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A simple analytical method for the characterization of the melt region of a semiconductor under focused laser irradiation

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Abstract

A simple analytical approach, based on an energy balance equation, is introduced to describe the melt region of a semiconductor under a focused pulsed laser irradiation. In this model, an approximate analytical solution of the time-dependent hemispherical melt radius is calculated, and satisfactorily compared with experiments on silicon irradiated with a focused, 1 μs beam diameter, visible laser of a few watts with pulse widths of 0.03–10 μs.

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1. Introduction

Focusing an energetic pulsed laser on a material usually leads to a melt zone, whose dimensions and melt time depend on both the laser parameters and the materials properties [1]. In general, these heating and melting effects constitute a three-dimensional (3D) heat flow problem, usually solved numerically. An analytical solution, even approximate, is very interesting as one could more easily analyze the influences of the various physical parameters involved. Usually, in sub-nanosecond laser processing, the short thermal diffusion distances and the relatively large dimensions of the laser beam, compared to the melt depth, limit the lateral thermal gradients, thus essentially reducing the melt process to a 1D heat flow problem. Many authors have proposed analytical solutions in this case [2–4].

On the other hand, for a pulsed focused beam in the time range of nanoseconds or longer, with beam dimensions comparable to or smaller than the melt depth, the lateral heat flow is of the same order of magnitude as the perpendicular component and the 1D approximation is no longer valid. Non-linear boundary conditions arising from a moving solid–liquid interface, make exact analytical solutions of the 3D heat flow equation very difficult. In this paper, we present a simplified 3D model based on the energy balance equation, which leads to an estimate of the time-dependent melt dimension of a semiconductor irradiated by a focused laser beam. Results are satisfactorily compared with experimental results from atomic force microscopy (AFM) measurements on laser-irradiated silicon,

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as well as from laser-induced dopant diffusion in a silicon microdevice.

2. The model

Fig. 1 shows schematically the problem considered in this paper. The laser beam, with an intensity (in W/cm^2), is focused on a semiconductor at the focal plane:

$$I(r,t) = I_0(t)\exp\left(-\frac{r^2}{r_0^2}\right) \quad (1)$$

where r_0 is the $(1/e)$ radius and $I_0(t)$ the time-dependent intensity at $r = 0$. The total laser power (in W) is $P = \pi r_0^2 I_0$ and the laser fluence (in J/cm^2) is $\Phi_0 = I_0 t_p$ (at the most energetical point of the beam) for a rectangular pulse width of t_p. In this paper, we will consider that t_p is in the range $0.03\,\mu s \leq t_p \leq 10\,\mu s$. Approximation on the pulse heating source can be made by comparing the heat diffusion length $l = \sqrt{Dt}$ to the light absorption length α^{-1} and r_0. Since for most semiconductors, the thermal diffusivity is $D \approx 0.5\ cm^2/s$ at the melt temperature [1], l is in the range of 1–20 μm for the t_p values considered. For a focused spot of 1 μm, and for a typical band-to-band absorptivity of $10^{-5}\ cm^{-1}$, we can therefore approximate the laser irradiation as a quasi-point-source. Assuming furthermore, that the materials properties are isotropic, the melt region can be described by a hemisphere, as shown in Fig. 1. In this paper, we are therefore interested in describing $r(t)$.

Describing the melt region behavior requires writing the energy balance equation. In the framework of the Stefan problem [5], the energy density balance is evaluated at the moving liquid–solid interface r_m:

$$j_{in}\,dt = j_{out}\,dt + L\,dr \quad (2)$$

where L is the latent heat, $j_{in} = -\kappa_l(\partial T/\partial r)_{r_m}$ in the liquid phase, in the solid phase where κ_l and κ_s are the thermal conductivities of the liquid and solid, respectively. In the presence of strong convective flow as usually seen in laser-irradiated materials [1,6], we will assume that the total energy absorbed at the liquid surface is transported to the liquid–solid interface. Furthermore, we neglect the energy lost by the heated surface, as it can be estimated to represent less than 1% of the input energy. Consequently, the energy balance at the outer surface of the molten pool may be written as:

$$dE_{in} = j_{out}S\,dt + LS\,dr \quad (3)$$

where $S = 2\pi r^2$ is the surface of the hemisphere, and $dE_{in} = P(1 - R_l)\,dt$ is the energy released by the laser

