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Impulse-coupling coefficients from a pulsed-laser ablation of semiconductor GaAs

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Abstract Impulse-coupling coefficients from 1.06-μm, 10-ns Nd:YAG pulsed-laser radiation to GaAs targets with different areas were measured using the ballistic pendulum method in the laser power density ranging from 4.0×10^8 to 5.0×10^9 W·cm^{-2}. A detonation wave model of the plasma was established theoretically. The expansion process of plasma after the laser pulse ends is described in detail, and the impulse-coupling coefficients from pulsed laser with different energies to GaAs with different areas were calculated using the given model. It is found that the theoretical results agree well with the experimental data.

Key words Laser-material interaction, Laser-supported detonation, Impulse coupling, GaAs

CLC numbers TN241, TN304. 2$^+$3

1 Introduction

When a pulsed-laser beam with sufficiently high power density is focused onto a solid surface, the area irradiated by the laser beam rapidly vaporizes, ionizes, and generates plasma [1]. The vaporized materials migrate from the surface and initiate a shock wave, then a laser-supported detonation (LSD) wave is ignited by either the breakdown of the vaporized material or the actual breakdown of the air above the surface [2, 3]. When the plasma apart from the surface and LSD waves propagate from the surface toward the laser source, a mechanical momentum that is much higher than the press induced by laser is transferred to the target. The impulse transformation is caused by the interaction between laser and the target. Many results [4, 5] have indicated that, in the interaction process, the impulse transferred to solid target is three to four orders of magnitude higher than the laser-induced press. The target surface will be destroyed severely when such high impulse is exerted on it. Conventionally, this interaction is described by the impulse-coupling coefficient, C_m, defined as the total impulse delivered to the target surface divided by the total energy of the laser pulse. Impulse coupling is an important aspect of the interaction process between the laser beam and target because it is one of the key destruction mechanisms of the target. Thus, measurement of the impulse coupling coefficient and modeling of the momentum transfer process are necessary. GaAs is an excellent material for infrared detectors and is widely used in many fields such as spaceflight, navigation, military affairs, and industry. So, it is important to study laser-GaAs impulse coupling process. In this article, the interest is focused on the impulse transfer to semiconductor GaAs under atmospheric background by a 10 ns, 1.06 μm pulsed-laser beam. The ballistic pendulum method was employed to measure the impulse coupling coefficients. On the basis of researches carried out by Pirri *et al.* [6] and Xu *et al.*[5], a novel model has been found to evaluate the total impulse-coupling coefficient in theory. The obtained results agree well

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with the experimental data.

2 Experimental measurement and results

The experimental setup for measuring the impulse-coupling coefficient is schematically shown in Fig. 1. The laser used in the experiment is a Quanta-Ray DCR-3 Nd:YAG laser operated in single TEM00 mode, and the laser pulse at 1.06 μm with a pulse duration of 10 ns (full width at half maximum) shows a typical Gaussian-like shape. The maximum output energy of a single pulse is 1 J. The energy of the laser pulse was measured using an OPHIR DGX-30A energy meter. The polished GaAs sample was stuck on the pendulum with a mass of 0.5 g. The laser pulse was focused onto the GaAs target surface by a quartz-focusing lens (f=6.3 cm). The spot size of the focused laser beam was 0.86 mm in diameter. When the laser pulse beam impinges on the target, the pendulum and the target move from their equilibrium positions. According to mechanical theory, the impulse delivered by the laser beam can be measured by $I = mx\sqrt{g/l}$, where m is the total mass of the pendulum including the mass of GaAs sample, x the shift distance from the equilibrium position, g the acceleration of gravity, and l the length of the pendulum. The impulse-coupling coefficient is given by $C_{\mathrm{m}} = I/E$, where E is the total energy of the laser pulse.

