

Si - Silicon

Electrical properties

Basic Properties

Mobility and Hall Effect

Transport Properties in High Electric Field

Impact Ionization

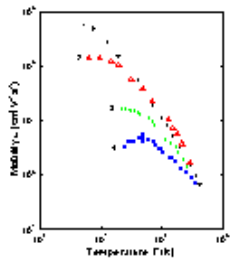
Recombination Parameters

Surface Recombination

Basic Properties

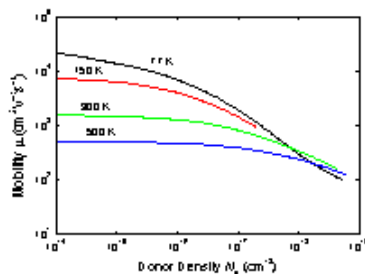
Breakdown field	$\approx 3 \cdot 10^5 \text{ V/cm}$
Mobility electrons	$\leq 1400 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Mobility holes	$\leq 450 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
Diffusion coefficient electrons	$\leq 36 \text{ cm}^2/\text{s}$
Diffusion coefficient holes	$\leq 12 \text{ cm}^2/\text{s}$
Electron thermal velocity	$2.3 \cdot 10^5 \text{ m/s}$
Hole thermal velocity	$1.65 \cdot 10^5 \text{ m/s}$

Mobility and Hall Effect



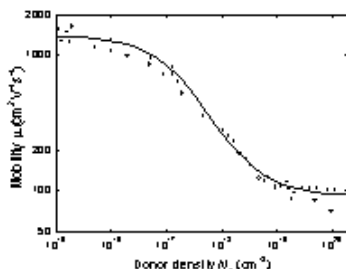
Electron mobility versus temperature for different doping levels.

1. High purity Si ($N_d < 10^{-12} \text{ cm}^{-3}$); time-of-flight technique ([Canali et al. \[1973\]](#)).
2. High purity Si ($N_d < 4 \cdot 10^{-13} \text{ cm}^{-3}$); photo-Hall effect ([Norton et al. \[1973\]](#)).
3. $N_d = 1.75 \cdot 10^{16} \text{ cm}^{-3}$; $N_a = 1.48 \cdot 10^{15} \text{ cm}^{-3}$; Hall effect ([Morin and Maita \[1954\]](#)).
4. $N_d = 1.3 \cdot 10^{17} \text{ cm}^{-3}$; $N_a = 2.2 \cdot 10^{15} \text{ cm}^{-3}$; Hall effect ([Morin and Maita \[1954\]](#)).



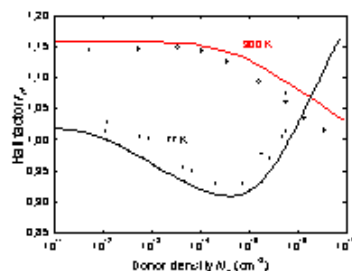
Electron drift mobility versus donor density at different temperatures

([Li and Thumber \[1977\]](#)).



Electron drift mobility versus donor density, T=300 K.

([Jacoboni et al. \[1977\]](#)).

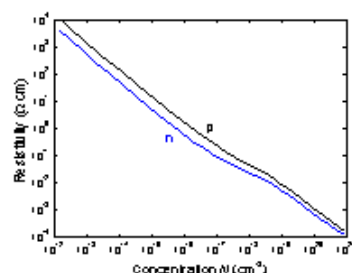


The electron Hall factor versus donor density. 77 and 300 K.

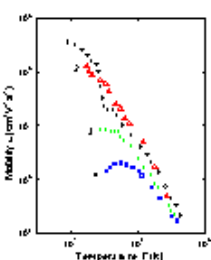
Solid lines show the results of calculations.

Symbols represent experimental data

([Kirmas et al. \[1974\]](#)).



Resistivity versus impurity concentration for Si at 300 K.



