Asian Journal of Applied Sciences (ISSN: 2321 – 0893)
Volume 02 – Issue 02, April 2014

Investigation of Some Physical Parameters of Laser Induced Copper plasma

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ABSTRACT— Electron temperature and density of laser induced copper plasma are investigated experimentally and theoretically. Pure Cu target was irradiated and ablated under vacuum of 0.04 mbar by pulsed Nd:YAG laser 10ns pulse duration and 6Hz pulse repetition rate in stainless steel chamber. Three self-fabricated Langmuir probes were used as an electric diagnostic tool . I-V characteristic curve of Langmuir probe was plotted by applying variable voltages to the probe and recording corresponding values of current. The effects of the axial distance between cooper target surface and Langmuir probe tip and pressure on the electron temperature and density were studied not only experimentally by using Langmuir probe and its calculations but also theoretically by applying Anisimov model.

Keywords— Laser induced plasma, electron temperature, electron density, Langmuir probe, Anisimov model

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1. INTRODUCTION

Laser-Induced Plasma (LIP) is the plasma produced by the interaction of high-energy laser pulses with matter in any state of aggregation[1,2]. Laser induced plasmas of metals and alloys are of great interest since they have different attractive and important applications, e.g. material processing, thin film deposition, the synthesis of nanoparticles, the elemental analysis of multicomponent materials, precision machining, laser induced breakdown spectroscopy (LIBS), surgery, and laser micro-probe mass spectroscopy [3-6] . Understanding and studying the spatial and temporal distribution of plasma produced by laser ablation, electron temperature, and ion velocity are important for improving and developing laser plasma deposition thin film techniques besides the quality of thin films , many workers have studied Cu plasma. Dreyfus detected the 3D3 metastable state of Cu+ by the LIF laser induced fluorescence technique. Plasma velocity was determined, and electron heating by inverse bremsstrahlung was investigated by Song and Alexander . Pietch studied the expansion of Cu plasma and its distribution using a CCD camera [3]. The generation of high-temperature and high density plasmas by focusing high peak power laser radiation onto a solid target has raised an increasing amount of interest in the last decades. Such laser-ablated plasmas have found applications in various research fields [7]. Laser matter interaction has explored many dimensions on the basis of laser ablation in fundamental studies and technological applications including thin film deposition, production of microclusters, cutting, drilling, surface treatment, laser patterning, fabrication of micro and nano-electronic devices and magneto hydrodynamic generators, etc. Laser solid interaction leads to the formation of laser induced plasma after a number of energy conversions, provided that energy of incident laser exceeds the ablation threshold of the solid. Plasma ejectants consist of a mixture of atoms, molecules, electrons, ions, clusters, micron-sized particles, and molten globules . Laser induced plasma is transient in nature whose characteristics depend on laser parameters, target material and ambient conditions, which may vary radically along axial and radial direction . The laser energy transferred to target material through electrons involves different mechanisms, viz. electron–phonon coupling, multi-photon ionization and cascade ionization, etc. Thus, it is imperative to study the behavior of electrons when laser radiation falls on target material and ablation of material has taken place. Plasma parameters may be characterized by behavior of electrons, i.e. electron density, temperature, ionization degree, relative number densities of neutral metal atoms and ions. These parameters show that the number density of metal species is separated in the axial direction from those along radial direction. Temperature of laser induced plasma may be explained by the expansion of the plasma. Plasma at its inner part has high and low varying ionization degree which decreases to low values near to front due to collision process between the plasma constituents [1,5,8-12].

