# 22C08

# Theoretical Study on Population Inversion of Hydrogenlike Nitrogen in Recombining Plasma II
# 水素様窒素再結合プラズマの反転分布形成に関する理論的研究II

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Discharge produced plasma (DPP) is a promising tool to generate effective extreme ultraviolet (EUV) light. A hydrogen-like nitrogen ion emits light at 13.4 nm with an optical allowed transition from $n$ = 3 to 2, where $n$ stands for a principal quantum number. We focus on the properties of population inversion between $n$ = 3 and 2 in recombining phase. Population inversion is calculated in the framework of population kinetics, and a gain coefficient $G$ is estimated. In this study, dielectronic-capture ladderlike (DL) processes are included. At high density and low temperature, the DL deexcitations make a large contribution to the population inversion.

## 1. Introduction

A short-wavelength light source has been used for such industrial applications as nanostructure science and technology. Extreme ultraviolet (EUV) light is one of the most promising candidates for the next generation lithography. The wavelength of EUV light is typically 5 ~ 40 nm, and can be obtained by creation of hot dense plasma. The EUV light generation has been experimentally done by intense laser light and high current discharge. In general, hot dense plasma creation by discharge seems to be more efficient due to its compact and simple scheme compared with that by laser irradiation.

In this study, hydrogen-like nitrogen is focused as one of EUV light emitters of which wavelength is 13.4 nm. The wavelength is near that for the next generation semiconductor lithography, and may be expected to have potential for the industrial use described above. The 13.4 nm light comes from an optical allowed transition from $n$ = 3 to 2 (Balmer-α). To get enough intensity of the radiation, nitrogen must be ionized up to the ionization degree of six. In a recombining scheme, hot dense fully stripped nitrogen plasma is created and the hydrogen-like nitrogen is populated by three body recombination with rapid plasma expansion and cooling, resulting in the creation of population inversion and the lasing of Balmer-α. Although a related experiment has been performed and a pulse waveform shaping is designed for the rapid cooling, there is no lasing [1]. A related numerical simulation with a magnetohydrodynamic (MHD) and an atomic population kinetics codes for Z-pinch recombination pumping was done [2]. In the research, a recommended pressure is estimated and the maximum gain of 0.11 cm$^{-1}$ is obtained. However, because of plasma motion, understanding of the lasing characteristics in the viewpoint of atomic population kinetics is not clear. We calculate population kinetics with a stepwise cooling to gain an insight into the lasing of nitrogen at 13.4 nm.

In the calculation, doubly excited states whose outermost electron is bound in a higher orbital are considered. Those states are implicitly included in an atomic model proposed by Fujimoto *et al*. [3]. The processes in the model are called dielectronic-capture ladderlike (DL) processes. Such atomic processes are not considered in the study done by Vrba *et al*. [2]. In a recombining plasma scheme, the DL deexcitation may play an important role to create the population inversion. Finally, the contribution of the DL processes to the population inversion is quantitatively estimated.

## 2. Estimation of lasing performance

The usual goal for lasing has been to achieve a gain-length product of $GL$ = 5. With the cross-section of stimulated emission $\sigma_{\mathrm{stim}}$, the gain coefficient of Balmer-α is

$$G = N_{n=3}\sigma_{\mathrm{stim}} \times [1 - (N_{n=2}/g_{n=2})/(N_{n=3}/g_{n=3})], \qquad (2)$$

$N_{n=2}$ and $N_{n=3}$ are the population density of $n$ = 2 and 3, respectively. $g_{n=3}$ and $g_{n=2}$ are the corresponding statistical weights. Because of a time-dependent property of population inversion, a time-averaged gain $G_{ave}$ is estimated, namely, $G_{ave} = \int_0^{\tau} G dt \big/ \tau$, where $\tau$ is the time at $G = G_{max}/e$ after reaching $G = G_{max}$.

## 3. Calculation conditions

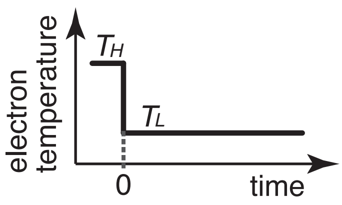


Fig. 1. Time evolution of electron temperature.

