Literature Review of Laser Cooling of Semiconductors—C.E. Mungan, Summer 2017

<u>Overview</u>

While direct-bandgap semiconductors such as GaAs have yet to show net cooling of bulk samples, overall reduced heating and localized cooling have been observed. Optical cooling of indirect-bandgap materials such as Si is unlikely, although anti-Stokes Raman scattering (rather than direct absorption) of pump laser photons may enable refrigeration if it can be made to dominate over competing optical processes. The only semiconductor which has shown significant laser cooling is nanometer ribbons of CdS, in contrast to the cryogenic temperature drops exhibited by bulk rare-earth-doped crystals. Key obstacles for semiconductor refrigeration include their high refractive index, surface recombination, Auger decay, and parasitic background absorption. There have also been efforts to obtain photoluminescent cooling of quantum dots and electroluminescent cooling of light-emitting diodes (LEDs). Theoretical modeling has emphasized the importance of exciton-phonon coupling, while experimentation has focused on the measurement of the external quantum efficiency and on developing sensitive noncontact probes of the localized sample temperature.

<u>Articles of main interest</u>

I.H. Nia, M. Rezaei, R. Brown, S.J. Jang, A. Turay, V. Fathipour, and H. Mohseni, "Efficient luminescence extraction strategies and antireflective coatings to enhance optical refrigeration of semiconductors," J. Lumin. ***170****, 841–854 (2016).*

Most semiconductors have large indices of refraction, as approximated in the following table at optical wavelengths below the bandgap (relevant for laser cooling) at room temperature.

Material	Refractive Index
Si	3.42
Ge	4.00
GaAs	3.30
AlAs	2.87
InAs	3.42
InP	3.08
InSb	3.95
GaP	2.90
GaInP	3.21
ZnS	2.20
ZnSe	2.41
ZnTe	2.64
CdTe	2.68
CdS	2.23
PbS	3.68
PbTe	5.66
GaN	2.38
AlN	2.17
InN	3.12
PbSe	4.75

Consequently, fluorescence emitted inside a bulk semiconductor has a small critical angle for escape into air (or vacuum). The anti-Stokes photons thus tend to be trapped inside the material, rattling around by internal reflection off the surfaces until the light is absorbed at some nonradiative center that generates unwanted heat.

This article considers the pros and cons of a number of methods to enhance the light extraction, briefly summarized as follows.

1. Make the dimensions of the active material smaller than the luminescence wavelength, so that the electromagnetic field modes leak out of it, thereby reducing the effective index. This idea is one of the keys to the successful laser cooling of sub-100-nm-wide CdS nanobelts. It also would work for quantum dots. However, two important disadvantages are that the mass and hence the cooling power of these materials are small, and the surface-to-volume ratio is large such that surface states (due for example to dangling bonds) can dominate their optical properties.

2. Use thin-slab or fiber waveguides engineered as photonic crystals designed to suppress radiation transport at the heating wavelengths and enhance transmission at the cooling wavelengths. The fabrication can be done by direct deposition of alternate chemical layers, by etching gratings into the slabs, or by drawing optical fibers with a pattern of cylindrical holes across their cross section. Problems with these methods include the accuracy with which the necessary structures need to be prepared, and the possible reduction of the in-coupling of the pump laser light and of the overall radiative decay rate.

3. Deposit antireflective coatings on the surfaces or vary the material composition to gradually reduce the index. For example, silicon oxide, subwavelength pores, or the creation of nanorod surface structures could do the trick. However, these methods are in general both angle- and wavelength-dependent, and may make the samples more fragile and susceptible to scratches.

4. A hemispherical dome lens can be attached to a cooling sample of much smaller diameter, where the two materials are approximately index matched. If the sample is positioned near the spherical center of the dome lens, then any emitted photons will couple into the lens and hit its spherical surface nearly perpendicularly so that they can escape. The same principle is used to encapsulate LEDs at the center of a plastic hemisphere and increase the photon escape efficiency. The disadvantages of this method are that the dome lens is cumbersome, and because it is in direct contact with the cooling material it has to be cooled which adds a great deal of thermal mass to the refrigerator.

