Report on Visit to Ruhr-University Bochum by International Training Program

Graduate school of Engineering, Nagoya University
Takayoshi Tsutsumi

I had an opportunity to study at the Department Plasmas with Complex Interactions Ruhr-Universität Bochum (RUB) from November 21, 2012 to January 20, 2013 sponsored by Japan Society for the Promotion of Science (JSPS) International Training Program (ITP). During this time, I was supervised by Professor Uwe Czarnetzki, who is leading the Institute for Experimental Physics V. I was taught two different experimental techniques during my stay at Germany; one is the plasma density diagnostic using Terahertz time-domain spectroscopy (THz-TDS), and the other is the electric field diagnostic based on a four-wave mixing scheme. In this report, I will briefly explain the experimental techniques I learned in the past two months. Also, I would like to report the experience I gained in Germany during my stay.

Introducion of RUB and the research group

RUB which is state university locate in Bochum in Land Nordrhein-Westfalen, was established as the first university at 1962 in West Germany after the 2nd World War. RUB with its 20 faculties and 80 departments, the life sciences, natural sciences, engineering, the humanities and social sciences, and so on, is home to 5,000 employees and over 36,500 students from 130 countries.

Since plasma physics and plasma technology have become prominent research fields at RUB during the last years, Plasma research is now represented by a total of 11 full professorships in the Faculty of Physics and Astronomy and in the Faculty of Electrical Engineering and Information Technology. Center for Plasma Science and Technology (CPST) has established. Main research topics are plasma technologies for biomedical applications, plasma process development and control and plasma based particle and photon sources.

Prof. Czarnetzki's research group is a part of CPST, which study plasma physics and technology by various spectroscopies, Laser Induced Fluorescence (LIF), Optical Emission Spectroscopy (OES), and Optical Absorption Spectroscopy (OAS).

My research theme on my Ph. D. course is to develop the measurement of substrate temperature using low coherence interferometer. Therefore, I got much knowledge about various plasma diagnostics through this visit and it makes my research in Japan expand widely and deeply.

Research

(a) Background & Motivation

Microwave techniques are well established as important tools for characterizing low density plasma.[(1)] The advent of the laser has extended these interferometric techniques to plasmas with densities as high as 10^{19} cm^{-3}.[(2)] Both microwave and laser techniques need to use a number of sources for different frequencies to determine the phase change induced by the real part of refractive index of the expanded plasma.

To solve these problem, Terahertz time-domain spectroscopy (THz-TDS) which uses electro-magnetic waves in the terahertz region has been applied to the measurement of electron densities.[(3,4)] THz-TDS provide a powerful time resolved method for fully characterizing gaseous plasma over a wide range of densities. Therefore, this method can apply to the characterization and monitoring of industrial plasma, tokomaks, wakefield accelerators, radiation sources based laser–plasma interactions, and conventional gas lasers plasma.

This time, we have measured electron densities in an inductively coupled plasma (ICP) by using THz-TDS.

(b) Principle of THz-TDS

The electron density and the collision frequency can be estimated from the phase shift and the transmissivity of THz waves that are transmitted through the plasma. The principle of THz-TDS is described below.

The plasma frequency,

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}, \quad (1)$$

is the natural resonant frequency of the plasma where n_e is the electron number density and m_e is the electron mass. The complex dielectric constant is

$$\varepsilon = \left(1 - \frac{\omega_p^{\ 2}}{\omega^2 + \nu^2}\right) - i\left(\frac{\nu}{\omega}\frac{\omega_p^{\ 2}}{\omega^2 + \nu^2}\right). \quad (2)$$

The complex field spectrum $E\ (\varpi)$ is obtained from the Fourier transform of the time resolved measurement of the electric field $E(t)$. The complex field spectrum is

$$E_{plas}(\omega) = TE_{ref}(\omega)\exp(i(k_{plas} - k_0)L)\exp(-\alpha L), \quad (3)$$

where L is length of plasma traversed by the THz pulse, k_0 is the propagation wavenumber in the absence of plasma, α is the absorption coefficient, and T is the Fresnel transmission coefficient of the boundaries. The propagation and attenuation constants, k and α, of the wave in the medium are given by k= Re$\{\varepsilon^{1/2}\}\omega$/c and α =Im$\{\varepsilon^{1/2}\}\omega$/c, respectively. The frequency dependent phase change is

$$\Delta\Phi = \arg\{E_{ref}(\omega)\} - \arg\{E_{plasma}(\omega)\}$$
$$\approx \frac{\omega L}{c}\left[1 - \left(1 - \frac{\omega_p^{\ 2}}{\omega^2 + \nu^2}\right)^{\frac{1}{2}}\right]. \quad (4)$$

For $\nu \ll \omega$ and Eq. (1), the electron density of a plasma averaged along the light path length can be estimated from the phase shift obtained by the transmission measurement of a THz wave.

