Research Article

# Effect of Temperature on Silicon Carriers Mobilities Using MATLAB

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**Abstract**
The effect of temperature on the electron and hole mobilities in silicon is studied using MATLAB. A theoretical study has been used for the electrons mobility and holes in silicon. The resulting data allows one to obtain the electron mobility and the hole mobility as a function of doping concentration and continuous temperature range between (200-550 K).

**Keywords:** Carrier Mobilities, Doping Concentration, Hole Mobility, Electron Mobility.

**الخلاصة**
تم دراسة تأثير درجة الحرارة على ناقلات الحركة للالكترون وناقلات الحركة للفجوة في السليكون باستخدام الماتلاب، وقد استخدمت دراسة نظرية لناقلات حركة الالكترونات وناقلات حركة الفجوات في السليكون. ان البيانات الناتجة تسمح بالحصول على ناقلات حركة الالكترون وناقلات حركة الفجوة كدالة لكثافة تركيز الإشابة وبدرجة حرارة تتراوح بين (200-550) K.

## Introduction

The valence band and the band of electrons are completely full for the band structure of the semiconductors. The conduction band occur when the electrons excited to the next highest band, otherwise there is no conduction of electrons when the voltage is applied because of no gaps to allow the electrons to transmit from band to band [1].

Normally, the conduction band separated by a barrier from the valence band therefore, to create a free electron and hole in the conduction and valence bands respectively which is normally empty in the conduction band and full in the valence band, valence electron must absorbed small amounts of energy such as light or heat to break this barrier [1].

The carriers are commonly refers to electrons and holes. In semiconductor physics, the electron mobility refers to how rapidly an electron will move through a metal or semiconductor, when pulled by an electric field [2]. In semiconductor, there is a homologous quantity for holes, called hole mobility. The conductivity of a semiconductor is directly proportional to the product of carrier concentration and carrier mobility. Whenever all the things are equal, higher mobility leads to better device performance [3].

Carrier bounces around and regularly changes direction and velocity in the semiconductor because of the scattering. Consequently Carriers do not follow a straight pathway along the electric field lines and this action occurs even when no electric field is applied because of the thermal energy of the electrons. A thermal energy for the electrons in a non-degenerate and non-relativistic electron gas which is equals to $\frac{KT}{2}$ per particle per degree of freedom where $K$ the Stefan–Boltzmann constant is and $T$ is the temperature. The typical drift velocity in the semiconductor is less than a typical thermal velocity which is a round $10^{+7}$ cm/s at room temperature. The carrier motion is shown in the Figure 1 when the electric fields are applied or without it in the semiconductor [3].

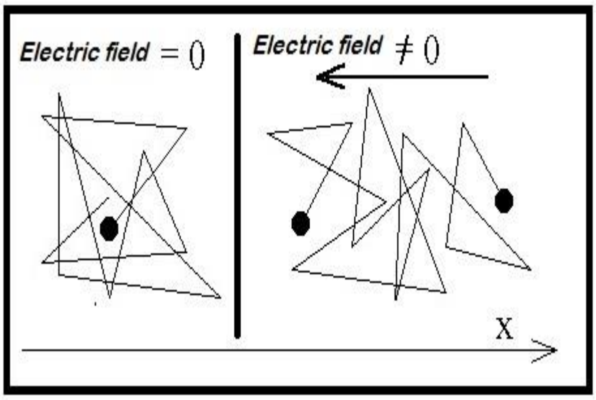


Figure 1: Random motion of carriers when the electric fields are applied or without it in the semiconductor [3].

The carrier motions are occurred randomly and quickly through the semiconductor when the electric field is not applied, otherwise a small difference when the electric field applied there is a net motion along the field.
By the analyzation of the net movement of the carrier motion according to the Newton's second law, the applied force is proportional to the acceleration of the carrier [3]:

$$\vec{F} = m\vec{a} = m\frac{d(\vec{v})}{dt} \quad (1)$$

Where $\vec{F}$ is the force, $\vec{a}$ is the acceleration, $m$ is the mass, $\vec{v}$ is the velocity and $t$ is the time, the force equal to the difference between the electrostatic force and the force due to the loss of momentum at the time of scattering divided by the average time between scattering events:

$$\vec{F} = q\vec{\varepsilon} - m\frac{(\vec{v})}{\tau} \quad (2)$$

The average particle velocity can be measured by the additions of equations (1) and (2):

$$q\vec{\varepsilon} = m\frac{d(\vec{v})}{dt} + m\frac{(\vec{v})}{\tau} \quad (3)$$