5. If a second surface is brought less than 100 nm away from an emitting surface, then electromagnetic energy can evanescently couple across that nanogap. At the same time, the hope is that maintaining a vacuum gap would prevent thermal conduction between the surfaces. To actually manufacture such a structure, small standoff pillars are used to separate the two surfaces. However, this idea does not work in practice because the small gap enhances not only the transmission of the fluorescence light but also of the thermal photons that are responsible for radiative heating.

J. Zhang, D. Li, R. Chen, and Q. Xiong, "Laser cooling of a semiconductor by 40 kelvin," Nature ***493****, 504–508 (2013).*

This letter reports the first observation of net optical cooling of a semiconductor, namely nanoribbons of CdS that are approximately 100 nm thick, 2 µm wide, and 10 µm long. Strong coupling between excitons (bound electron-hole pairs which behave like hydrogen atoms) and longitudinal optical (LO) phonons is believed to be responsible for the success. Enhanced coupling is expected for more polar II-VI compounds (such as CdS) compared to III-V materials (such as GaAs), which bodes favorably for investigation of quantum dots of CdSe, PbS, PbSe, or CdTe. Weak Auger recombination (which competes with radiative relaxation of the excited electrons) is also expected in these high-bandgap materials. Finally, many of them have comparatively low refractive indices which improves the photon escape probability.

Starting at 290 K leads to a temperature drop of 40 K for CdS nanobelts laser pumped at a wavelength of 514 nm with a cooling efficiency of 1.3%, whereas starting at 100 K results in a temperature drop of 15 K when pumped at 532 nm with 2.0% efficiency. The belts are stretched across holes in a silicon substrate through which the pump laser is directed. (Reabsorption of the fluoresence is minimal due to the small distance an internally emitted photon has to travel to reach the sample surface.) The exciton-phonon coupling strength is enhanced by the nanoscale size of the ribbons, leading to the annihilation of several LO phonons per laser photon absorbed and thereby increasing the cooling. The successful cooling is also due in part to the low carrier mobility of CdS which results in a reduced surface recombination rate.

D. Huang, T. Apostolova, P.M. Alsing, and D.A. Cardimoma, "Theoretical study of laser cooling of a semiconductor," Phys. Rev. B ***70****, 033203:1–4 (2004). Also see T. Apostolova, D. Huang, P.M. Alsing, and D.A. Cardimoma, "Comparison of laser cooling of the lattice of wide-bandgap semiconductors using nonlinear or linear optical excitations," Phys. Rev. A* ***71****, 013810:1–6 (2005.)*

Rather than using rate equations, a nonlocal model is developed in these articles that depends on the changes in the carrier distribution during the laser cooling process, with separate accounting of the temperatures of the excited electrons and of the lattice. The wide- bandgap material AlGaN is specifically considered. To avoid having to use a UV pump laser, multiphoton excitation is (unrealistically) proposed.

G. Sun, R. Chen, Y.J. Ding, and J.B. Khurgin, "Upconversion due to optical-phonon-assisted anti-Stokes photoluminescence in bulk GaN," ACS Photonics ***2****, 628–632 (2015). Also see S.K. Tripathy, Y.J. Ding, and J.B. Khurgin, "Anti-Stokes photoluminescence in GaN single crystals and heterostructures," Proc. SPIE* ***7228****, 07:1–7 (2009).*

These articles experimentally investigate the potential cooling of another wide-bandgap polar III-V semiconductor, namely GaN grown as a free-standing wafer by chemical vapor deposition and laser pumped in the near UV between 4 and 300 K. Gallium nitride has a particularly large

LO phonon energy, which is advantageous for laser cooling. Phonon-assisted anti-Stokes fluorescence is observed, but its quantum efficiency (i.e., the fraction of the relaxations that are radiative rather than nonradiative) is not high enough to drive net cooling.

