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# Some physical properties of $SiO_2$ laser induced plasma

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## Abstract

In this work; Silicon dioxide ($SiO_2$) plasma plume was prepared by laser induced plasma (LIP). The electron number density, plasma frequency and Debye length were calculated by reading the data of I-V curve of Langmuir probe which was used as a diagnostic method of measuring plasma properties. Pulsed Nd:YAG laser was used for measuring the electron number density of $SiO_2$ plasma plume under vacuum environment with varying both vacuum pressure and axial distance from the target surface. Some physical properties of the plasma generated such as electron density, plasma frequency and Debye length have been measured experimentally and the effects of vacuum pressure and Langmuir probe distance from the target were studied on those variables. An inverse relationships between electron density, Debye length and plasma frequency with axial distance from the target were observed as well direct proportionality between both plasma density and plasma frequency with vacuum pressure while the exception is true in case of Debye length which is proportional inversely with vacuum pressure.

**Keywords** : Laser induced plasma, Langmuir probe, electron density, plasma physics, $SiO_2$, Debye length, plasma frequency.

# بعض الخصائص الفيزيائية لبلازما ثنائي اوكسيد السليكون المحتثة بالليزر

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## الخلاصة

في هذا العمل؛ تم اعداد عمود بلازما ثنائي اوكسيد السليكون ($SiO_2$) المتولدة من طريقة البلازما المستحثة بالليزر . حسبت كثافة عدد الإلكترونات، تردد البلازما وطول ديباي من خلال قراءة البيانات من منحنى I–V لمجس لانكمور الذي تم استخدامه كوسيلة تشخيصية لقياس خصائص البلازما. وقد استخدم ليزر YAG لقياس كثافة عدد الإلكترونات في عمود البلازما لمادة ثنائي اوكسيد السليكون $SiO_2$ تحت بيئة فراغ مع تغيير كل من ضغط الفراغ والمسافة المحورية من سطح الهدف. بعض الخصائص الفيزيائية للبلازما المتولدة مثل كثافة الإلكترونات، تردد البلازما وطول ديباي تم قياسها تجريبيا وتمت دراسة آثار ضغط فراغ وبعد مجس لانكمور عن سطح المادة الهدف على تلك المتغيرات. لقد لوحظت علاقات عكسية بين كثافة الإلكترونات،

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طول ديباي وتردد البلازما مع المسافة المحورية عن الهدف كما كان التناسب طردي مباشر بين كل من كثافة البلازما وتردد البلازما مع ضغط الفراغ في حين أن الاستثناء هو صحيح في حالة طول ديباي الذي يتناسب عكسيا مع ضغط الفراغ .

## 1. Introduction

Pulsed laser ablation (PLA) has different applications making it as attractive field of fundamental research. One of the applications of PLA is laser-induced plasma (LIP) [1]. Due to various key applications in material processing, thin film deposition, environmental monitoring, biomedical studies, military safety usage, art restoration/conservation and metal analysis, the pulsed laser-induced plasmas (LIPs) created as a result of laser irradiance is of a great importance. In this method a highly intense laser pulse interacts with a target material leading to the formation of a micro-plasma in nanosecond due to high intensity plume propagate. The initial part of the plasma is re-heated by the inverse bremsstrahlung (IB) absorption [2]. Dependence of the propagation and expansion behavior of the plasma on the laser pulse parameters is due to post-ablation interaction of the generated plasma plume [3].

