Analysis of Electron Transport Coefficients in SiH$_4$ Gas Using Boltzmann Equation in the Presence of Applied Electric Field

Mohammad M. Othman$^1$, Sherzad A. Taha$^1$, and Idrees H.$^2$

1- Department of Physics, College of Education, Salahaddin University, Erbil, Kurdistan Region, Iraq.
2- Tishk International University, Erbil, Kurdistan Region, Iraq

**A R T I C L E  I N F O**

**ABSTRACT**

Monosilane (SiH$_4$) plasma has numerous applications in plasma processing, transport coefficients are better to understanding and modeling of these gas discharge processes. The electron swarms in a monosilane gas under influence of uniform electric field can be calculated using two term approximation of Boltzmann equation for the range 1 \(\leq \frac{E}{N} \leq 1000\) Td (1 Td= \(1 \times 10^{-17}\) V.cm$^2$). The effective ionization coefficient's ($\alpha - \eta$)/$N$ and electron swarm parameters are calculated and compared with experimental and theoretical values of drift velocity, characteristic energy, mean electron energy and ionization coefficient. The critical field strength ($E/N_{cr}$) is calculated from the effective ionization curves. A set of electron molecule collisions has been assembled for monsilane gas which gave a good fit between the calculated and experimental values over the range of $E/N$ investigated. The calculated distribution functions (EEDF) are found to be non-Maxwellian, having energy variations which reflect the important electron / molecule energy exchange processes. In addition, the percentages of energy lost by different types of elastic and inelastic collisions are given as a function of electric field strength $E/N$.

**Keywords:** Swarm parameters, EEDF, Effective ionization coefficient, Plasmas, Boltzmann equation

*Corresponding Author: Sherzad A. Taha
Sherzad.taha@su.edu.krd

**1. INTRODUCTION**

In the present paper, the behavior of electron swarms in monosilane (SiH$_4$) gas is studied for $E/N$ from 1 to 1000 Td by two term approximation of Boltzmann equation. Where, $E$ is the electric field and $N$ is the gas number density.

Monosilane, silane (SiH$_4$) gas is a colorless, extremely flammable, pyrophoric in air, very toxic gas and it is lighter than air, silanes refers to many compounds including organosilicon compound like, triethoxysilane (Yoshida et al., 2011), tetramethyilsilane (TMS) and tetraethoxysilane (TEOS) (Kawaguchi et al., 2017). Silane has been widely used not only in the form of pure but also in mixtures with other gases for both in semiconductor industry and in thin film technologies (Shimozuma et al., 1986, Vasenko, 1999, Yamaguchi et al., 1989, Peck, 2014, Kovalgin et al., 2009, and Xi-Feng et al., 2017). The weakly ionized gas plasmas of different discharge types (DC, rf, microwave) in pure monosilane and mixtures with other gas (Haq,
2005, Nagpal and Garscadden, 1994, Shimada et al., 2003, Lisovskiy et al., 2007, Wen-Zhu et al., 2017, and Lyka et al., 2006) have been used to fabricate hydrogenated amorphous silicon (a-Si:H) film in plasma CVD (chemical vapor deposition) processing for use in solar cells (Xiaojiang, et al., 2016, Matsui et al., 2016 and Tachibana et al., 1982), and the mixture of monosilane and nitrogen have been used for deposition of a silicon nitride thin film for interlayer insualtion of integrated circuits and semiconductor device surface passivation (Sueoka et al., 1994, Tachibana et al., 1982). The properties of these films can be influenced by changing the plasma process parameters such as RF power, pressure, RF frequency and gas mixture. Study of the complicated chemistry in a SiH₄/H₂ discharge is of importance to optimize the material properties (Akdim and Goedheer, 2003).

The electron energy distribution function (EEDF) plays a central role in defining the physical properties of plasma (Boogaard et al., 2007). Transport coefficients of electron are dependent on EEDF, theoretically can be obtained by solving Boltzmann equation (Nighan, 1970). Because of its physical and industrial importance, a reliable set of electron collision cross sections for the SiH₄ molecule (Verma et al., 2017) and electron transport coefficients in binary mixtures of the SiH₄ molecule with buffer gases are necessary for understanding discharges plasma (Sto et al., 1989, Pfau and Winkler, 1990). Therefore, electron collision cross sections and swarm parameters in monosilane may be required to make clear the properties of monosilane plasmas on which the electric and optoelectronic properties of the deposited films depend. In addition, in SiH₄ the details of electron collision cross-section are important to understand the behavior of mono-silane plasma, since the properties of amorphous silicone film prepared in plasma vapor deposition (PVD) are sensitive to the plasma excitation conditions (Kurachi and Nakamura, 1989, Nakamura, 2013).

