Error in measurement of electron concentration in copper vapor laser from Stark profile of hydrogen line

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Received October 7, 2001

The experimentally observed behavior of the electron density and plasma conductivity in the near afterglow is analyzed. It is shown that the observed increase of the electron concentration in the near afterglow as determined from the Stark broadening of the H_β hydrogen line reflects, in fact, the variation of the active medium temperature; and the increase of the plasma conductivity reflects the ~ 0.1 eV increase of the electron temperature due to additional energy deposition into the active medium after an excitation pulse.

Introduction

Power characteristics of a copper vapor laser (CVL) are governed not only by the processes occurring in the active medium during an excitation pulse, but also by plasma relaxation processes in the interval between pulses. The kinetics of these processes significantly depends on the electron component of the plasma, and therefore the knowledge of the time behavior of the electron concentration (n_e) is very important for understanding of the CVL physics. The n_e relaxation in CVL was measured in Refs. 1–8. As to the behavior of n_e in the near afterglow, the available data are contradictory: measurements from the Stark profile of the H_β hydrogen line[2–4] regularly give the peak of n_e several microseconds after the end of the excitation pulse, and n_e in this peak may increase several times, whereas other methods show the monotonic decrease of n_e.

Computer simulation also does not predict the n_e peak in the afterglow.[9] In Ref. 10 it was shown that some extra energy is pumped into the active medium in the near afterglow. This energy is stored during the excitation pulse by a shunt inductance connected in parallel to a gas-discharge tube (GDT), and this fact was ignored in computer simulation. Under these conditions, the plasma conductivity increases in the near afterglow, and the character of variation of the plasma conductivity corresponds to that of the electron concentration observed from broadening of the hydrogen line (Fig. 1).

The nature of the observed increase of n_e in the near afterglow is still unclear. Such an increase may be caused by ionization cooling of electrons before the beginning of the recombination process in plasma on the assumption that the populations of excited copper levels are significant by the end of the excitation pulse.[4] However, the populations of the excited levels in CVL are low at the end of the excitation pulse (except for metastable levels). In addition, in the case of ionization cooling of electrons, the increase of n_e should be observed regardless of the measurement technique. By the same reason, the significant increase of n_e cannot be explained by the extra energy pumped into the active medium, especially because it is much less than that during the excitation pulse. Therefore, Ref. 11 justifies the assumption that the observed peak of n_e in the afterglow does not reflect the actual situation, but is connected with peculiarities of the measurement technique based on broadening of the hydrogen line or, more precisely, with the presence of additional broadening factors ignored at the processing of the results. In this case, additional factors of the hydrogen line broadening must be directly connected with the processes occurring in the active medium. Revealing the relation between them, we can reveal the nature of the observed phenomenon.

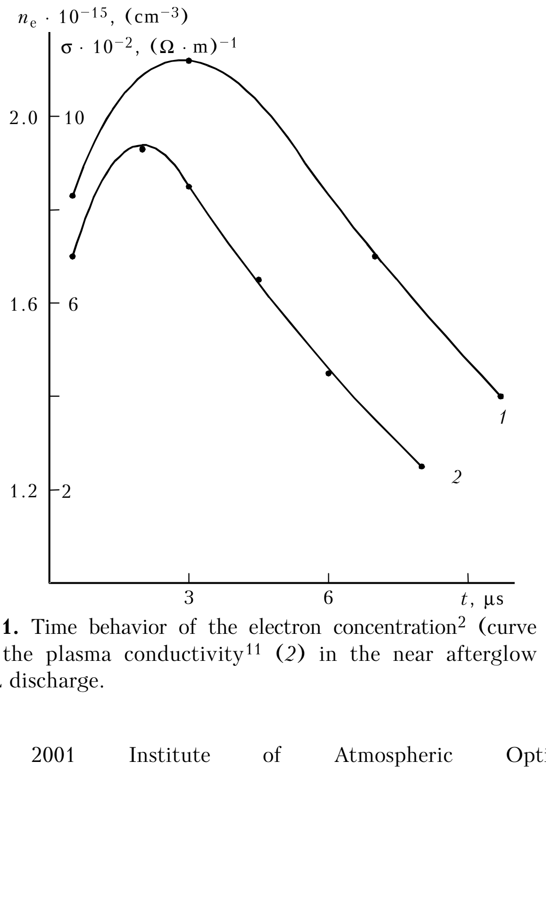

Fig. 1. Time behavior of the electron concentration[2] (curve *1*) and the plasma conductivity[11] (*2*) in the near afterglow of CVL discharge.

