Electron Impact Excitation Rate Coefficients of Laser States In The Copper Vapor Laser Discharge As a Function Of Electron Temperature

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Abstract : In the present work electron impact excitation rate coefficients of laser states by the processes like electron impact excitation, Penning excitation and Duffenduck reaction are obtained as a function of electron temperature. The electron impact excitation rate coefficient of the laser states of CdII from the ground state of CdI and CdII are obtained by considering the equation of electron The Penning excitation and Duffenduck reaction rate both increase as the gas temperature is increased. The rate coefficients of both processes are proportional to the square root of gas temperature. Gas temperature determines the collision frequency and hence the rate coefficient.

***Key Words* - Electron impact excitation, Penning excitation, Duffenduck excitation, Direct excitation, stepwise excitation**

I. Introduction

It has been found that the energy states are populated by electron collisions [1,2]and the collisions with the helium metastable states [3,4,5] and the helium ions [6,7]. In addition to this the energy states are found to be populated by the process of recombination. The energy states can be depopulated by collision with slow electrons. The electrons passing through the discharge transfers their energies to the gas particle by two types of collisions 1) Elastic collision and 2) Inelastic collision

In the elastic collision, the transfer of kinetic energy of the electron into kinetic energy of the gas particle takes place. The kinetic energy of the colliding particle is conserved and this type of collision process causes the heating of the gas particle to some extent. In second type of collision, kinetic energy of the electron is converted into potential energy of colliding gas particle and gas particle gets excited. This type of collision is called as Inelastic collision. The particles in the excited states either transfer back their energy to low energy electrons or they undergo a transition giving radiative emission. The rate of transfer of energy from the discharge electron to the gas particles may be written as

$$\frac{dE}{dt} = N_g n_e C_e E_c + \sum_j N_{gj} n_e C_{in} E_j - \sum_j N_{gj} n_e C_{dex} E_i \qquad 1$$

Where, N_g is number of gas particles
C_e is rate coefficient of elastic collision
C_{in} is rate coefficient of inelastic collision
E_j is energy of j^{th} state excited by elastic collision
C_{dex} is de-excitation rate coefficient
E_i is energy of excited particle, which transfer the energy to the electron.

The processes which can populate and depopulate the states are excitation and de-excitation; only dominant processes are to be discussed in detail. In CVL the laser states are excited probably by the process like Electron impact excitation**,** Penning transfer, charge transfer and cascading processes.

Excitation rates and Rate Coefficients

The CVL operates on two wavelengths 5106 A^0 and 5782 A^0.The electronic states that are involved in the transitions are $^2P_{1/2}$, $^2P_{3/2}$, $^2D_{3/2}$ and $^2D_{3/2}$. The rate equations of the upper and lower laser states are

$$\frac{dN_u}{dt} = Cu^* R_u n_e + Cu^* N_{He}^* P_u + Cu^* N_{He} T_u + \sum_j A_{ju} N_j \qquad 2$$

$$\frac{dN_l}{dt} = Cu^* R_l n_e + Cu^* N_{He}^* P_l + Cu^* N_{He} T_l + \sum_j A_{jl} N_j + S(N_u - N_l) \qquad 3$$

The terms in the above equations stand for the rate of excitation of states by different processes respectively
1. The first term represents the rate of excitation of the states by electron impact excitation from the ground state of CuI
2. The second term represents the rate of excitation by Penning process
3. The third term shows the rate of excitation by Charge transfer process (Duffenduck process)
4. The fourth term stands for the excitation of the states by cascading processes.

The excitation rate and excitation cross section are entirely different from each other. When a particle collides with another particle there may be transfer of energy between them. The probability of transfer of energy in the collision is called transfer cross section. The total amount of energy transferred is governed by the number of collision made by the species and rate of transfer per second per particle is called transfer rate coefficient.

Electron Impact Excitation

In this case an electron with energy more than the excitation energy of an electron rotating about an atom or ion collides with atom or ion, transfers its energy to the system and excites the rotating electron to a higher energy orbit. The probability of excitation depends upon the energy of an excited electron and the cross-section of excitation at that particular energy. The excitation rate depends upon the excitation cross-section and number of effective collisions made by electron. The number of effective collisions is a function of electron velocity, which in turn is a function of electron temperature. The electron impact excitation rate coefficient is expressed in terms of excitation cross-section σ_s and electron velocity V_e as

$$R = <\sigma_s V_e>$$

The velocity of an electron energy E by the relation

$$v = 5.9 * 10^7 * \left(E^{1/2}\right) \quad 4$$

From the Maxwellian distribution the number of electrons dN with energy between E and E+dE is given by function as

$$dN = N\left[\frac{2}{kT}\left(E^{1/2}/_{\pi kT^{1/2}}\right) exp\left(-E/_{kT}\right)\right] dE \quad 5$$