Several experimental and theoretical studies have been carried out on electron swarm parameters in monosilane, and determined sets of cross sections for the molecule. (Shimozuma and Tagashira, 1989) measured the ionization and attachment coefficients, (Cottrell and Walker, 1965) determined the electron drift velocity in the range $E/P_o < 10$ V cm$^{-1}$ Torr$^{-1}$. (Pollock, 1968) measured the electro drift velocity and characteristic energy in the range $0.06 \leq E/P_o \leq 26$ V cm$^{-1}$ Torr$^{-1}$, and measured electron collision cross sections for electron energies greater than 5 eV. Townsend first ionization coefficient and electron attachment coefficient for the range $80 \leq E/P_o \leq 300$ V cm$^{-1}$ Torr$^{-1}$ measured by Shimozuma et al., 1983 using steady-state Townsend method. For the theoretical approach, (Ohmori et al., 1986) who have estimated electron swarm parameters by the Boltzmann equation method. A set of electron collision cross section is determined
by fitting the calculated values of the electron drift velocity, characteristic energy and effective ionization coefficient to experimental values. (Garscadden et al., 1983) have calculated dissociation rates for monosilane-argon mixtures at low monosilane concentration which agreed well with experimental values of (Nolet, 1975). However, the other swarm parameters, e.g. electron drift velocity and longitudinal diffusion coefficients in SiH4-Ar mixtures measured by (kurachi and Nakamura, 1991). A sets of electron collision cross sections of monosilane derived by electron swarm parameters from previous study were reported by (Hayashi, 1987). (Kurachi and Nakamura, 1988) they have measured the electron swarm parameters (the drift velocity, the longitudinal diffusion coefficient) in SiH4-Ar mixtures due to the energy dependence of the vibrational excitation cross sections for monosilane molecules, and the ionization coefficient in SiH4-Kr mixtures containing 5.15 and 9.65% monosilane over a wide range of electric field strength E/N. Because the momentum transfer cross section of the krypton atom is similar to that of the argon atom, and the metastable krypton atom cannot ionize a vibrational excited monosilane molecule, then krypton gas, was use instead of argon to study EEDF and electron swarm parameters in SiH4-Kr mixtures using two term approximation Boltzmann equation (Othman, 2011) in the range of 1x10^{-18} \leq E/N \leq 1x10^{-14} \text{ V.cm}^2. In recent years electron kinetic quantities have been studied in dc plasmas (Pham et al., 2013) by solving Boltzmann equation for pure silane and BF3-SiH4 mixture varying the mixture composition from pure SiH4, up to pure BF3. By such a study electron collision cross sections for BF3 molecule and electron transport coefficients were calculated.

Finally, The binary mixtures of TEOS-N2 have been also used instead of SiH4-based gas mixtures to reduce the dangerous of explosion and toxicity while improving quality of the deposition of SiO2 by plasma-enhanced chemical vapor deposition (PECVD) in remote microwave oxygen plasma reactors because the deposited films show good step coverage compared with films deposited from SiH4 (Tochitani, 1993).

2. TRANSPORT PARAMETERS

The transport coefficient calculated for pure gas and mixtures were obtained by the method of (Frost and Phelps, 1962, 1964), where the Boltzmann transport (Nighan, 1970, Morgan and Penetrante, 1990) equation was solved to obtain the distribution function for electrons as a function of energy. The Boltzmann equation can be described as,

$$
\frac{E^2}{3} \frac{\partial}{\partial u} \left( \frac{u}{NQ} \frac{\partial f}{\partial u} \right) + \frac{2m}{M} \frac{\partial}{\partial u} \left( u^2 NQ \frac{\partial f}{\partial u} \right) + \frac{2mK_B T}{Me} \frac{\partial}{\partial u} \left( u^2 NQ \frac{\partial f}{\partial u} \right) 
$$

$$
+ \sum_j \left( u + u_j \right) f \left( u + u_j \right) NQ_j \left( u + u_j \right) - uf \left( u \right) N \sum_j Q_j \left( u \right) + 
$$
\[ \sum_j (u-u_j) f(u-u_j) N Q_{-j}(u-u_j) - u f(u) N \sum_j Q_j(u) = 0 \] 
(1)