G. Rupper, N.H. Kwong, and R. Binder, "Large excitonic enhancement of optical refrigeration in semiconductors," Phys. Rev. Lett. ***97****, 117401:1–4 (2006). Also see G. Rupper, N.H. Kwong, and R. Binder, "Optical refrigeration of GaAs: Theoretical study," Phys. Rev. B* ***76****, 245203: 1–12 (2007) and G. Rupper, N.H. Kwong, and R. Binder, "Theory of time-resolved photoluminescence and carrier lifetime measurements in GaAs/GaInP heterostructures," Proc. SPIE* ***7614****, 0D:1–11 (2010).*

A general theory is presented for semiconductor laser cooling based on exciton resonances in the temperature-dependent absorption and emission spectra of GaAs including screening effects.

Y.-C. Chen and G. Bahl, "Raman cooling of solids through photonic density of states engineering," Optica ***2****, 893–899 (2015). Also see Y.-C. Chen, I. Ghosh, A. Schleife, P.S. Carney, and G. Bahl, "Optimization of anisotropic photonic density of states for Raman cooling," arXiv:1705.00078v1 [physics.optics] 1–21 (2017).*

Because silicon and germanium are indirect-bandgap semiconductors, their radiative efficiency is low in that they must simultaneously emit a photon and a phonon to satisfy momentum conservation. However, Raman scattering only involves a virtual excited state, in contrast to the real excited state needed for photoluminescence. Thus, even indirect-bandgap materials can in principle be cooled by anti-Stokes Raman scattering. However, the key challenges are to suppress both the more probable Stokes Raman scattering and any direct pump absorption. These challenges could be overcome by tailoring the photon density of states in a three-dimensional photonic crystal structure. Band structure calculations are performed that demonstrate the idea theoretically for Si, but practical considerations imply that it would be difficult to obtain net cooling experimentally.

M. Sheik-Bahae and R.I. Epstein, "Can laser light cool semiconductors?" Phys. Rev. Lett. ***92****, 27403:1–4 (2004). Also see D.V. Seletskiy, R.I. Epstein, and M. Sheik-Bahae, "Laser cooling in solids: Advances and prospects," Rep. Prog. Phys.* ***79****, 096401:1–23 (2016) and M. Sheik-Bahae, B. Imangholi, M.P. Hasselbeck, R.I. Epstein, and S. Kurtz, "Advances in laser cooling of semiconductors," Proc. SPIE* ***6115****, 18:1–13 (2006).*

In addition to the advantage of directly cooling the interior of semiconductor devices where the heat is actually being generated, another potential advantage of optically cooling semiconductors (compared to laser cooling of rare-earth-doped crystals and glasses) is that it should theoretically be possible to refrigerate them down to nearly 10 K (as opposed to only about 100 K for rare-earth materials) because the valence band is always populated by electrons (as described by Fermi-Dirac statistics) in contrast to the Boltzmann thermal depopulation of the discrete excited states of rare-earth ions. The competition between radiative and nonradiative relaxation in semiconductors such as GaAs is analyzed in these articles, including the effects of reabsorption and the photon escape probability. Net laser cooling should be more easily achievable by starting at a sample temperature of about 100 K rather than room temperature. Experimentally, the quantum efficiency is measured using laser calorimetry and the optimum GaAs sample thickness is found to be 1 μm. Practical designs and applications of optical refrigerators are also reviewed.