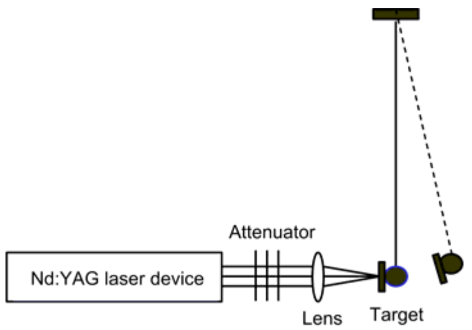

Fig. 1 Experimental setup used to measure impulse-coupling coefficients.

The obtained experimental results are shown in Fig. 2. Two kinds of target with the area of 7 mm× 7 mm and 4 mm×4 mm are used. It can be seen that the impulse-coupling coefficient does not change with the increase in the laser power density at low laser power density. When the laser power density is above 8.0×10^{8} W·cm^{-2}, the impulse-coupling coefficient decreases with the increase of the laser power density. By comparing the impulse-coupling coefficient obtained using different areas, it was found that the impulse-coupling coefficient is related to the area of target. Under the experimental condition, the impulse-coupling coefficient for a large area is greater than that for a small area.

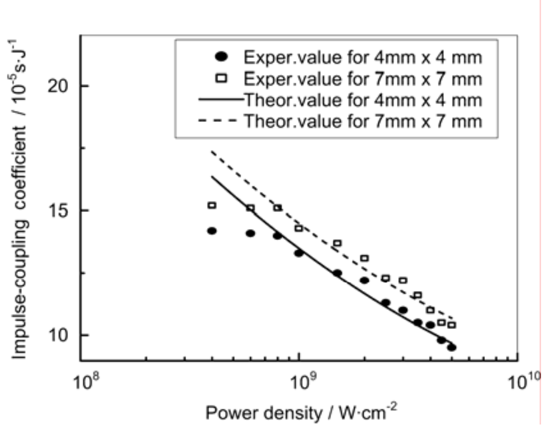

Fig. 2 Impulse-coupling coefficient versus power density of laser pulse. The hollow squares and solid circles are the experimental results for the targets of 7 mm×7 mm and 4 mm×4 mm, respectively. The dotted and solid lines are the corresponding theoretically calculated results.

3 Theoretical analyses

For calculating the impulse-coupling coefficient of interaction between laser pulse and GaAs sample in theory, the impulse transfer process is divided into three periods. The first period is from the initiation of vaporization of the GaAs material to the initiation of the LSD wave. The second is from the initiation of the LSD wave to the end of the LSD wave. The third is from the end of the LSD wave to the end of the expansion of plasma. After the third period, the pressure of plasma is equal to the background pressure.

A pure vaporization process is assumed in the first period. In this period, the momentum transferred to unit target area is as follows:

$$I_1 = \int_{\tau_{\mathrm{v}}}^{\tau_{\mathrm{LSD}}} P_{\mathrm{eff}}\,\mathrm{d}t = \int_{\tau_{\mathrm{v}}}^{\tau_{\mathrm{LSD}}} 0.5P_{\mathrm{v}}\,\mathrm{d}t \qquad (1)$$

where τ_{v} is the initiation time of vaporization of GaAs material, τ_{LSD} the initiation time of LSD wave, and P_{eff} the effective pressure exerted on the target surface by the vaporization wave. When the contribution to the flow of atoms that can condense on the surface is neglected, P_{eff} is equal to the half of the Clausius–Clapeyron vapor pressure P_{v}. So, for the first period, the impulse-coupling coefficient is

$$C_1 = \frac{I_1}{E} = \frac{1}{I_0\tau_{\text{P}}}\int_{\tau_{\text{v}}}^{\tau_{\text{LSD}}} 0.5P_{\text{v}}\,\mathrm{d}t \tag{2}$$