Thus the rate of excitation of the energy levels by the collision with the electrons having energy between E and E+dE is expressed as

$$dR = N\left[\frac{2}{kT}\left(E^{1/2}/_{\pi kT^{1/2}}\right) \sigma_s V_e\, exp\left(-E/_{kT}\right)\right] dE \quad 6$$

If T, E and dE are expressed in eV and all the cross-section values are in cm^2, the equation for rate coefficient becomes

$$R = \frac{6.7*10^7}{T^{3/2}} \int_{E_s}^{\infty} \sigma_s E\, exp\left(-E/_{kT}\right) dE \;\; cm^3/sec \quad 7$$

Darwin [8] in his paper has given semimprical expression for the calculations of electron impact excitation rate coefficient of several kinds of electronic transitions, which shows that electron impact excitation rate coefficient is directly proportional to the electron temperature for the forbidden transitions and cube root of electron temperature for the allowed transitions. Since the transitions of copper atoms from the upper laser state and lower laser state to the ground state are almost forbidden. The electron impact excitation rate coefficient may be assumed to be directly proportional to the square root of the electron temperature. Darwin's formula may be employed for the calculations of electron impact excitation rate coefficient when the excitation cross sections of the states of the atoms are not known. In case of CVL, electron impact excitation cross sections are measured by Trajamar [9]. The experimental values of the integral cross sections may be used and excitation rate coefficients may be obtained.

When an electron having some energy is incident on the atom (ion), the electron transfers its energy to an electron rotating about an ion and the energy of the incident electron is shared by the incident electron and the electron rotating about the atom (ion). In the process of excitation of the energy levels of the ions, energy of the incident electron is divided into three parts (1) a part of
the energy is utilized in ionizing the atom (2) another part is utilized in exciting the produced ion and (3) the remaining part is kept by the incident electron itself. When energy states of an atom (ion) are to be excited, energy of the incident electron is divided into two parts (1) a part is given to the electron rotating about an atom (ion) and (2) the remaining amount of energy is kept by the incident electron itself. The former process may contribute towards the process of ionization and may indirectly excite the laser states via the process of recombination. Obviously, the contribution of the former process is negligibly small.

Penning Excitation

When the helium atom is in the metastable state, collides with a copper, there is a probability of ionizing copper and getting excited to the upper or lower laser state. atom then there is a probability of ionizing cadmium atoms and getting excited to upper and lower laser states. This process is referred as Penning excitation. The Penning excitation rate coefficient of the upper and lower laser states are represented by second term in the equations 2 and 3 as $Cu^* N_{He}^* P_u$ and $Cu^* N_{He}^* P_l$.

The excitation rates of the laser states by Penning process are determined by the fractional abundance of CuI, density of HeI metastable states and Penning transfer cross-section of the individual state of CuI and the gas temperature in the discharge. In the Penning process, energy of the excited electron of helium is transferred to cadmium atoms that results in ionization and excitation of CuI. As this process involves many sub processes, the cross-section is very small. The Penning ionization rate coefficient may be obtained from the cross section using the equation

$$P = <\sigma_p vHe> \quad 8$$

where σ_p is Penning excitation cross section
vHe is velocity of helium atoms relative to copper atom which can be determined by temperature.

The velocity of helium gas follows Maxwellian distribution as the density of helium atoms is about 10^{16} cm^{-3}. Thus for the Maxwellian velocity distribution, the total Penning excitation rate coefficient can be expressed as

$$P = 7.23 * 10^3 \sigma_p \left(\theta^{1/2}\right) cm^3 sec^{-1} \quad 9$$

where θ is the gas temperature in degree Kelvin.

The total Penning transfer rate coefficient for He-Cd$^+$ laser has been calculated by using the values of total excitation cross-section measured by Shearer and Padovani [10].The Penning excitation cross-section in case of CVL is about 4.0 x 10^{-15} cm^2 . For obtaining the excitation rate coefficient of the individual level the Penning transfer cross section to the individual level must be measured as it has been measured for Cadmium by Inaba[11]

In case of copper atoms the penning transfer process excites about 25 energy levels of the copper ion [12]. The excitation of the individual level of copper ion by the penning transfer process must be smaller by a factor of 25 than tht of the copper ion as a whole. The ion then would recombine and forms the copper atoms in the laser states. The cross section of the direct excitation of the laser states by the penning transfer would be very small. The penning transfer rate coefficient is obtained by substituting $\sigma_p = 4x10^{-15}cm^2$ I the equation (9) and the results are displayed in figure 2.