In LIPS method, a micro-plasma is generated in nanosecond when highly intense laser pulse interacts with a target material; vaporization take place and thus plasma produced expand in the form of vapor plume. During the expansion process of vapor plume the Inverse Bremsstrahlung (IB) absorption also happened repeatedly which is considered as heat loss through plasma routine applications [4]. During ablation process, laser energy is used in dissipation into the sample target through heat conduction, melting and vaporization of the target material to create plasma plume [5]. In the process of pulsed laser ablation of solid target, highly energetic species are ejected from the target surface. The energy reaches up to several hundreds of eV. The ejected species compose a plasma plume. In the plume, the ablated species undergo various chemical reactions by themselves and also with ambient species. By using these species, thin films or fine particles can be obtained [6]. Laser-generated plasma characteristics are strongly dependent upon different key parameters, such that laser intensity, pulse duration and wavelength, target material and geometry, and the nature and pressure of any ambient gas [7,8]. The key parameters of laser ablated plumes are density and temperature. The characteristics of the plasma plume are controlled initially by electron contributions to temperature and density. There are various diagnostic techniques employed for the determination of these parameters including Langmuir probe, mass spectroscopy, optical emission spectroscopy, laser absorption spectroscopy, microwave interferometry, laser interferometry, Thomson scattering, laser-induced fluorescence, beam deflectometry, etc.[8,9]. Langmuir probes have been widely used to diagnose the low-temperature plasmas generated by laser ablation . These probes have been used to measure the plasma density and temperature, the plasma flow velocity and the shape of the ablation plume expansion [8,10]. The probe measurements are based on the I–V curve of a circuit consisting of metallic electrode that is immersed in the plasma under study . Electron density of laser-induced plasma can be computed by the relation given below:

$$n_e = I_0/Ae\sqrt{2\epsilon_0 kT_e} \qquad (1)$$

where “$I_0$” is probe current at zero biasing voltage ,‘‘A’’ is the area of the probe tip inside the plasma.
Debye’s length can be calculated by the formula:

$$\lambda_D = \sqrt{\epsilon_0 kT_e/e^2 n_e} \qquad (2)$$

Plasma frequency can be calculated as:

$$\omega_p = \sqrt{n_e e^2/\epsilon_0 m_e} \qquad (3)$$

where ‘$m_e$’’ is the mass of electron.

In this research some physical properties of $SiO_2$ laser induced plasma like electron density, plasma frequency and Debye length have been investigated as a function of vacuum pressure and Langmuir probe axial distance from the target surface [8].

## 2. Experimental

The target of the laser induced plasma (LIP) process was $SiO_2$ powder with purity 99.999%, and compressed under the pressure (10 tons) in order to make it shaped liked disc with a diameter of 3cm and then sintered in oven to temperature (500 $^oC$) for 2 hours. LIP experiment was achieved under vacuum pressure (0.1mbar by using Varian DS219 Rotary pump).The beam of Nd: YAG laser with fundamental harmonic frequency (λ=1064nm, 10ns, 6Hz) was focused onto $SiO_2$ target with quartz lens (f=10cm), the target was kept onto rotating motor (speed 4 rev/min) to prevent fast drilling. The cylindrical Langmuir probe distance from the target was fixed at 1cm. The LIP experiment was performed at room temperature. LIP setup scheme with the electric circuit of the Langmuir probe has been shown in Figure- 1. Electron density of the $SiO_2$ ablated atoms were calculated by analyzing the I-V data of the Langmuir probe. The $SiO_2$ target was ablated by 1000 pulses. The vacuum pressure was varied from (0.04-0.2) mbar, also the distances between the $SiO_2$ target and the tip of the Langmuir probe was changed from (0.5-1.5) cm to study their effects on the value of electron density hence on the plasma frequency and Debye length.

