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INTERACTION OF LASER RADIATION WITH SOLIDS -REVIEW ARTICLES

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ABSTRACT

A historical highlight to Laser acronym is given .Moreover, Laser heating effects induced in solid targets for one phase and multiphase cases are provided. Metallic and nonmetallic materials are highlighted. The effect of the temperature dependence of the front surface of the irradiated targets on the thermal response are considered. A bibliography of some fundamental papers published on the subject up to 2014 is presented.

Keywords: Laser heating of thin solid films, Laser-induced damage thresholds. Laser induced phase transitions, Laser cutting ,CW and pulsed laser sources, Laser processing of metallic and nonmetallic materials, Laser heating of finite and infinite slabs, Laser heating of monolayer and two-layer targets, Laser heating considering constant and temperature dependent surface thermal absorptance.

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Contribution/ Originality

This review highlights original mathematical trials to solve laser heating problems. The study considers laser induced phase transitions, multilayer systems and temperature dependence of surface absorptance. This study covers some semi-empirical expressions to predict the experimental laser pulses. This review documents the concept of "transit time" in laser heating problems.

1. INTRODUCTION

The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation. It also refers to the laser generator. Lasers have become a vitally important tool in contemporary research in different fields of science and technology. Lasers are also used extensively in everyday life, such as in optical communications and processing materials and for many types of measurements. Stimulated emission (a concept introduced by Einstein in 1916) produces a coherent light where multiplicity of photons, identical in frequency, phase and direction are obtained. The concept of stimulated emission contrasts sharply with the chaotic nature of light emitted from the traditional sources due to

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spontaneous emission. The coherence in laser light is responsible for its extra ordinary properties of narrow spectral line width (i.e. temporal coherence) and directionality (spatial coherence).

This coherence also allows laser light to be focused to a spot only a few wave lengths across [1] with high intensity that is useful in heating and cutting many different materials. It is worth to note that, the first use of stimulated emission to achieve a high brightness was in the microwave spectrum; historically the maser was developed several years before the laser.

In 1953 Gordon, et al. [2] demonstrated stimulated emission between the two lowest levels of ammonia molecule, giving a very narrow emission line at a wave length of 12-6 millimeters [1].

For this achievement,, Townes shared the 1964 noble Prize in Physics with N. Basov and A. Prokhorov of the USSR [1].

The first laser, originally called the optical maser followed in 1960, when T.H. Maiman produced red light at wave length 694.3 nm from the chromium ions Cr^{3+} in a ruby crystal.

2. LASER ACTION MECHANISM

Three components are needed [1] to realize laser action mechanism, which are:

i) An active laser (or gain) medium with suitable energy levels.

ii) The injection of energy so as to provide an excess of atoms in an excited state (population inversion condition).

iii) A resonator system (or cavity), in which multiple reflections allow the build- up of the coherent laser light. One of the resonator mirrors has a non-zero transmittance to allow the emission of laser beam through this end. It is worth to note that a Particular laser wavelength can be selected and obtained by a suitable choice of the resonator.

3. THE ADVANTAGES OF LASER BEAM WITH APPLICATIONS

Indeed the high power laser density up to 10^{22} W/m^2 [3] is one of the principal advantages of laser beam. Such high intensity means also high electric field intensities for which dielectrics may behave non-linearly producing effects such as the generation of shorter wavelength laser light at a harmonic of the laser frequency. In addition, such high intensity makes laser useful for a variety of material processing ,such as spot welding, scribing, drilling of holes, Laser cutting, Laser shock hardening and Laser glazing [4-12]. In the semiconductor industry it is useful to initiate local diffusion and alloying [13] to form p-n junctions. Laser pulses of moderate power are used in a variety of fields, for example, to alter thin films on low-conductivity substrates, especially for information recording [7, 14, 15]. The temperature gradients during re-solidification process induced by an incident CW Ar Laser beam is best utilized [16] to obtain complete single- crystalline Silicon films on SiO_2 insulators. Heating and phase changes such as melting and evaporation caused by a laser beam are of primary interest in many of the proposed laser applications, and have been the subject of many trials [17-55].The first serious consideration on the use of laser to produce a high-density, high-temperature plasma were presented by Basov and Krokhine [56]; Basov and Krokhine [57] and by Dawson [58] who considered the interaction of the laser radiation with a small solid hydrogen pellet. A bibliographical review [59] of papers is published on the subject of high power laser interaction with solids. A single femtosecond laser pulse interaction inside a bulk of transparent matter (sapphire, glass, and polymer) with formation of plasma is studied [60]. The plasma generates strong shock and rarefaction waves which result in the formation of a tiny void. To realize explosion effects within the medium, the laser beam must be focused into a volume less than λ^3 (where λ is the laser wavelength) using high numerical aperture optics. As a result, this technique [61-64] could be used for the formation of photonic crystals, waveguides and gratings for application in photonics.