Duffenduck Excitation Rate Coefficient

The discharge plasma in the tube consists of mixture of atoms, electrons and ions. There is a possibility of collision among these species and with the walls of the discharge tube also. The process in which an ion of the buffer gas when collides with the atoms of active material and results in the formation of an ion of the active material and the atoms of the buffer gas, is known as Charge transfer process which is also known as Duffenduck reaction. In this process charge from an ion is transferred to the other ion.

The Penning excitation rate coefficient of the upper and lower laser states are represented by third term in the equations 2 and 3 as $Cu^* N_{He}^* T_u$ *and* $Cu^* N_{He}^* T_l$. The Duffenduck reaction rate coefficient is expressed in the same way as the Penning excitation rate coefficient as

$$T = < \sigma_d vHe > \qquad 10$$

where σ_d is cross section of the Duffenduck reaction

Assuming the Maxwellian distribution for the helium metastable state and applying the same logic as in the charge transfer, the ultimate equation for the Duffenduck excitation rate coefficient has been obtained from the above equation as

$$T = 7.23 * 10^3 \left(\theta^{1/2}\right)(\sigma_d) \qquad 11$$

In the calculations of McKenzie [13] for the He-Cd+ discharge it is assumed that the cross section for the Duffenduck reaction is same as the cross section for Penning excitation. In fact cross section of Duffenduck process must be same as the cross section of the Penning process because in one process helium atom in the metastable state transfer energy and in another process helium ion transfers the energy i.e. the energy is transferred between atom and atom and between atom and ion. In the present work we assume the cross section of Duffenduck reaction same as the cross section of the Penning reaction. However there is a difference in the excitation rate of the individual energy states. Kushner and Culick computed the cross section for Penning and Duffenduck transfer reactions. According to them Penning transfer cross section is 4x10^{-15} cm^2 and Duffenduck cross section is 2.5x10^{-15} cm^2. In the Penning reaction the helium atom in metastable state transfers it's energy to CuI to produce CuII in one of 25 energy levels. In the Duffenduck process the CuII ions are produced in one of the 125 energy levels.

II. RESULTS AND DISCUSSION

We have calculated penning ionization rate coefficient P as a function of gas temperature θ. The maximum value of θ is taken as 2000 ^{0}K as the operating temperature of the CVL is 1400 ^{0}C [7]. For the calculations of penning reaction rate coefficient the metastable density is considered as 5x10^{12} cm-^{3}. The equation for penning reaction rate coefficient shows that as the gas temperature is increased the penning reaction rate coefficient increases. It also increases as the density of copper atoms in the ground state increases. The behavior is as shown in fig 1.

We have calculated charge transfer rate coefficient as a function of gas temperature. The behavior is as shown in fig 2. The behavior of charge transfer rate coefficient is same as that shown in fig 1 except dividing factor 2. The electron density in the discharge is of the order of 10^{13} cm^{-3} [2] for the optimum conditions of the laser operation. Obviously the density of helium ions and copper atoms should not exceed 10^{13} cm^{-3}. The density of helium ions is less than 10^{13} cm^{-3}. This indicates that the Duffenduck rate is less than penning rate by a factor of 2.

We have calculated ionization rate coefficient for HeI and HeII as a function of electron temperature for the electron temperature ranging from 0 to 10 eV by using Lotz formula and the results are displayed in figure 3. The ionization of HeI starts from T = 1. 5 eV and goes on increasing up to T= 4 eV. Above this electron temperature the ionization rate gets saturated. The ionization of HeII starts at about T=4.5 eV and it increases as the electron temperature is increased up to 6 eV. For the electron temperature higher than 6 eV the ionization rate get saturated.

The ionization rate coefficient for CuI, CuII and CuIII are obtained using Lotz formula as a function of electron temperature. The results are displayed in figure 4. In computations of ionization of CuI, CuII and CuIII the removal of 3d electron is also considered in addition to the removal of 4s electron. The contribution of removal of 3p electron is not considered as they are tightly bounded and the probability of their removal is also very small. The ionization of CuI starts from electron temperature 0.5 eV and increases up to 2.5 eV. When the temperature is increased above 2.5 eV the increase in the rate of ionization decreases. The ionization of CuII starts at about 1.5 eV and go on increasing up to 5 eV. Above this temperature rate of increase of this coefficient becomes less and starts saturating for higher temperatures. The ionization of CuIII starts at about T= 3 eV and increases as electron temperature is increased. The rate coefficient gets saturated at temperatures more than 9 eV.

We have calculated ionization rate coefficient for NeI and NeII as a function of electron temperature and the results are displayed in figure 5. The behavior of rate coefficient as analogous to the behavior of He and Cu.