Here \( e \) and \( m \) are charge and mass of electron, \( M \) is the mass of a molecule, \( K_B \) is a Boltzmann's constant, \( N \) is the gas density and \( u \) is the electron energy in volts. Thus, \( u = \frac{mv^2}{2e} \). Where \( v \) is the velocity of electron. \( Q_m \) is the elastic cross section and \( Q_j \) and \( Q_{-j} \) are defined as the cross-section for a collision in which the electron loss and gain energy \( u_j \), respectively from \( j \)th inelastic process. The electron energy distribution function (EEDF) \( f(u) \) is obtained by solving the Boltzmann equation using all the collision cross sections. By using electron energy distribution function and collision cross section the swarm parameters are defined as follows:

The relation between drift velocity \( V_d \) and electron energy distribution function is (Smith and Thomson, 1978):

\[
V_d = -\frac{1}{3} \left( \frac{2e}{m} \right)^{1/2} \frac{E}{N} \left[ \sum_j \delta_j Q_m(u) \right]^{-1} \frac{df(u)}{du} du
\]

(2)

Where, \( \delta_j = \frac{N_j}{N} \) represents the fractional concentration of the \( (s) \) species and \( N_j \) is the number of molecules of species \( (s) \) in the excited state \( (j) \).

Here, \( Q_{sm} = Q_m(u) + Q_v(u) + Q_{ex}(u) + Q_i(u) + Q_a(u) \), denotes the total collision cross section, where, \( Q_m \), \( Q_v \), \( Q_{ex} \), \( Q_i \), and \( Q_a \) are the electron cross sections of momentum transfer, vibration, excitation, ionization, and attachment, respectively.

The electron energy distribution function is normalized by,

\[
\int_0^\infty u^{1/2} f_u(u) du = 1
\]

(3)

From the computed drift velocity, the electron mobility \( \mu \) is calculated by the relation,

\[
\mu = v_d E
\]

(4)

The diffusion coefficient \( D \) is given by (Al-Amin and Lucas, 1988):

\[
D = \frac{1}{3} \left( \frac{2e}{m} \right)^{1/2} \frac{1}{N} \sum_j \delta_j Q_m(u) du
\]

(5)

If the distribution is non-Maxwellian, the Einstein relationship is useful for defining characteristic energy (Morgan and Penetrante, 1990),

\[
\varepsilon = \frac{eD}{\mu}
\]

(6)

Using the distribution function one can compute the electron mean energy,

\[
\overline{\varepsilon} = \int_0^\infty f(u) u^{1/2} du
\]

(7)

For Maxwellian energy distribution

\[
\frac{2}{3} \langle \varepsilon \rangle = \frac{D}{\mu}
\]

Therefore, obtaining the EEDF, the reduced ionization \( \alpha/N \) and \( \eta/N \) attachment coefficient are calculated according to the following definitions (Yasumori, 2004).
\[
\frac{\alpha}{N} = \frac{1}{v_d} \left(\frac{2e}{m}\right)^{1/2} \sum_i \int \frac{N_i}{N} Q_i(u) f(u) du \quad (8)
\]

\[
\frac{\eta}{N} = \frac{1}{v_d} \left(\frac{2e}{m}\right)^{1/2} \sum_i \int \frac{N_i}{N} Q_a(u) f(u) du \quad (9)
\]

Where, \( N_k/N \) is the relative concentration of the \( k \)-component, \( v_d \) is drift velocity given by equation (4), \( (i) \) is the ionization onset energy for SiH\(_4\) equal to 11.6 eV, and \( Q_i(u), Q_a(u) \) are ionization and attachment cross-section respectively. An electron avalanche can occur when the effective ionization coefficient \( \left(\alpha - \eta\right)/N > 0 \). A zero effective ionization coefficient is therefore a critical value for electrical breakdown phenomena of gases. Which give \( \left(\alpha - \eta\right)/N = 0 \), then the reduced critical electric field strength \( (E/N)_{cr} \) is therefore determined when the formation and loss electrons reach a balance, this mean that the effective ionization coefficient equal to zero (Xingwen Li., 2012).

\[
\frac{\alpha}{N} - \frac{\eta}{N} = 0 \quad \text{or} \quad \frac{\alpha - \eta}{N} = 0 \quad (10)
\]

Since both drift velocity and characteristic energy are sensitive to changes in the elastic (momentum transfer) and inelastic cross-sections, the momentum transfer and energy exchange collision frequencies \( v_m/N \) and \( v_a/N \) respectively are introduced to separate the elastic and inelastic collisions. The definition of effective elastic collision frequency is (Engelhard and Phelps., 1963),

\[
\frac{v_m}{N} = \frac{e}{m} \left[ \frac{E}{N V_d} \right] \quad (11)
\]

and an energy exchange collision frequency \( v_a/N \) defined by the equation,

\[
\frac{v_a}{N} = eV_d \left[ \frac{E}{N} \right] \left( \frac{1}{e_k - kT} \right) \quad (12)
\]