(c) Experiment

A schematic layout of the THz-TDS system used in this study is shown in Fig. 1. A laser beam emitted from the femtosecond laser is polarized by a half-wave plate and split by a beam splitter into the pump beam and the probe beam. The probe beam is then delayed by an optical time delay mirror and reaches the detector. The pump beam is focused to the gap of a dipole-type photoconductive antenna, which is installed on the emitter and biased at a alternating voltage. THz waves radiated from the emitter are collimated and directed to the plasma chamber. THz waves passing through the plasma chamber are then directed to the detector. When the THz wave and the pump beam arrive at the detector simultaneously, the magnitude of the instantaneous electric field of the THz wave is recorded. Moreover, time resolved measurements of the electric field spectrum are obtained by the varying the delay time by use of an optical delay line.

The diameter and height of the chamber for the ICP discharge are 15 cm and 33 cm, respectively. The distance between the rf antenna and the observation line is 4.0 cm. In this chamber, magnetic columns connected with yokes at the backside confine a low-pressure, high density plasma and provide homogenization of the density across the chamber.

(d) Results

We have measured electron densities in Ne inductively coupled plasma (ICP) by using THz- TDS. The Ne pressure was fixed at 2 Pa and the RF power applied to the rf-antenna was changed from 100W to 1000W. Also, I developed a computer program to perform Fourier transform and to determine phase shift without artificial phase jumps automatically.

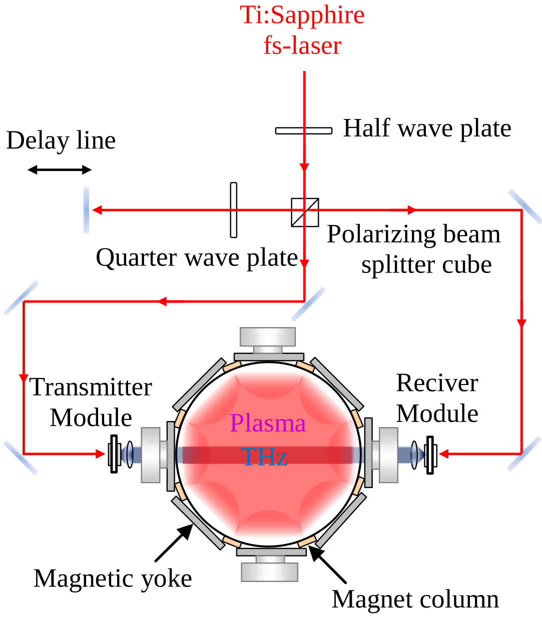

Fig. 1. The electron density measurement system by using THz-TDS.

The electric field spectrums of the THz pulse without plasma and with 200 W to 1000 W in the time domain are shown in Fig. 2. This result confirmed that the electric field spectrum of the THz pulse was changed by passing through the plasma. Moreover, comparing the 200 W case with the 1000 W case, it was found that the electric field spectrums in the time domain changed with the propagation wavenumber and the complex index of refraction, i.e. by the corresponding dependence on the electron density. The complex field spectrum of the THz pulse in the frequency domain which is described by eq. (3) is obtained from the Fourier transform of the electric field spectrums in the time domain. The electron density is deduced from the phase shift difference with and without plasma. Figure 3 shows the phase shift in a Ne ICP as a function of RF power. These results showed that THz-TDS can measure the change of the phase shift depending on the electron density. The plasma frequency is obtained from the phase shift by fitting eq. (4) to the measured data, and the electron density is deduced from eq. (1). The lines shown in Fig. 3 are fitted by eq. (4) on my program. The measurement results of the electron density as a function of RF power is shown in Fig. 4. With increased RF power, the electron density in the Ne ICP increased. However, the scaling is not linear because the increasing RF power also leads to an increased gas temperature and according reduction of the neutral gas density. Therefore, the electron density increases only sub-linearly.

This time, we invested that THz-TDS has a potential for application to higher electron densities by using Xe gas. Because the ionization energy of Xe, which is 12.12 eV, is lower than that of Ne (21.55 eV), the electron density in the Xe ICP is expected to become higher. The experimental set-up is the same when using Ne gas. The measurement results for the electron density in the Xe ICP as a function of RF power is shown in Fig. 5. Compared to the electron density in the Ne ICP, 2.91×10^{19}~$1.44\times10^{19}/m^{-3}$, the electron density in the Xe ICP increased from 3.21×10^{19} to $6.59\times10^{19}/m^{-3}$. These result confirmed that THz-TDS can measure the electron density of plasma of various gases.

