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Development of Computer Simulation Code of Excimer Lasers and Experimental Confirmation

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In order to analyze the discharge-pumped KrF excimer laser, computer simulation code is developed. On the other hand, the electron velocity distribution in a discharge plasma, measured by the Thomson scattering method, showed the Maxwellian, while the code predicted non-Maxwellian. This disagreement was solved by introducing the electron-electron collision into the simulation code. We also developed a simulation code on the CO_2 laser-heated plasma in high-pressure Ar gas, and estimated the formation process of Ar_2 excimer. The code predicted the possibility of the Ar_2 laser action at 126 nm.

1. Introduction

Discharge-pumped rare-gas-halide excimer lasers are important for applications such as chemical material processing and photo-lithography. The kinetics of discharge-pumped excimer lasers include complex electrical and chemical processes. In order to analyze the characteristics of these lasers, a computer simulation code was developed based on complicated rate equations and the Boltzmann equation. This provides useful knowledge on the detailed performances of excimer lasers. [1]

On the other hand, we measured the electron density and the electron velocity distribution in the discharge plasma of the excimer laser using Thomson scattering method. The result shows that the electron velocity distribution is Maxwellian, while the simulation code predicts non-Maxwellian. This disagreement can be solved by introducing an electron-electron collision into the code.[2]

Ar_2 excimer laser operating at 126 nm is expected as the source of the next-generation photo-lithography. However, the pump scheme of this laser is limited only electron-beam pumping which is not practical. We also developed a computer simulation code for the CO_2 laser-heated plasma in Ar gas, and estimated the density of plasma and the gain coefficient of Ar_2 excimer emission. [3] The results show that there is a possibility to attain laser action when the Ar gas pressure is increased. In the preliminary experiment, we obtained strong Ar_2 emission in VUV from CO_2 laser plasma with pre-ionization.

2. Simulation Code of Rare-Gas-Halide Excimer Lasers

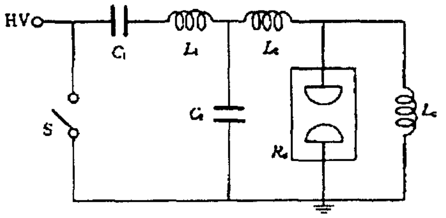

Fig.1 Pulse-power circuit of a discharge-pumped excimer laser

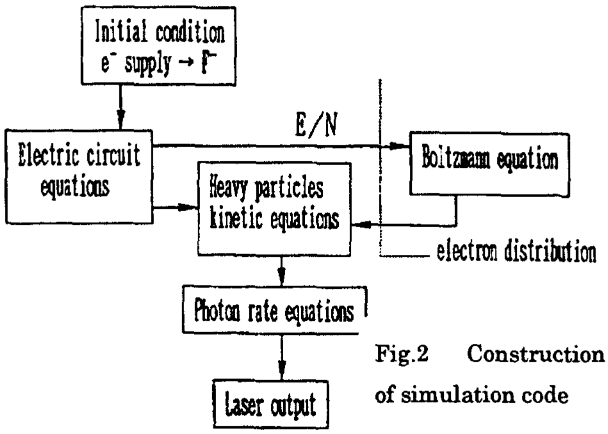

Fig.2 Construction of simulation code

Fig.1 shows the pulse-power circuit of a discharge-pumped excimer laser. In the case of a KrF laser, a high-pressure gas mixture of F_2/Kr/He (or Ne) is filled in the discharge tube. After the pre-ionization, the gap switch S is triggered, and the electric charge in C_1 is transferred to C_2 that is called the peaking capacitor. Then very fast self-break-down occurs in the discharge tube.

The modeling technique of these self-sustained discharge excimer lasers has already established basically. The construction of the simulation code is shown in Fig.2. The code is composed of the circuit equations and the rate equations for atoms, molecules, ions, electrons, and photons. Electron processes depend on the velocity distribution of electron, which is determined by the Boltzmann equation. Initial electron density is given by pre-ionization. After the triggering of the gap switch, the circuit equations calculate the E/N value, and the rate equations give the electron density. The Boltzmann code calculates the electron velocity distribution and the rate constants on electron collision, and they are returned to the circuit and rate equations, again.