0235-6880/01/11 940-04 $02.00

Error of n_e measurement from the Stark profile of H_β hydrogen line

Cooling of electrons in the discharge near afterglow is connected with the loss of electron energy in the process of ionization (ionization cooling) or in the process of elastic collisions with particles of the active medium, in the first turn, with atoms of the buffer gas (collisional cooling). The significant increase of n_e due to ionization cooling of electrons is unlikely and can be observed for ~ 10^{-7}–10^{-6} s after the excitation pulse.[12,13] The loss of electron energy in the process of elastic collisions with atoms of the buffer gas must lead to the increase of the gas temperature.

The maximal possible fluctuations of the gas temperature (T_g) in the GDT for the interpulse gap were estimated in Refs. 14 and 15 based on the assumption that all energy pumped into the discharge for the excitation pulse is expended for heating. The estimates have shown that at $T_g = 3000$ K, buffer gas pressure $p_{Ne} = 3.3$ kPa, and pumped energy of 0.13 J, fluctuations of the gas temperature can be $\Delta T_g \approx 500$ K, and $\Delta T_g \approx 130$ K at $p_{Ne} = 13.3$ kPa. In this case, the characteristic time of gas heating is 3 μs and this value far exceeds the duration of the excitation pulse. This means that the gas temperature increases in the near afterglow of the discharge, and its peak coincides in time with the maximal value of the electron concentration measured from the hydrogen line broadening.[2–4]

Let us consider whether the variation of the gas temperature affects the shape of the H_β hydrogen line or not and whether this can lead to the error in measurement of the electron concentration. The electron concentration n_e is measured from the Stark profile of the H_β line in the case that the Stark profile is wider than the Doppler one. It should be kept in mind that the Doppler profile is determined by the temperature of the medium, whereas the Stark profile is determined by the electron concentration. However, as known from the theory of spectral line broadening, for the Stark profile of the H_β line having no central component, Doppler broadening leads to variation of the intensity $I(\omega_0)$ at the line center.[16] At the Maxwell distribution, the intensity $I(\omega_0)$ at the line center is described by the equation

$$I(\omega_0) = 1/\sqrt{\pi}\, \Delta\omega_D, \tag{1}$$

where $\Delta\omega_D = \omega_0\, \upsilon_0/c$, $\upsilon_0 = \sqrt{2kT_g/m}$, c is the speed of light, k is the Boltzmann constant, and m is the mass of a particle. Consequently, in the case that the width of the H_β line is determined by the Stark effect and the intensity at the line center is determined by the Doppler effect, the increase of the gas temperature, according to Eq. (1), leads to the decrease of the intensity at the line center and the increase of the measured line halfwidth. It becomes clear from the above-said that the observed increase of the electron concentration in the near afterglow of discharge can reflect, in fact, the variation of the active medium temperature in this period.

It should be noted that at the processing of the measurements,[2] the typical Stark profile of the H_β line without the central component was observed only as n_e achieved the maximum. Such an error in the measurement of the time behavior of the electron concentration is likely characteristic of measurements at the boundary of applicability of the method. The so long mistaking in correctness of measurements of the time behavior of n_e is connected with the fact that the gas temperature in self-heating metal vapor lasers is characterized, with the sufficient degree of accuracy, by the time-averaged temperature, which only slightly differs from the maximal and minimal temperature values.[17]

In Ref. 10, as was already mentioned, an attempt was undertaken to justify the observed increase of n_e in the near afterglow by the extra energy pumped into the active medium. This is supported by the observed increase of the plasma conductivity in the near afterglow, from which the time behavior of n_e was estimated providing that the plasma conductivity is proportional to the density and mobility of electrons and equals to

$$\sigma = e\mu_e\, n_e = e^2\, n_e/m_e\nu_m, \tag{2}$$

where e and m_e are the charge and mass of the electron; μ_e is the electron mobility; ν_m is the frequency of electron collisions with particles of the active medium.