At present, this system cannot monitor the electron density due to problems with the delay line software to perform Fourier transform and calculate phase

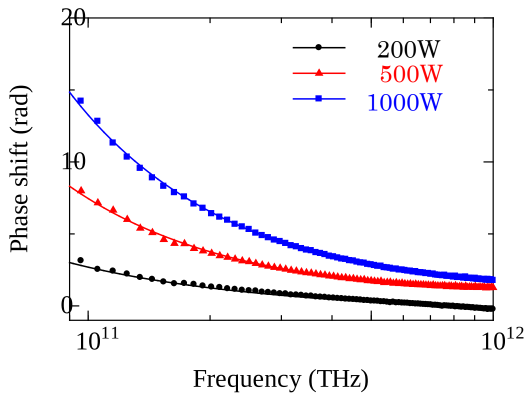

Fig. 3. The phase shift as a function of RF power in Ne ICP.

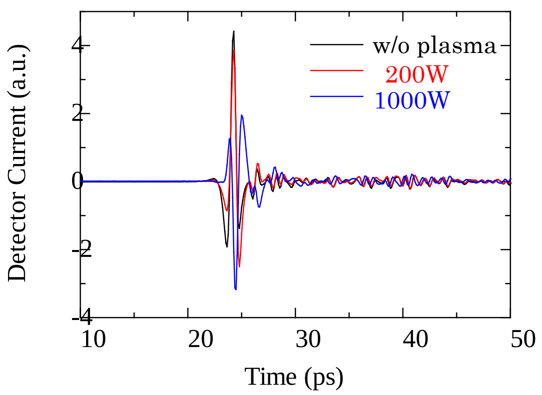

Fig. 2. Electric field measurements of THz pulses in the time domain in Ne ICP.

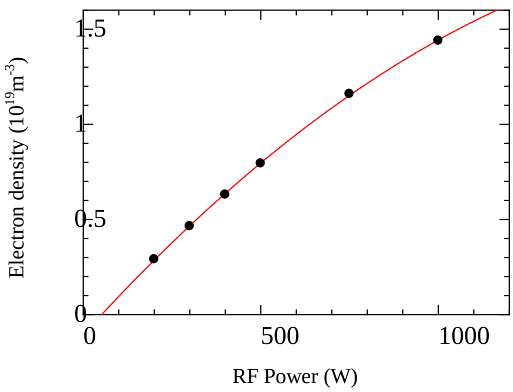

Fig. 4. The measurement results of the electron density as a function of RF power in Ne ICP.

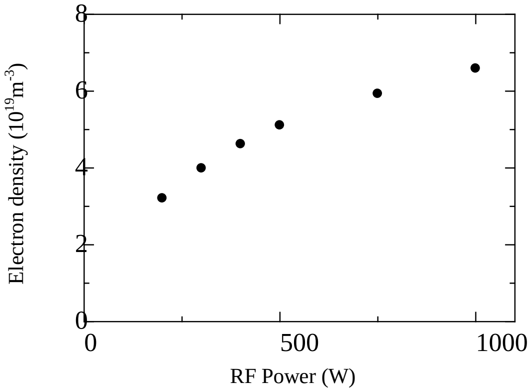

Fig. 5. The measurement results of the electron density as a function of RF power in Xe ICP.

shifts, and fit the phase shift dependence. A real time monitoring of the electron density is important to investigate surface reactions for plasma processes. To monitor it, I have made the program to perform Fourier transform and calculate phase shifts, and fit the phase shift continuously by Lab View (National Instruments Corporation). This work approached the development of a real time monitoring system and gave me a deeper understanding about THz-TDS.

Conclusion

We had mainly studied about THz-TDS as a novel plasma diagnostics in Prof. Czernetzki's research group at Ruhr-University Bochum (RUB) in Germany for two months. Moreover, I had learned about what to do to be a global researcher and what is important for life, research, and communication in Germany. In spite of the short term of two months, I think that many experiences obtained from this stay lead to my growth as a researcher and it was really priceless for me.

I deeply appreciate Prof. Hori, Prof. Toyoda, and Ms. Era for giving me such a great opportunity, Ms. Tajima and all of people for assisting my stay. Finally, I thank Prof. Czernetzki and the member of the research group for kind supporting for my stay in Germany.

Reference

(1) Lawrence J. Overzet and Michael B. Hopkins, J. Appl. Phys. **74**, 4323 (1993).
(2) D. J. Spence, P. D. S. Burnett, and S. M. Hooker, Opt. Lett. **24**, 993 (1999).
(3) S. P. Jamison, Jingling Shen, D. R. Jones, R. C. Issac, B. Ersfeld, D. Clark, and D. A. Jaroszynski, J. Appl. Phys. 93, 4334 (2003).
(4) A. Ando, H. Kitahara, T. Kurose, K. Kitano, K. Takano, M. Tani, M. Hangyo and S. Hamaguchi, J. Appl. Phys. 110, 073303 (2011).