The particle in semiconductor has accelerated to reach a constant velocity as considered in the situation above; otherwise under such conditions the particle has velocity which is proportional to the applied electric field. Equation (4) shows the mobility as the velocity to field ratio:

$$\mu \triangleq \frac{|\vec{v}|}{\vec{\varepsilon}} = \frac{q\tau}{m} \quad (4)$$

From equation (4) we can expected that if the mass of the particle is small the mobility of a particle will be large and proportional to the time between scattering events in a semiconductor.
Therefore, the drift of velocity ($v_d$) of holes and electrons in a solid equal to the mobility tensor as denotes ($\vec{\mu}$) multiplied by an applied electric field ($E$).

$$v_d = \vec{\mu}E \quad (5)$$

There is a difference between the mobility of electrons and the holes in a semiconductor, because of the different band structure and scattering mechanisms of these two carrier types. When one charge carrier is dominant the conductivity of a semiconductor is directly proportional to the mobility of the dominant carrier [4] [5] [6] [7].

## Materials and Methodology

In this theoretical study, the MATLAB program calculates the following outputs:
1. Tables of electron and hole mobility (Table 1 and Table 2).
2. Graphical representation of mobilities in the silicon as a function of the doping concentration at continuous temperature range (200-550) K shown in Figures 2, 3, 4, 5, 6, 7, 8 and 9.
Using user defined functions and function files many functions are programmed inside MATLAB program, where the user saved as a one or many functions file, and then can be used as a built in mathematical expression function.
Using these theoretical ideas we can calculate the density of the ionized impurities for hole and electron mobility and deal with them as array matrixes.

## Results and Discussion

The results can be explained as follow, when semiconductor n-type silicon doped with a shallow donor impurity in concentration ($10^{14}$ – $10^{20}$) cm$^{-3}$, at room temperature and above, all the shallow donor impurity atoms will be ionized providing free electron carriers concentration in n-type silicon in concentration ($10^{14}$ – $10^{20}$) $cm^{-3}$. The relationship between conductivity and free carriers mobility is well known in the theory of semiconductors. Semiconductor theory considers two major mechanisms for free carriers' mobility dependency of crystal temperature:

Table 1 and Table 2 show the carrier mobility (hole) and the carrier mobility (electron) in Silicon respectively. Figures (2-9) below show the mobility of electrons and holes in silicon at temperature T= (200-550) K.

Table 1: Carrier Mobility (Hole) in Silicon

| Doping $cm^{-3}$ | Hole Mobility ($cm^2$ V-sec) T=200K | Hole Mobility ($cm^2$ V-sec) T=250K | Hole Mobility ($cm^2$ V-sec) T=300K | Hole Mobility ($cm^2$ V-sec) T=350 K | Hole Mobility ($cm^2$ V-sec) T=400K | Hole Mobility ($cm^2$ V-sec) T=450K | Hole Mobility ($cm^2$ V-sec) T=500K | Hole Mobility ($cm^2$ V-sec) T=550K |
|---|---|---|---|---|---|---|---|---|
| 1e14 | 10731 | 6711 | 4611 | 3381 | 2601 | 2081 | 1711 | 1441 |
| 2e14 | 10712 | 6712 | 4612 | 3382 | 2602 | 2082 | 1712 | 1442 |
| 5e14 | 10685 | 6705 | 4615 | 3385 | 2605 | 2085 | 1715 | 1445 |
| 1e15 | 10631 | 6681 | 4601 | 3381 | 2601 | 2081 | 1711 | 1441 |
| 2e15 | 10532 | 6642 | 4582 | 3372 | 2602 | 2072 | 1712 | 1442 |
| 5e15 | 10235 | 6545 | 4545 | 3355 | 2585 | 2075 | 1705 | 1435 |
| 1e16 | 9781 | 6371 | 4471 | 3311 | 2571 | 2061 | 1701 | 1431 |
| 2e16 | 8992 | 6062 | 4332 | 3242 | 2532 | 2042 | 1682 | 1422 |
| 5e16 | 7275 | 5315 | 3975 | 3065 | 2435 | 1985 | 1655 | 1405 |
| 1e17 | 5581 | 4431 | 3501 | 2801 | 2281 | 1881 | 1591 | 1361 |
| 2e17 | 3922 | 3392 | 2872 | 2412 | 2042 | 1732 | 1492 | 1292 |
| 5e17 | 2295 | 2145 | 1965 | 1775 | 1595 | 1425 | 1275 | 1145 |
| 1e18 | 1561 | 1481 | 1401 | 1321 | 1231 | 1141 | 1051 | 971 |
| 2e18 | 1142 | 1082 | 1022 | 972 | 932 | 882 | 832 | 792 |
| 5e18 | 875 | 805 | 755 | 715 | 685 | 655 | 625 | 595 |
| 1e19 | 781 | 701 | 651 | 611 | 571 | 551 | 521 | 501 |
| 2e19 | 732 | 652 | 602 | 552 | 522 | 492 | 472 | 452 |
| 5e19 | 705 | 625 | 565 | 525 | 485 | 465 | 435 | 415 |
| 1e20 | 961 | 611 | 551 | 511 | 471 | 441 | 421 | 401 |
| 2e20 | 692 | 612 | 552 | 502 | 472 | 442 | 412 | 392 |
| 5e20 | 695 | 605 | 555 | 505 | 465 | 435 | 415 | 395 |