4. REVIEW OF SOME LITERATURES ON LASER RADIATION INTERACTION WITH SOLIDS

A change of properties induced in a bulk solid by laser irradiation is studied [60]. This can be realized by two different ways [60].

First, through nondestructive and reversible phase transitions (photorefractive effect, color-centers, photo darkening in chalcogenide glasses, etc.) can be induced by lasers at intensity below the damage threshold.

Second, irreversible structural changes may be produced at high intensity above the optical breakdown threshold. Gamaly, et al. [60] performed experimental and theoretical studies of the latter case.

As a result, the possibility to create the extreme conditions (temperature rise rate $\approx 10^{18}$ K/s, pressure up to several T Pa, temperature $\approx 1000eV$) by a single laser pulse in controlled laboratory conditions has been demonstrated, opening a field for studying the extreme states of matter or unusual material transformations. This study has also applications in the photonics (three-dimensional optical memories and arrangements of waveguides).Indeed, the distinct physical processes in laser-solid interaction induced by the ultrafast time scale pulses open new routes of modifying the structure and morphology of materials in general and their surface in particular and offer interesting perspectives in laser material processing [61, 62]. The introduction of new solid state lasers and technological developments in multidimensional intensified detectors has made possible the seeking of new possibilities to exploit fully the analytical advantages of Laser-induced plasma spectroscopy [LIPS].

A review that outlines the fundamental principles of [LIPS] relevant to sample surface studies is given by Vadillo et al. [63]. This review discusses the experimental parameters governing its spatial resolution and presents the applications concerning surface examination.

The early analytical work for the temperature distribution in a semi-infinite solid with a moving heat source was introduced by Eager and Tsai [64] and Rosenthal [65]; Yilbas, et al. [66] on simulating the heating process with a moving laser heating source introduced a three-dimensional electron-kinetic theory approach. It is suggested that the moving source scans the irradiated surface at a constant speed. Moreover, the spatial distribution of the power intensity is considered. The model is based on the assumption that the energy gained by the electron due to the laser beam source is transferred to the phonons in the surface vicinity through successive electron-phonon collisions. As a result the energy of the phonons increases. The laser power intensity distribution is considered as Gaussian .The pulse length and the pulse power intensity of the laser beam is taken as 25 μs and $0.12x10^{10}$ W/m^2 respectively. The work piece is considered to move with constant speed $0.3 m/s.$ along the x-axis. CO_2 Laser cutting of medium-density. Fiberboard (MDF) is studied experimentally [67] to determine the process parameters and to achieve optimum cutting conditions. Continuous (CW) and pulse mode (PM) cutting and associated cut quality effects have been commented. This material is available in sheet form in varying thicknesses ranging from 3-60 mm. and is constructed from wood fibers held together by a synthetic resin binder. Pulsed lasers have been successfully applied for annealing of radiation damage associated with ion implantation during device fabrication by Bhattacharya and Streetman [20] who studied the dynamics of pulsed CO_2 laser annealing of ion implanted Si . Detailed calculations are obtained using the finite differences method. Calculations are based on a thermal melting model. The temperature dependencies of all pertinent material parameters are taken into account. The laser pulse in Bhattacharya and Streetman [20] is assumed to be Gaussian and so the time part of the source is given [20] in the form:

$$S(t) = \frac{1}{\sqrt{\pi}\ \Gamma} \exp\left[-\left(\frac{t - t'}{\Gamma} \right)^2 \right] \qquad (1)$$

Where Γ, is the parameter which determines the full width at half maximum (FWHM) and t' is the time when the pulse reaches its maximum value.

