Study on AC-DC Electrical Conductivities in Warm Dense Matter Generated by Pulsed-power Discharge with Isochoric Vessel

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Abstract. To observe AC and DC electrical conductivity in warm dense matter (WDM), we have demonstrated to apply the spectroscopic ellipsometry for a pulsed-power discharge with isochoric vessel. At 10 µs from the beginning of discharge, the generated parameters by using pulsed-power discharge with isochoric vessel are 0.1 ρs (ρs: solid density) of density and 4000 K of temperature, respectively. The DC electrical conductivity for above parameters is estimated to be 10⁴ S/m. In order to measure the AC electrical conductivity, we have developed a four-detector spectroscopic ellipsometer with a multichannel spectrometer. The multichannel spectrometer, in which consists of a 16-channel photodiode array, a two-stages voltage adder, and a flat diffraction grating, has 10 MHz of the frequency response with covered visible spectrum. For applying the four-detector spectroscopic ellipsometer, we observe the each observation signal evolves the polarized behavior compared to the ratio as I₁/I₂.

1. Introduction

Warm dense matter (WDM) is one of the states of matter, in which is neither the solid nor the plasma. The related physical phenomena in WDM are the implosion process of fuel pellet in inertial confinement fusion [1], the formation of giant planets (e.g. Jupiter) [2], and so on. The WDM is unclear physical properties such as the equation of state and the transport properties of both electrons and ions. To understand the physical properties, the quantum molecular dynamics or ab-initio simulations have predicted the AC-DC electrical conductivity and the equation of state in WDM regime [3, 4]. Desjarlais [5] has been predicted the low density WDM in disagreement with the Drude model. Yoneda, et. al. [6] has experimentally demonstrated the ultrashort-pulse ellipsometric pump-probe experiments and the pump-probe transmission experiments, respectively. However, these experimental results have obtained the single wavelength of probe light. Thus, the experimental data is lacking to evaluate the numerical results.

Recently, the isochoric heating of foamed metal using pulsed power discharge as a making technique of warm dense matter have been developed by Amano, et. al.[7]. Because of usable transparent tamper as a sapphire, the method is possible to observe in WDM with well-defined density-temperature. The lifetime of generated WDM in this method is longer than that of laser...
Figure 1. Experimental setup for observing AC and DC electrical conductivities in WDM by using pulsed-power discharge with isochoric vessel. (a)schematic diagram for observing AC conductivity, (b) photograph of spectrometer, and (c) topview of spectrometer.

experiments. Because of prolonged timescale, a spectroscopic ellipsometry is possible to apply the method.

The spectroscopic ellipsometry is generally used as the condense matter physics [8]. To observe the AC electrical conductivity as an optical properties, the ellipsometer requires four sensitive spectrometers, in which observe the reflectivity and the phase for each polarization. In case of WDM generated by the pulsed-power discharges, the typical timescale of emission from WDM is several tens of microseconds [7]. The spectrometer with fast response is required to analyze the optical properties observed by the spectroscopic ellipsometry.

To observe AC and DC electrical conductivity in warm dense matter (WDM), we have demonstrated to apply the spectroscopic ellipsometry for a pulsed-power discharge with isochoric vessel. In order to measure the AC electrical conductivity, we have developed a four-detector spectroscopic ellipsometer with a multichannel spectrometer and observed the polarization parameters.

2. Experimental Setup
Figure 1 shows an experimental setup for observing AC and DC electrical conductivities in WDM by using pulsed-power discharge with isochoric vessel [7].To achieve isochoric heating, copper metallic foam with pore sizes ranging from 50 to 600 μm and with ~ 90 % porosity was packed into a hollow sapphire capillary (φ 5 mm × 10 mm), in which can sustain up to 4 GPa. To avoid surface creepage on the sapphire, the interior pressure of chamber is less than 10⁻³ Pa by using turbo-molecular and rotary pumps. Low-inductance capacitors (3 or 6 × 1.87μF) were charged up to 15 kV to ensure vaporization of the foam. Time evolutions of current \( I(t) \) and voltage \( V(t) \) in the foam and plasma were measured by a Rogowski coil and by high-voltage probes.

To observe the AC electrical conductivity on WDM, a four-detector spectroscopic ellipsometer which is used to determine reflectivity and phase for each polarization is developed. The four-detector spectroscopic ellipsometer consists of a flash lamp, a polarizer, beam polarizers, and spectrometers. The flush lamp as an probe light for observing generated by Xe gas filled pulsed-discharge with 20 μs of duration. The radiation temperature of flush lamp is estimated to be
Figure 2. Typical time-evolutions of (a) voltage, (b) current, (c) input energy, and DC electrical conductivity for copper with 0.1ρs of density.