The schizophrenic nature of plasma is still a mystery and different diagnostic techniques are used to unveil its characters. The key parameters of laser ablated plumes are density and temperature. Mostly, the characteristics of the plume are governed primarily by electron contributions to temperature and density [6]. The minimum fluence needed to detect charged species in the vaporized materialis defined as the ablation threshold, approximately between 1 and 102 J/cm-2. Successively the vaporized material expands in vacuum at super- sonic velocities. By increasing the fluence over the ablation threshold, the saturation of the produced plasma density allows the increase of the ions and electrons temperatures [7]. the plasma temperature, electron density, and ion velocities depend strongly on the parameters of the laser such as wavelength, pulse duration, irradiance, etc. After production, the plasma expands at supersonic velocity and its parameters, such as temperature, density, and expansion velocity, begin to have the values that depend upon the expansion time, expansion length, and plasma species [4]. The nature of the laser generated plasma significantely influence film characteristics. A full understanding of the plasma processes, in adddition to its intristic interest, opens the way to reliable control of the film deposition process [13]. Anisimov et al. treated the adiabatic expansion of a one component vapour cloud into vacuum using a particular solutuion of the gas-dynamic equations, which applies when describing flows with self similar expansion (for more details see [14]) [14]. the adiabatic expansion model of Anisimov et al. has proved to be very useful for the understanding and interpretation of laser ablation experiments. That model considers the adiabatic expansion of a small volume of hot gas into vacuum. The Anisimov model considers the expansion of the plume to be isentropic, which essentially means that there is no heat conduction between parts of the plume[15]. The characteristics of the laser induced plasma are diagnosed by several optical and electrical diagnostics [16].These includes emission and absorption spectroscopy, laser induced fluorescense, mass spectrometry, interferometry, charge collectors, Thomson scattering, beam deflectometry, and Langmuir/ion probe methods [4,6,17,18]. Langmuir probes have been widely used to diagnose the low-temperature plasmas produced by laser ablation for pulsed laser deposition of thin films . These probes have been used to measure the plasma density and temperature, the plasma flow velocity and the shape of the ablation plume expansion [19,20].

2. DETERMINATION OF PLASMA PARAMETERS

Plasma parameter such as electron density and temperature can be calculated by applying bias voltage to the Langmuir probe and recording the current on the oscilloscope , then plotting I-V characteristic , the electron temperature T_e and electron density n_e can be given as:-

$$T_e = eV_a/k \ln\left(\frac{I_p}{I_0}\right) \qquad (1)$$

$$n_e = I_0 A e[m_e/2\epsilon_0 k T_e]^{1/2} \qquad (2)$$

where Va is applied biasing voltage to the Langmuir probe , I_0 is Langmuir probe current at zero voltage, Ip is Langmuir probe current at certain voltage , A is the area of the Langmuir probe tip, e is electron temperature, m_e is the electron mass , k is Boltzmann constant and ϵ_0 is the vacuum permittivity [6].

3. EXPERIMENTS

A schematic diagram of the experimental set-up is shown in figure (1).

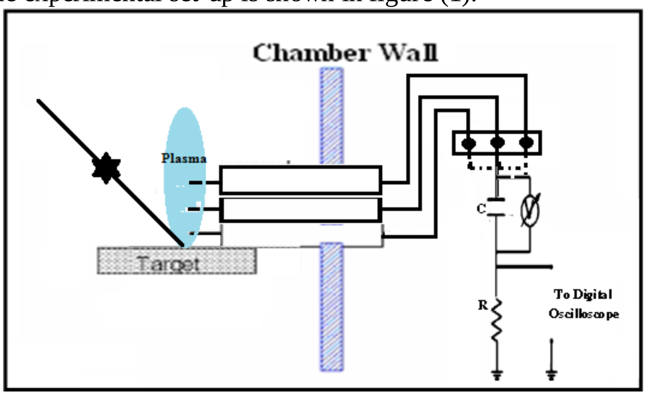
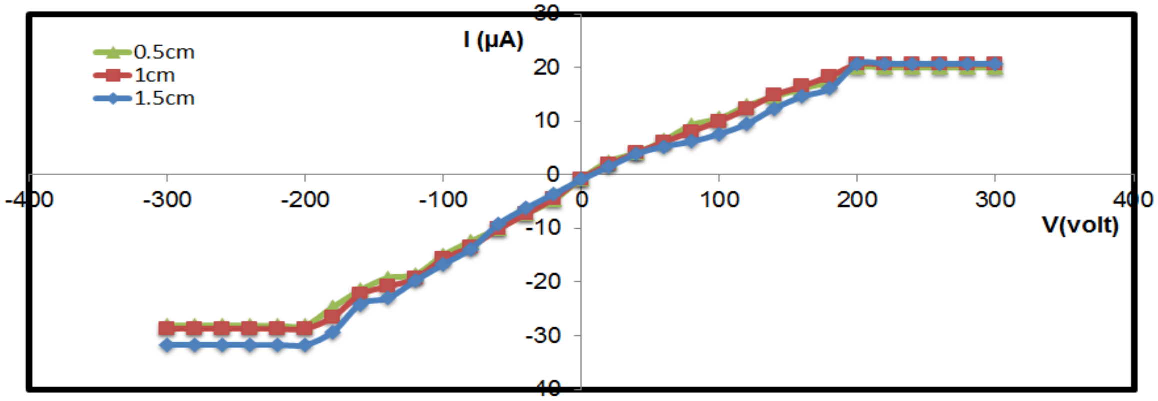