The spatial part of the source term is given by Bhattacharya and Streetman [20]:

$$S(x) = E\alpha(x)(1-R)\exp\left[-\int_0^\infty \alpha(x')dx' \right] \qquad (2)$$

Where "E" is the laser influence in Jm^{-2}, R is the reflectivity and α is the temperature dependent absorption coefficient. As a result of their trial, they provide values of laser influences or power densities required to melt a particular thickness for a laser pulse of 25 ns (FWHM).

El-Adawi et al. published a number of articles on laser heating and melting problem neglecting plasma formation at the irradiated surface. Their model is based on the assumption that the temperature attained by the irradiated surface is far from the level required to initiate plasma.

One of their earlier trials [68] covers the whole problem of heating, melting and evaporation induced by high power laser through a simple mathematical model, according to which the authors suggested a temperature profile as a solution to the parabolic heat conduction equation (PHCE). This suggestion is based on some physical considerations for the heating problem. No ablation for the molten layer is assumed. Applying the suitable boundary and initial conditions makes it possible to obtain the parameters of the given profile for the one and multi- phase stages. The same trend was considered later by Hassan, et al. [28] to study the general problem of laser heating. According to El-Adawi model [68] melting starts and continues along the solid thickness as soon as the surface temperature reaches the melting point. According to their model during the melting process (two phase problem), the molten layer temperature is kept constant at the phase change temperature, and while the temperature within the solid layer rises (the same assumption is considered for the evaporation regime). At the end of the melting process, the liquid surface temperature rises till it reaches the boiling temperature. As a result, they obtained the following expression for the surface temperature for the one phase heating stage [68]:

$$T_{os}(t) = \sqrt{\frac{2\alpha_s q^2 A^2 t}{\lambda_s^{\ 2}}} \qquad (3)$$

This relation is similar to that obtained through approximate mathematical treatments by Sparks and loh [18] except that $\sqrt{2}$ is $2/\sqrt{\pi}$ in Sparks and loh [18].

The thickness of the molten layer and the rate of melting and the time required to melt the considered solid phase are also obtained. Moreover, the liquid-vapor system is also studied in El-Niclawy, et al. [68]. The rate of vaporization and the threshold time required to initiate evaporation are also determined.

Besides, the threshold laser energy required to initiate evaporation is established. As a result authors [68] concluded from the obtained mathematical expressions that melting and evaporation processes each occur with constant rate.

The same heating problem is considered later by El-Adawi and El-Shehawey [23] on the assumption that a part of the incident laser flux will be reflected at the front surface of the irradiated slab and a part will be absorbed . The Fourier series expansion technique is applied to get the solution of the parabolic type of heat conduction equation (PHCE). Such an equation is first transformed into a non- homogeneous equation subjected to homogeneous boundary conditions encountered on the space variable. According to their model ,the heating problem is considered as a two stage problem ,one for intervals $0 \prec \tau \leq \tau_s$ and the second is for intervals $\tau \succ \tau_s$,where τ_s is the transit time, defined as the time taken for the excess temperature $\theta(= T - T_0)$ of the rear surface to change from zero and T_0 is the ambient temperature. The expressions for the temperature function of the front surface, and the temperature distribution within the irradiated target for both stages. In addition, the expression for the thermal penetration depth in the first stage is also obtained. A special case of constant irradiance is considered .For such a case, the model gives for the first stage $\delta(\tau) = \sqrt{6\alpha\tau}$ and thus the transit time τ_s is obtained by substituting the thickness ℓ for δ. The temperature of the front surface is obtained in the form:

$$\theta(0,\tau) = \sqrt{1.5}\ \frac{q_0(1-R)\sqrt{\tau}}{\sqrt{\lambda^2/\alpha}} \qquad (4),$$

From which one can obtain the critical time required to initiate melting. Where $\alpha = \lambda / \rho C_P$ is the thermal diffusivity of the slab material in terms of the thermal conductivity λ and the heat capacity per unit volume (ρC_P).

