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An Approach to Quantitative Description of Positive-Column He-Cd$^+$ Laser Power Output ($\lambda=441.6$ nm)*)

by

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Summary. The results of theoretical determination of characteristics of positive-column He-Cd$^+$ laser power output at 441.6 nm, based on measured data of plasma parameters and known cross-sections and electron energy distribution functions are presented. Comparisons show a good agreement between the characteristics of He-Cd$^+$ laser power output calculated and measured. The importance of processes determining the He-Cd$^+$ laser power output is pointed out.

1. Introduction. Since the proposal and development of He-Cd$^+$ laser (Fowles and Hopkins [1], Silfvast [2]) many papers have been reported (see reviews: Hattori [3], Mizeraczyk [4], Willett [5]), in which the excitation mechanisms and operating characteristics of a positive-column (PC) He-Cd$^+$ laser were made clear to some extent qualitatively.

The purpose of the present work is to make an approach to quantitative description of PC He-Cd$^+$ laser power output ($\lambda=441.6$ nm) on the basis of measured plasma parameters, and cross sections and electron energy distribution functions taken from literature. Our effort is to extend the qualitative explanation of saturation effects in PC He-Cd$^+$ lasers presented in [6], by taking into account the electron energy distribution functions given by Vokaty and Mašek [7, 8] which are more proper for He-Cd mixture than the ones (Postma [9]) used in [6]. Also, other atomic processes, neglected in [6], are taken into consideration in the present calculations of behaviour of PC He-Cd$^+$ laser power output.

2. Rate equations. There are some theoretical and experimental evidences that the role of the lower $5p^2P_{3/2}$ Cd$^+$ laser level in the population inversion of 441.6 nm $5pP_{3/2}$ laser levels is negligible (Janossy *et al.* [10], Browne and Dunn [11], Giallorenzi

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and Ahmed [12]). Since population of lower laser level may be neglected, the PC He-Cd$^+$ laser power output at 441.6 nm is simply proportional to the population of the upper $5s^2\ ^2D_{5/2}$ Cd$^+$ laser level.

The excitation of the upper $5s^2\ ^2D_{5/2}$ Cd$^+$ laser level is generally held to be mainly due to Penning collisions between He triplet metastable atoms and Cd ground state atoms (Silfvast [13], Browne and Dunn [11], Miyazaki *et al.* [14]). The destruction processes of the upper laser level can take place either through the radiative decay to the lower laser level and ambipolar diffusion of the Cd$^+$ ions or collisions with electrons.

The rate equation for the population of the upper Cd$^+$ laser level in the steady state may be written as

$$(1) \qquad M_T N_2 \sigma_P^* v_{T2} - N_2^+ \tau_{\text{eff}}^{-1} - n N_2^{+*} \langle \sigma_2 v \rangle = 0,$$

where N_2, N_2^{+*}, M_T and n are the densities of Cd atoms in ground state, Cd$^+$ ions in the upper laser state, He triplet metastable atoms, and electrons, respectively. The cross sections σ_P^* and σ_2 stand for Penning ionization and electron collisional deexcitation of Cd$^+$ ion upper laser state, respectively. v_{T2} is the relative velocity between colliding He triplet metastable atoms and Cd atoms, v — the velocity of electrons, and τ_{eff} is the effective lifetime of the Cd$^+$ ions in the upper laser level owing to radiative decay and ambipolar diffusion. The bracket denotes averaging over the electron distribution function.

The estimation of the role of electron impacts in excitation of $5s^2\ ^2D_{5/2}$ Cd$^+$ laser level shows that these processes can be ruled out as an important source of population of this level in the case of "quiet" discharge, i.e. without moving strations. In the case of discharge with moving strations (Willgoss and Thomas [15, 16]) Eq. (1) probably it does not hold.

The He triplet metastable density M_T necessary to solve Eq. (1) can be obtained from the following equation, adopted for the case of He-Cd discharge from the discussions given originally by Miller *et al.* [17], and Browne und Dunn [11] for the discharge in pure He:

$$(2) \qquad nN_1\langle\sigma_{1T}v\rangle - M_T\tau_D^{-1} - nM_T\langle\sigma_{Ti}v\rangle - M_T N_2\sigma_P v_{T2} - M_T^2\sigma_{TT}v_{TT} = 0.$$

In Eq. (2) N_1 denotes the ground-state helium-atom density, τ_D is the characteristic diffusion time for the metastables, σ_P — the total cross section for Penning ionization, $\langle\sigma_{1T}v\rangle$ — the rate coefficient for production of triplet metastable atoms by electronic collisions with ground-state helium-atoms, $\langle\sigma_{Ti}v\rangle$ — the rate coefficient for loss of triplet atoms by ionizing collisions with electrons, $\sigma_{TT}v_{TT}$ — the rate coefficient for loss of triplet atoms through mutual triplet-metastable collisions leading to ionization.