Y.P. Rakovich, J.F. Donegan, M.I. Vasilevkiy, and A.L. Rogach, "Anti-Stokes cooling in semiconductor nanocrystal quantum dots: A feasibility study," Phys. Status Solidi A ***206****, 2497–2509 (2009).*

Quantum dots with a diameter of the order of 10 nm combine the advantage of nanoscale size with ease of fabrication by solution-based colloidal chemistry. However, a distribution of dot sizes results, with a concomitant range of optical absorption and emission peaks. The surfaces need to be passivated, for example by surrounding a CdSe core with a ZnS shell. The samples typically have to be initially cooled to achieve high quantum yields (i.e., the ratio of the number of photons emitted to that absorbed) and are usually suspended in an organic liquid such as toluene. Experimentally it is found that the average upconversion photon energy shift is more than that of a single LO phonon. The presumed explanation is that a sequence of upconversions occurs as a light wave travels through the sample, being absorbed and emitted in quantum dots of progressively smaller sizes and hence of increasing resonant energies. Unfortunately, increasing the pump laser intensity to increase the cooling power density competes with photodegradation of the samples and nonlinear effects such as two-photon absorption.

M. Kern, J. Jeske, D.M.W. Lau, A.D. Greentree, F. Jelezko, and J. Twamley, "Optical cryocooling of diamond," arXiv:1701.08505v1 [quant-ph] 1–8 (2017).

Nitrogen-vacancy (NV) and silicon-vacancy (SiV) defects in diamonds (of diameter less than 0.2 mm) can be pumped in the near IR. The microdiamonds would ideally be levitated in vacuum, but in practice would be placed on a glass slide or suspended in water. The temperature of the particles can be inferred either from thermally dependent spectroscopic features (such as the linewidths) or from the diffusion rates in solution. A key experimental challenge would be to achieve high enough sample purity to obtain near-unity quantum efficiency.

M.P. Hasselbeck, M. Sheik-Bahae, and R.I. Epstein, "Effect of high carrier density on luminescence thermometry in semiconductors," Proc. SPIE ***6461****, 07:1–5 (2007).*

This conference paper analyzes a previously published report of localized laser cooling in AlGaAs quantum wells grown on a GaAs substrate. It proves that the conclusions are erroneous due to a misinterpretation of the spectra by Coulomb screening of the excitons. In fact, the substrate is heated by the large amount of laser power that is not absorbed by the quantum wells, overwhelming the small expected cooling effect. The key issue is that semiconductor luminescence peaks are a function of both the sample temperature and the excited electron carrier density. The authors recommend that a different laser be used to pump the sample than the one employed to optically monitor its temperature.

Z. Li, J. Xue, and R.J. Ram, "A design of a photonic-crystal-enhanced LED for electroluminescence cooling," Proc. SPIE ***10121****, 08:1–10 (2017). Also see P. Santhanam, D.J. Gray, and R.J. Ram, "Thermoelectrically pumped light-emitting diodes operating above unity efficiency," Phys. Rev. Lett.* ***108****, 097403:1–5 (2012) and P. Santhanam, D. Huang, R.J. Ram, M.A. Remennyi, and B.A. Matveev, "Room temperature thermoelectric pumping in mid-infrared light-emitting diodes," Appl. Phys. Lett.* ***103****, 183513:1–5 (2013).*

It may be possible to fluorescently cool a diode that is electrically pumped rather than optically pumped, provided that the Joule heating of the electrical current can be overcome. The idea is to forward bias the device such that the electrical energy per injected electron is less than the optical bandgap energy. Instead of encapsulating the LED, the surface could be roughened to increase the light extraction or it could be etched into a photonic crystal structure. Experimentally a small amount of electroluminescent cooling (on the order of 40 pW) is observed for a GaSb/InGaAsSb diode operated near 2.15 µm at 135ºC. Further work at longer pump wavelengths (namely 3.4 and 4.7 µm) suggests that cooling can occur even starting from room temperature.