The authors [23] indicated that the obtained expression for $\theta(0,\tau)$ is the same as that obtained by Sparks and loh [18]. The model gives the front surface temperature for the case of thermally insulated rear surface in the form:

$$\vartheta(0,\tau) = [q_0(1-R)\tau / \rho C_P \ell] + [q_0(1-R)\ell / 3\lambda] \qquad (5)$$

The authors [23] indicated also that the first term on the right-hand side of this equation is exactly the asymptotic surface temperature obtained by Warren and Sparks [17] for the case of negligible surface cooling and constant laser flux. For intervals $0 \prec \tau \le \tau_s$ the problem is equivalent to the case of a thermally insulated slab. This result corresponds to the adiabatic limit referred to by Ghez and Laff [8].

[24] makes use of the temperature profile obtained with constant laser flux [23] to start studying the melting stage for the suggested slab and obtained an exact solution for time intervals less or equal to the transit time $(\tau_s = \ell^2 / 6\alpha)$. The integral form of the heat conduction equation and heat balance equation as a boundary condition at the interfacial surface between the liquid and solid phases are applied to get the required solutions. For simplicity, the authors assumed that :i) the thermal properties of the slab are temperature independent ii) The temperature in the molten layer is kept constant at the phase-change temperature T_m, by the passage of time ,the thickness of the molten layer increases, while the temperature distribution in the solid back layer rises gradually. Also the temperature at the interfacial surface between the two phases is kept constant at the phase-change temperature T_m. Expressions for the thickness of the molten layer and the rate of melting as functions of the exposure time are obtained. Both functions for constant flux density $(10^{14}\ \text{W/m}^2)$ for an

aluminum slab of thickness $(\ell = 3x10^{-4}\, m)$, are computed. The results show that the rate of melting is no longer constant but it increases gradually and then after a certain delay time it attains a constant value [9].

The same problem is studied by El-Adawi and Shalaby [25] for time intervals greater than the transit time. The same procedure as in El-Adawi [24] is accepted. Two cases are considered, one for which the slab target is thermally insulated at the rear surface, while the other case for targets with cooling at the rear surface.

The starting point to study the melting stage [25] is the temperature profile obtained by the same author for $\tau \succ \tau_s$ [23]. For such a case the critical time required to initiate melting is obtained [23] in the form :

$$\tau_{cr} = \left[\frac{\theta_m \ell \lambda}{q_0 (1-R)\alpha}\right] - \left(\ell^2 / 3\alpha\right) \ , \qquad (6)$$

Where, $\theta_m = (T_m - T_0)$, is the excess temperature for the phase change.

For the case when cooling takes place at the rear surface the following boundary condition is considered: $-\frac{\partial \theta}{\partial x} 1_{x=\ell} = h\theta(\ell, \tau) \quad (7)$,

Where, h is the heat transfer coefficient at the rear surface .

In both cases , the thickness of the molten layer and the rate of melting are expressed as a quadratic algebraic equation .Computations are carried out for an Aluminum slab with thickness $\ell = 10^{-3}\, m$, subjected to constant laser flux of irradiance $q_0 = 10^{11}$ W/m^2.

For the case, when cooling at the rear surface is present, two values for the heat transfer coefficient "h" are considered namely: $h = 50\ \text{W/m}^2 K$, and $\text{h} = 10^5\, \text{W/m}^2 K$.

Laser heating and melting of thin films with time-dependent absorptance $A(\tau) = (1 - R(\tau))$ are studied [26, 27] for two cases:

i) For time intervals less than or equal to the transit time [26]

ii) ii) For time intervals greater than the transit time [27] .