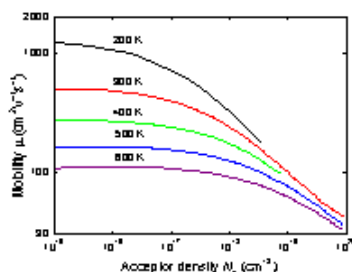
Temperature dependences of hole mobility for different doping levels.

1. High purity Si ($N_a = 10^{12} \text{ cm}^{-3}$); time-of-flight technique ([Ottaviani et al. \[1975\]](#));

2. High purity Si ($N_a \sim 10^{14} \text{ cm}^{-3}$); Hall-effect ([Logan and Peters \[1960\]](#)).

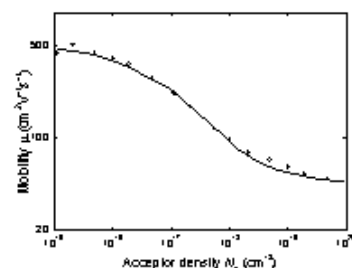
3. $N_a = 2.4 \cdot 10^{16} \text{ cm}^{-3}$; $N_d = 2.3 \cdot 10^{15} \text{ cm}^{-3}$; Hall-effect ([Morin and Maita \[1954\]](#)).

4. $N_a = 2 \cdot 10^{17} \text{ cm}^{-3}$; $N_d = 4.9 \cdot 10^{15} \text{ cm}^{-3}$; Hall-effect ([Morin and Maita \[1954\]](#)).



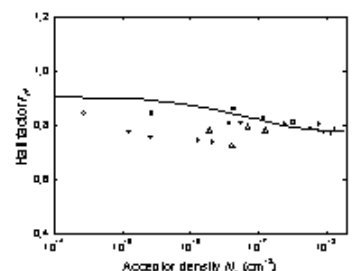
Hole drift mobility versus acceptor density at different temperatures

([Dorkel and Leturcq \[1981\]](#)).



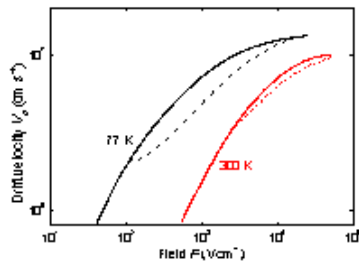
Hole drift mobility versus acceptor density. 300 K.

([Jacoboni et al. \[1977\]](#)).



The hole Hall factor versus acceptor density. 300 K.

([Lin et al. \[1981\]](#)).

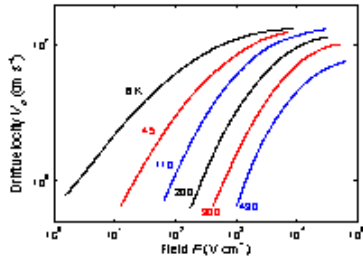


Si. Electron drift velocity vs. electric field.

Solid lines: $F \parallel (111)$.

Dashed lines: $F \parallel (100)$.

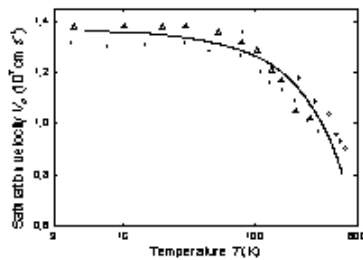
[Jacoboni et al. \(1977\)](#).



Si. Electron drift velocity vs. electric field at different temperatures.

$F \parallel (111)$.

[Jacoboni et al. \(1977\)](#).



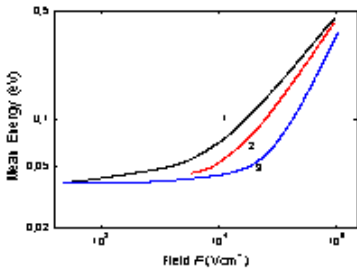
Temperature dependence of the saturation electron drift velocity

[Jacoboni et al. \(1977\)](#).