C. Wang and M. Sheik-Bahae, "Accurate measurement of external quantum efficiency in semiconductors," Proc. SPIE ***8638****, 0H:1–11 (2013). Also see D.A. Bender, J.G. Cederberg, C. Wang, and M. Sheik-Bahae, "Development of high quantum efficiency GaAs/GaInP double heterostructures for laser cooling," Appl. Phys. Lett.* ***102****, 252102:1–4 (2013) and C. Wang, C.-Y. Li, M.P. Hasselbeck, T. Rotter, K. Malloy, and M. Sheik-Bahae, "GaAs/GaInP double heterostructure characterization for laser cooling of semiconductors," Proc. SPIE* ***7951****, 0D:1–14 (2011).*

Semiconductors potentially can have very high quantum efficiency. A record external efficiency of 99.5% is reported for a GaAs/GaInP double (i.e., sandwich) heterostructure at 100 K bonded to a ZnS dome lens. The small amount of heating is due to surface recombination and Auger processes, thereby precluding net laser cooling.

B. Jalali, "Making silicon lase," Sci. Amer. ***296*** *(2), 58–65 (2007).*

Stimulated emission of Si is limited by excited-state absorption and Auger recombination. To get silicon to lase, one must therefore create Si nanostructures, use Raman pumping, or fabricate hybrid devices.

C.E. Mungan, "Thermodynamics of optical cooling of bulk matter," in Optical Refrigeration: Science and Applications of Laser Cooling of Solids, edited by R.I. Epstein and M. Sheik-Bahae (Wiley-VCH, Weinheim Germany, 2009), Chap. 8, pp. 197–232, [*https://www.usna.edu/Users/physics/mungan/_files/documents/Publications/LCSchapter.pdf*](https://www.usna.edu/Users/physics/mungan/_files/documents/Publications/LCSchapter.pdf)*. Also see C.E. Mungan, "Radiation thermodynamics with applications to lasing and fluorescent cooling," Am. J. Phys.* ***73****, 315–322 (2005).*

In these publications, I explain how laser cooling is compatible with the first and second laws of thermodynamics. In particular, the entropy of the light increases more than that of the cooling sample decreases as the radiation is converted from a directed, coherent, monochromatic laser beam into isotropic, incoherent, broadband fluorescence. Brightness and flux temperatures are defined for light, so that a Carnot coefficient of performance can be calculated. A rate equation analysis is used, including the absorption and emission cross sections and the effect of pump saturation at high intensities. It is also possible to use radiative cooling to balance the heat generated by stimulated emission in an optically pumped laser.

Other articles of lesser interest

J. Zhang, Q. Zhang, X. Wang, L.C. Kwek, and Q. Xiong, "Resolved-sideband Raman cooling of an optical phonon in semiconductor materials," Nature Photon. ***10****, 600–606 (2016).*

One specific phonon in a ZnTe nanobelt is laser cooled, rather than the entire sample.

R.S. Daveau, P. Tighineanu, P. Lodahl, and S. Stobbe, "Optical refrigeration with coupled quantum wells," Opt. Express ***23****, 243562:1–10 (2015).*

It is theoretically proposed that two coupled semiconductor quantum wells could have relaxation times of their relevant energy levels that would result in a quantum efficiency exceeding 99%, which would be promising for bulk optical cooling.

Y. Xiong, C. Liu, J. Wang, J. Han, and X. Zhao, "Near-infrared anti-Stokes photoluminescence of PbS quantum dots embedded in glasses," Opt. Express ***25****, 285580:1–9 (2017).*

Anti-Stokes photoluminescence (ASPL) is observed for PbS quantum dots dispersed in oxide glass, but the emission spectrum depends on the excitation wavelength and power, indicating that defect states may be responsible for the ASPL.

S. Klembt, E. Durupt, S. Datta, T. Klein, A. Baas, Y. Léger, C. Kruse, D. Hommel, A. Minguzzi, and M. Richard, "Exciton-polaron gas as a nonequilibrium coolant," Phys. Rev. Lett. ***114****, 186403:1–5 (2015).*

Rather than pumping bare photons, the authors propose exciting coupled photon-excitons (i.e., polarons) in a semiconductor microcavity. Less than 1 pW of cooling is predicted and only at a starting sample temperature of 50 K.