We focus the recombining phase after the maximum compression relevant to discharge produced plasma (DPP). To demonstrate the recombining phase, atomic processes are calculated with rapid plasma cooling shown in Fig. 1. This cooling condition is expected to give us strong nonequilibrium properties on atomic processes. Since the plasma cooling is assumed to be a stepwise to exclude the effect of plasma motion, we can see the property of the population inversion in the viewpoint of only population kinetics.

## 4. Simulation results and discussion

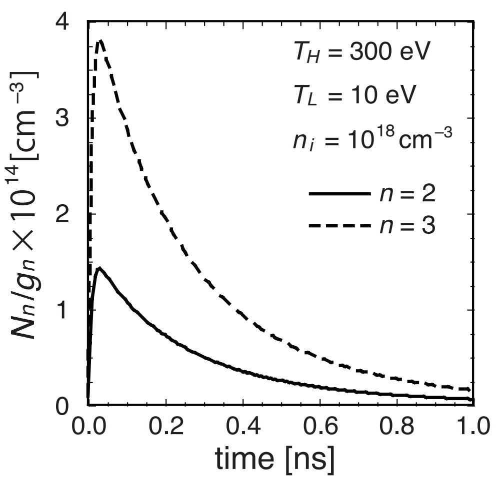


Fig. 2. Population densities of hydrogen-like nitrogen ions per statistical weights at $n_i = 10^{18}$ cm$^{-3}$ ($n$ stands for a principal quantum number).

Figure 2 shows the population densities of hydrogen-like nitrogen ions per statistical weights ($N_n/g_n$) without the DL processes. The initial electron temperature $T_H$ is assumed to be 300 eV, and the final one $T_L$ is 10 eV. The ion density $n_i$ is $10^{18}$ cm$^{-3}$. The population inversion is created, and we can see that $N_{n=3}/g_{n=3}$ is higher than $N_{n=2}/g_{n=2}$. The time-averarged gain $G_{ave}$ is ~ 2.8 cm$^{-1}$. The plasma length $L$ can be approximately estimated by the product of $\tau$ and the speed of light $c$, and $L$ is ~ 8.4 cm at $n_i = 10^{18}$ cm$^{-3}$.

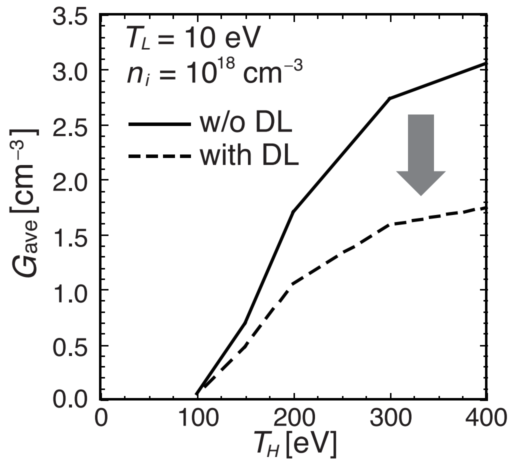


Fig. 3. Time-averaged gain with and without DL processes at $n_i = 10^{18}$ cm$^{-3}$.

At $n_i = 10^{18}$ cm$^{-3}$, DL deexcitations from $n = 4$ to 2 and from $n = 3$ to 2 are dominant. These processses make a large population in $n = 2$ and reduce an order of magnitude of the time-averaged gain shown in Fig. 3.

## 5. Conclusions

To get an optimum condition for the generation of 13.4 nm laser light relevant to discharge produced nitrogen plasma, we focus on the pouplation inversion and the gain coefficient of Balmer-α in recombining phase. In recombining phase, the DL deexcitation is found to be dominant to determine the population inversion between $n = 2$ and 3. With $T_L$ ~ 10 eV, the DL deexcitation make a large contribution to the population inversion, resulting in the reduction of the gain. The processes are indispensable for accurate estimation of the gain.


**References**

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