Table 2: Carrier Mobility (Electron) in Silicon

| Doping $cm^{-3}$ | Electron Mobility ($cm^2$ V-sec) T=200K | Electrons Mobility ($cm^2$ V-sec) T=250K | Electrons Mobility ($cm^2$ V-sec) T=300K | Electrons Mobility ($cm^2$ V-sec) T=350 K | Electrons Mobility ($cm^2$ V-sec) T=400K | Electrons Mobility ($cm^2$ V-sec) T=450K | Electrons Mobility ($cm^2$ V-sec) T=500K | Electrons Mobility ($cm^2$ V-sec) T=550K |
|---|---|---|---|---|---|---|---|---|
| 1e14 | 33061 | 19911 | 13211 | 9381 | 7001 | 5421 | 4331 | 3541 |
| 2e14 | 33032 | 19902 | 13212 | 9382 | 6992 | 5422 | 4332 | 3542 |
| 5e14 | 32975 | 19885 | 13205 | 9375 | 6995 | 5425 | 4335 | 3545 |
| 1e15 | 32851 | 19841 | 13191 | 9371 | 6991 | 5421 | 4331 | 3541 |
| 2e15 | 32632 | 19772 | 13152 | 9352 | 6982 | 5412 | 4322 | 3542 |
| 5e15 | 31995 | 19555 | 13065 | 9315 | 6965 | 5405 | 4325 | 3545 |
| 1e16 | 30981 | 19191 | 12911 | 9241 | 6921 | 5381 | 4301 | 3531 |
| 2e16 | 92132 | 18512 | 12622 | 9102 | 6852 | 5342 | 4282 | 3512 |
| 5e16 | 24745 | 16765 | 11835 | 8705 | 6645 | 5215 | 4205 | 3465 |
| 1e17 | 19841 | 14491 | 10721 | 8121 | 6311 | 5031 | 4091 | 3391 |
| 2e17 | 14312 | 11462 | 9062 | 7182 | 5762 | 4692 | 3882 | 3252 |
| 5e17 | 8055 | 7205 | 6285 | 5395 | 4605 | 3935 | 3375 | 2905 |
| 1e18 | 4911 | 4641 | 4291 | 3901 | 3511 | 3131 | 2791 | 2491 |
| 2e18 | 3032 | 2922 | 2792 | 2642 | 2482 | 2312 | 2142 | 1972 |
| 5e18 | 1785 | 1705 | 1635 | 1575 | 1515 | 1455 | 1395 | 1335 |
| 1e19 | 1331 | 1251 | 1181 | 1131 | 1091 | 1051 | 1011 | 981 |
| 2e19 | 1112 | 1012 | 952 | 892 | 852 | 812 | 782 | 762 |
| 5e19 | 975 | 875 | 805 | 745 | 705 | 665 | 635 | 605 |
| 1e20 | 931 | 821 | 751 | 691 | 651 | 611 | 581 | 551 |
| 2e20 | 902 | 802 | 722 | 672 | 622 | 582 | 552 | 552 |
| 5e20 | 895 | 785 | 715 | 655 | 605 | 575 | 535 | 515 |