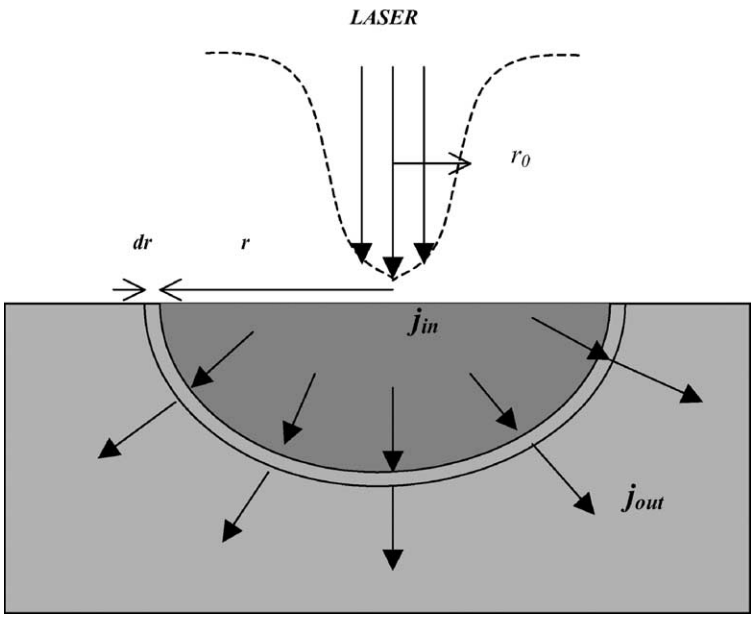

Fig. 1. Schematics showing the hemispherical melt region of a semiconductor irradiated by a focused laser beam.

during dt in a liquid semiconductor of reflectivity R_l. On right-hand side of Eq. (3), j_{out} is approximated by the linearization to $j_{out} = -\kappa_s(\partial T/\partial r)_{r_m} \approx (\kappa_s \Delta_m T/\xi\sqrt{Dt})$, where $\Delta_m T = T_m - T_\infty$ and T_∞ is the substrate temperature, D the thermal diffusivity in the solid at the fusion temperature T_m and ξ is a constant usually fixed at 1. With these approximations, Eq. (3) becomes:

$$P(1 - R_l)\,dt = \frac{\kappa_s \Delta_m T}{\xi\sqrt{Dt}} 2\pi r^2\,dt + L\,2\pi r^2\,dr \qquad (4)$$

Introducing the following dimensionless quantities

$$x = \frac{2\pi}{(1 - R_l)r_0} r, \qquad \tau = \frac{4\pi^2 D}{(1 - R_l)^2 r_0^2} t,$$

$$p = \frac{P}{DLr_0}$$

Eq. (4) can be rewritten in the equivalent form

$$x^2 \frac{dx}{d\tau} + Ax^2\tau^{-1/2} = p \qquad (5)$$

where we have introduced a dimensionless material-properties-only constant

$$A = \frac{\kappa_s \Delta_m T}{\xi DL} \qquad (6)$$

whose value is close to 1 for most semiconductors. Unfortunately, it seems that the ordinary differential equation (ODE) (5) does not have an *exact* analytical solution. A comprehensive study of Eq. (5) can be found in [7]. An analysis of the asymptotic behavior of $x(\tau)$ for $\tau \to \infty$ allowed to obtain the following approximate analytical solution, using the initial value $x(0) \approx 0$:

$$x(\tau, p) \approx \frac{2A^{1/4}p^{1/4}\tau^{3/8}}{\sqrt{1 + 4A^{3/2}p^{-1/2}\tau^{1/4}}} \qquad (7)$$

When compared with numerical solutions, it was found that the error of the approximation (7) is smaller than 3% for $t \geq 0.03$ µs.

3. Comparison with experimental results on silicon

To test the validity of our simplified approach, we performed experiments on silicon. For this semiconductor, A was found to be equal to 0.78 by using Eq. (6) and the following parameters: κ_s (1500 K) = 0.23 W/(cm K), D (1500 K) = 0.1 cm^2/s, $L = 4130$ J/cm^3,

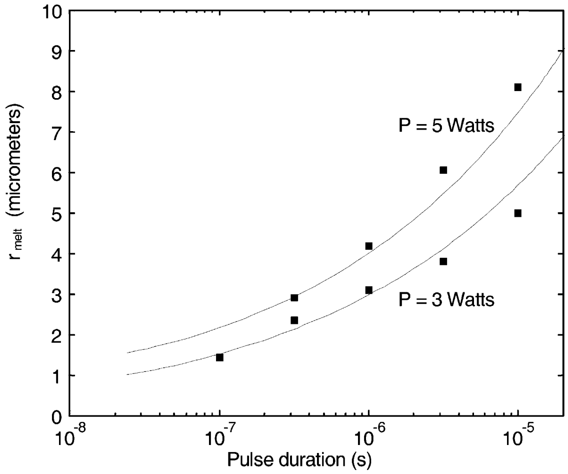

Fig. 2. Melt radius on silicon irradiated by a 532 nm laser source with $r_0 = 0.4$ µm. Measurements are from AFM and the lines are calculated using Eq. (7).

$\Delta T_m = 1400$ K and $\xi = 1$. Fig. 2 shows the melted radius as measured by AFM, when silicon is irradiated by a 532 nm laser source focused down to $r_0 = 0.4$ µm (1/e radius). The agreement between the analytical solution (Eq. (7) with $R_l = 0.7$) and the experimental results, for laser powers of 3 and 4 W, are very good.

In a second attempt to validate the simplified model, we performed laser melting experiments on a structure consisting of two highly doped n+ Si regions (5×10^{19} cm^{-3}) separated by a p-well of weakly doped Si having a 1.7 µm width (see the structure of the micro-device in Fig. 3a). The electrical circuit of this device has an infinite resistance due to the p-well.