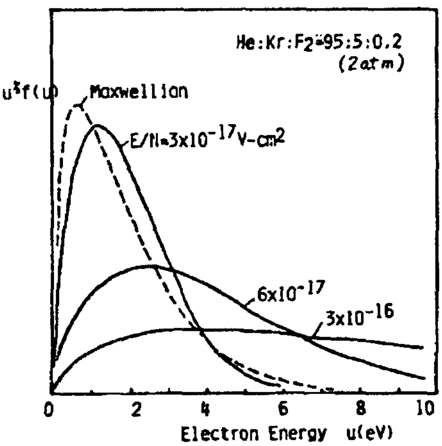

Fig.3 Calculated electron velocity distribution function

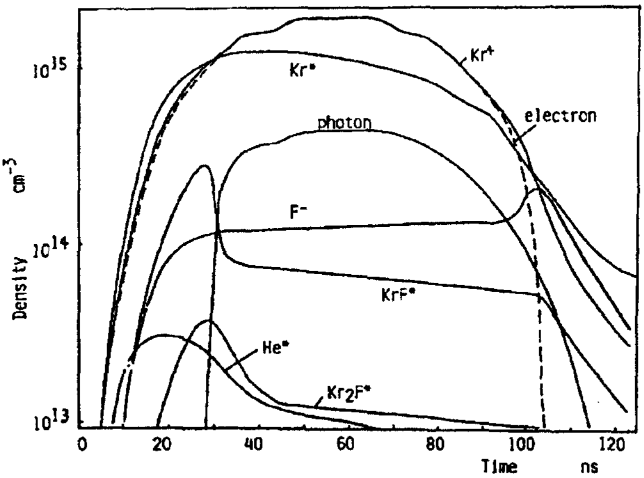

Fig.4 Simulation of various particles in KrF laser F_2/Kr/He (4Torr/30Torr/3atm)

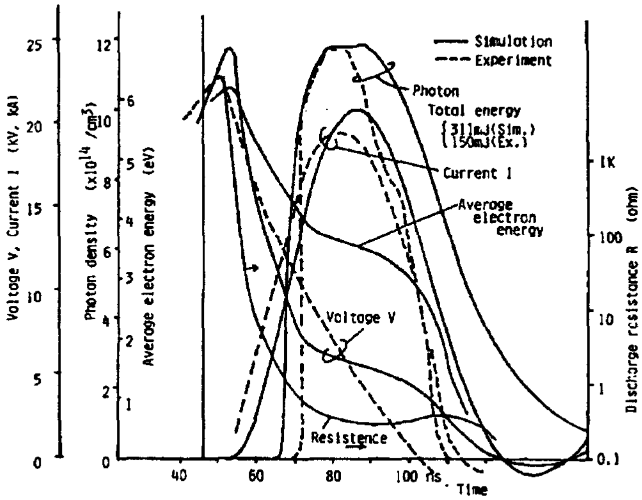

Fig.5 Simulation of photons, voltage and current in KrF laser F_2/Kr/He (4Torr/30Torr/3atm)

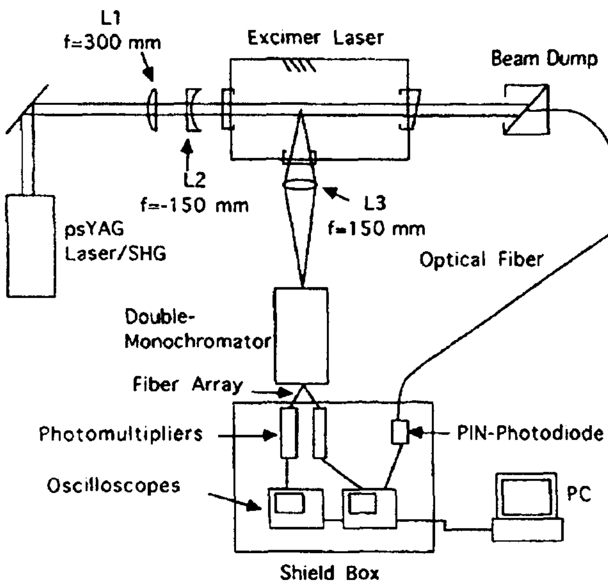

Fig.6 Experimental setup for Thomson-scattering measurements in an excimer laser discharge

An example of calculated result for a KrF laser with a mixture gas of F_2/Kr/He (4Torr/30Torr/3atm) is shown in Figs.3 -5. Examples of electron velocity distributions are shown in Fig.3 for different E/N values. The shape is not Maxwellian. Fig.5 shows a comparison with parameters such as the photon density, the electrode voltage and the main current, which can be experimentally available. This simulation technique on rare-gas halide excimer lasers has already established in 1980s basically. These simulation studies have greatly contributed to understand the kinetics of excimer lasers, and to improve their efficiencies.