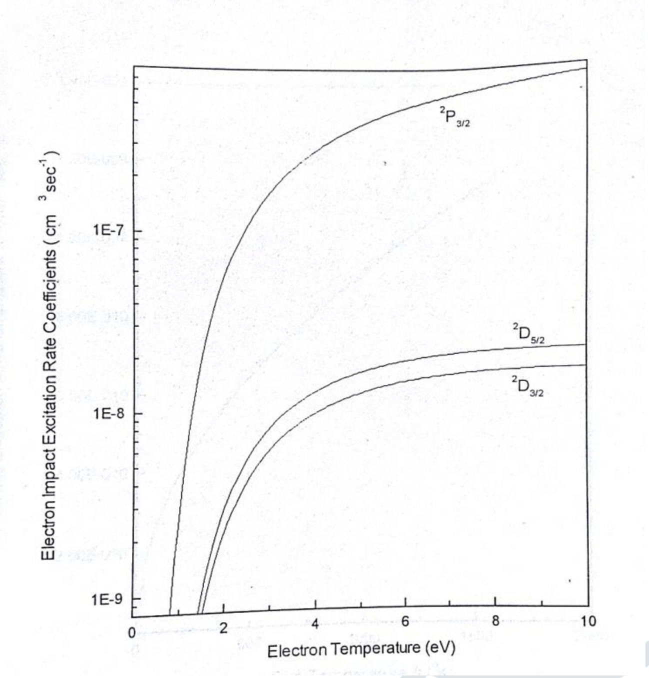

Fig.1 Electron Impact Excitation rate coefficients of 2P3/2,2D5/2 and 2D3/2 energy levels of copper atom as a function of electron temperature

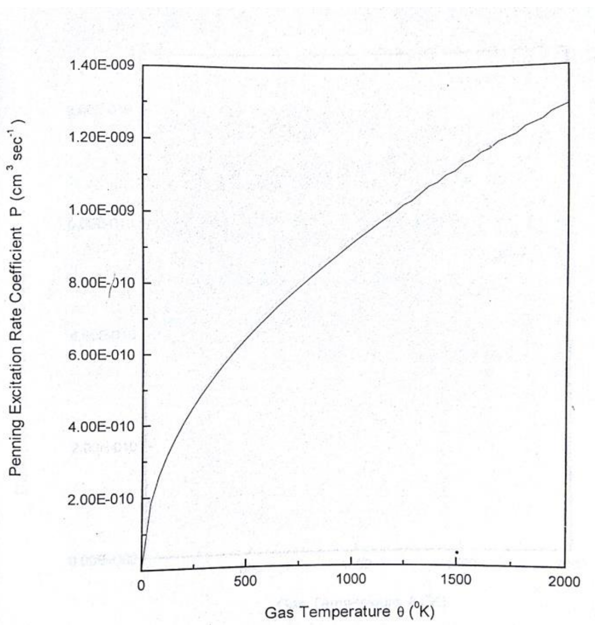

Fig.2 Penning excitation rate coefficient P as a function of gas temperature Θ

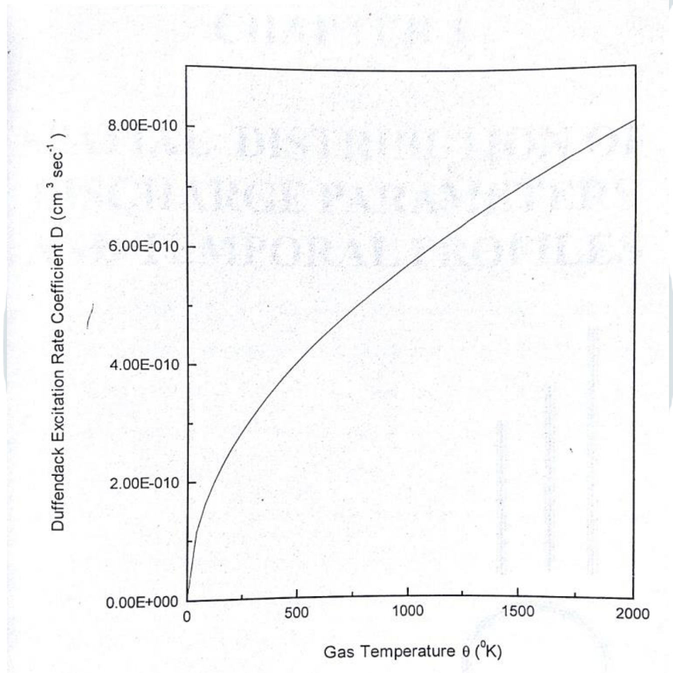

Fig3. Duffendack excitation rate coefficient D as a function of gas temperature Θ

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