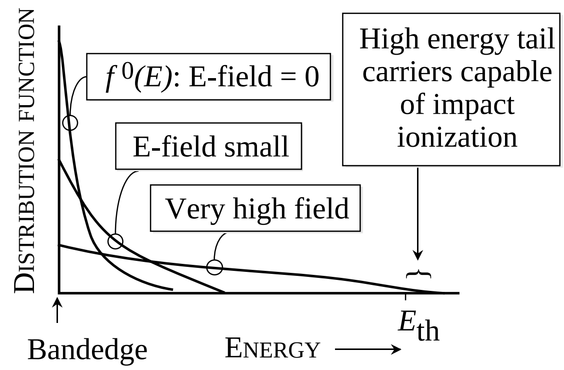
A schematic of how velocity overshoot occurs in a direct bandgap material like GaAs.

VERY HIGH FIELD TRANSPORT: IMPACT IONIZATION

Impact ionization (or avalanche breakdown) occurs at very high fields when carrier energies become larger than the bandgap.



The impact ionization proccess where a high energy electron scatters from a valence band electron producing two conduction band electrons and a hole. Hot holes can undergo a similar process.



A schematic of how the carrier distribution function change as field is increased. The high energy tail responsible for impact ionization is shown.

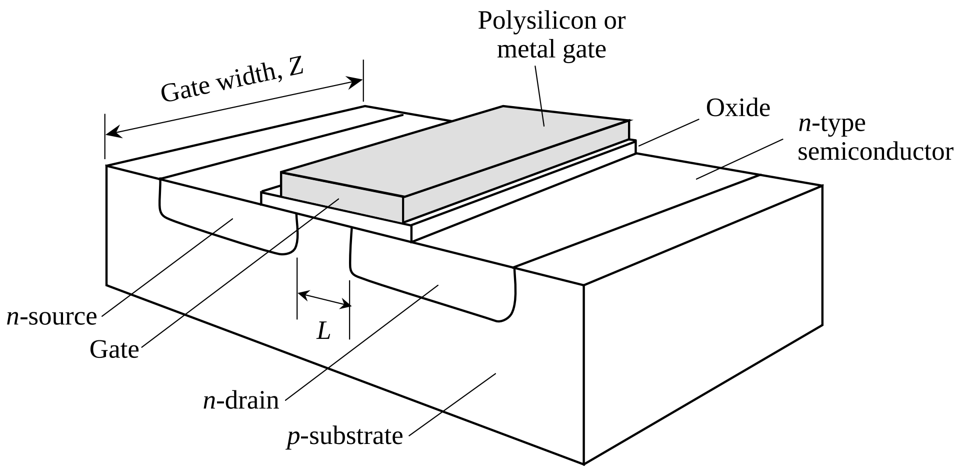
MATERIAL	BANDGAP (eV)	BREAKDOWN ELECTRIC FIELD (V/cm)
GaAs	1.43	4×10^5
Ge	0.664	10^5
InP	1.34	
Si	1.1	3×10^5
$In_{0.53}Ga_{0.47}As$	0.8	2×10^5
C	5.5	10^7
SiC	2.9	$2\text{-}3 \times 10^6$
SiO_2	9	10^7
Si_3N_4	5	10^7

Breakdown electric fields in some materials.

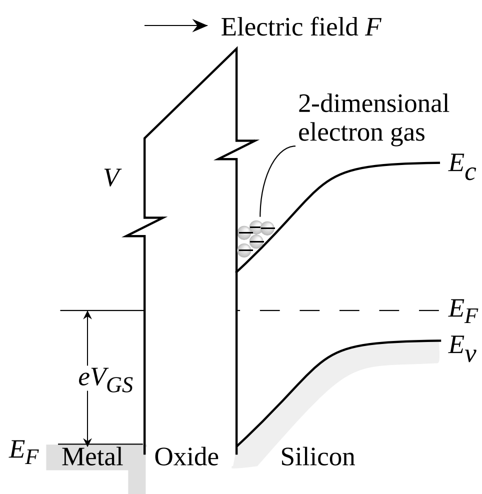
TRANSPORT IN QUANTUM WELLS

In devices such as MOSFETs and MODFETs 2 dimensional electron gas (2DEG) is formed and the nature of scattering is altered.

- Interface roughness effects can be important.
- Inter-subband scattering + 2 dimensional intra-subband scattering ocurs.
- Ionized impurity scattering can be eliminated by modulation doping.



(a)



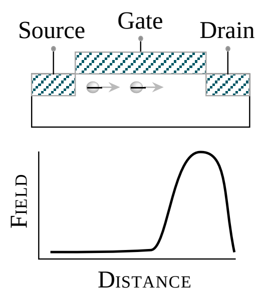
(b)

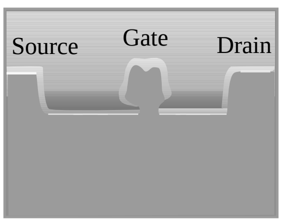
(a) A schematic of a MOSFET with gate length L. (b) By applying a gate bias the semiconductor bands can be “inverted” as shown, inducing electrons in the triangular quantum well.

IMPORTANT ISSUES IN ELECTRNIC DEVICES

DEVICE	IMPORTANT CONSIDERATIONS

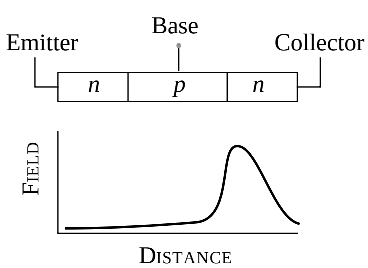
FIELD EFFECT TRANSISTORS

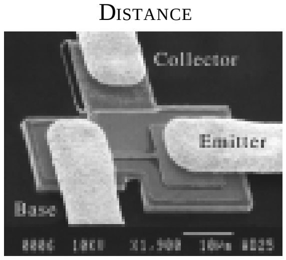




- Superior low field moblity
  ➤ improved source-gate resistance
- Si ➤ GaAs ➤ InGaAs
- Superior high field velocity
  ➤ high frequency/high speed operation
- Low impact ionization coefficient
  ➤ high power devices
  Si ➤ GaAs ➤ SiC ➤ GaN ➤ C(?)

BIPOLAR JUNCTION TRANSISTORS





- Superior hole mobility ➤ low base resistance
- Superior electron low field mobility (diffusion coefficient) ➤ small base transit time
- Superior high field electron velocity ➤ small base-collector transit time, high frequency/high field response
- Power devices ➤ high bandgap collector region.

An overview of two important classes of electrnic devices nad influences of carrier transport on their performance.