3. Measurement of Electron Distribution Function and Comparison

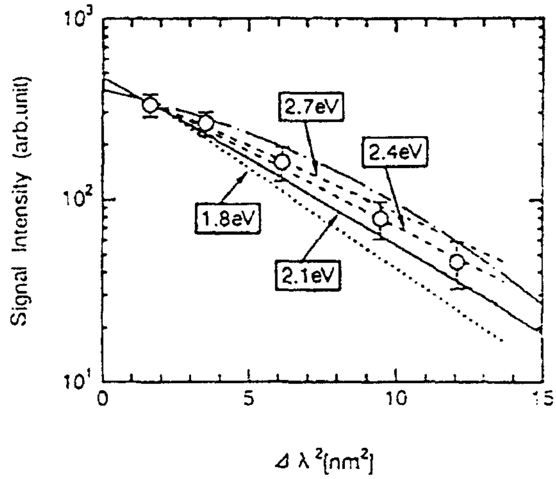

Fig.7 Measured electron velocity distribution for F_2/Kr/Ne = 1.5 Torr : 30 Torr : 3atm.

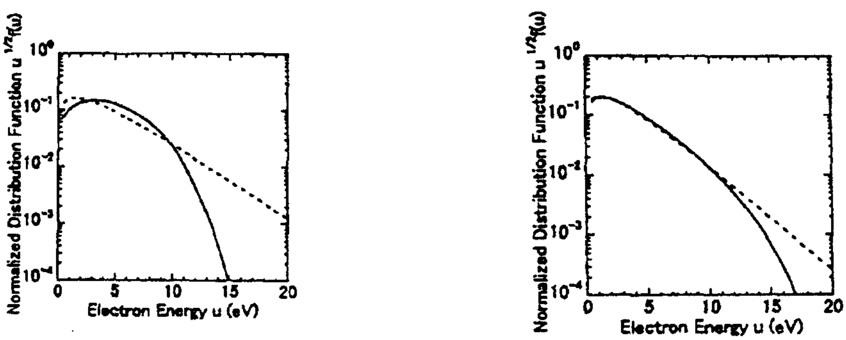

Fig.8 Calculated electron distribution function (solid line) and Maxwell distribution function (dotted line) without electron-electron collision (left) and with electron-electron collision (right)

The experimental setup is shown in Fig.6. To increase the temporal resolution, a high power ps Nd:YAG laser is used, which can provide an output energy of 0.3 J in 300psFWHM at 532 nm. The scattered light was collected in a perpendicular to both the laser axis and the discharge current direction. A double-monochromator was used to reject large Rayleigh-scattering light from the high pressure gas. The spectral resolution was 0.54 nm. A fast-response photomultiplier tube with a response time of 300 ps was used.

Fig.7 shows an example of the measured electron velocity distribution function, which shows the Maxwellian distribution. We never observed non-Maxwellian distribution also in other gas conditions, while the simulation code predicted non-Maxwellian. This discrepancy can be solved by introducing the electron-electron collision term into the simulation code. The electron velocity distribution is approaching to Maxwellian in the energy region smaller than 10 eV by considering the electron-electron collision, as shown in Fig.8.

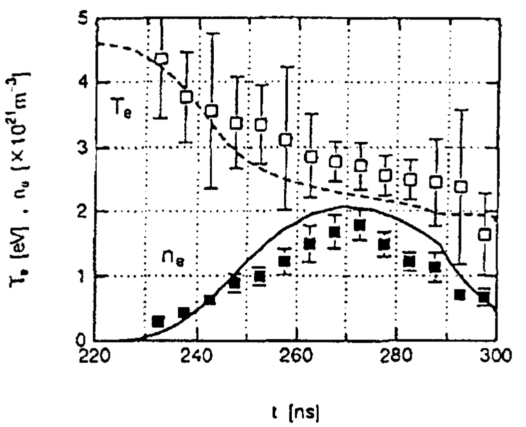

Fig.9 Comparison of time resolved electron density and temperature of measured values with simulation

Fig.9 shows the temporal change in the electron density and the electron temperature compared with the simulation results.