The electron concentration was estimated on the assumption that the principal contribution to ν_m is due to the frequency of inelastic collisions of electrons with atoms of the buffer gas, which practically does not vary at the electron temperature typical of the near afterglow.[13] However, collisions with ions hamper electron acceleration by the field, as well as collisions with neutral atoms. Because of the high Coulomb cross section, electron-ionic collisions begin to decrease the conductivity at the far from complete ionization of the gas. Electron-ionic collisions become significant already at the degree of ionization about 0.1%. At the higher ionization, they become dominant, and then the conductivity becomes practically independent of the gas and electron density, depending only on the electron temperature T_e (Ref. 18). Such a degree of ionization is characteristic of CVL by the end of the excitation pulse, and therefore the decrease of the plasma conductivity does not reflect the behavior of n_e. The conductivity of strongly ionized plasma with monovalent ions is determined by the equation

$$\sigma = (1.9 \cdot 10^2)\, T_e^{3/2}\, [\mathrm{eV}]/\ln\Lambda, \tag{3}$$

where $\ln\Lambda$ is the Coulomb logarithm:

$$\ln\Lambda = \ln\left(\frac{3\sqrt{\pi}}{2}\frac{(kT_e)^{3/2}}{e^3 n_e^{1/2}}\right) = 7.47 + \frac{3}{2}\log(T_e[K]) - \frac{1}{2}\log n_e. \tag{4}$$

Table

n_e, cm^{-3}	Electron temperature, eV							
	0.86		0.69		0.52		0.34	
10^{15}	5.97	25.4	5.82	18.7	5.64	12.6	5.37	7.0
$8{\cdot}10^{14}$	6.02	25.17	5.87	18.6	5.69	12.5	5.42	6.94
$6{\cdot}10^{14}$	6.08	24.9	5.93	18.4	5.75	12.4	5.48	6.87
$4{\cdot}10^{14}$	6.17	24.6	6.02	18.1	5.84	12.2	5.57	6.76
$2{\cdot}10^{14}$	6.32	24.0	6.17	17.7	5.99	11.9	5.72	6.6
10^{14}	6.47	23.5	6.32	17.2	6.14	11.6	5.87	6.4
	lnΛ	σ, $(\Omega{\cdot}cm)^{-1}$	lnΛ	σ, $(\Omega{\cdot}cm)^{-1}$	lnΛ	σ, $(\Omega{\cdot}cm)^{-1}$	lnΛ	σ, $(\Omega{\cdot}cm)^{-1}$

The values of the Coulomb logarithm and plasma conductivity for the electron temperature and concentration typical of CVL after the excitation pulse, calculated according to Eqs. (3) and (4), are presented in the Table. The observed increase of the conductivity (see Fig. 1) in the near afterglow and, as follows from the tabulated values, the corresponding increase of the electron temperature ~ 0.1 eV are connected with the extra energy stored in the shunt inductance and then pumped into the medium.

The current traversing the inductance during the excitation pulse depends on its reactance and does not depend on the GDT volume. Consequently, with the increase of the GDT working volume, the specific extra energy, pumped into the active medium from the shunt inductance, decreases, and this manifests itself in the behavior of the gas temperature and plasma conductivity in the near afterglow.

The above-said is confirmed, in particular, by measurements of the electron concentration from the hydrogen line profile,[2–4] because the highest increase of n_e (actually, the gas temperature) is observed in the GDT with the smallest diameter of the discharge channel.

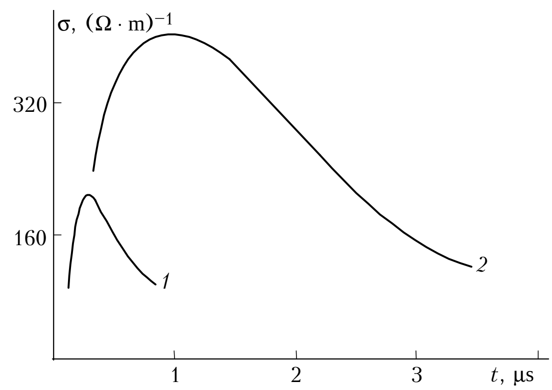

Fig. 2. Variation of plasma conductivity after excitation pulse in UL-102 GDT with reservoir capacitance of 1350 pF (*1*) and 3300 pF (*2*) in the discharge circuit.

As known, the reactance depends on the frequency of free oscillations in the discharge circuit and increases with its increase. The frequency of free oscillations in the discharge circuit can be increased by decreasing the reservoir capacitance. Consequently, the extra energy pumped into the active medium will decrease with the decrease of the reservoir capacitance, and this must correspondingly affect the behavior of the plasma conductivity in the near afterglow. Figure 2 depicts the time behavior of the plasma conductivity in the CVL near afterglow as measured in a UL-102 GDT with the reservoir capacitance of 1350 and 3300 pF providing the power supplied from a high-voltage rectifier is unchanged. The time behavior of the plasma conductivity in the near afterglow depicted in Figs. 1 and 2 clearly illustrates the above-said.