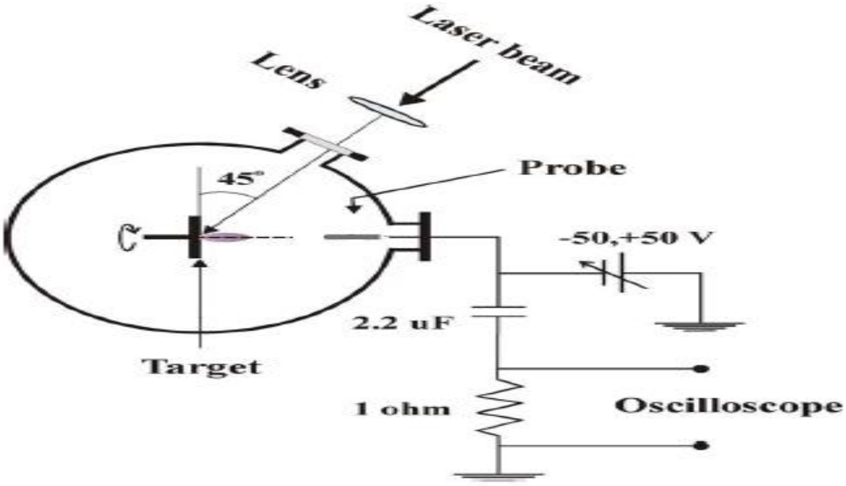

**Figure 1-** Schematic diagram of the LIP experimental setup .

## 3. Results and Discussion

Electron density in laser induced plasma depends strongly on the vacuum background pressure for $SiO_2$ target. In order to measure electron density ($n_e$) laser pulse energy has been set constant at 500mJ and vacuum pressure has been altered. Electron density has been calculated by using eq.(1) after getting $T_e$ values from I-V curve of Langmuir probe data as in Figure-2.

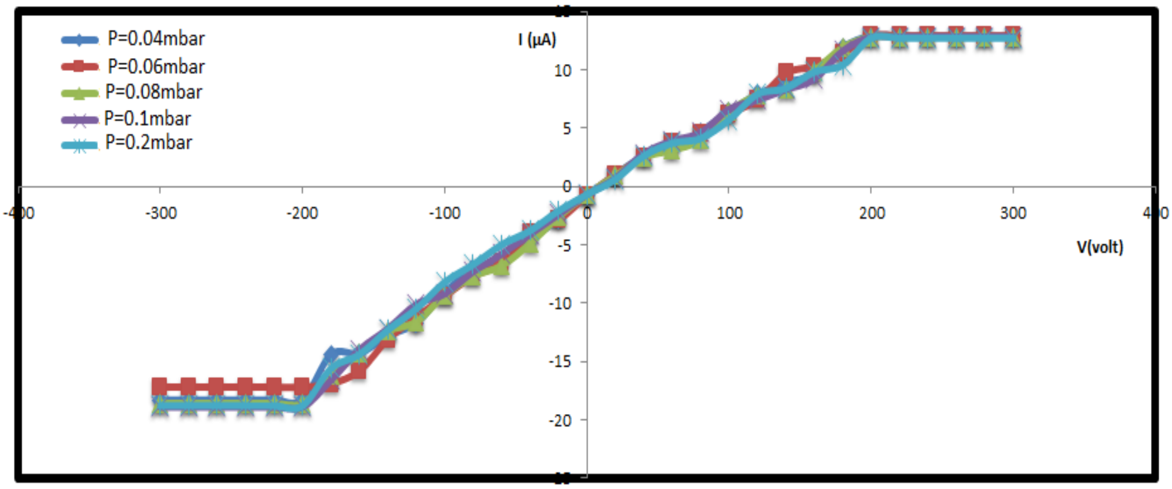

**Figure 2-** I-V chart of langmuir probe at different background vacuum pressure

The electron temperature $T_e$ can be obtained from the slopes of the electron saturation part of the I-V characteristic curve at different background vacuum pressure by using the relation $T_e$=1/Slope. Electron density $n_e$ against vacuum pressure ranged from $4x10^{-2}$ to $2x10^{-1}$ mbar using fundamental wavelength of Nd: YAG laser has been illustrated in Figure -3.