τ_{v} and P_{v} at temperature T can be obtained according to the models given by Xu *et al.* [5] and Xia *et al.* [7]. In calculation, the energy of evaporation per particle, the effective optical absorption rate of the target surface, the melting point, the normal boiling point at one atmosphere, the boiling heat and the latent heat of fusion, the thermal conductivity, and density of the GaAs material are used. The accurate initiation time of LSD wave is difficult to estimate. In this experiment, a photoelectric diode (YAG-200) and a storage oscilloscope (Tektronix TDS 620A) were used to detect the reflected laser pulse's shape. τ_{LSD} can be estimated according to the initiation time of the departure from the Gaussian shape. Obtained results show that τ_{LSD} decreases with the increase of the laser power density. For the laser power density used in the experiment, τ_{LSD} is about 4–6 ns. The influence of τ_{LSD} on the impulse-coupling coefficient is not great, so, $\tau_{\text{LSD}} = 5$ ns was used in this calculation. At the same time, the ignition threshold of the LSD wave is also obtained, which is around 7.0×10^{8} W·cm^{-2}.

The second period is the process of the formation and propagation of the LSD wave. It is assumed that the LSD wave disappears once the laser pulse ends. In this period, because the LSD wave already exists on the target surface, plasma absorbs the laser energy and considerably weakens the laser energy, thereby preventing its migration to the target surface. Therefore evaporation during this period can be neglected approximately. The impulse-coupling coefficient in this period is given by

$$C_2 = \frac{I_2}{E} = \frac{1}{I_0\tau_{\text{P}}}\int_{\tau_{\text{LSD}}}^{\tau_{\text{P}}} P_{\text{S}}\,\mathrm{d}t \tag{3}$$

where P_{S} is the pressure exerted on the target surface. According to the LSD model by Raizer [8], P_{S} can be expressed by

$$P_{\text{S}} = \frac{\rho_0}{\gamma+1}\left(\frac{\gamma+1}{2\gamma}\right)^{\frac{2\gamma}{(\gamma-1)}}\left[2(\gamma^2-1)\frac{I_0}{\rho_0}\right]^{2/3} \tag{4}$$

where γ is the ratio of specific heat of the background air and ρ_0 the density of the air.

The third period includes two parts differentiated by the time and the migration of the shock wave toward the edge of the target sample. The total impulse-coupling coefficient in the third period is given by

$$C_3 = \frac{I_3}{E} = \frac{1}{\pi R_0^{\,2} I_0\tau_{\text{P}}}\left(\int_0^R\int_{\tau_{\text{P}}}^{\tau_{\text{T}}} P_3(2\pi r)\,\mathrm{d}r\,\mathrm{d}t + \pi R_T^{\,2}\int_{\tau_{\text{T}}}^{\tau_0} P_3\,\mathrm{d}t\right) \tag{5}$$

where R_0 is the size of laser beam in radius, R the position of shock wave at anytime, R_{T} the sample's radius, τ_{T} the time for shock wave arriving at the edges of the sample, τ_0 the time for the plasma expanding up to a pressure that is equal to the background pressure, and P_3 the pressure exerted on the target surface during the third period. The duration in the third period is much longer as compared with those in the former two periods, and the pressure exerted on the surface decreases with the expansion of plasma. For calculating the pressure in this period, an expansion model of plasma was used. In the present model, it is assumed that the plasma, having a hemispherical shape, pushes and compresses the ambient air in front of it just as a piston, and almost all the ejected particles are concentrated near the boundary of the compressed air layer, the so-called contact front [9]. The density of this layer is [10]

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 \tag{6}$$

Using mass conservation condition $2\pi R^2\Delta r\rho_1 = \frac{2}{3}\pi R^3\rho_0$, the thickness of the layer is

$$\Delta r = \frac{R\rho_0}{3\rho_1} = \frac{R(\gamma-1)}{3(\gamma+1)} \tag{7}$$

For a strong shock, the pressure on the wave front, P_1 and the velocity of the ejected particle u_1 are given by [10]

$$P_1 = \frac{2}{\gamma+1}\rho_0 D^2 \tag{8}$$

$$u_1 = \frac{2}{\gamma+1}D \tag{9}$$

where $D = \mathrm{d}R/\mathrm{d}t$ is the velocity of the wave front. The pressure in the hemisphere (that is the pressure exerted on the target surface) is regarded approximately as uniform and is directly proportional to P_1, that is

$$P_3 = \alpha P_1 \tag{10}$$

Neglecting the effect of the atmosphere, the kinetic equation for the thin layer is:

$$\frac{\mathrm{d}}{\mathrm{d}t}(2\pi\rho_1 R^2 \Delta r u_1) = 2\pi R^2 P_3 \tag{11}$$