Solid line is calculated according to equation:

$$v_s = v_{s0} \cdot [1 + C \cdot \exp(T/I)]^{-1},$$

where $v_{s0} = 2.4 \cdot 10^7 \text{ cm s}^{-1}$, $C = 0.8$, $I = 600 \text{ K}$.



Mean energy of electrons as a function of electronic field F at different donor densities.

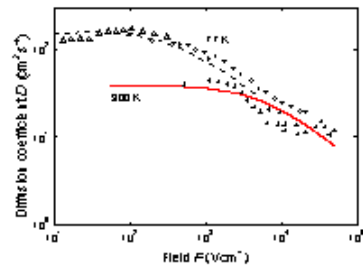
$F \parallel (111)$. 300 K.

1. $N_d = 0$;

2. $N_d = 4 \cdot 10^{18} \text{ cm}^{-3}$;

3. $N_d = 4 \cdot 10^{19} \text{ cm}^{-3}$.

[Jacoboni et al. \(1977\)](#).

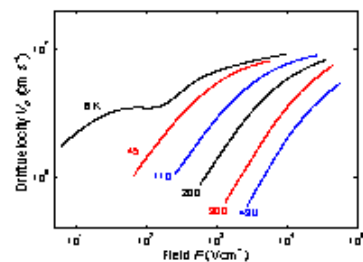


The field dependence of longitudinal electron diffusion coefficient D for 77 K and 300 K.

$F \parallel (111)$. Dotted and solid lines show the results of Monte-Carlo simulation.

Symbols represent measured data.

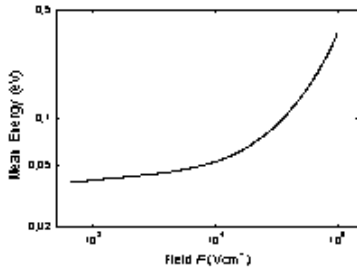
[Canali et al. \(1985\)](#).



Field dependences of the hole drift velocity at different temperatures.

$F \parallel (100)$.

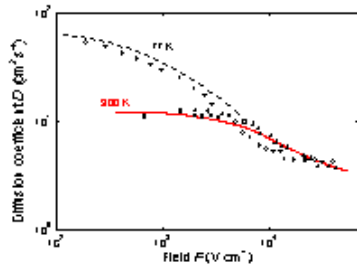
[Jacoboni et al. \(1977\)](#).



Mean energy of holes as a function of electronic field F .

$N_a = 0$, $T = 300$ K.

([Jacoboni et al. \[1977\]](#)).



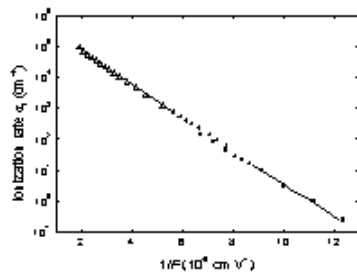
The field dependence of longitudinal hole diffusion coefficient D for 77K and 300 K.

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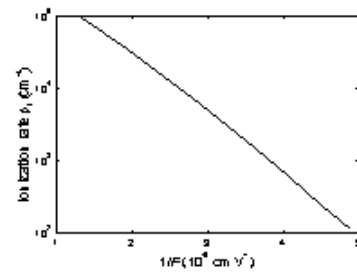
([Canali et al. \[1985\]](#)).

Impact Ionization



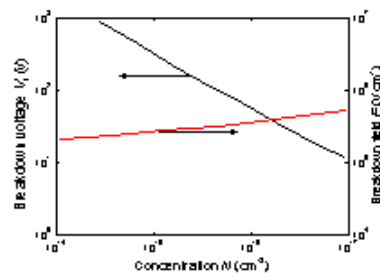
Electron ionization rate α_i vs. $1/F$.

$T = 300$ K. ([Maes et al. \[1990\]](#)).