In such a case, the reflectance for silver is shown experimentally [18] to be in the form:

$$\begin{aligned} R(\tau) &= R_0 - \beta\tau \quad \text{for} \quad \tau \prec \tau_m \\ &= \text{R}_m = constant \quad \text{for } \tau \geq \tau_m \qquad (8) \end{aligned}$$

Authors [26, 27] treated the published curve for $R(\tau)$ of silver [69] and get the value ,

$\beta = 2.5x10^6$ s^{-1}

The obtained results reveal that the thickness of the molten layer and the rate of melting are no longer expressed in terms of a quadratic equation. They are expressed in terms of an algebraic equation of fourth degree. Moreover, the rate of melting is no longer of constant value. Computations for laser irradiance $q_0 = 9x10^{10}$ W/m^2 incident on a silver slab of thickness $\ell = 5x10^{-5} m$, are given.

Laser heating effects induced in a metallic finite slabs with constant thickness 5 micron and with constant surface absorptance are studied by El-adawi and Shalaby [70]. The targets are subjected to CW laser $(10^{12} W/m^2)$. Laplace integral transform technique are applied to solve the heat diffusion equation. The material of the slabs: Aluminum, Copper, Silver, and Gold. The critical time required to initiate damage (melting) for each target is computed. The dependence of the temperature profiles on the incident laser power density is revealed to be linear.

El-Adawi, et al. [31]; El-Adawi, et al. [71] studied laser heating problem considering the temperature dependent absorptance of the front surface of the irradiated slab. Such dependence is written in the form: $A = [A_1 + A_2 \, T_0(0,t)]$ (9).

They solved the heat diffusion equation using Laplace integral transform technique. Such a problem is more complicated than that for which the time dependence of the absorptance is considered, because the absorptance in such a case depends on the temperature of the irradiated front surface which is among the unknowns of the problem. Expressions for the temperature profile within the slab are obtained. Thus, the temperature of the front surface and the temperature of the rear surface are also obtained. Computations for four elements: Aluminum, Copper, Silver and Gold are given. Each slab target is of 5 μm thickness, subjected to laser of power density 10^{12} W/m^2. The critical time interval required to initiate melting for the four elements are obtained. Results reveal that the obtained temperature profiles are no longer linear functions of laser irradiance compared with the case of constant surface absorptance. Moreover it is concluded that such temperature dependence of the front surface absorptance is of predominant effect on the time interval required to initiate melting t_m and must be taken into consideration when estimating t_m ,though such factor is revealed to be less effective on t_m at higher values of laser irradiance.

Besides, computations revealed that cooling effects at boundary surfaces are of negligible influence. It is more detectable at the front surface than at the rear surface.

Laser heating of a two-layer system is studied by El-Adawi, et al. [29]; El-Adawi, et al. [30] .

Two cases are considered, one with constant surface absorptance the other with temperature dependent surface absorptance. Laplace integral transform method is applied to find the required solutions for a system of two heat diffusion equations, one for the front thin film and the other for the backward substrate. Suitable initial and boundary conditions are considered. One of which is of fourth kind at the interface between the front thin film and the substrate. The authors succeeded to overcome the difficulty of applying Laplace Integral transform for such a problem by suggesting two coincident coordinate systems normal to the irradiated free surface along the direction of the incident laser flux. The boundary x=o represents the front surface of the front thin film, while z=0 represents the interface between the two layers. The thin film layer is of thickness x=d. The materials of the thin film considered are aluminum, copper .silver, and gold (Al, Cu, Ag and Au) .The substrate is made of glass. Each system is subjected to laser irradiance $10^{12} W/m^2$,and the metal thickness is $5\mu m$ in all cases. The temperature profiles for the thin film and the substrate are obtained. The obtained expressions for such profiles reveal that they are linear functions of the absorbed heat power at the irradiated front surface. Moreover, the considered profiles also revealed that they are no longer linear functions of the thermal properties of materials constituting the two –layer system. It is worth to note that the computed results for t_m make it possible to decide whether damage can be initiated within one laser pulse duration or not. For the case when considering the temperature dependence of the optical absorptivity of the target lower values of the time intervals required to initiate damage (melting) are obtained.