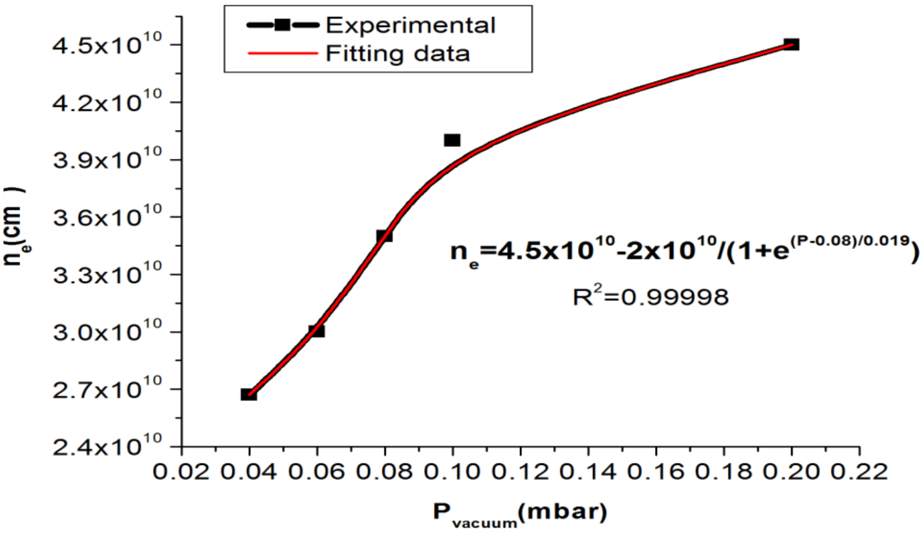

**Figure 3-** Electron density versus different vacuum pressure by using Nd:YAG laser wavelength 1064nm , laser pulse energy 500mJ.

Obviously from the Figure -3 that the electron density $n_e$ increases exponentially with increasing vacuum pressure. This is because of the increasing pressure will lead the plasma to be confined in small volume and hence increasing the collisions between the plasma species (electrons, ions, atoms and molecules), consequently the neutral atoms and molecules will be ionized by the liberated electrons and ions due to that collision and more electrons will be produced and there will be increment in their number and density. The curve fitting of the electron density as a function of vacuum pressure has been performed with fitting equation

$$n_e = 4.5x10^{10} - 2x10^{10}/(1 + e^{(P-0.08)/0.019})$$

Figure- 4 shows also the inverse relationship between the electron density and the axial distance from the $SiO_2$ target, it is noted that the experimental data coincide with the fitting data.

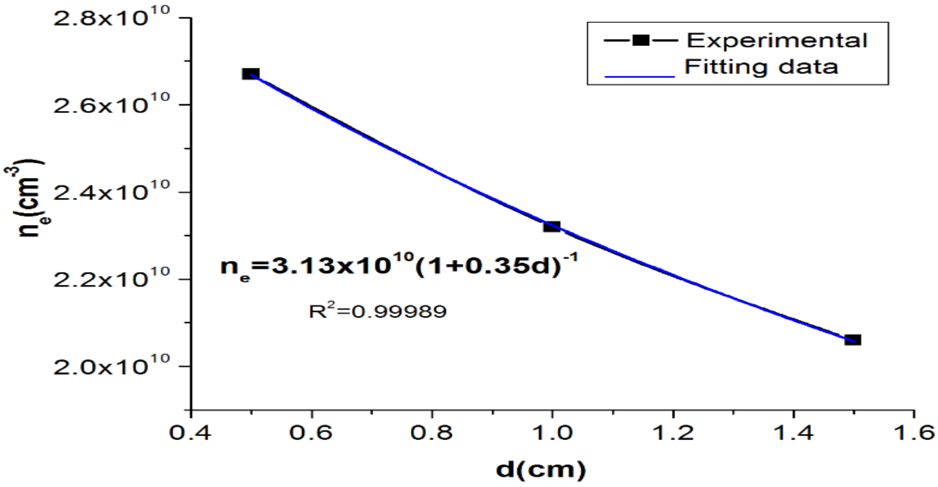

**Figure 4-** Electron density as a function of different axial distance from the target by using Nd:YAG laser wavelength 1064nm , laser pulse energy 500mJ

As the axial distance from the $SiO_2$ target surface increases the electron density decreases. When the axial distance from the target increases the plasma plume continue propagation and the recombination process between the ionized atoms and molecules with electrons happens at large distance to form a neutral atoms which leads to decrease number of free electrons hence decreasing the electron density (ion-electron recombination at large distances from the target surface), The curve fitting equation is

$$n_e = 3.31x10^{10}(1+0.35d)^{-1} \quad (4)$$

In Figures -5and 6 the relationship between Debye length and vacuum pressure and axial distance from target are shown respectively.