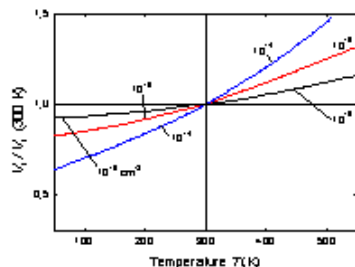
Hole ionization rate β_i vs. $1/F$.

$T = 300$ K. ([Grant \[1973\]](#)).



Breakdown voltage and breakdown field vs. doping density for an abrupt p - n junction.

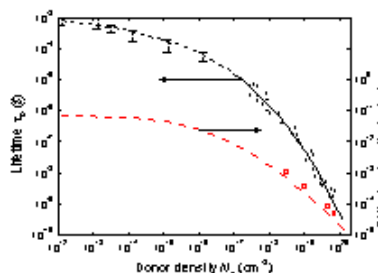
$T = 300$ K. ([Sze \[1981\]](#)).



Normalized breakdown voltage vs. temperature for an abrupt p - n junction at different doping levels.

(Crowell and Sze [1981]).

Recombination Parameters



Lifetime τ_p and diffusion length L_p of holes in n -type Si vs. donor density. $T = 300$ K.

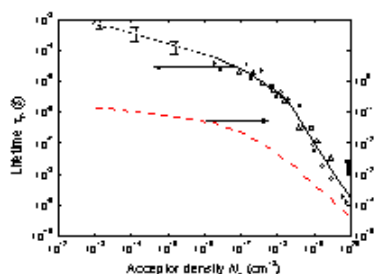
For $10^{12} \text{ cm}^{-3} < N_d \leq 10^{17} \text{ cm}^{-3}$ - from numerous experimental data for good quality industrial produced n -Si.

For $N_d \geq 10^{17} \text{ cm}^{-3}$ - (Alamo and Swanson [1987]).

$L_p(N_d)$ dependence (dashed line) is calculated as

$$L_p(N_d) = [D_p(N) \cdot \tau_p(N)]^{1/2},$$

where $D_p = (k_B \cdot T/q) \cdot \mu_p$.



Lifetime τ_n and diffusion length L_n of electrons in p -type Si vs. acceptor density. $T = 300$ K.

For $10^{13} \text{ cm}^{-3} < N_a \leq 10^{16} \text{ cm}^{-3}$ - from numerous experimental data for good quality industrial produced p -Si.

For $N_a \geq 10^{16} \text{ cm}^{-3}$ - (Tyagi and Van Overstraeten [1983]). $L_n(N_a)$ dependence (dashed line) is

$$\text{calculated as } L_n(N_a) = [D_n(N) \cdot \tau_n(N)]^{1/2},$$

where $D_n = (k_B \cdot T/q) \cdot \mu_n$.

Surface recombination

Surface recombination rate depending on treatment of Si surface lies in the range between $10^2 \div (6-8) \cdot 10^4 \text{ cm/s}$.

Surface recombination rate on the Si-SiO₂ interface can be as small as $\leq 0.5 \text{ cm/s}$.

Si

Remarks Referens

The longest lifetime of holes t_p

Diffusion length $L_p = (D_p \times t_p)^{1/2}$

Surface Recombination Velocity

Radiative recombination coefficient B $1.1 \times 10^{-14} \text{ cm}^3/\text{s}$

(Gerlach et al. (1972).

Auger coefficient C_n $1.1 \times 10^{-30} \text{ cm}^6/\text{s}$ 300 K

Auger coefficient C_p $0.3 \times 10^{-30} \text{ cm}^6/\text{s}$ 300 K

Auger coefficient $C = C_n + C_p$ $1.4 \times 10^{-30} \text{ cm}^6/\text{s}$ 300 K

For $180 \text{ K} \leq T \leq 400 \text{ K}$ - $C \approx 1.4 \cdot 10^{-30} \cdot (T/300)^{1/2} (\text{cm}^6/\text{s})$.