Figure 1: Schematic diagram of laser induced copper plasma system setup

The Q switched 1064nm, 10ns Nd :YAG laser source was used for ablation. The laser beam was focused at 450 incidence angle onto rotating copper target in a vacuum stainless steel chamber with a base pressure of 4x10-2mbar, the spot area on the surface of copper was 78.5x10-4cm2. The vacuum vessel can be evacuated by using the rotary pump. Three cylindrical Langmuir probes were used in this experiment. All of them were small probes made of tungsten wire with dimensions 3mm in diameter and 0.3mm in length. The purpose of the small probe was to ensure reproducibility of the ablation plume. They were oriented to face the Cu target and were biased at -300V to record the ion signal due to the plasma flow. For all probes, the current was determined by using a digital oscilloscope to measure the voltage across a load resistor as in fig.(1).The IV characteristic at a particular time was then obtained by plotting the current against the bias voltage. the variable factors in this experiment are the distance between the Cu target and the Langmuir probe and the background gas pressure to study their effects on the electron temperature and density in laser induced copper plasma. The distances were taken the values (0.5,1, and 1.5 cm) while the pressure varied gradually from 0.04 to 0.2 mbar.

4. RESULTS AND DISCUSSION

Figure (2) describes the I-V characteristics curve of Langmuir probe for laser induced copper Cu plasma by the first wavelength λL= 1064 nm , under vacuum, incident laser pulse energy is 700mJ as a function of distance from the target surface.



Figu

re 2: I-V characteristic curve of Langmuir probe for Cu LIP with different distance from the target surface

From the slope of the electron retarding region which is ranged from 0 to 200V we can find the electron temperature in the plasma as a practical method and compare them with the theoretical result using Anisimov theoretical model to find Te. Figure (3) illustrates the variation of the electron temperature with the distance from the target surface at the fundamental wavelength, under vacuum and laser pulse energy 700mJ.

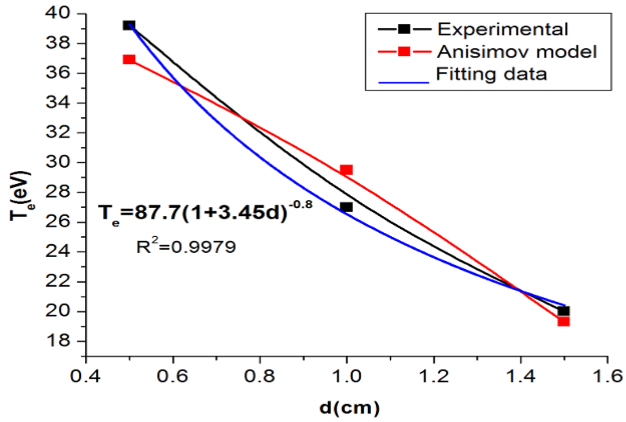


Figure 3: Electron temperature as a function of distance from the Cu target in LIP

We find that the relationship is inverse between the electron temperature and the distance from the target surface, the large distance from the target surface the small electron temperature, and the reason of this is due to the decreasing in the electron thermal energy as a result of its transforming into kinetic energy in the plasma plume and also as a result of three body recombination at high distances, these results are consistent with the results of theoretical curve of the electron temperature by using Anisimov model. When a curve fitting has been computed for the practical results, it was found that the electron temperature is proportional to d-0.8. Figure (4) describes the I-V characteristics curve of Langmuir probe for laser induced Cu plasma as a function of vacuum pressure.

