Opto-Thermionic Refrigeration in Semiconductor Heterostructures

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(Received 5 April 2001)

Combining the ideas of laser cooling and thermionic cooling, we have proposed an opto-thermionic cooling process, and investigated its cooling effect caused by the light emission from a quantum well embedded into a semiconductor *pn* junction. For a GaAs/AlGaAs opto-thermionic refregerator in which the Auger recombination is the major nonradiative process, cooling can be achieved in a finite range of bias voltage. Using the measured values of the Auger coefficient, our calculated cooling rate is at least several watts/cm^2.

DOI: 10.1103/PhysRevLett.86.5570 PACS numbers: 72.20.Pa, 73.40.Kp, 78.60.Fi

The basic structure of thermionic refrigeration is two electrodes separated by a potential barrier. Under an applied bias, thermally excited carriers can transfer heat over the barrier from the cold cathode to the hot anode. After understanding the fundamental problem of the thermionic process in a metal-vacuum-metal system [1], semiconductor layer structures have been considered as better thermionic systems [2,3]. Here doped quantum wells separated by undoped barriers play the role of metallic electrodes. However, the barriers are crystalline materials in which the lattice thermal conductivity is not small. Under an external electric field, when thermally excited carriers transfer heat from a cold quantum well to a hot one, the opposite heat flow due to the lattice heat conduction will reduce the temperature difference. Using the results in Ref. [2], for a typical value of semiconductor thermal conductivity, it is easy to see that the refrigeration efficiency is very low with a very small value of the thermoelectric figure of merit. Only when the thermal conductivity in the barriers becomes as low as that of glasses, the thermoelectric figure of merit approaches the value of unity.

One way to suppress the unwanted opposite heat flow is to increase the barrier width. However, this may also lower the thermionic efficiency, and hence reduces the required heat transfer over the barriers from the cold side to the hot side. This is an intrinsic dilemma. We will overcome this problem with an entirely different approach of heat pumping, which combines the ideas of laser cooling and thermionic cooling. We call this cooling process *opto-thermionic refrigeration*. The carriers in the thermionic processes are both electrons in an n-doped semiconductor at one side and holes in a p-doped semiconductor at the other side. In between this *pn* junction, there is an undoped quantum well (QW). When thermally excited electrons and holes are driven into the QW by the applied bias voltage, they can recombine radiatively. The so-created photons carry the thermal energy out of the system, so then release the heat outside. We would like to point out that the idea of cooling a *pn* junction with light emission was proposed about 40 years ago [4]. To our knowledge, however, there was no quantitative investigation of the competing effects of cooling by radiative recombination and heating by nonradiative recombination. In this Letter, we will study this problem of heat pumping in a system where the dominant nonradiative recombination channel is the Auger scattering.

We consider an opto-thermionic system consisting of a p-doped AlGaAs, an undoped AlGaAs spacer, an undoped GaAs QW, an undoped AlGaAs spacer, and an n-doped AlGaAs, connected in series. Under a bias voltage V_b, the energy levels are shown schematically in Fig. 1. E_c and E_v are the conduction and the valence band edges in the QW, respectively. The system is so biased that E_c is above the chemical potential μ_c in the n-doped AlGaAs, while E_v is below the chemical potential μ_v in the p-doped AlGaAs. Hence, only thermally excited carriers can be driven into the empty states in the QW. Since the carriers in the QW thermalize within a time interval of the order of a picosecond, their energy distribution follows the thermal equilibrium with a quasichemical potential μ_c^* for the carriers in the conduction band, and a quasichemical potential μ_v^* for the carriers in the valence band. The band gaps of

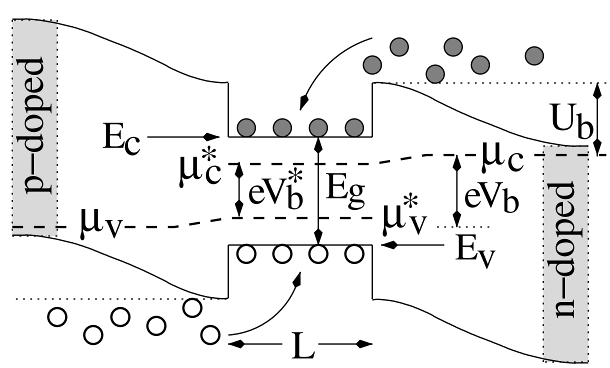

FIG. 1. Schematic illustration of the energy levels in a p-AlGaAs/GaAs/n-AlGaAs junction under a bias voltage V_b. Shaded areas are p-doped and n-doped regions.