[72] suggested a pulse shape in the form:

$$q(t) = \beta\, q_{max} \left(\frac{t}{t_d}\right)\left(1-\frac{t}{t_d}\right) \exp - B\left(\frac{t-t_0}{t_d}\right) \qquad (10),$$

Where, β and B are parameters. Considering the shape of the experimental pulse published by Ready [4] the authors [72] suggested some boundary conditions that make it possible to determine β and B in the form:

$$\beta = \frac{1}{\left(\frac{t_0}{t_d}\right)\left(1-\frac{t_0}{t_d}\right)} \quad , \quad B = \left(1 - \frac{2t_0}{t_d}\right) \qquad (11)$$

Where, t_0 is the time interval required to reach the maximum value q_{max} of the incident power density of the considered pulse, and t_d is the" pulse time duration". Fourier series expansion technique is considered in El-Adawi, et al. [72] to solve the problem.

Four metallic elements (Aluminum, Copper, Silver and Gold) and five semiconductors (Cadmium sulfide, Germanium, Silicon, Alpha beryllium, Silicon carbide) are studied .Moreover, five pulses with different characteristic parameters are considered. Computations revealed that the thermal response of the targets is highly affected by q_{max} and t_0 , while the pulse time duration is less effective in determining the critical time required to initiate melting t_m .The obtained temperature profiles depend linearly on q_{max} ,while their dependence on t_0 and t_d is not linear. Computations reveal also that the melting time intervals required to initiate damage increases `with t_0 at constant q_{max} and t_d .This result may be attributed to the fact that the rate of heating the target for pulses with larger values of t_0 is less than that for pulses with less values of t_0 along the period in which the power density of the pulse increases at constant q_{max} and t_d of the compared cases. Indeed the thermal inertia of the irradiated target ($\alpha = \lambda / \rho C_p$) plays an important role together with the rate of heating in determining the value of t_m .

Laplace integral transform method is used to study a similar problem [73] considering another shape for the suggested laser pulse in the form:

$$q(t) = q_{max} \left(\frac{t_d - t}{t_d - t_0} \right)^m \left(\frac{t}{t_0} \right) \qquad (12)$$

On considering an experimental pulse shape published elsewhere [4] "m" is revealed to be in the form :

$$m = \left(\frac{t_d}{t_o} - 1 \right), \qquad (13)$$

Laplace integral transform method is used to solve the heat diffusion equation.

In such an article, the authors took cooling conditions at the front and rear surfaces of the irradiated targets into considerations .Two elements are studied namely, Silicon and Germanium. The results of computations confirmed the previous conclusions [72] that is the pulse parameters of predominant effect in heating response are q_{max} and t_0 (*the time required* to reach q_{max}), while the pulse time duration is of less influence. Comparative study for the obtained computed values show that the time required to initiate melting (damage) in Silicon is greater than that for Germanium at the same operating conditions. The effect of (t_0) is clarified. This pulse parameter affects the shape of the pulse and it affects principally the rate of heating of the target during the growth of the pulse. Smaller values of t_0 with higher values of q_{max} means higher rates of heating. On the other hand the area under this part of the pulse shape is related to certain amount of absorbed energy. The parameter 'm" itself changes the shape of the pulse and hence changes the total area under the curve representing the pulse. This total area represents the total energy incident on the irradiated surface during the pulse time duration. The pulse after the time interval (t_0) starts to decay and the rate of heating decreases.