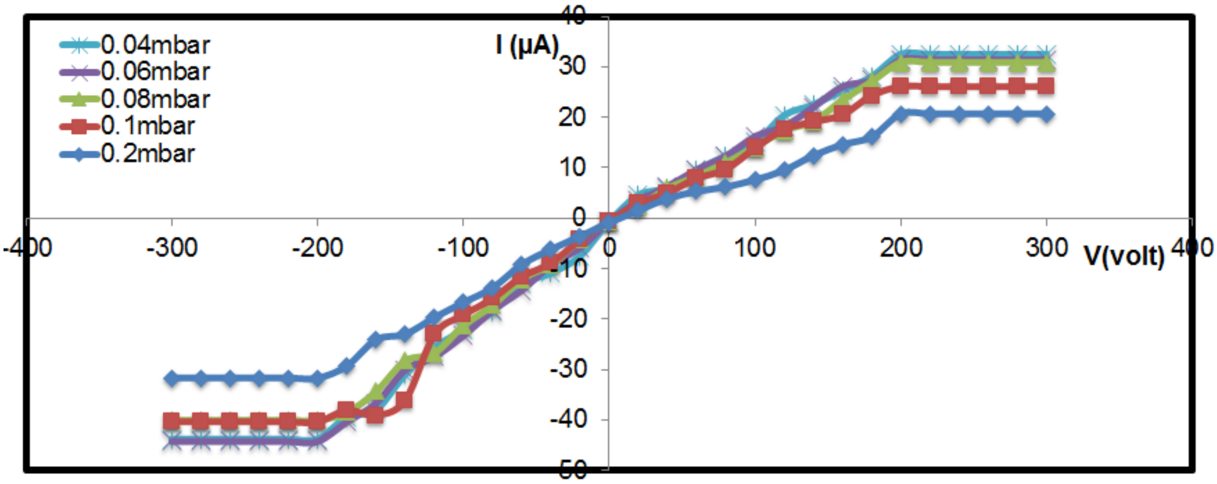


Figure 4: I-V characteristic curve of Langmuir probe for Cu LIP with different vacuum pressure.

The effect of vacuum pressure on the electron temperature Te for laser induced Cu plasma by the fundamental wavelength has been studied as in figure (5).

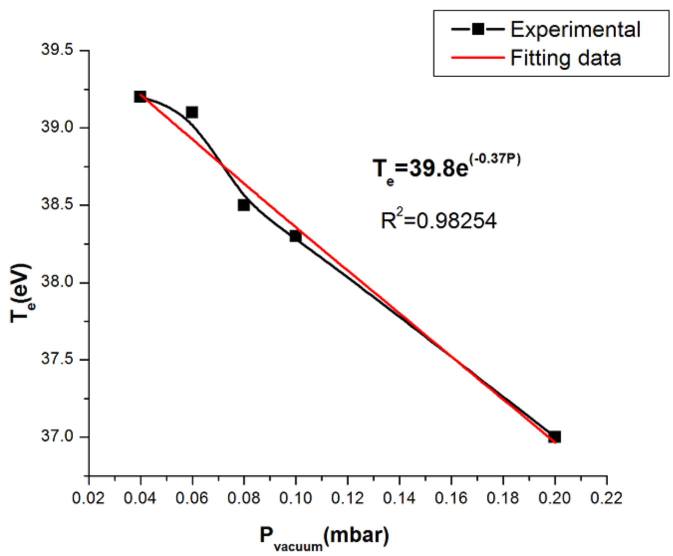


Figure 5: Electron temperature as a function of vacuum pressure in LIP

It was found from figure (5) that the relationship is decreasing exponentially between the electron temperature and vacuum pressure, as the vacuum pressure increases the electron temperature decreases. The reason of this behavior is in the case of increasing vacuum pressure the plasma will be confined in small volume and it will be in confinement state and recombination rate and plasma species excitation collisions will be increased and consequently the emission intensity will be increased significantly and the electron temperature will decrease. Also curve fitting for the experimental results was computed while the fitting equation of the electron temperature was also included. Electron density is an important parameter used to describe the plasma environment and it is crucial in establishing its stability condition. Figure (6) shows the variation of the electron density ne versus distance from the Cu target surface and it is shown that the relationship is an inverse between them and follows ne $\propto \frac{1}{d}$.