R. Chen, G. Sun, Y.J. Ding, H.P.T. Nguyen, and Z. Mi, "Photoluminescence upconversion study of GaN nanowires: Potential for optical refrigeration," OSA Technical Digest CLEO ***FM2D.6****:1–2 (2015).*

Gallium nitride nanowires grown on silicon substrates when pumped at 383 nm (which corresponds to one LO phonon below the bandgap) exhibits anti-Stokes emission at 475 K, as required for laser cooling.

N. Giannini, Z. Yang, A.R. Albrecht, and M. Sheik-Bahae, "Investigation into the origin of parasitic absorption in GaInP/GaAs double heterostructures," Proc. SPIE ***10121****, 0F:1–8 (2017).*

Pump-probe *z*-scan thermal lensing is used to measure the local heating in a semiconductor heterostructure at 1020 nm. The parasitic absorption that obviates net laser cooling is believed to originate from bulk impurities in the GaInP layers.

G. Nemova and R. Kashyap, "Laser cooling of solids under the influence of surface phonon polaritons," J. Opt. Soc. Am. B ***34****, 483–488 (2017).*

Two samples can theoretically be brought close enough together that their near-field thermal radiative modes are coupled. For example, one sample can be a rare-earth-doped laser-cooled crystal and the other could be a slab of SiC, such that surface waves evanescently tunnel from one to the other.

S.D. Melgaard, A.R. Albrecht, M.P. Hehlen, and M. Sheik-Bahae, "Solid-state optical refrigeration to sub-100-kelvin regime," Sci. Rep. ***6****, 20380:1–6 (2016). Also see A. Gragossian, M. Ghasemkhani, J. Meng, A. Albrecht, M. Tonelli, and M. Sheik-Bahae, "Optical refrigeration inches toward liquid-nitrogen temperatures," SPIE Newsroom* ***10.1117/2.1201704.006840****:1–3 (2017).*

These articles report the lowest temperatures currently achieved for bulk samples by laser cooling starting from room temperature. A YLF crystal doped with 10% Yb^{3+} reached 91 K (which is only 2 K higher than the theoretically predicted minimum achievable temperature) by pumping it with a 54-W continuous-wave fiber laser at 1020 nm, and a 5% doped sample reached 87 K by placing it in a cavity so that the pump laser beam executed over 150 roundtrips through the crystal.

J.B. Khurgin, "Surface-plasmon-assisted laser cooling of solids," Phys. Rev. Lett. ***98****, 177401: 1–4 (2007).*

The threshold and efficiency of laser cooling of a semiconductor such as GaN can theoretically be improved by bringing the sample about 10 nm away from a metal surface such as silver that supports surface plasmon polaritons. The lack of any subsequent experimental work in this area is probably due to the difficulty in fabricating such a nanogap.

N. Vermeulen, C. Debaes, P. Muys, and H. Thienpont, "Mitigating heat dissipation in Raman lasers using coherent anti-Stokes Raman scattering," Phys. Rev. Lett. ***99****, 093903:1–4 (2007). Also see N. Vermeulen, C. Debaes, and H. Thienpont, "Coherent anti-Stokes Raman scattering in Raman lasers and Raman wavelength converters," Laser Photonics Rev.* ***4****, 656–670 (2010).*

The intrinsic heating in a Raman laser (such as a silicon-on-insulator waveguide pumped at 2.7 µm) can be reduced by 35% using CARS to enhance the anti-Stokes compared to the Stokes emission.

R.S. Fontenot, V.K. Mathur, J.H. Barkyoumb, C.E. Mungan, and T.N. Tran, "Measuring the anti-Stokes luminescence of CdSe/ZnS quantum dots for laser cooling applications," *Proc. SPIE* ***9821****, 03:1–7 (2016).*

Anti-Stokes fluorescence is observed for CdSe quantum dots dispersed in solid PMMA polymer and in liquid toluene at room temperature. Although a possible 2.3ºC cooling signal was seen for the toluene samples due to the absorption of 2LO phonons of CdSe, the comparatively low 80% quantum efficiency suggests that bulk cooling of the sample cannot in fact occur.