Where \( m \) is the electron mass, \( V_d \) is electron drift velocity, \( eV_d(E/N) \) is the power input per electron due to electric field and \( (e_k - kT) \) is excess of electron energy. The effective elastic collision frequency \( v_m/N \) is sensitive to changes in the elastic collision cross section and slightly affected by the inelastic cross section, while \( v_a/N \), being closely related to the fractional energy loss, is most sensitive on changes in the inelastic cross-section (Frost and Phelps, 1962).

However, energy loss also occurs due to inelastic collisions, collision frequency coefficient for \( l \)th inelastic process (Engelhard and Phelps, 1963) define by,

\[
\frac{v_j}{N} = \frac{2}{m} \left[ \int_0 u f(u) Q_m(u) du \right]^{1/2} \quad (13)
\]

The mean rate \( R_j \) of collision for the \( j \)th inelastic collision process may be calculated from knowledge of the cross-sections and the electron energy distribution as follows (Nakamura and Lucas, 1978),

\[
R_j = \frac{2}{m} \left[ \int_0 u NQ_m(u) f(u) du \right]^{1/2} \quad (14)
\]
Where $Q_{sj}$ is the cross-section of excitation of level $j$ in species $s$, and the fractional energy loss $F_j$ by the $j$th inelastic process is,

$$F_j = \frac{u_j R_{\alpha_j}}{eV}$$

Where $u_j$ is the onset energy for the excitation.

3. COLLISION CROSS SECTIONS IN MONOSILANE ($\text{SiH}_4$)

Silane is taken as a sample problem in order to calculate the electron distribution function and the transport parameters. Four types of cross sections are used for the analysis, momentum transfer, vibration, electronic excitation, ionization and attachment. During past 30 years theoretical calculations and experimental techniques were used for calculating collision cross sections from electron swarm parameters. In the analysis of the electron swarm data according to (Pollock, 1968), and (Ohmori et al., 1986) the maximum momentum transfer cross-sections were observed at 4-4.5 eV which has a Ramsauer-Townsend minimum around 0.35 eV. (Chatham et al., 1984) measured the total and partial ionization cross sections by using electron beam technique. (Garscadden et al., 1983) has derived cross-sections for the mono-silane molecule using two-term method up to 20 eV. In years 1986-1994, (Ohmori et al., 1986 , Hayashi, 1987, Mathieson et al., 1987 and Nagpal and Garscadden, 1994) have calculated cross-sections from electron swarm parameters in pure mono-silane using Boltzmann equation analysis and Monte Carlo simulation.

The monosilane (Silane) molecule has two vibrational modes, the bending mode $(v_2, v_4)$ and the stretching mode $(v_1, v_3)$, which been reported by (Ohmori et al., 1986) used in the present calculation. The onset energies for $Q_{24}$ and $Q_{13}$ are 0.113 eV and 0.271eV, respectively, the other cross sections electronic excitation $Q_{ex}$ and attachment $Q_a$ compiled by (Hayashi, 1987), momentum transfer cross section derived by (Kurachi and Nakamura, 1988) and the ionization cross section $Q_i$ obtained by (Chatham et al., 1984) were used in the present study.

4. RESULT AND DISCUSSION

The numerical solution of the two term approximation Boltzmann equation is used for calculating electron swarm parameters in DC uniform fields in the range $1 \text{Td} \leq E/N \leq 1000 \text{Td}$. One of the most important parameters for gas discharge phenomena is the electron energy distribution (EEDF). The Boltzmann equation used to calculate the EEDF, using these parameters (EEDF) other swarm parameters are obtained by appropriate integration. The Equation (1) was solved numerically for wide range of E/N values, the E/N values were chosen to yield mean electron energies in the range 0.05 eV - 6.5 eV. The calculation of electron distribution function in $\text{SiH}_4$ is shown in figure (1), the distribution function is normalized by equation ( 2 ), at
E/N=10 Td Maxwellian distributions would appear as straight lines. The calculated electron energy distribution functions are non-Maxwellian having the dominant electron-molecule energy exchange processes. For example, at E/N values approximately 10 Td the distribution function in SiH₄ is characterized by the absence of electrons with energy greater than 1.6 eV.