According to Eqs. (6)～(10), Eq. (11) becomes

$$R\frac{\mathrm{d}D}{\mathrm{d}R} + 3D(1-\alpha) = 0 \tag{12}$$

Integrating this equation,

$$D = cR^{-3(1-\alpha)} \tag{13}$$

where c is integral constant. Using energy conservation, the α and c values can be obtained, respectively, as given below:

$$\alpha = \frac{1}{2},$$

$$c = \left[\frac{3(\gamma-1)(\gamma+1)^2 E}{2\pi(3\gamma-1)\rho_0}\right]^{\frac{1}{2}} \tag{14}$$

The detailed resolving process can be found in Ref. [10].

By substituting $D = \mathrm{d}R/\mathrm{d}t$ for D in Eq. (13) and integrating both sides, R is obtained as a function of t:

$$R = [R_0^{5/2} + \frac{5}{2}c(t-\tau_{\mathrm{P}})]^{2/5} \tag{15}$$

Using Eqs. (8), (10), and (13), the pressure exerted on the target surface after the LSD wave ends is obtained as:

$$P_3 = \frac{\rho_0 c^2}{\gamma+1}R^{-3} \tag{16}$$

From Eq. (15), the time for the LSD wave arriving at the edge of the target sample is:

$$\tau_{\mathrm{T}} = \tau_{\mathrm{P}} + \frac{2}{5c}(R_{\mathrm{T}}^{5/2} - R_0^{5/2}) \tag{17}$$

From Eqs. (15) and (16), the total interaction time in the third period is:

$$\tau_0 = \frac{2}{5c}[(\frac{\gamma+1}{\rho_0 c^2}P_0)^{-5/6} - R_0^{5/2}] \tag{18}$$

where P_0 is the background pressure. Using Eqs. (15)~(18) to solve Eq. (5), the impulse-coupling coefficient in the third period can be obtained. The total impulse-coupling coefficient is equal to the sum of the three parts obtained in three periods, that is, $C = C_1 + C_2 + C_3$. The calculated results are shown in Fig. 2.

The calculated results shown in Fig. 2 indicate that the impulse-coupling coefficient is related to the size of the target, that is, it increases with the increase in the target's size. For two targets with different sizes, the calculated impulse-coupling coefficients using the proposed model agree well with the experimental result when the laser power density is above 8.0×10^8 W·cm^{-2}, that is, approximately equal to the ignition threshold of the LSD wave. However, at low laser power density, the calculated impulse-coupling coefficients are deviated from the measured values; the reason is that a LSD wave is difficult to ignite at low laser power density. The evaporation is the most important in the total process; so, the use of LSD wave in the second period results in a severe error. When laser power density is over 8.0×10^8 W·cm^{-2}, the LSD wave is ignited; at this moment, the plasma considerably absorbs the laser energy and weakens the laser energy, thereby preventing its migration to the target surface, and then reduces the impulse-coupling coefficient. It is obvious that the above-mentioned model is only suitable under the condition that the laser power density is greater than the ignition threshold of the LSD wave.

4 Conclusions

Impulse-coupling coefficients from 1.06 μm, 10 ns Nd:YAG pulsed-laser radiation to GaAs targets with different areas were measured using the ballistic pendulum method. The results show that the impulse-coupling coefficient remains almost unchangeable with an increasing laser power density at low laser power density. When the laser power density is above the ignition threshold of the LSD wave, the impulse-coupling coefficient decreases as the laser power density increases. In theory, a novel model was proposed to calculate the impulse-coupling coefficients; the calculated impulse-coupling coefficients from pulsed laser with different energies to GaAs with different areas agree well with the experimental values. In addition, the theory as well as the experiment proved that the impulse-coupling coefficient increases with the increase of the target's area.

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