However, by inducing dopants to diffuse from the n+ regions into the p-well, using a laser source, a link can be created [8]. The diffusion of dopants is effectively confined to the melt phase, giving an indication of the melt dimension. For example, the diffusion coefficient of arsenic in solid Si is around 10^{-11} cm^2/s near 1683 K, the melting temperature of Si, and 3×10^{-4} cm^2/s in the liquid phase [9]. The corresponding diffusion length is of the order of 0.06 nm in the solid phase versus 200 nm in the liquid phase for a typical laser pulse duration of 1 µs. For a reasonable temperature of molten Si ($T = 3000$ K), this diffusion length becomes close to 2 µm. Clearly, dopant diffusion is confined to the melt phase and, during the pulse period, the dopants have the time to diffuse almost uniformly in the melt region. By increasing the laser pulse duration, the radius

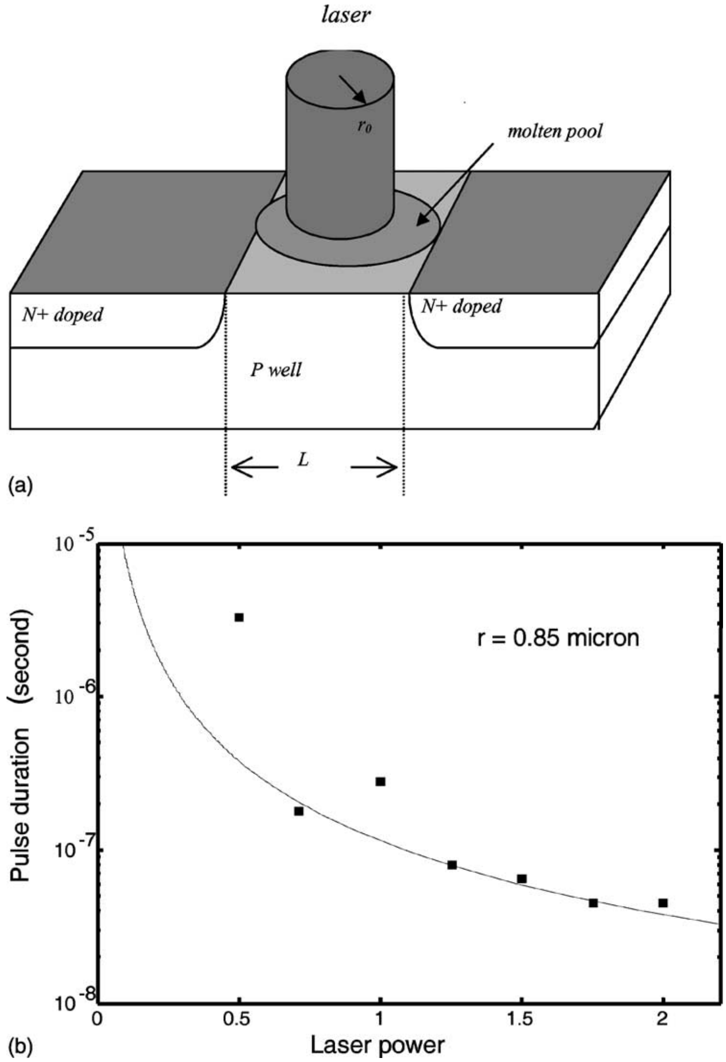

Fig. 3. (a) Schematics of the test microdevice consisting of two n+ doped regions separated by a fixed distance of 1.7 μm. (b) Minimum time and power to induce a dopant diffusion between the doped regions. The line corresponds to Eq. (8).

of the melt region can be increased up to the point that the melt phase reaches the two n+ regions, and dopants quickly diffuse into the center of the structure. For a given laser power, a minimum pulse width is required to diffuse a sufficient amount of dopants to produce a resistance. Fig. 3b shows experimental results to produce a resistance of a finite value (readable on the multimeter, i.e. between 10^7 and $10^8\ \Omega$) with only one laser pulse. Even at the shortest pulse duration of 0.07 μs (at few watts, Fig. 3), we estimate that this time is long enough to assure sufficient dopant diffusion leading to a finite resistance readable by the multimeter. For fixed values of τ and x, the corresponding power p can be obtained by solving Eq. (7) for p. The solution, which is the positive real root of a second order polynomial, is

$$p = \frac{x^2}{32A\tau^{3/2}}\left(32A^2\tau + x\left(x + \sqrt{x^2 + 64A^2\tau}\right)\right) \quad (8)$$

The agreement between the results and our calculation using Eq. (8) with $r_{\mathrm{melt}} = 0.85\ \mu\mathrm{m}$, is very good. Divergences at laser powers smaller than 0.5 W are probably due to the fact that the assumption of neglecting the temperature gradient term in the liquid in Eq. (3) is no longer valid.

4. Conclusion

A simplified method describing the melt region radius as a function of time of a semiconductor irradiated by a focused laser beam has been described. Eqs. (7) and (8) are satisfactorily compared with experiments on silicon, with the following laser beam parameters: a few watts over a 1 μm beam diameter with a pulse width of 0.03–10 μs.

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