As E/N increases, the energy input to the electron gas increases, therefore, for mean electron energy near 2.0 eV and above, has substantially more high-energy electrons than the corresponding Maxwellian function. As seen in figure (1), \( f(u) \) will tend toward zero at high energy for E/N value such that the high-energy portion of the distribution function is cutoff by the large cross section for vibrational excitation. The electron energy distribution function (EEDF) is strongly affected by changing the electric field strength (E/N) value.

Using EEDF electron swarm parameters have been calculated throughout the whole range of E/N values, the calculated electron drift velocity as a function of E/N is shown in figure (2) with comparison theoretical and experimental values. The agreement between the present calculation and other studied values (Shimada et al., 2003, Cottrell and Walker, 1965, Pollock, 1968, Ohmori et al., 1986 and Pham et al., 2013) are excellent. The experimental results of (Millicant and Walker, 1987) in the range E/N ≤ 10 Td is less than present results and experimental results of (Lisovskiy et al., 2007) in the E/N ≥ 420Td greater than present calculation.

The electron drift velocity \( v_d \) in pure monosilane molecule is linear up to values of E/N=10 Td, and then exhibits a maximum at E/N ~15Td. In the linear mode, the EEDF is linear independent on the field. Using equation (2) the electron drift velocity in SiH₄ with low fields, from which it follows that the drift velocity is defined by the integral over energies of the elastic cross section \( Q_m(u) \).

This mode of linear dependence \( v_d(E/N) \) is disturbed at value of E/N exceeding the upper limit of the range reassigned by conditions $e^{-1}u(3Q_m(u)Q_2u)^{1/2} \leq E/N \leq e^{-1}u(3\delta Q_m(u))$, where \( u_i \) is threshold energy, \( \delta = \frac{2m}{M_{\text{H}_4}} \) is the parameter of elastic loss of electron energy,
between the present calculation and the various experimental data of (Pollock, 1968, Millicant and Walker, 1987 and Garscadden et al., 1983).

![Graph showing characteristic energy as a function of E/N.](image)

Figure (3) shows mean electron energy, which increases with increasing E/N value, it is seen that the present calculation agree well with the experimental values of (Lisovskiy et al., 2007) and theoretical values of (Ohmori et al., 1986).

![Graph showing mean electron energy as a function of E/N.](image)

The Townsend ionization coefficient, α/N and effective ionization coefficient, has been calculated for the range (170Td ≤ E/N ≤ 1000Td),
where \((1 \text{Td} = 1 \times 10^{-17} \text{V.cm}^2)\), using Equations (8 and 10) respectively. The results for ionization coefficients are shown in figure (5), good agreement has been obtained with the theoretical data of (Pham et al., 2013) and experimental data of (Shimozuma et al., 1986) for ionization coefficient. An electron avalanche can occur when the effective ionization coefficient \((\alpha-\eta)/N\) is positive.

A zero effective ionization coefficient is therefore a critical value for electrical breakdown phenomena of gases. Critical electric field strengths, which gives \( [(\alpha-\eta)/N] = 0 \). Figure (6) shows the density normalized effective ionization coefficient \((\alpha-\eta)/N\) in SiH\(_4\) calculated over a range of \(E/N\) from 170-800 Td by using two-term solution of Boltzmann equation. The calculated limiting \(E/N = 181\) Td corresponds closely to the theoretically (Nagpal and garscadden, 1994) and experimentally (Shimozuma and Tagashirae, 1986) determined value of \(E/N = 180\) Td and \(E/N = 183.7\) Td, respectively.

The effective ionization coefficient is almost zero, since ionizing collisions are balanced by attaching collisions, and for \(E/N\) values smaller than the \((E/N)_{cr.}\) attachment processes that becomes dominant, yielding negative values for the effective ionization coefficient as \(E/N\) is decreased and, on the other hand, for \(E/N\) values above the \((E/N)_{cr.}\), the effective ionization coefficient increases with increasing \(E/N\) where the ionization collisions become dominant whereas the effect of the attachment processes is not significant. The effective ionization coefficient \((\alpha-\eta)/N\) values for the range \(150 \leq E/N \leq 850\) Td may be represented by the equation:

\[
\frac{\alpha - \eta}{N} = 2 \times 10^{-6} \left( \frac{E}{N} \right)^2 - 2 \times 10^{-4} \left( \frac{E}{N} \right) - 0.036
\]

Collision frequency is a parameter closely related to drift velocity \(v_d\), figure (7) shows the effective collision frequency \(v/N\) as a function of \(E/N\). The influence of the Ramsauer–Townsend minimum below 0.5eV and abroad maximum in the range 2.5eV on the elastic collision frequency which has been observed near \(E/N \sim 10\) Td, the hump in the inelastic
collision frequency is very sensitive to the position of the higher energy peak of the vibrational excitation cross sections. The inelastic collisions are predominantly due to excitation as shown figure (7).