7000 K with the continuum spectrum. The flush lamp is triggered by a delay pulser after the onset of the discharge as generating WDM. The light from flush lamp polarized at 45 degree, in which means equivalent p- and s-polarized components. The probe light arrives at 60 degree as θi from the target normal.

The four-detector spectroscopic ellipsometer has two components denoted I_1/I_2 ∝ |r_p|^2/|r_s|^2 and (I_3 - I_4) / (I_3 + I_4) ∝ |r_s||r_p|sin δ/ (|r_s|^2 + |r_p|^2). To observe the spectroscopic information, spectrometers have been constructed as shown in Fig 1 (b) and (c). The spectrometer consists of a slit, a flat-field polychrometer, and detectors made with 16ch photodiode array having voltage adders. The voltage adders merge the detection signals from 16ch of the signals of photodiode to 4ch signals. The merged signals means the regime of observation wavelength corresponded to 340 - 370 nm, 370 - 530 nm, 530 - 680 nm, and 680 - 800 nm. Each signal is observed by the fast data logger. The time resolution of the 16ch photodiode array having voltage adders is estimated to be 10 MHz from the sinusoidal LED signals. The detectors are calibrated using data from cold copper.

3. Experimental results and Discussions
Figure 2 shows typical time-evolutions of voltage, current, input energy and DC electrical conductivity for copper foam with 0.1ρs of density. The voltage waveform eliminates the inductive voltage in the circuit. As shown in Figs. 2 (a) and (b), the peak voltage and current are 3 kV and 45 kA, respectively. The oscillation frequency is estimated to be 125 kHz. The input energy achieves 400 J at 10 μs from the beginning of discharge. The copper foam with 0.1ρs of density ensure the vaporization at 5 μs from the beginning of discharge. From spectroscopic observations, the temperature of copper is estimated to be about 4000 K. As shown in Fig. 2 (d), the DC electrical conductivity increases at the beginning of discharge because of the decrease of effective cross section for copper foam compared to the solid copper. After the ablation of copper foam, the DC electrical conductivity is estimated to be 10^4 S/m.

Figure 3 shows typical time-evolutions of detection signals obtained by the four-detector spectroscopic ellipsometer. The onset time as t = 0 indicates the triggered timing of the flash lamp. The results indicates that the each observation signal evolves the polarized behavior compared to the ratio as I_1/I_2 after the onset time of the flash lamp when the timing for WDM generation corresponds to 8 μs. However, the observation signals also evolve an oscillating behaviors before the onset time of the flash lamp. The oscillation frequency of the observation
Figure 3. Typical time-evolutions of detection signals obtained by the four-detector spectroscopic ellipsometer, (a)340-370 nm, (b)370-530 nm, (c)530-680 nm, and (d)680-800 nm. The onset time as $t = 0$ indicates the triggered timing of the flash lamp.

signal before the onset time of the flash lamp corresponds to the oscillation frequency of the pulsed-power discharge for WDM generation. It means that the observation signals integrated the noise from the pulsed-power discharge for WDM generation. To confirm the AC electrical conductivity by using pulsed-power discharge, we should care the noise from the pulsed-power discharge for WDM generation and the intensity of the probe light.

4. Concluding Remarks
To observe AC and DC electrical conductivity in WDM, we have demonstrated to apply the spectroscopic ellipsometry for a pulsed-power discharge with isochoric vessel. At 10 μs from the beginning of discharge, the generated parameters by using pulsed-power discharge with isochoric vessel are 0.1 $\rho_s$ of density and 4000 K of temperature, respectively. The DC electrical conductivity for above parameters is estimated to be $10^4$ S/m. In order to measure the AC electrical conductivity, we have developed a four-detector spectroscopic ellipsometer with a multichannel spectrometer. The multichannel spectrometer, in which consists of a 16-channel photodiode array, a two-stages voltage adder, and a flat diffraction grating, has 10 MHz of the frequency response with covered visible spectrum. For applying the four-detector spectroscopic ellipsometer, we observe the each observation signal evolves the polarized behavior compared to the ratio as $I_1/I_2$. To confirm the AC electrical conductivity by using pulsed-power discharge, we should care the noise from the pulsed-power discharge for WDM generation and the intensity of the probe light. To observe the quantitatively AC electrical conductivity in WDM, the improvement of the light source and the detector will be considered.

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