The measurements of the time behavior of n_e (Ref. 2) and plasma conductivity (Ref. 10) in the near afterglow were conducted under the close pumping conditions and geometric dimensions of the gas-discharge tubes. This allows us to analyze comparatively the regularities observed in Refs. 2 and 10. If the above reasoning is valid, then these regularities are caused by variations of the gas and electron temperatures.

Figures 3 and 4 depict the time behavior of the electron concentration depending on the buffer gas pressure in the GDT and the time behavior of the plasma conductivity observed in Refs. 2 and 10.

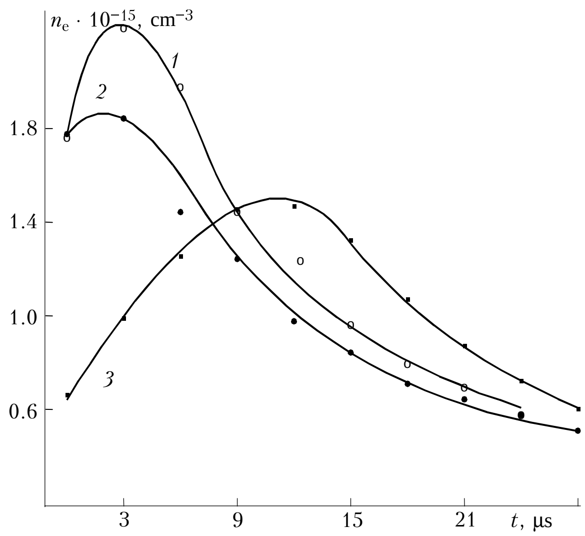

Fig. 3. Time behavior of the electron concentration depending on the pressure of the buffer gas Ne: 26.4 (*1*), 13.2 (*2*), and 3.3 kPa (*3*) (Ref. 2).

As is seen from Fig. 3, with the decrease of the buffer gas pressure, the time for which n_e reaches the maximum becomes longer, whereas in the conductivity (see Fig. 4) only the drop rate decreases. The observed regularities can be easily explained. As the buffer gas pressure decreases, the frequency of elastic collisions between electrons and buffer gas atoms decreases, thus decreasing the rate of electron cooling in the near afterglow and decelerating the drop of the plasma conductivity. Deceleration of electron cooling by the buffer gas atoms leads to the increase of the time, during which the gas temperature reaches the maximum.

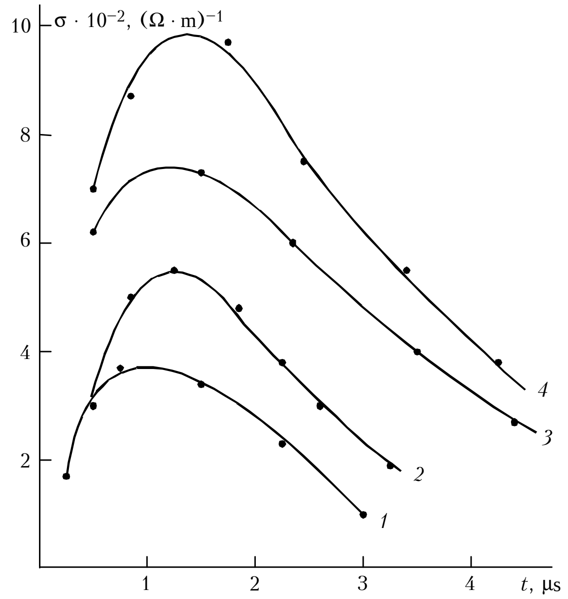

Fig. 4. Time behavior of the conductivity of CVL plasma in the discharge afterglow at the following parameters (Ref. 10): p_{Ne} = 26.4 (*1*, *2*) and 13.2 kPa (*3*, *4*); voltage at the rectifier of the power supply of 4 (*1*, *3*) and 5 kV (*2*, *4*).

An additional confirmation of the validity of our reasoning of the n_e behavior in the near afterglow is the following. According to Ref. 12, ionization can be observed after the excitation pulse due to the stored kinetic energy of electrons during the time

$$\tau_i \approx (n_m \beta I)^{-1}, \tag{5}$$

where n_m is the concentration of metal atoms; β is the coefficient of stepwise ionization; I is the energy of ionization of a metal atom. The electron temperature T_e drops down to the temperature of ionization T_i ~ 0.6 eV corresponding to the equilibrium between ionization and recombination. As follows from the Table, the increase of T_e at $n_e \sim 10^{14}$–10^{15} cm^{-3} does not exceed T_i for the measured values of the plasma conductivity. Consequently, in the near afterglow we must observe the monotonic decrease or the constant value of n_e. Reference 12 considered two mechanisms of electron cooling: diffusion and collisional. At $T_e > T_g$, electrons are cooled through elastic collisions with atoms and the role of the diffusion mechanism is low. Therefore, the corresponding correlation is observed between the electron and gas temperatures in the period under consideration.