 0031-9007/01/86(24)/5570(4)$15.00

the two doped AlGaAs alloys are wider than the band gap of the QW, and so there is no reabsorption of photons when they are emitted from the QW due to the recombination of carriers.

Let J be the current under the bias V_b, and Q_{ph} the energy carried out by photons from the QW. It is important to notice that the current J, which produces the dissipation heating JV_b, is determined not only by the radiative recombination, but also by the nonradiative processes. If the total heat

$$Q = JV_b - Q_{ph} \tag{1}$$

released from the system is negative, then, the opto-thermionic refrigeration can be realized.

Let N_{nr} be the nonradiative recombination rate, and $W^\lambda(\mathbf{q})$ the probability of emitting a photon with the wave vector $\mathbf{q}$ and the polarization λ. Under thermal equilibrium, the photon occupation number $N_{\mathbf{q}}^\lambda$ obeys the Bose-Einstein distribution $N_{\mathbf{q}}^\lambda = [\exp(\hbar\omega_{\mathbf{q}}^\lambda/k_BT) - 1]^{-1}$, characterized by a temperature which may be different from the temperature of the carriers outside the QW. However, such a possible difference is not crucial to our analysis and we will ignore it. We also assume the same temperature throughout the entire junction system, which is reasonable for typical heat conductance in semiconductors. Let $\Delta N_{\mathbf{q}}^\lambda$ be the nonequilibrium part of the photon momentum distribution function, and so the total photon occupation number is $N_{\mathbf{q}}^\lambda + \Delta N_{\mathbf{q}}^\lambda$. By defining $eV_b^* = \mu_c^* - \mu_v^*$ and $F(V_b) = 1 - \exp(-eV_b^*/k_BT)$, we can rewrite (1) as

$$Q = F(V_b)\left[eV_bN_{nr} - \sum_{\mathbf{q},\lambda}(\hbar\omega_{\mathbf{q}}^\lambda - eV_b)W^\lambda(\mathbf{q})(N_{\mathbf{q}}^\lambda + 1)\right] - \sum_{\mathbf{q},\lambda}(\hbar\omega_{\mathbf{q}}^\lambda - eV_b)W^\lambda(\mathbf{q})\Delta N_{\mathbf{q}}^\lambda \times\left[1 - \exp\left(\frac{\hbar\omega_{\mathbf{q}}^\lambda - eV_b^*}{k_BT}\right)\right]. \tag{2}$$

The above equation is very general, and we must specify our system in order to be able to calculate Q. Both the rate of thermionic injection of carriers into the QW and the rate of recombination of carriers in the QW are important to our theoretical analysis. We will first consider the case that thermionic injection of carriers into the QW is sufficiently fast that the carrier recombination rate plays the primary role in determining the dynamical processes in the QW. Let $I_{R,n}^{\leftarrow} = A^*T^2\exp(-U_b/k_BT)$ be the Richardson current over the barrier from the n-doped AlGaAs into the QW, and $I_{R,n}^{\rightarrow}$ the over the barrier current in the opposite direction, where the barrier height U_b is indicated in Fig. 1. Then, $J = I_{R,n}^{\leftarrow} - I_{R,n}^{\rightarrow}$. We define similarly $I_{R,p}^{\rightarrow}$ and $I_{R,p}^{\leftarrow}$ for the Richardson current between the QW and the p-doped AlGaAs. We are interested in the situation that both $I_{R,n}^{\leftarrow}$ and $I_{R,n}^{\rightarrow}$ are much larger than J. We will show later that this situation can be easily achieved. Then, $\mu_c - \mu_c^* = k_BTJ/I_{R,n}^{\leftarrow} \ll k_BT$ and $\mu_v^* - \mu_v = k_BTJ/I_{R,p}^{\rightarrow} \ll k_BT$. Hence, in our calculation below we can neglect the difference between μ_c (or μ_v) and μ_c^* (or μ_v^*).

For the QW we choose the semiconductor with a sufficiently wide gap E_g such that under the bias voltage V_b, we have $E_g \geq eV_b \geq eV_b^* \gg k_BT$. This condition is satisfied with a GaAs QW under room temperatures. In this case, $F(V) \simeq 1$. In our opto-thermionic refrigeration, the relevant photon energy $\hbar\omega_{\mathbf{q}}^\lambda$ is of the order of E_g. Hence, we have $N_{\mathbf{q}}^\lambda \simeq 0$. Here we will study a photon system under thermal equilibrium, for which $\Delta N_{\mathbf{q}}^\lambda$ vanishes. The effect of nonequilibrium processes will be discussed later.