J. Li, "Laser cooling of semiconductor quantum wells: Theoretical framework and strategy for deep optical refrigeration by luminescence upconversion," Phys. Rev. B ***75****, 155315:1–10 (2007).*

A 15-nm GaAs quantum well is modeled at room temperature by considering the kinetics of the electron-hole pairs and lattice phonons interacting with the ambient surroundings.

A. Manor, L. Martin, and C. Rotschild, "Conservation of photon rate in endothermic photoluminescence and its transition to thermal emission," Optica ***2****, 585–588 (2015).*

At high sample temperatures T, there is a competition between the excitation and subsequent emission due to the pump laser and that due to thermal absorption (when kT is comparable to the bandgap energy, where k is the Boltzmann constant). The balance between both the incoming and outgoing photon rates and powers is determined by the sample temperature and chemical potential. Theoretical and experimental results are compared for a neodymium-doped silica fiber at temperatures ranging from 300 to 1800 K.

X.Y. Chen, H.Z. Zhuang, G.K. Liu, S. Li, and R.S. Niedbala, "Confinement on energy transfer between luminescent centers in nanocrystals," J. Appl. Phys. ***94****, 5559–5565 (2003).*

The phonon density of states is different in a nanocrystal than in the corresponding bulk material. Assuming a spherical shape with a radius less than 50 nm, the vibrational modes form a discrete spectrum with a low-frequency cutoff. The energy transfer between neighboring dopant ions is Monte Carlo modeled. The fluorescence decay depends on the temperature, concentration, and size of the nanocrystals.

J.C. de Mello, H.F. Wittmann, and R.H. Friend, "An improved experimental determination of external photoluminescence quantum efficiency," Adv. Mater. ***9****, 230–232 (1997).*

The radiative quantum efficiency is a key parameter that determines whether a given sample will exhibit laser cooling or heating. This communication presents a method to experimentally quantify the external quantum efficiency at a given laser pump wavelength by performing three measurements using an integrating sphere.

M.P. Hehlen, M. Sheik-Bahae, and R.I. Epstein, "Solid-state optical refrigeration," in Handbook on the Physics and Chemistry of Rare Earths, Vol. 45 (Elsevier, 2014), Chap. 265, pp. 179–260, http://www.phys.unm.edu/msbahae/publications/HPCRE_SolidStateOpticalRefrigeration_Hehlen_Final.pdf.

An excellent recent review of the field of laser cooling of rare-earth-doped solids. Many of the key ideas carry over to optical cooling of semiconductors.

J. Oksanen and J. Tulkki, "LEDs feed on waste heat," Nature Photon. ***9****, 782–784 (2015). Also see J. Oksanen and J. Tulkki, "Thermophotonic heat pump: Towards the first demonstration of electroluminescent cooling?" Proc. SPIE* ***7614****, 0F:1–9 (2010).*

Indium gallium nitride LEDs heated up to 615 K extract thermal energy from the lattice to increase their optical emission. However, net electroluminescent cooling has not yet been observed.

D.V. Seletskiy, S. Melgaard, M. Sheik-Bahae, S. Bigotta, A. DiLieto, and M. Tonelli, "Laser cooling of a semiconductor load using an Yb:YLF optical refrigerator," Proc. SPIE ***7614****, 09: 1–5 (2010).*

Although direct optical cooling of a bulk semiconductor has not been achieved, a semiconductor sample can be indirectly cooled by attaching it to a rare-earth laser refrigerator. In this way, a 2-µm-thick GaAs/InGaP double heterostructure has been cooled to 165 K. However, one loses the advantage of directly cooling the interior of a semiconductor to avoid producing thermal gradients within it.