Conclusion

1. The time behavior of the electron concentration in afterglow of lasers at self-limited transitions of metal atoms, as well as other pulsed gas-discharge devices, can be measured from the Stark profile of the H_β hydrogen line in the case that not only the Stark broadening mechanism prevails over the Doppler one, but also the line intensity is determined by the Stark effect.

2. The time behavior of the plasma conductivity in the near afterglow of a laser does not reflect the variation of the electron concentration in this period, because at the degree of ionization of the active medium above 0.1% the plasma conductivity is determined by electron-ionic collisions and reflects the character of variation of the electron temperature.

References

1. V.M. Batenin, V.A. Burmakin, P.A. Vokhmin, A.I. Evtyunin, I.I. Klimovskii, M.A. Lesnoi, and L.A. Selezneva, Kvant. Elektron. **4**, No. 7, 1572–1575 (1977).
2. V.F. Elaev, V.S. Mel'chenko, V.V. Pozdeev, and A.N. Soldatov, in: *High-Efficiency Gas-Discharge Metal Vapor Lasers* (IAO SB AS USSR, Tomsk, 1978), pp. 179–188.
3. T.M. Gorbunova, V.F. Elaev, T.A. Reutova, G.B. Sukhanova, Z.S. Teodorovich, and V.F. Fedorov, in: *Population Inversion and Lasing at Atomic and Molecular Transitions* (SPhTI, Tomsk, 1986), pp. 194–195.
4. E.Le Guyadec, C. Chamouard, J.-P. Gossens, and P. Lemaire, Opt. Commun. **100**, 461–466 (1993).
5. V.M. Batenin, I.I. Klimovskii, M.A. Lesnoi, and L.A. Selezneva, Kvant. Elektron. **7**, No. 5, 988–992 (1980).
6. C.E. Webb and G.P. Hogan, in: *Pulsed Metal Vapour Lasers*, ed. by C.E. Little and N.V. Sabotinov (Kluwer Academic Publishers, Dordrecht, 1996), pp. 29–42.
7. G.P. Hogan, C.E. Webb, C.G. Whyte, and C.E. Little, in: *Pulsed Metal Vapour Lasers*, ed. by C.E. Little and N.V. Sabotinov (Kluwer Academic Publishers, Dordrecht, 1996), pp. 67–72.
8. G.P. Hogan and C.E. Webb, Meas. Sci. Techol. **8**, 1095–1104 (1997).
9. R.J. Carman, D.J.W. Brown, and J.A. Piper, IEEE J. Quant. Electron. **30**, 1876–1895 (1985).
10. V.F. Elaev, A.N. Soldatov, and N.A. Yudin, Atmos. Oceanic Opt. **9**, No. 2, 104–107 (1996).
11. G.G. Petrash, *Atomic and Molecular Pulsed Laser*, ed. by V.F. Tarasenko, G.V. Mayer, and G.G. Petrash, Proc. SPIE **2619**, 68–75 (1995).
12. L.G. D'yachkov and G.A. Kobzev, Zh. Tekh. Fiz. **48**, No. 11, 2343–2346 (1978).
13. V.F. Elaev, A.N. Soldatov, and G.B. Sukhanova, Teplofizika Vysokikh Temperatur **19**, No. 2, 426–428 (1981).
14. V.M. Batenin, I.I. Klimovskii, and L.A. Selezneva, Teplofizika Vysokikh Temperatur **18**, No. 4, 707–712 (1980).
15. V.M. Batenin, V.A. Burmakin, P.A. Vokhmin, I.I. Klimovskii, M.A. Lesnoi, and L.A. Selezneva, Teplofizika Vysokikh Temperatur **16**, No. 5, 1145–1151 (1978).
16. I.I. Sobelman, *Introduction to Theory of Atomic Spectra* (Fizmatgiz, Moscow, 1963), 640 pp.
17. V.M. Batenin, V.V. Buchanov, M.A. Kazaryan, I.I. Klimovskii, and E.I. Molodykh, *Lasers at Self-Limited Transitions of Metal Atoms* (Nauchnaya Kniga, Moscow, 1998), 554 pp.
18. Yu.P. Raizer, *Gas Discharge Physics* (Nauka, Moscow, 1987), 592 pp.