Combining Eqs. (1) and (2), the Cd$^+$ ($5s^2\ ^2D_{5/2}$) ion density in PC He-Cd$^+$ laser discharge can be calculated with the help of the measured values of plasma parameters, presented in [18] and the other data taken from literature. The data taken for calculation of Cd^+ ($5s^2\ {}^2D_{5/2}$) ion density are as follows.

The cross section σ_P is equal to $6.5\cdot10^{-15}$ cm^2 (Collins [19]), σ_P^* is taken to be equal to half of σ_P; v_{T2} is calculated as $2\cdot10^{-5}$ cms^{-1} at 600 K, τ_{eff} is equal to 670 ns (Klein and Maydan [20]); $\langle\sigma_2 v\rangle$ is obtained from measurements of Klein and Maydan [20] with the help of the data on plasma parameters [18] to be equal to $0.15\cdot10^{-6}$ cm^3 s^{-1} which is very close to the results of Sakurai [21], and Browne and Dunn [22]. The rate coefficient $\langle\sigma_{1T} v\rangle$ is recalculated by the present authors following the procedure of Miller *et al.* [17], assuming also the electron energy distribution functions given by Vokaty and Mašek [7, 8]. An example of the recalculated rate coefficient $\langle\sigma_{1T} v\rangle$ is given in Fig. 1. We assume the value of $6\cdot10^{-8}$ cm^3 s^{-1}, calculated originally by Miller *et al.* [17] as the average triplet ionization rate coefficient for pure He discharge within the compass of our interest, as the effective rate coefficient $\langle\sigma_{Ti} v\rangle$ including two loss processes of triplet metastable: by ionization collisions with electrons and by triplet-singlet conversion. The latter process, not included in Eq. (2), was suggested (Miller *et al.* [17], Browne and Dunn [11]) as an important loss process for He triplet metastable atoms. The rate coefficient $\sigma_{TT} v_{TT}$ is taken from [23] (Johnson and Gerardo) to be equal $4.5\cdot10^{-9}$ cm^3 s^{-1}, τ_D is calculated as $8\cdot10^{-6}\,p$ (τ_D in s if He pressure p is expressed in torr) for 3 mm bore discharge tube (Phelps [24]).

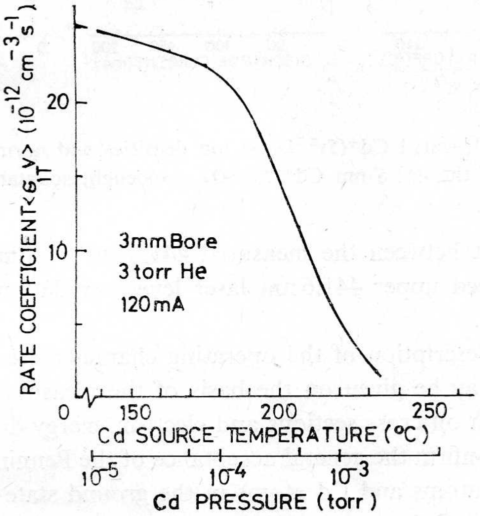

Fig. 1. Example of the calculated He(2^3S) excitation rate coefficient $\langle\sigma_{1T} v\rangle$

3. Results and discussion. Figs. 2 (*a*, *b*, *c*) show the typical results of calculations of Cd^+ ($5s^2\ {}^2D_{5/2}$) ion densities for the same discharge conditions as in [18]. The behaviour of the calculated plots of Cd^+ ($5s^2\ {}^2D_{5/2}$) ion density, describing also the behaviour of PC He-Cd+ laser power output, is compared with the measured values of the 441.6 nm spontaneous emission sidelight, which follows the laser power output (Giallorenzi and Ahmed [12], Browne and Dunn [11]). The 441.6 nm sidelight is normalized at the peak of Cd$^+$ ($5s^2\ ^2D_{5/2}$) density.