Laser heating and melting is considered by Abd El-Ghany [74]. Ready pulse [4] is approximated by him according to the following relations:

$$g(t) = \begin{cases} \left(\dfrac{(n+1)^{n+1}}{n^n}\right)\dfrac{t}{\delta t}\left(1 - \dfrac{t}{\delta t}\right)^n & \text{for } 0 \le t \le \delta t \\ 0 & \text{for } t = \delta t \end{cases} \quad (14)$$

Where,

δt , is the laser pulse duration. The best fitting with Ready published experimental pulse is obtained for n= 3. Such time-dependent laser profile is considered [74] to study laser melting of a finite Aluminum Slab. The two dimensional Laplace Transform Technique is applied to solve the heat diffusion equations written for the solid and molten layers. The temperature dependent absorption coefficient of the irradiated surface is taken into consideration. It is revealed that the thickness of the molten layer increases with the increase of the exposure time and it exhibits maxima. Cooling conditions play an important role in increasing and decreasing the molten layer thickness. Increasing the laser pulse duration results in increasing the thermal penetration depth. Three phase problem solid –liquid- vapor is considered by Abd El-Ghany [75]. The two dimensional integral transform technique is applied to get the solutions of the heat diffusion equation. Pulsed laser is considered. Aluminum finite slab is the target. All the parameters are assumed to be temperature independent except the absorption coefficient at the front irradiated surface. The dependence is taken as linear relation. It is proved that the evaporated thickness increases with the increase of the pulse duration and the laser power density. The obtained expressions for the thickness of the molten layer and that for the evaporated part are useful for practical applications.

Laser damage thresholds of optical coatings is studied by Ristau, et al. [76] where a brief review is given on selected fundamental damage mechanisms in thin films considering different operating conditions of modern laser systems . Currents results for optical coatings optimized for laser pulses in the fs-regime are discussed. Fundamental set-up for the measurement of laser induced damage thresholds [LIDT] are described in this article [76]. Selected examples for investigations in the power handling capability of optical coating are presented. An analytical expressions for the temperature rise in the center of the irradiated circular component with Gaussian beam profile is indicated. An elementary description of damage mechanisms in the ultra-short pulse region is discussed. The electron density in the conduction band of the dielectric material may be calculated on the basis of the rate equation for such function.

Laser – induced breakdown resulting in damage to optical materials is one of the confining factors in high- intensity laser system and it has aroused the interest of many investigators. The interaction between laser and optical material is a complex process. A theory based on the rate equation of free electron is used by Shang, et al. [77] to analyze the process of free electron multiplication in optical materials under laser irradiation. Investigation with SiO_2 is processed. High- intensity is considered. The dependence of laser induced damage threshold on avalanche ionization is also considered. The damage thresholds under different avalanche models are analyzed .The calculated results agree well with the experimental data. A perpendicular heat flow model is introduced by Weber, et al. [78] to study laser damage in carbon fiber reinforced plastics (CFRP). These materials are of the most important materials in automotive applications. The model describes the sublimation process providing one-dimensional analytical solution of the heat conduction equation. According to such model the optimum pulse parameters for a certain quality needs can be deduced. The maximum cutting speeds of CFRP is discussed and it is revealed to be limited by the average laser power. It is assumed in Weber, et al. [78] that the perpendicular heat flow solution might also be applied to laser processing of other flat inhomogeneous materials such as cutting of thin isolated coated metal plates.

A report is given by Fu, et al. [79] on an experimental investigation on laser induced damage behavior in Silicon-On-Insulator (SOI) material at room temperature for laser pulses with duration ranging from 190 picosecond to 1.14 s. Such material is widely recognized as a promising substrate material because it possesses considerable advantage as compared to bulk silicon. So it has found extensive applications in optoelectronics, such as optical waveguides, optical couplers and photonic crystals which have been widely implemented on SOI substrate. Such material is investigated [79] with 1064 nm laser pulses. Gaussian laser beam profile is assumed. The experimental results are fitted with a theoretical model. It is found that as the laser pulse duration is increased from 190 picosecond to 1.14 s the damage threshold of SOI material decreases from 1.3 10^{10} to 7.7 10^{3} W/cm^{2} in laser flux. It is found also that the damage threshold varies inversely as the pulse duration for a short irradiation time, and is independent of pulse duration for a long irradiation time. It is suggested that the obtained results on material damage can be used to predict the damage thresholds of SOI-based devices

Laser cutting is of great interest and has essential technological applications.