Figure (8) shows the percentage energy losses by different processes (elastic and inelastic) as a function of E/N, for low values of E/N vibrational excitation is the only loss mechanism. For example, at E/N = 1 Td, 5% of the energy is lost through elastic collision and in the range 2 Td ≤ E/N ≤ 60 Td, 99% of the energy is lost through vibration excitation. For 80 Td ≤ E/N ≤ 1000 Td, i.e. the mean electron energy 1.5ev < ε < 10eV, there is a competition between vibrational, electronic excitation, ionization and attachment fraction. Figure (8) shows that for an E/N of approximately 200 Td, nearly 16% of the electron energy goes into the vibrational excitation, where 78% into electronic excitation and 5.5% into ionization, the energy transfer to attachment is very small at higher E/N only electronic and ionization fraction dominated.

5. CONCLUSION
In the present work, we have attempted to use the two term solution of Boltzmann equation method to calculate the electron swarm parameters of SiH₄ gas for the range 1 ≤ E/N ≤ 1000 Td, which the effect of ionization coefficient may be considered. The calculated swarm parameters, that is drift velocity, characteristic energy, mean electron energy and ionization coefficient are agree well with experimental and theoretical results. The electron energy distribution functions and represented of energy losses by different types of elastic and inelastic collisions have been explained. The critical field strength has been determined from the effective ionization curves.
REFERENCES

Akdim, M. R., and W. J. Goedheer, W. J. (2003). Modeling of Dust in a Silane/Hydrogen Plasma, J. Appl. Phys., 94(1), 104-109.

Al-Amin, S. A. J., and Lucas, J. (1988). Electron swarm in mixtures of metal vapor and argon gas, J. Phys. D: Appl. Phys., 21(8), 1261-1270.

Boogaard, A., Ozturk, M., Gusev, E., Kovalgin, Alexej Y., Brunets, I. Iwai, H., Antonius A.J., Aarnink, Koester, S., Robertus A.M. Wolters, Kwong, D.J., Holleman, J., Roozeboom, F., Timans, P. and Jurriaan Schmitz, (2007). On the verification of EEDFs in plasmas with silane using optical emission spectroscopy, ECS Transactions, 6(1), 259-270.

Chatham, H., Hills, D., Robertson, R. and Gallagher, A. (1984). Total and Partial Electronic Collision Ionization Cross Sections for CH₄, C₂H₆, SiH₄ and Si₂H₆. J. Chem. Phys., 81(4), 1770-1777.

Cottrell, T. L. and Walker, I. C. (1965). Drift Velocities of Slow Electrons in Polyatomic Gases, Transactions of the Faraday Society, 61, 1585-1593.

Engelhardt, A. G. and Phelps A. V. (1963). Elastic and Inelastic Collision Cross Sections in Hydrogen and Deuterium from Transyort Coefficients, Phys. Rev., 131(5), 2115-2128.

Frost, L. S. and Phelps, A. V. (1962). Rotational Excitation and Momentum Transfer Cross Sections for Electrons in H₂ and N₂ from Transport Coefficients, Phys. Rev., 127(5), 1621-1633.

Frost, L. S. and Phelps, A. V. (1964). Momentum transfer cross section for slow electrons in He, Ar, Kr and Xe from transport coefficient. Phys. Rev., 136(6), A1538-A1545.

Garscadden, A., Duke, G. L. and Bailey, W. F. (1983). Electron Kinetics of Silane Discharges, Appl. Phys. Lett., 43(11), 1012-1014.

Haq, S. U. (2005). Electron collision cross-sections in monosilane (SiH₄) molecule: an investigation and analysis, Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp.39-42.

Hayashi, M. (1987). Electron collision cross sections for molecules determined from beam and swarm data, in Swarm Studies and Inelastic Electron-Molecule Collisions, L. C. Pitchford, B. V. McKoy, A. Chutjian, and S. Trajmar, Eds. Berlin, Springer-Verlag.

Kawaguchi, S, Takahashi, K., Satoh, K. and Itoh, H. (2017). Electron collision cross section sets of TMS and TEOS vapours, Plasma Sources Science and Technology, 26(5), 101384(13pp).

Kitamori, K., Tagashira, H. and Sakai, Y. (1980). Development of electron avalanches in argon-an exact Boltzmann equation analysis, J. Phys. D: Appl. Phys., 13(4), 535-550.