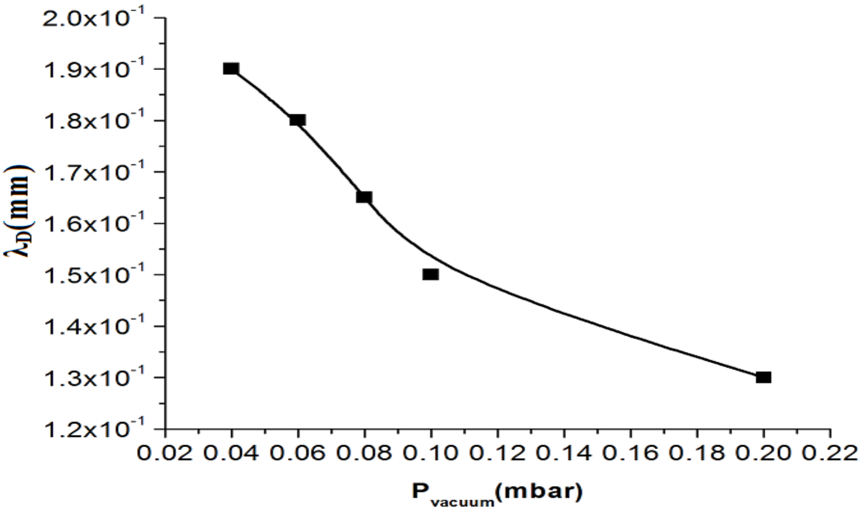

**Figure 5-** Debye length versus different vacuum pressure by using Nd:YAG laser wavelength 1064nm , laser pulse energy 500mJ.

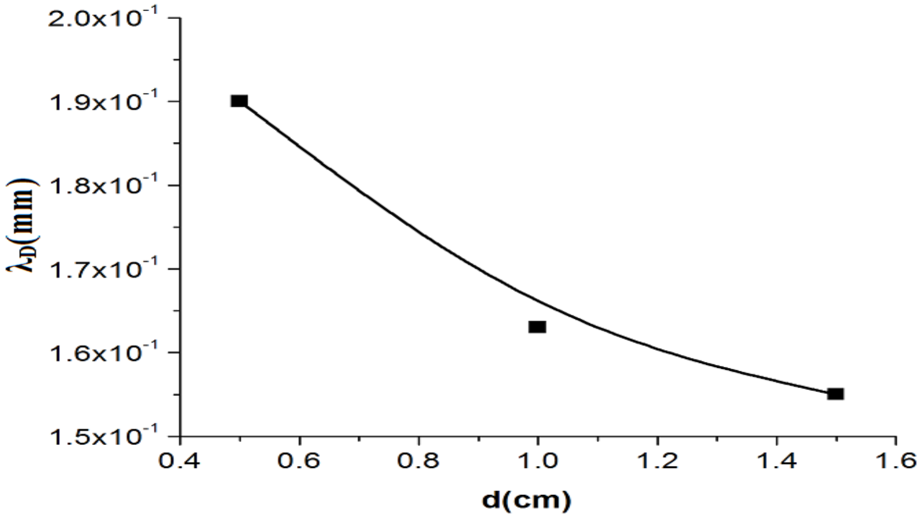

**Figure 6-** Debye length as a function of different axial distance from the target by using Nd:YAG laser wavelength 1064nm , laser pulse energy 500mJ

From the figures above, we observe that Debye length decreases with increasing both vacuum pressure and axial distance from the surface of $SiO_2$ target, and the reason for this is due to equation (2), in Figure-5 the reason of this behavior of Debye length versus vacuum pressure belongs to the inverse relationship between the Debye length with the electron density $n_e$. Since electron density is direct proportional with vacuum pressure so as a result, the Debye length decreases exponentially with vacuum pressure.The plasma frequency depends on both vacuum pressure and axial distance from the target surface as shown in Figures -7 and 8 below.

