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

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I studied about plasma density measurement with Terahertz time-domain spectroscopy (THz-TDS) at Professor Czarnetzki's Laboratory in Ruhr-University Bochum (RUB). The duration of stay in RUB was from January 24 to March 23 in 2012. During two month period, I could study not only the THz-TDS for measuring the plasma density, but also the plasma physics based on measurement results with several plasma diagnostics. Therefore it was a very meaningful experience for me. The summary of the stay is reported below.

The RUB was founded in 1965 and is financed and administered by the state of North Rhine-Westphalia. Currently, about 34,000 students are enrolled, and the university employs over 5,000 staff (about 450 of which are professors), making it one of the ten largest universities in Germany. The university is organized in twenty different faculties. In the faculties, there are departments about Japan. The students belonging to the departments are learning about Japanese history, Japanese language and literature. The RUB is located in the distance for 10 minutes by subway from Bochum central station. Therefore, since RUB has separated from the downtown of Bochum, it is very suitable for concentrating on research in a quiet environment.

Recently, researches in the RUB are placing now importance on science courses. And Center for Plasma Science and Technology (CPST) was founded. In the CPST, plasma physics and industrial applications such as plasma bio, plasma discharge and source, plasma diagnostics, simulation, etc. are studied. Prof. Czarnetzki's group which is in the center study about the plasma physics based on plasma diagnostics such as laser induced fluorescence spectroscopy, optical emission spectroscopy, absorption spectroscopy, etc. On the other hand, the group is conducting cooperative research on plasma science with many research groups in Japan. During my visit in the group, an associate professor from Kyushu University stays in the group from September 2011 for one year, Moreover, doctor course student was sent from other group in Kyushu University.

Fig.1 Park in Ruhr-University Bochum.

Fig.2 Dinner with researchers staying in Prof. Czarnetki's Laboratory.

In order to measure a plasma parameter such as electron density and temperature in low temperature plasma, measurement methods with Langmuir probe (plasma-contact type), microwave interferometer (plasma-noncontact type), etc. are used, frequently. On the other hand, measurements of electron energy distribution function are carried out using Thomson scattering spectroscopy with a large laser system. Recently, terahertz time domain spectroscopy (THz-TDS) with electromagnetic (EM) wave in the terahertz frequency region is applied for the measurement of electron density in the plasma. In the THz-TDS technique, the amplitude of EM waves are obtained as a function of time with sub-pico-second time resolution, and the phase and amplitude spectra of the pulse wave can be obtained by Fourier transformation of the pulse wave. By introducing THz pulse wave to plasma, its absorption or delay in the phase may appear in the frequency spectra. From the phase change, the electron density can be measured. Moreover, since vibrational frequencies of large molecules and electron plasma frequency of high density plasma can fall into the THz region. Therefore, THz-TDS is expected to serve as a diagnostics tool for high density plasma and some molecular gases.

In the experimental setup, dipole-type photo-conductive antennas are used as an emitter and a receiver of THz pulse wave. The electrode gap of emitter is 5 μm and biased by a peak-to-peak voltage of 45 V. When the gap of the antenna electrodes on the emitter is irradiated by a laser light with photon energy higher than the band gap energy of the semiconductor, photo-excited carriers (electrons and holes) are generated and accelerated by the bias voltage so that a small electric current flows in the semiconductor under the electrode gap. The EM wave generated by the time varying current and emitted as THz waves through a high resistivity silicon lens attached to the emitter. The magnitude of the electric field of the emitted wave is proportional to the time derivative of the current density. When a femto-second probe beam and THz-wave reach the receiver simultaneously, photo-excited carriers are generated in the semiconductor of the receiver and a current proportional to the oscillating electric field of the THz wave flows across the electrode gap. The measurement of this current provides information on the electric field of the incoming THz EM waves. The time dependence of the pulsed electric field is obtained by measuring the instantaneous fields of many pulses with scanning of the delay time, under the assumption that each pulse has nearly the same time-dependent

