3. Heating by Laser Light

Heat treatments serve a wide range of purposes in today’s material technology. Examples include softening or hardening of metals, “annealing” of crystals, dopant diffusion in semiconductors, compound formation in mixtures or thin-film couples, oxide-layer growth, polymerization of plastics and many others. The use of lasers as heat sources in place of furnaces is being adopted or explored in a growing number of heat-treatment processes. What advantages do lasers have to recommend them for the job?

The main advantage, obviously, is that heating can be done in a localized mode, both in space and in time. By matching the wavelength and the beam power to the optical and thermal material properties, the amount of heating can be chosen accurately to suit the needs of a process. If surface heating is required and/or volume heating is to be avoided, a large absorption coefficient and a short interaction time can be selected. Sharply delimited areas can be heated to high temperature while the remainder of the workpiece stays virtually cold. Rapid cooling of the heated material can be achieved by using short pulses or rapidly moving beams. Apart from localization, laser beams are chemically “pure” and free of inertia, can be moved easily and passed through windows to reach remote or inaccessible parts of a workpiece.

This chapter presents fundamental facts and current examples of laser solid-state thermal processing. Beam powers and pulse energies are generally moderate in this regime. The only effect of the irradiation is to raise the temperature of the material, which then reacts according to its own laws. Before discussing specific processes, we devote a section to the calculation of temperature distributions in the solid (excluding latent heat effects) for a variety of irradiation conditions and material responses.

3.1 Temperature Distributions

3.1.1 Thermalization and Heat Transport

The primary product of absorbed laser light is, strictly speaking, not heat but particle excess energy – excitation energy of bound electrons, kinetic energy of free electrons, perhaps excess phonons. The partition of the ab-
sorbed energy among the degrees of freedom of the material is not thermal at first. The degradation of the ordered and localized primary excitation energy into uniform heat involves three steps. The first step is spatial and temporal randomization of the motion of excited particles, proceeding with the collision time (i.e., momentum relaxation time) of the particles in question. This time is shorter than even the shortest laser pulses, perhaps shorter than an optical cycle. The next step, energy equipartition, tends to involve a large number of elementary collisions and intermediate states, notably in nonmetals. Several energy transfer mechanisms may be involved, each with its own characteristic time constant. For example, hot carriers in nonmetals lose energy first by phonon emission in the conduction band (Fig. 2.8), and subsequently with a different time constant upon recombination. Nonthermal phonon populations may be created in the process, which decay with yet another time constant. Energy equipartition is particularly slow in dielectrics and organic polymers. Intense optical excitation of such materials by UV lasers has been found to result in photodesorption of molecules without a significant temperature rise [3.1].

To describe thermal effects one usually ignores the intricacies of elementary relaxation channels and characterizes equipartition by an overall energy relaxation time \( \tau_E \), as was done in (2.41). Typical orders of magnitude for \( \tau_E \) are \( 10^{-13} \) s in metals and between \( 10^{-12} \) and perhaps \( 10^{-6} \) s in nonmetals, depending on the material and on the irradiance. In semiconductors energy can be transported by hot carriers before it is given to the lattice (Sect. 2.2.3). This will be relevant whenever the carrier lifetime is not negligible compared to the laser-pulse duration.

The last step is heat flow. Once the laser energy is converted to heat it still tends to be highly localized on a macroscopic scale. The mathematical theory of heat conduction is based on the assumption that the heat flux across a plane in a solid is proportional to the local temperature gradient

\[ \Phi(z_0) = -K \left( \frac{dT}{dz} \right)_{z_0} \]  

(3.1)

where \( K \) is the thermal conductivity of the material. Accepting this for the moment, we can express the energy balance of a slab of material bounded by planes at \( z \) and \( z + \Delta z \) in terms of its volumetric heat capacity \( c_p / V \)

\[ \Delta t [\Phi(z) - \Phi(z + \Delta z)] = \Delta T \frac{c_p}{V} \Delta z. \]  

(3.2)

Here \( \Delta T \) is the change in temperature brought about by a net heat flux across the boundaries. Letting \( \Delta z \to 0 \), the bracketted term on the Left-Hand Side (LHS) can be expressed as \( (\partial \Phi / \partial z) \Delta z \). Replacing the finite differences by differentials and using (3.1) then yields