Resistivity and Carrier Transport Parameters in Silicon

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A Introduction

This paper contains information on the resistivity, mobility, and diffusivity of electrons and holes in silicon. It also contains information on minority carrier lifetimes and diffusion lengths.

In general, carrier lifetimes and diffusion lengths must be measured experimentally, but the equations and values given in the paper are reasonable approximations for resistivities less than about 1 ohm-cm.

B Resistivity, Mobility, and Diffusivity for n-type and p-type doped silicon

In one dimension, the current density of electrons can be approximated with the following equation

$$J_n = \left(n \cdot q \cdot u_n \cdot E\right) + \left(q \cdot D_n \left(\frac{dn}{dx}\right)\right) \qquad (\text{Amps/cm}^2) \qquad (1)\ [1]$$

where "q" is the charge, "u_n" is the mobility, "E" is the electric field, "D_n" is the diffusion coefficient, n is the carrier concentration (c), and

$$n \approx N_D = c \quad \text{at 300K} \quad (\text{ohm-cm}).$$

The current density of holes is given by a similar equation

$$J_p = \left(p \cdot q \cdot u_p \cdot E\right) - \left(q \cdot D_p \left(\frac{dp}{dx}\right)\right) \qquad (\text{Amps/cm}^2) \qquad (2)\ [1]$$

where

$$p \approx N_A = c \quad \text{at 300K} \quad (\text{ohm-cm}).$$

The resistivity is,

$$p = \frac{1}{c \cdot q \cdot u} = \frac{1}{N_A \cdot q \cdot u_p} = \frac{1}{N_D \cdot q \cdot u_n} \quad . \qquad (3)$$

For J ≈ 0, and equilibrium conditions

$$\frac{D_n}{u} = \frac{k \cdot T}{q} \qquad (4)$$

where k is the Boltzmann constant.
Tables 1,2 use the above equations 3,4 for *u* and *D*, as well as the data from reference [2]. High resistivity silicon can only be produced using the Float Zone (FZ) crystal growth method. The FZ method does not use a crucible during crystal growth. The Czochralski (CZ) method uses a quartz crucible during crystal growth, and oxygen from the crucible dopes the material. The unintentional oxygen dopant behaves as an n-type impurity and precludes solidification of oxygen-free material and high resistivity. Intentional dopants are introduced to FZ material during solidification using doping gases. This limits the maximum concentration of doping during the FZ method. The typical p-type impurity for silicon is Boron. Although, Gallium doping has been used for certain applications related to solar cells. Silicon is doped n-type using Phosphorous, Arsenic, or Antimony. Low resistivity n-type material is achieved using Arsenic doping.

P (ohm-cm)	n (cm^{-3})	N_D (cm^{-3})	u_n (cm^2/(V-s))	D_n (cm^2/s)	Grow Method
0.0001	1.60E+21	1.60E+21	39.063	1.011	Cz
0.001	7.38E+19	7.38E+19	84.688	2.191	Cz
0.01	4.53E+18	4.53E+18	137.969	3.570	Cz
0.1	7.84E+16	7.84E+16	797.194	20.627	Cz
1	4.86E+15	4.86E+15	1286.008	33.275	Cz,Fz
10	4.45E+14	4.45E+14	1404.494	36.341	Cz,Fz
100	4.27E+13	4.27E+13	1463.700	37.873	Cz,Fz
1000	4.20E+12	4.20E+12	1488.095	38.504	Fz
10000	4.00E+11	4.00E+11	1562.500	40.430	Fz

Table 1 shows electron properties in n-type Si at 300K [2]

P (ohm-cm)	p (cm^{-3})	N_A (cm^{-3})	u_p (cm^2/(V-s))	D_p (cm^2/s)	Grow Method
0.0001	1.20E+21	1.20E+21	52.083	1.348	Cz
0.001	1.70E+20	1.70E+20	36.765	0.951	Cz
0.01	8.49E+18	8.49E+18	73.616	1.905	Cz
0.1	2.77E+17	2.77E+17	225.632	5.838	Cz
1	1.46E+16	1.46E+16	428.082	11.077	Cz,Fz
10	1.34E+15	1.34E+15	466.418	12.069	Cz,Fz
100	1.33E+14	1.33E+14	469.925	12.159	Cz,Fz
1000	1.30E+13	1.30E+13	480.769	12.440	Fz
10000	1.30E+12	1.30E+12	480.769	12.440	Fz