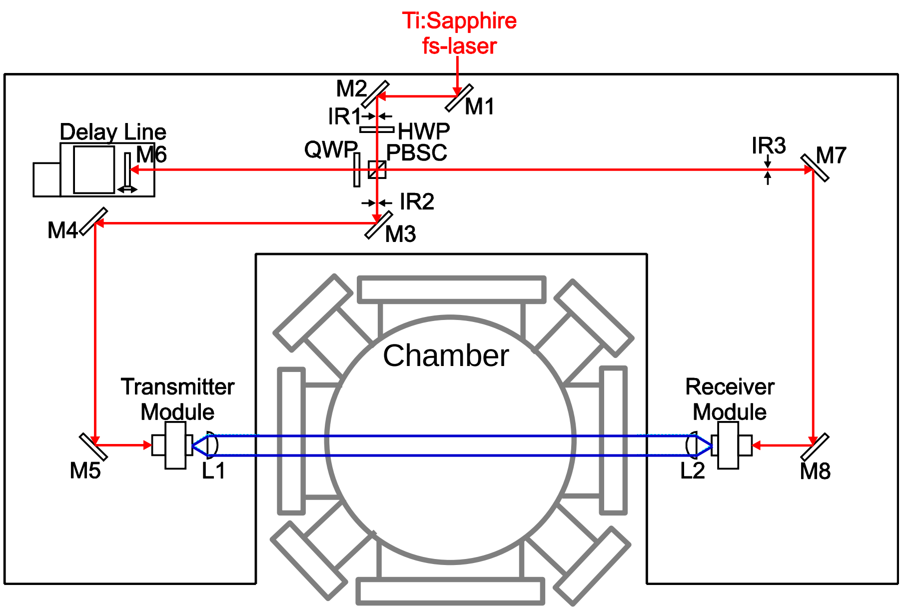

Fig.3 Experimental setup of THz-TDS for measurement of plasma density.

wave form. A lock-in amplifier is required for the measurement of a current in the receiver semiconductor on the order of nano amperes (nA) as a high sgnal-to-nise (S/N) ratio.

Figure 3 shows an experimental setup of THz-TDS system for measurement of electron density in inductively coupled plasma (ICP). The system consists of a Ti-Sapphire laser as the pulse source, an optical system for guiding laser beams to emitter and receiver of THz pulse wave. The THz pulse wave emitted from emitter went through the plasma chamber and detected by the receiver antenna. The incident time of probe beam into receiver was changed by the optical time delay line, and then, the THz pulse wave form was measured. The amplitude and phase spectra of THz wave were obtained by pulse obtained by the system Fourier transformation of the pulse wave. In the measurement of electron density in the plasma, it is necessary to measure a phase shift ΔΦ of THz pulse wave between with and without the plasma. If the frequency of THz wave pulse is sufficiently higher than the plasma frequency and collision frequency, the phase shift ΔΦ is

$$\Delta\Phi = \frac{L}{2c\omega}\frac{n_e e^2}{\varepsilon_0 m} \qquad \cdots \ (1).$$

where L denotes the length of the EM wave path in the plasma, ne is the line average of the electron density over the path, ε_0 is the vacuum permittivity, ω is the frequency of THz wave, m, c are the mass and velocity of electrons, and e is the elementary charge.

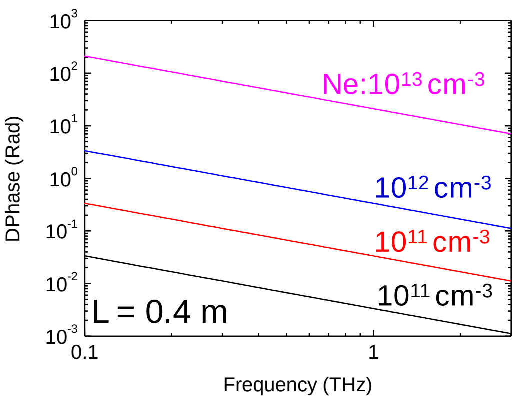

Fig.4 Calculated phase shift of THz pulse wave transmitted through plasmas.

The calculating results of phase shift with eq. (1) are shown in Fig.4. In the higher density condition and lower frequency region, the larger phase shift could be observed. Therefore, in the case of measurement of conventional processing plasmas with the electron density of around 10^{11} cm^{-3}, it is supposed that higher S/N ratio measurement of phase shift is required.

Figure 5 shows a phase shift of THz pulse wave transmitted through ICP with Ar discharge gas. The discharge condition of ICP was a pressure of 40 Pa, RF power of 100 W. From the result fitted by eq (1), the electron density in the condition was around 3×10^{-12} cm^{-3}.