Kovalgin, A. Y., Boogaard, A. and Wolters, R. A. (2009) Impact of Small Deviations in EEDF on Silane-based Plasma Chemistry. ECS transactions, 25(8), 429-436.

Kurachi, M. and Nakamura, Y. (1989). Electron collision cross sections for the monosilane molecule, J. Phys. D: Appl. Phys., 22(1), 107-112.

Kurachi, M. and Nakamura, Y. (1991). Electron Swarm Parameters in SiH₄-Rare Gas Mixtures and Collision Cross Sections For Monosilane Molecules, IEEE Transaction on Plasma science, 19(2), 262-269.

Kurachi, M. and Nakamura, Y. (1988). Electron swarm parameters in SiH₄-Ar mixtures, J. Phys. D: Appl. Phys., 21(4), 602-606.

LISOVSKIY, V., BOOTH J.-P., LANDRY K., DOUAI, D., CASSAGNE, V. and YEGORENKOV, V. (2007). Electron Drift Velocity in Silane in Strong Electric Fields Determined from rf Breakdown Curves, J. Phys. D: Appl. Phys., 40(11), 408-3410.

Liu Xiaojiao, Yin Junchuan, Zhang Jiawei, Li Ming, Yang Peizhi, Hu Zhihua, (2016). Boron Doped a-SiOx:H Prepared by H₂ Diluted SiH₄+CO₂ Plasma, Int. J. Electrochem. Sci., 11(12), 10827-10836.

Lyka, B., Amanatides, E. and Mataras, D. (2006). Simulation of the Electrical Properties of SiH₄/H₂ RF Discharge, Jap. J. Appl. Phys., 45(10B), 8172-8176.

Mathieson, K. J., Millican, P. G., Walker, I. C. and Curtis, M. G. (1987). Low-energy-electron Collision Cross-sections in Silane, Journal of the Chemical Society Faraday Transactions 2, 83(6), 1041-1048.

Matsui, T., Maejima, K., Bidiville, A., Sai, H., Koida, T., Suezaki, T., Matsumoto, M., Saito, K. Yoshida, I. and Kondo, M. (2016). High-efficiency thin-film silicon solar cells realized by integrating stable a-Si:H absorbers into improved device design, Japanese Journal of Applied Physics, 54(8S1), 08KB10(4pp).

Millican, P. G. and Walker, I. C. (1987). Electron swarm characteristic energies (D/μ) in methane, perdeuteromethane, silane, perdeuterasilane, phosphine and hydrogen sulphide at low E/N. J. Phys. D: Appl. Phys., 20(2), 193-196.

Morgan, W. L. and Penetrante, B. M. (1990). ELENDIF: A time-dependent Boltzmann solver for partially ionized plasmas, Computer Physics Communications, 58(1-2), 127-152.

Nagpal, R. and Garscadden, A. (1994). A new Collision Cross Section Set for Silane, Gaseous Dielectrics VII, pp.39-45.

Nakamura, Y. (2013). Electron Swarm Parameters and Electron Collision Cross Sections, Fusion Science and Technology, 63(3), 378–384.
Nakamura, V. and Lucas, J. (1978). Electron drift velocity and momentum cross-section in mercury, sodium and thallium vapors. II. Theoretical, J. phys. D: Appl. Phys., 11(3), 337-345.

Nighan, W. L. (1970). Electron Energy Distributions and Collision Rates in Electrically Excited $N_2$, CO, and CO$_2$. Phys. Rev., 2A(5), 1989–2000.

Nolet, G. (1975). Kinetics of Decomposition of Silane (Diluted in Argon) in a Low Pressure Glow Discharge J. Electrochem. Soc., 122 (8), 1030-1034.

Ohnori, Y., Shimozuma, M. and Tagashira, H. (1986). Boltzmann equation analysis of electron swarm behaviour in monosilane, J. Phys. D: Appl. Phys., 19(6), 1029-1040.

Othman, M. M. (2011). Electron transport coefficients in SiH$_4$-Kr mixtures in D.C. field, Proceedings of the 4th International Science Conference of Salahaddin University- Erbil, Kurdistan, Iraq, October 18-20, vol. 3, 833-842.

Peck, J.A. (2014). Modeling and Experimental Process Optimization for a SiH$_4$+H$_2$ Surface wave Plasma Discharge for Silicon Photo voltages. Master Thesis, University of Illinois at Urbana-Champaign.