Table 2 shows hole properties in p-type Si at 300K [2]

C Electron and Hole Minority Carrier Lifetime and Diffusion Lengths
The electron minority carrier diffusion length in p-type Si is approximated by

$$L_e = \sqrt{\left(\frac{kT}{q}\right) u_e \tau_e} \quad \text{cm} \qquad (5)[1][2][3]$$

where k is the Boltzmann constant, T is the absolute temperature (K), q is the charge, u_e is the electron mobility, and τ_e is the electron minority carrier lifetime estimated by

$$\frac{1}{\tau_e} = \left[\left(3.45\times10^{-12} N_a\right) + \left(9.5\times10^{-32} N_a^2\right)\right] s^{-1} \qquad (6)[1][2][3]$$

where N_a is the acceptor density and $N_a > 1 \times 10^{17}$ (cm^{-3}). The hole diffusion length in n-type Si is given by

$$L_h = \sqrt{\left(\frac{kT}{q}\right) u_h \tau_h} \quad \text{cm} \qquad (7)[1][2][3]$$

where k is the Boltzmann constant, T is the absolute temperature (K), q is the charge, u_h is the hole mobility, and τ_h is the hole lifetime estimated by

$$\frac{1}{\tau_h} = \left[\left(7.8\times10^{-13} N_d\right) + \left(1.8\times10^{-31} N_d^2\right)\right] s^{-1} \qquad (8)[2][3]$$

where N_d is the donator density and $N_d > 1 \times 10^{17}$ (cm^{-3}).
Tables 3,4 use the above equations to estimate the minority carrier properties in silicon at 300K.

N_D (cm^{-3})	T_h s^{-1}	L_h cm
1.60E+21	2.164E-12	1.708E-06
7.38E+19	9.635E-10	3.029E-05
4.53E+18	1.384E-07	5.136E-04
7.84E+16	1.606E-05	9.687E-03

Table 3 shows Lifetimes and Diffusion Lengths of hole Minority Carriers [2]

N_A (cm^{-3})	T_e s^{-1}	L_e cm
1.20E+21	7.095E-12	2.679E-06
1.70E+20	3.001E-10	2.565E-05
8.49E+18	2.767E-08	3.144E-04
2.77E+17	1.038E-06	4.630E-03

Table 4 shows Lifetimes and Diffusion Lengths of electron Minority Carriers [2]

Lifetimes for high resistivity material are difficult to predict and widely varying depending on the FZ or CZ technique used. Direct experimental measurement is generally required to estimate the carrier lifetime in high resistivity material. The lifetime is controlled by the total concentration Na+Nd, while the resistivity is controlled by the difference in dopants, Na-Nd. At high resistivities Na-Nd is very small, but Na+Nd can be large and widely varying for a given resistivity. The opposite is true at low resistivity making estimation of the lifetime more consistent.

D Summary

This paper contains estimations of silicon resistivity, as well as carrier mobility, and diffusivity for electrons and holes at 300K. It also contains information on minority carrier lifetimes and diffusion lengths. The reader is directed to reference [2] for further details related to temperature, electric field, and processing dependencies to the resistivity and transport properties.

E References

[1] S.M. Sze [*Physics of Semiconductor Devices* (John Wiley and Son s, Inc, New York, 1981)]

[2] R. Hull [*Properties of Crystalline Silicon* (INSPEC, London, 1999)]

[3] D. Huber, A. Bachmeier, R. Wahlich, H. Herzer [*Proc. Conf. Semiconductor Silicon 1986* Eds. H.R. Huff, T. Abe, B. Kobessen (Electrochemical Society, USA, 1986) p.1022-32]