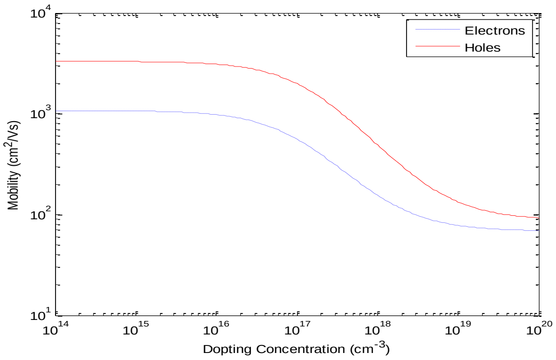

Figure 2: variation of Electron and hole mobility with doping concentration for silicon at T=200 K.

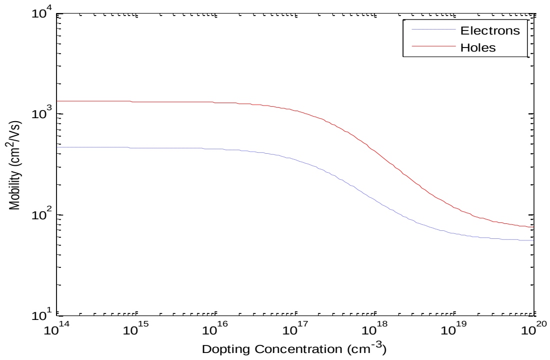

Figure 4: variation of Electron and hole mobility with doping concentration for silicon at T=**3**00 K.

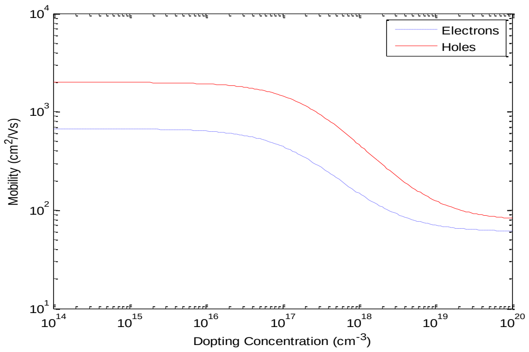

Figure 3: variation of Electron and hole mobility with doping concentration for silicon at T=2**5**0 K.

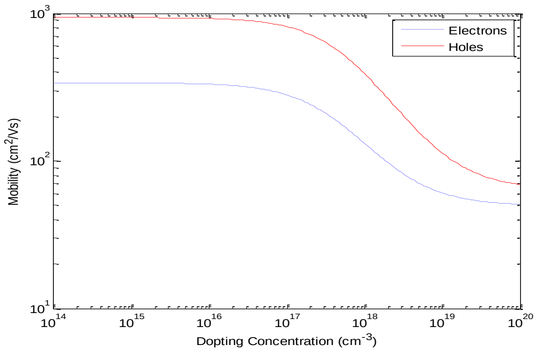

Figure 5: variation of Electron and hole mobility with doping concentration for silicon at T=**35**0 K.

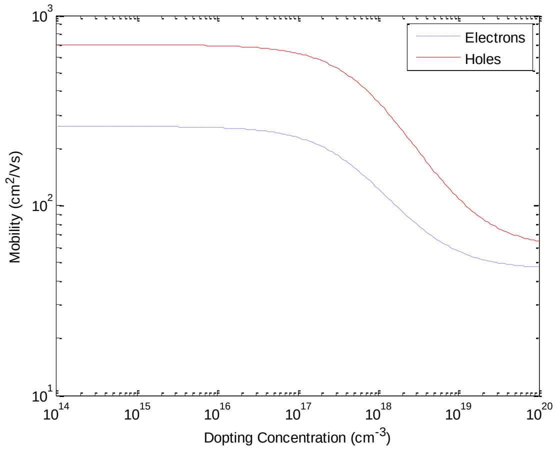


Figure 6: variation of Electron and hole mobility with doping concentration for silicon at T=**4**00 K.