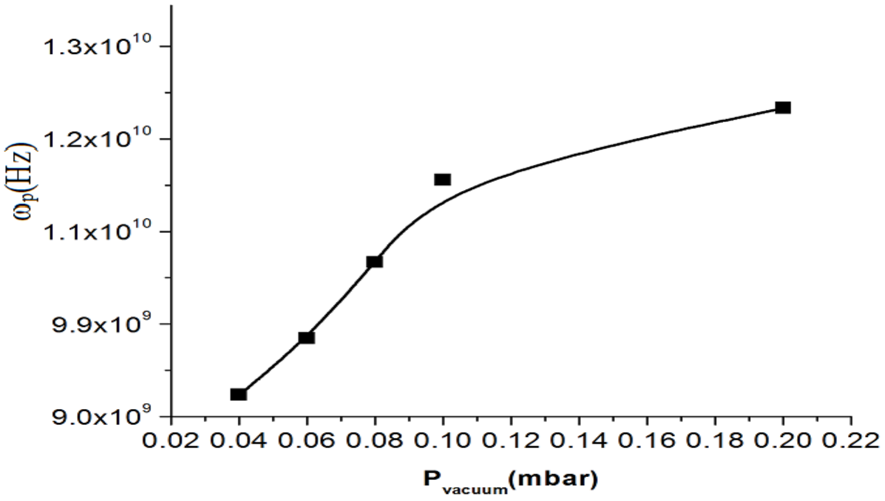

**Figure 7-** The variation of plasma frequency as a function of pressure at distance 0.5cm.

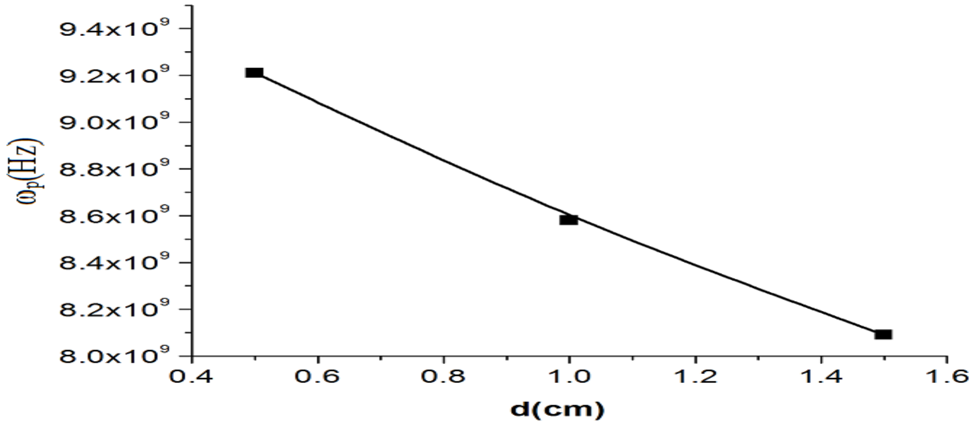

**Figure 8-** The variation of plasma frequency as a function of distance from the $SiO_2$ target at pressure 0.04mbar.

It is clear in Figure-7 that as vacuum pressure increase, the plasma frequency exponentially increases too because of dependence of the plasma frequency on electron density according to the equation (3), which is in turn depends on the pressure. So consequently the plasma frequency increases with increasing the pressure while in Figure- 8 the plasma frequency decreases linearly with the distance from the target because of the electron density is inversely proportional to the distance from the target surface (d) Therefore, the plasma frequency $\omega_p$ is inversely proportional to the distance from the target surface (d).

## 4. Conclusions

It has been concluded from the results that the electron density, Debye length and plasma frequency of laser induced plasma of $SiO_2$ target depend clearly on the LIP conditions such as vacuum pressure and axial distance from the target surface. The electron density increased exponentially with increasing vacuum pressure and decreased with increasing the distance from the $SiO_2$ target. This is due to the recombination processes of the constituents of plasma plume and confinement phenomena. Debye length is proportional inversely with both vacuum pressure and the axial distance from the target because of the dependence on the electron temperature. The plasma frequency is related directly with vacuum pressure and inversely with the distance from the target. This behavior of plasma frequency can be explained in term of the dependence on the electron density in the plasma plume of $SiO_2$ target.

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