Laser cooling in semiconductors

The recent advances in the development and fabrication of semiconductor lasers have stimulated growing interest in semiconductors as candidates for optical cooling. The essential difference between semiconductors and rare-earth (RE) doped materials is in their cooling cycles. In the case of RE-doped glasses or crystals, the cooling transition occurs in localized donor ions within the host. In the case of semiconductors, the cooling cycle involves transition between extended valence and conduction bands of a direct band gap semiconductor (Fig.1). Laser photons with energy $h\nu_p$ create a cold distribution of electron-hole carriers. As a result of subsequent thermalization, electrons and holes become redistributed among the system’s excited states by interacting with the phonons. The charge carriers then recombine by luminescent. Indistinguishable

charge carriers in Fermi-Dirac distributions allow semiconductors to be cooled to lower temperatures than RE-doped materials. Indeed the highest energy levels of the ground manifold in the RE-doped systems become less populated as soon as the temperature is lowered, due to Boltzmann distribution. As noted above, the cooling cycle in RE-doped hosts ceases, when the Boltzmann constant times the lattice temperature, $k_B T$, becomes comparable to the width of the ground state. No such limitation exists in undoped semiconductors. Following theoretical estimations, temperatures as low as 10 K may be achieved in laser cooled undoped direct-bandgap semiconductors (Rupper et al. 2006). An optical refrigerator based on a semiconductor can be easily integrated with electronic and optical devices.

History of optical refrigeration in semiconductors

The foundations of optical refrigeration in semiconductors based on a rate-equation theory, in which the effects of nonradiative, radiative and Auger recombination are taken into account, were presented by Oraevsky (Oraevsky 1996); Gauck and colleagues (Gauck et al. 1997). In 1997, Rivlin and Zadernovsly developed an energy balance theory for semiconductors (Rivlin & Zadernovsly 1997). In the work of Rivlin and Zadernovsly the possibility of excitonic luminescence in the limit of vanishing electron-hole pair density is taken into account, but not excitonic absorption. In 2004, Sheik-
Bahae and Epstein (Sheik-Bahae & Epstein 2004) extended a rate-equation theory to analyze the laser cooling of bulk GaAs based on a microscopic theory for the luminescence and absorption spectra. The effect of luminescence reabsorption was taken into account. The main feature of the rate-equation approach is simplicity, but these early theories neglected the change of carrier distributions with temperature and are valid only for a small change in the temperature. Comprehensive theoretical studies of laser cooling of semiconductors have been carried out by a research team at Kirkland Air Force Base (Huang et al. 2004 & 2005; Apostolova et al. 2005). The change in the carrier distribution with temperature as well as temperature diffusion of phonons has been calculated. It has been shown that the lattice and the carriers can have different temperatures varying in space and time. They have suggested multiphoton excitation for pumping wide-band-gap semiconductors (Apostolova et al. 2005). Following their theoretical estimations, the linear excitation scheme seems more favorable for laser cooling. However, nonlinear excitation allows one to use a different range of photon energies for achieving laser cooling of wide-band-gap semiconductor. The best cooling effect can be reached in wide-bandgap semiconductors under near band-edge interband pumping by a weak field (Huang et al. 2004). In 2005, a four-step model for spatially selective laser cooling of carriers in undoped semiconductor AlGaAs/GaAs/AlGaAs quantum wells was developed (Huang et al. 2005). In 2007, Li developed a cooling theory for semiconductor quantum wells at the Hartree-Fock level (Li 2007). Any indications that quantum wells are better suited to optical refrigeration than bulk semiconductors are not found under the assumption of quasi-thermal equilibrium. To enhance the cooling efficiency Khurgin has proposed the use of surface plasmons on a metal surface close to the semiconductor (Khurgin 2007). Actual samples used in experiments are doped, often unintentionally. Rupper and colleagues (Rupper et al. 2008) who investigated the influence of impurities on the cooling process, found that the additional low-frequency fluorescence and absorption channel (acceptors are also considered) does not significantly deteriorate the cooling process until concentrations exceed $3 \times 10^{16}$ cm$^{-3}$. Heavily doped semiconductors have been investigated by Eliseev (Eliseev 2008), who showed that the minimum obtainable temperature in such kind of semiconductors is about 60-120K depending on the doping concentration.

**Experimental prospects for laser cooling in semiconductors**

Experimental investigation of laser cooling in semiconductors has been discussed in a number of papers (Gauck et al. 1997, Finkeissen et al. 1999, and Eshlaghi et al. 2008). In the first work (Gauck et al. 1997), an external quantum efficiency as high as 96% was achieved, but no net cooling was observed. Later, a local cooling in AlGaAs quantum wells was reported (Finkeissen et al. 1999). Later these results were considered as misinterpretation of spectra caused by Coulomb screening of the excitons (Hasselbeck et al. 2007). Although semiconductors are very promising materials for laser cooling of solids and their external quantum efficiency increases with decreasing temperature there are a number of problems, which have to be solved on a way to net cooling of semiconductors. First of all the surface recombination rate has to be reduced. Well developed epitaxial growth technique such as metal organic chemical vapor deposition
(MOCVD), which can provide very low surface recombination rates (A < 10^4 sec^{-1}) can be considered as a promising solution to the problem. In this case a GaAs active layer is sandwiched between two thin layers of AlGaAs or InGaP. These lattice-matched cladding layers (AlGaAs or InGaP) provide surface passivation and carrier confinement. At the same time, the extraction luminescence efficiency has to be enhanced and the background absorption has to be reduced tremendously. The background absorption can be reduced during material preparation with well-developed epitaxial methods. The extraction efficiency can be enhanced if the total internal reflection, which causes trapping and re-absorption of spontaneous emission, can be prevented. Index matched dome lenses can be recommended as a solution to this problem (Gauck et al. 1997). At the present time the purity of the samples is the main obstacle to achieving net laser cooling in semiconductors. A very promising method based on frustrated total internal reflection across a vacuum “nano-gap”, where the cooling heterostructure and luminescence absorber are optically contacted but thermally insulated is presented in the papers (Epstein et al. 2002, and Martin et al. 2007).

In 2013, the first laser cooling of semiconductor using group II-VI cadmium sulphide (CdS) nanobelts starting from 290K was announced (Zhang et al. 2013). The pump laser with a wavelength of 514 nanometres was used. An estimated cooling efficiency of about 1.3 per cent and an estimated cooling power of 180 microwatts were achieved. Nowadays laser cooling of semiconducor nanobelts is one of the most promising approaches to laser cooling of semiconductors.

References