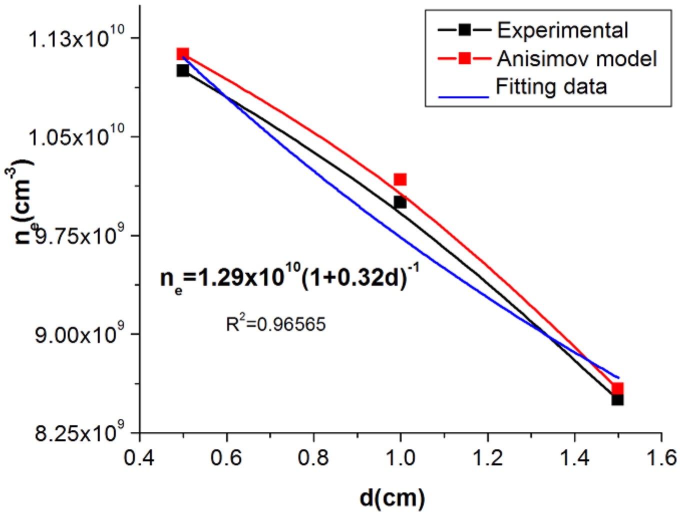


Figure 6: Electron density as a function of distance from the Cu target in LIP

As the distance from the target surface increases the electron density decreases. Experimental equation has been also deduced by using the curve fitting for the experimental results, also the experimental results are compatible with the theoretical results of Anisimov model. The decrease in the electron density with distance from the target surface can be interpreted due to the propagation of the plasma plume and also because of the electron recombination with ions to form neutral atoms and molecules at large distances from the target surface. Figure (7) illustrates the effect of vacuum pressure on electron density and it is clear that the relationship between them is an exponential relationship, the electron density increases with increasing vacuum pressure until it reaches the saturation at about 0.1mbar.

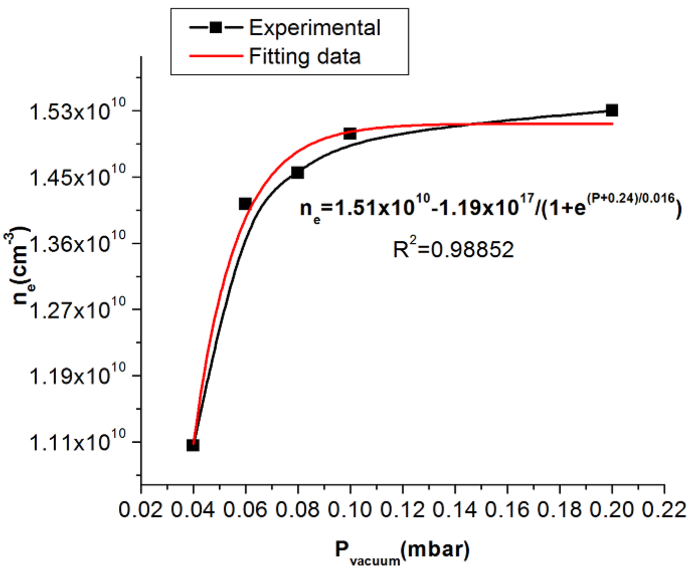


Figure 7: Electron density as a function of vacuum pressure in LIP

The reason of this behaviour is when the vacuum pressure increases the plasma will be confined in small volume, leading to increase the collisions between the plasma species such as electrons, ions, atoms and molecules and hence atoms and molecules will be ionized due to these collisions and electrons liberate and there will be increment in their number and density. Experimental equation for the electron density versus vacuum pressure is concluded by using curve fitting of the experimental data of the results.

5. CONCLUSION

The effects of axial distance and vacuum pressure on the electron temperature and density in laser induced copper plasma were discussed. Langmuir probe results indicate that the electron temperature and density decrease with increasing the axial distance between Langmuir probe and Cu target surface and because of the conversion of the thermal energy of electrons to the kinetic energy and also three body recombination. On the other hand, electron temperature and density decrease with increasing the vacuum pressure due to the occurrence of "Confinement effect" at high pressure and increasing collision of electrons and ions. The relationship between both electron temperature and density with each of axial distance between Langmuir probe and Cu target and vacuum pressure can be expressed as empirical equations using curve fitting technique.

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