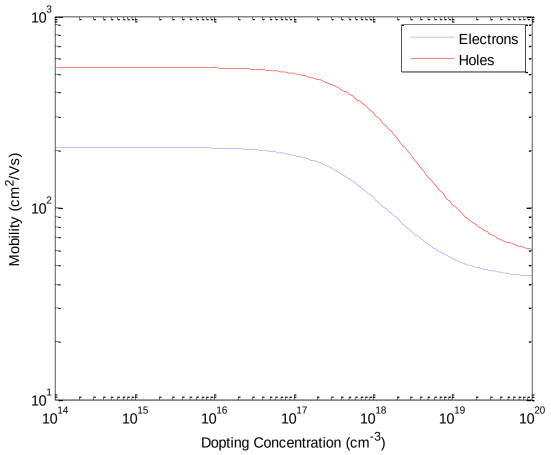


Figure 7: variation of Electron and hole mobility with doping concentration for silicon at T=**45**0 K.

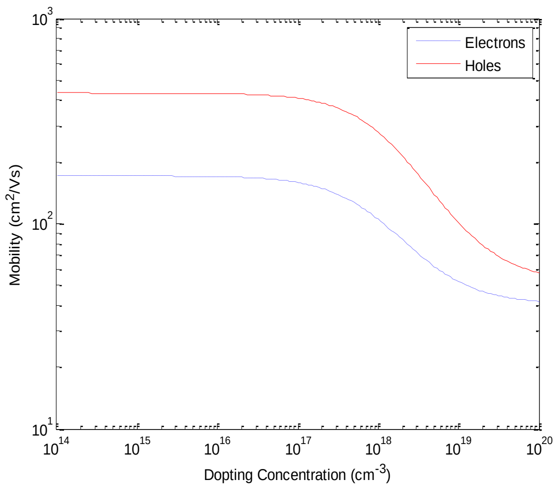


Figure 8: variation of Electron and hole mobility with doping concentration for silicon at T=**50**0 K.

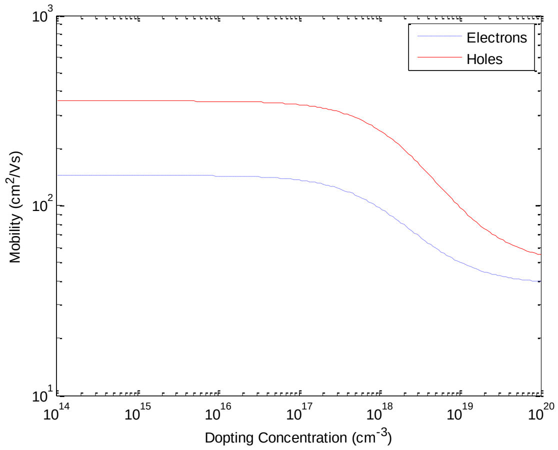


Figure 9: variation of Electron and hole mobility with doping concentration for silicon at T=**55**0 K.

From the Figures above which are represented the variation of electrons and holes mobility with doping concentration for silicon at different temperatures; the mobilities have the same doping behavior:

- The mobility is constant and is limited by phonon scattering for low doping concentrations.
- The mobility decreases because of ionized impurity scattering with the ionized doping atoms for high doping concentrations. The real mobility also depends on the type of doping.

## Conclusions

In summary, knowing type and concentration of doping impurities and their energy level in the forbidden band and measuring a semiconductor's conductivity, one can determine mobility of free electrons or holes. There is an intermediate region of temperatures between low and high regions where a mixture of both scattering mechanisms can co-exist.

At high temperatures; where phonon and electron momentums become comparable, so that a free electron can change its initial direction in just one collision with a phonon. Also, the phonon concentration is growing with the temperature. It is shown that mobility depends of temperature as ($\mu \sim T^{-3/2}$). In high temperature region (typically well above room temperature), scattering of free carriers on phonons with growing temperature lead to the carriers' mobility reduction.

While; low temperature region (typically well below room temperature) where shallow donors are not completely ionized and the concentration of free electrons changes according to the Fermi level temperature dependence – the lower the temperature, the less free electrons concentration, that is concentration becomes a function of (T). It is shown that the dominating scattering mechanism is scattering of free carriers on ionized impurity centers where ($\mu \sim T^{3/2)}$. Free carriers' mobility is growing with the temperature increase in this region.

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