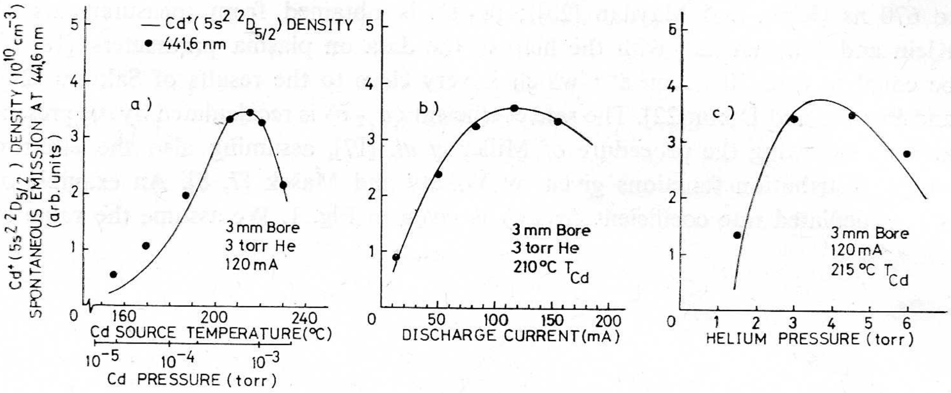

Fig. 2. Comparison of calcucated Cd$^+$($5s^2\ ^2D_{5/2}$) ion densities and normalized measured values of intensities of the 441.6 nm Cd$^+$($5s^2\ ^2D_{5/2}$) sidelight spontaneous emission

A good agreement between the measured 441.6 nm spontaneous emission sidelight and the calculated upper 441.6 nm laser level population allows to draw the following conclusions.

The quantitative description of the operating characteristics of the PC He-Cd$^+$ laser ($\lambda = 441.6$ nm) may be given on the basis of the measured plasma parameters and the published data on cross sections and electron energy distribution functions.

The calculations confirm the general acceptance of the Penning collisions between He triplet metastable atoms and Cd atoms in the ground state as the predominant excitation mechanisms of the upper 441.6 nm laser level.

Analysis of Eqs. (1) and (2) shows that the saturation and the decrease of Cd$^+$ ($5s^2\ ^2D_{5/2}$) density (or laser power output corresponding to it) with increasing Cd pressure (Fig. 2*a*) are because of the decrease of He (2 ^{3}S) density, resulting from the decreasing mean electron energy.

The saturation and then the decrease of Cd$^+$ ($5s^2\ ^2D_{5/2}$) density with increase of discharge current (Fig. 2*b*) occur mainly as a result of the decrease of the rate of pumping processes of the He(2 ^3S) level owing to the reduction of the mean electron energy, and as a result of the increase of the rate of electron-collisional deexcitation of this level owing to the increase of electron density.

Also the decrease of the rate of pumping processes of the He (2 ^3S) level caused by the decrease of the mean electron energy as well as the increase of the rate of electron-collisional deexcitation of this level owing to the increase of the electron density are the main reasons of the such a behaviour of Cd$^+$ ($5s^2\ ^2D_{5/2}$) density versus helium pressure, as shown in Fig. 2*c*.

Summarizing, mainly two processes determine the behaviour of Cd$^+$ ($5s^2\ ^2D_{5/2}$) ion density (or laser power output):

— primarily the reduction of the mean electron energy resulting first of all in the decrease of the pumping rate of He(2 ^{3}S) metastable level,

— and the increase of the electron density, which results in the increase of depopulation of He(2 ^{3}S) metastables.

The other processes taken into account in Eqs. (1) and (2) are of secondary importance. The optimum conditions for lasing at 441.6 nm occur at current of about 120 mA,He pressure of about 4 torr in discharge in 3 mm bore tube (i.e. *pD* product equals to 12 torrmm). These conditions result from the compromise between the pumping and the deexcitation processes, i.e. between the mean electron energy and the electron density.

The method of calculations presented herein can be used for evaluation of other excited states of helium and cadmium in the He-Cd$^+$ laser discharges, for example for determination of the densities of He$^+$ and Cd$^+$ ions.

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Е. К. Мизерачик. Т. Гото, Ш. Хаттори, **Попытка квантового описания выходной мощности положительно заряженного столба** He-Cd$^+$ **лазера** ($\lambda=441{,}6$ nm)

Содержание. В работе представляются результаты теоретического определения характеристик выходной мощности положительно заряженного столба He-Cd$^+$ лазера на 441,6 nm, основанных на измерительных данных параметров плазмы, на известных поперечных сечениях и на функциях распределения энергии электронов. Сравнения показывают хорошее согласие между характеристиками выходной мощности He-Cd$^+$ лазера вычисленными и измеренными. В работе указывается на важность процессов определяющих выходную мощность He-Cd$^+$ лазера.