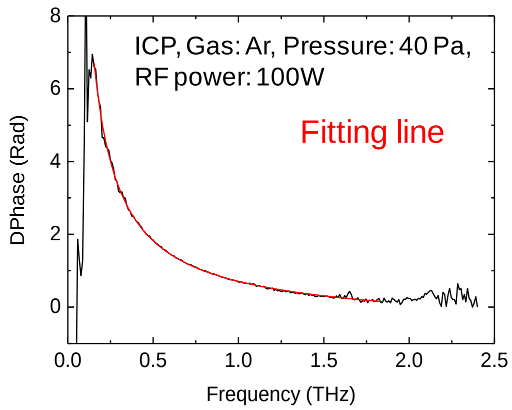

Fig. 5 Phase shift of THz pulse wave transmitted through Ar ICP at 40 Pa and 100 W.

In order to evaluating the system, RF power dependence of electron density in Ar ICP has been measured with the system. Ar pressure was fixed at 2 Pa and RF power was changed from 20 W to 200 W. Figure 6 shows the measurement results of the electron density as a function of RF power. With increasing RF power, the electron density in Ar ICP proportionally increased from 5.0×10^{10} cm^{-3} to 4.4×10^{10} cm^{-3}. However, in the low density plasma, relatively-high measuring errors were observed compared with high density condition because enough S/N ratio was not achieved. Next, electron density in the Ar ICP has been measured as a function of pressure. The RF power was fixed at 100 W and pressure was changed from 2 Pa to 40 Pa. The measurement results are show in Fig. 7. The electron density increased from 2.0×10^{11} cm^{-3} to 3×10^{12} cm^{-3} with increasing the pressure. In the measurement of pressure dependence, the measuring error was relatively low compared with measurement of power dependence. From these results, in the condition of the electron density more than 10^{11} cm^{-3}, the THz-TDS system in this study can realize measurement with relatively high S/N ratio.

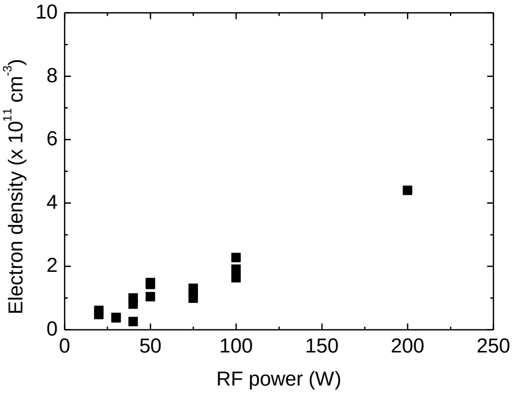

Fig.6 Electron density in Ar ICP measured by THs-TDS system as a function of RF power.

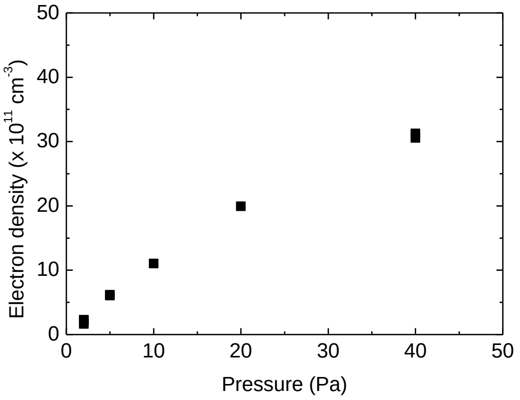

Fig.7 Electron density in Ar ICP measured by THs-TDS system as a function of pressure.

During my staying in Ruhr University Bochum for two month, I could study about not only new spectroscopic method for measurement of plasma density using THz-TDS, but also the other spectroscopic method for diagnostics of plasma. It was very meaningful for me to develop the breadth of knowledge for approach to plasma physics research based on spectroscopic methods.

I am deeply grateful to Professor Czarnetzki for the opportunity to study in his Lab. And I would like to thank Professor Toyoda, and Ms. Era for supporting this program and my visit to Ruhr University Bochum. Finally, I would like to thank Professor Hori, Professor Sekine, Professor Ishikawa, and Professor Kondo for assisting my study in Ruhr University.