On the basis of theoretical predictions and experimental results [80] concluded that cutting of nonmetallic materials such as paper, plastic, wood, glass and rubber materials can be performed by a low power Nd:YAG laser . It is noticed that cutting depth does not increase linearly with the increase of laser input power. For deep cutting a laser of an extra power is required. It is shown that no significant effect of speed on cutting depth is noticed with the speed being larger than 30 mm/s.

The given analysis may provide a guideline for laser-based industry when it is necessary to select a suitable laser power for cutting, scribing, engraving and marking nonmetallic materials.

Bending of fibers creates mechanical stress inside the material. The influence of mechanical stress on nanosecond laser-induced damage threshold of fused silica is studied by Mann, et al. [81]. Indeed optical multimode fibers play a prominent role for the transfer of high power laser radiation in different fields like automotive, defense, aviation, medicine and industrial production. Therefore the breakdown behavior of those fibers is of permanent interest. Optical multimode fibers made of fused silica are widely used in such fields. In the work of Mann [81] fiber preform material F300 was loaded mechanically with pressures up to 220 M Pa representing 20% of the pressure resistance of fused silica. Bulk laser-induced damage thresholds (LIDT) were evaluated using a longitudinal multimode Q-switched Nd:YAG laser ((1064nm) at a pulse duration of 12ns with polarization states parallel and perpendicular to the stress direction. laser-induced damage thresholds (LIDT) of fused silica samples of fused silica samples of about 700 J/cm^2 were found. It also revealed that laser-induced damage thresholds did not show a dependence on mechanical pressure and polarization states. Laser induced damage and phase transition in a homogeneous slab of Slver Selenide material is studied by El-Adawi and Al-Fanakh [82]. This compound is of great technological importance as a promising thermoelectric power generator material [83]. This substance has two phases, a low temperature phase below 400K and was identified as β-phase with a structure of orthorhombic and a high temperature α -phase with body-centered-cubic (bcc) form. This substance shows a semiconducting nature up to 403K and then it shows a metallic nature with rise in temperature [84]. The parabolic heat diffusion equation for the considered problem is solved [82] using the Fourier series expansion technique to determine the critical time interval required to initiate damage(melting) at the front surface, and the time interval required to initiate to initiate phase transition for the considered slab . A laser pulse of Gaussian form is considered.

The laser induced damage property of oxyfluoride glasses irradiated by a 351nm laser has been investigated [85] experimentally. It is found that the variation of laser induced damage threshold ($LIDT_s$) in oxyfluoride glasses is associated with photoluminescence originated structural defects. Decrease of the photoluminescence intensity in an oxyfluoride glass could improve the (LIDT) of the material. It is found that the damage growth stops when laser fluence is below 70% of the (LIDT) of the material. The 351 nm (LIDT) of two oxyfluoride prepared glasses were found to be 9.0 J/cm^2 and 13.6 J/cm^2 by damage testing. The results of damage growth indicated that the growth in oxyfluoride glass is developed in the longitudinal direction of laser propagation. The laser-induced damage threshold for four crystals CaF_2, MgF_2, Al_2O_3 and Si O_2 and fused silica is measured by Zhen [86] using a triplet Nd:YAG laser system . The results obtained from the pure crystals are in accordance with their specific optical, mechanical and thermal properties. An empirical law based on Franz-Keldysh effect is applied to interpret the experimental results.

Interests in laser drilling have been escalated due to the growing number of scientific and manufacturing applications utilizing various kinds of high power laser. Laser drilling is a complicated process. Experiments alone are far insufficient from revealing the mechanism of the interaction between laser and materials. A (2D) model of long pulsed laser drilling process on aluminum is considered [87] on theoretical basis to simulate laser drilling process and the results are compared with the experimental data. The validity of the established model is verified. The mathematical formulation is based on the system of governing three equations: continuity, momentum, and energy equations. The thermal enthalpy-porosity method is also used to track the solid-liquid interface.

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