Pfau, S. and Winkler, R. (1990). Electron Collision Rates and Transport Coefficients of a Weakly Ionized dc Plasma in Ar/SiH$_4$ mixtures, Contrib. Plasma Phys., 30(5), 587-597.

Pham Xuan Hien, Byung-Hoon Jeon and Do Anh Tuan, (2013). Electron Collision Cross Sections for the BF$_3$ Molecule and Electron Transport Coefficients in BF$_3$-Ar and BF$_3$-SiH$_4$ Mixtures, Journal of the Physical Society of Japan, 82(3), 034301(pp.8).

Pollock, W. J. (1968). Momentum transfer and vibrational cross-sections in non-polar gases, Transactions of the Faraday Society, 64, 2919-2926.

Shimada, T., Nakamura, Y., Lj Petrović, Z. and Makabe, T. (2003). Electron Transport Coefficients in SiH$_4$ and SiH$_6$ in dc and rf Fields, J. Phys. D: Appl. Phys., 36(16), 1936–1946.

Shimozuma, M. and Tagashira, H. (1986). Measurement of the Ionization and Attachment Coefficients in Monosilane and Disilane, J. Phys. D: Appl. Phys., 19(9), L179-L182.

Shimozuma, M., Kaneko, Y., Taneda, A., Hasegawa, H. and H. Tagashira, H. (1983). Papers of Tech. Grp. Electrical Discharges, (Tokyo: IEE Japan), no. ED-83-86.

Smith, K. and Thomson, R. M. (1978). Computer Modeling of Gas Lasers, New York, Plenum Press.

Sto, N., Kawashima, Y. and Tagashira, H. (1989). Electron Swarm Parameters in SiH$_4$/H$_2$, Ann. Rep. Fac. Educ., 49(1), 69-78.

Sueoka, O., Mori, S., and Hamada, A. (1994). Total cross section measurements for positrons and electrons colliding with molecules I. SiH$_4$ and CF$_4$, J. Phys. B: At. Mol. Opt. Phys., 27(20), 1453-1465.

Tachibana, K., Tadokoro, H., Harima, H. and Urano, Y. (1982). Diffusion of Si atoms and thin film deposition in a silane-argon plasma, J. Phys. D: Appl. Phys., 15(1), 177-184.

Tochitani, G., Shimozuma, M. and Tagashira, H. (1993). Deposition of Silicon Oxide Films from TEOS by Low Frequency Plasma Chemical Vapor Deposition, J. Vac. Sci. Technol., 11A(2), 400-405.

Vasenkov, A. V. (1999). Monte Carlo Simulation of Electron Beam Plasma in a Silane-Argon Mixtures, J. Phys. D: Appl. Phys., 32(3), 240-L245.

Verma, P. Kaur, J. and Antonya, B. (2017). Electron-silane scattering cross section for plasma assisted processes, Physics of Plasma, 24(3), 033501(pp. 9).

Wen-Zhu J, Xi-Feng W. Yuan-Hong S. and You-Nian W. (2017). Fluid simulation of RF capacitively coupled SiH$_4$/N$_2$/O$_2$ and SiH$_4$ dusty plasmas, 1st Asia-Pacific Conference on Plasma Physics, Chengdu, China, 18-23.

Xi-Feng, W. Wen-Zhu, J. Yuan-Hong S. Ying-Ying, Z. Zhong-Ling, D. and You-Nian, W. (2017). Hybrid Simulation of Electron energy Distributions and Plasma Characteristics in Pulsed RF CCP Sustained in Ar and SiH$_4$/Ar discharges, Physics of Plasmas, 24(11), 113503(11pp.).

Xingwen Li, Hu Zhao and Shenli Jia. (2012). Dielectric breakdown properties of SF6–N2 mixtures in the temperature range 300–3000K, J. Phys. D: Appl. Phys., 45(44), 445202(7pp).

Yamaguchi, Y., Sumiyama, A., Hattori, R. I., Morokuma, Y. and Makabe, T. (1989). A Model of Amorphous Silicon Deposition in DC Glow Discharge in Silane, J. Phys. D: Appl. Phys., 22(4), 505-511.

Yasunori, T. (2004). Prediction of dielectric properties of N$_2$/O$_2$ mixtures in the temperature range of 300–3500K, J. Phys. D: Appl. Phys., 37(6), 851–859.

Yoshida, K., Sato, R., Yokota, T., Kishimoto, Y. and Date, H. (2011). Electron Transport Properties in HSi(OC$_3$H$_3$)$_3$ Vapor, Japanese Journal of Applied Physics, 50(12R), 120210(6pp).