4. Ar_2 Formation in High Pressure Ar by CO_2 Laser Heating

Ar_2 excimer laser is one of the important candidates as the light source in the next-generation lithography, because it can be operated at 126 nm. However, laser action has not realized by usual discharge pumping scheme. Because of the low stimulated emission cross-section, generation of high-density Ar_2 is required to attain the laser action.

We developed a simulation code of CO_2 laser-heated plasma in high-pressure Ar, and estimated the Ar_2 formation. This code is also consists of the Boltzmann equation and the rate equations.

Fig.10 shows the Ar_2 excimer density generated by the heating of CO_2 laser pulse of 100 nsFWHM, where the Ar pressure is 16 atm and the initial electron density is 10^7 m^{-3}. The plasma density is built up after the CO_2 laser pulse, because the electron density increases by impact ionization between electrons and particles. The maximum excimer density is about $4x10^{22}$ m^{-3} which corresponds to the gain coefficient of 40 %/cm for a stimulated cross-section of $9x10^{-22}$ m^2.

Figs.11(a) and (b) show the maximum excimer density as a function of Ar pressure and CO_2 laser power. Pressures above 10 atm are required to obtain a sufficient gain, because the main channel of excimer production is the three-body reaction between Ar and Ar*. Fig.2(b) shows that the excimer density can be increased by increasing the initial electron density which is generated by pre-ionization.

Since the possibility of Ar_2 laser action at 126 nm is confirmed by computer simulation, we are now performing the experiment using the setup shown in Fig.12. We have already observed intense spontaneous radiation at 126 nm, only when the pre-ionization was done.

References

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Phys. B61 (1995) 165.
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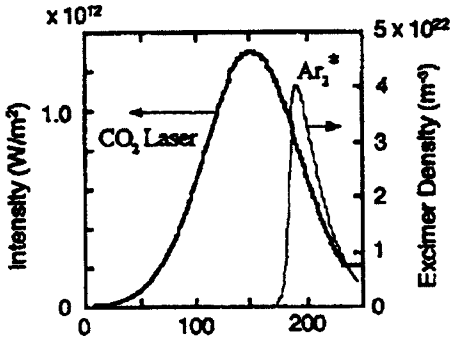

Fig.10 Temporal behavior of Ar_2 excimer density heated by a CO_2 laser pulse

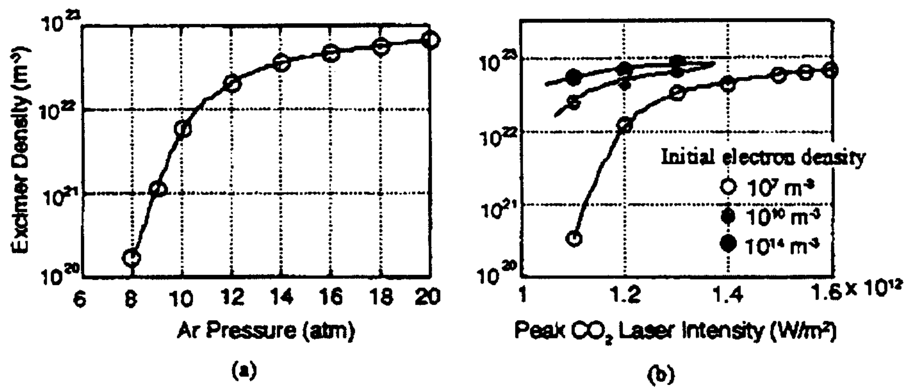

Fig.11 (a) Maximum Ar_2 density on Ar pressure for $1.4\text{x}10^{12}$ W/m^2 input
(b) Generated Ar_2 density on peak CO_2 laser power for various initial electron density

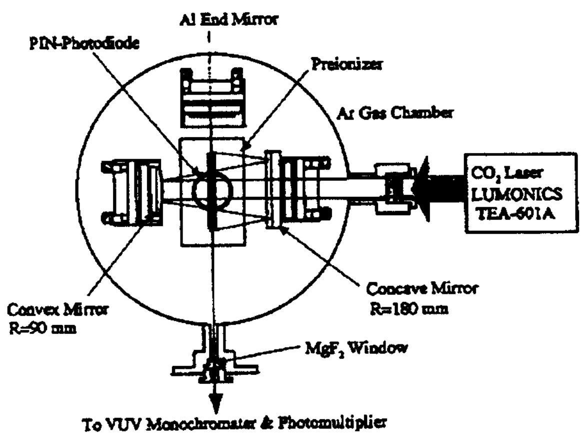

Fig.12 Experimental setup of Ar_2 excimer laser