In order to increase the cooling power, it is necessary to suppress the nonradiative recombination. In the region where the electron-hole recombination occurs, there should be as few deep traps and charged impurities as possible. Therefore, it is desired to introduce an undoped high quality GaAs QW between the two AlGaAs alloys. In this structure the radiative recombination is mainly due to the direct band-to-band transitions, while the nonradiative recombination is determined by the Auger processes [5]. It is well known that due to the momentum conservation among the interacting carriers, the Auger recombination in a bulk semiconductor has an energy threshold [5]. In a quantum well, carriers are confined along the growth direction, and so the corresponding momentum conservation requirement is removed. This gives rise to the so-called thresholdless and quasithreshold Auger processes [6,7]. Consequently, as a QW gets narrower, the Auger recombination rate increases. Hence, for our opto-thermionic cooler, we need a wider QW. In a GaAs the main contribution to the Auger recombination comes from the collision processes with the excitation of a hole to the split-off valence band [5], the so-called CHHS (conduction, hole, hole, split-off) process. In Ref. [6] a condition is given under which the Auger recombination effect in a QW is almost the same as that in a bulk semiconductor. For the CHHS contribution mentioned above, we found that at room temperature this condition is satisfied if the width L of the QW is wider than 1000 Å. The Auger coefficient for bulk GaAs can then be used in our study. In such a wide QW at room temperature, we can also neglect the electron-hole recombination via the exciton states, which can be important for narrower QW at lower temperatures [8]. Furthermore, in our calculation the spatial confinement effects are ignored because the thermal energy k_BT is larger than the quantization energies of electron subbands and hole subbands. Consequently, the radiative recombination theory for bulk semiconductors can be applied.

The details of band-to-band radiative recombination can be found in Ref. [9], and we will use these results to complete our calculation. Let m_c, m_{lh}, and m_{hh} be the effective masses in the conduction band, the light hole band, and the heavy hole band, respectively. We define $\mu_{lh} = m_c m_{lh}/(m_c + m_{lh})$, $\mu_{hh} = m_c m_{hh}/(m_c + m_{hh})$, and $\mu = (\mu_{lh}^{3/2} + \mu_{hh}^{3/2})^{-3/2}$. Then, (2) can be rewritten as

$$Q = eV_b N_{nr} - \left[(E_g - eV_b) + (2E_g - eV_b)\frac{3k_BT}{4E_g} + \frac{15(k_BT)^2}{16E_g}\right]\frac{8Le^2\sqrt{\epsilon_\infty}\,P_{cv}^2 E_g}{3\hbar^2 c^3 m_0}\left(\frac{k_BT\mu}{\hbar}\right)^{3/2}\exp\left(\frac{eV_b - E_g}{k_BT}\right), \tag{3}$$

where m_0 is the electronic mass, $\sqrt{\epsilon_\infty}$ the refraction index, and P_{cv} the momentum matrix element for electron transitions between the conduction and the valence bands.

We have used the GaAs material parameters to calculate Q from (3) at $T = 300$ K, assuming equal density n of electrons and of holes in the QW. Then, the Auger recombination rate can be expressed as $N_{nr} = L\gamma n^3$ [5]. The calculated value [10] of the Auger coefficient γ for bulk GaAs is $\gamma \simeq 5 \times 10^{-30}$ cm^6/sec. The experiment at room temperature [11] gives a higher value $\gamma \simeq 6 \times 10^{-29}$. However, in the measurement it is difficult to separate the contribution from the intrinsic band-to-band transitions and the contribution from the impurity assisted Auger recombination [5]. Therefore, in Fig. 2 we present our calculated Q for three cases: a strong Auger recombination with $\gamma = 4 \times 10^{-29}$ cm^6/sec, a medium Auger recombination with $\gamma = 10^{-29}$ cm^6/sec, and a weak Auger recombination with $\gamma = 4 \times 10^{-30}$ cm^6/sec. In the region of E_g-eV_b where the system exhibits a maximum cooling rate, the carrier concentration is around 5×10^{17} cm^{-3}. For such a value of carrier concentration, the Auger recombination is the major nonradiative recombination process. The cooling rate is very sensitive to the value of Auger coefficients. Nevertheless, even at a large $\gamma = 4 \times 10^{-29}$ cm^6/sec, the cooling rate can still reach about 2 W/cm^2. We would like to point out that it is possible to have a phonon assisted and Auger assisted *radiative* recombination which can contribute an additional heating. However, in high quality samples such a heating effect is negligibly small.

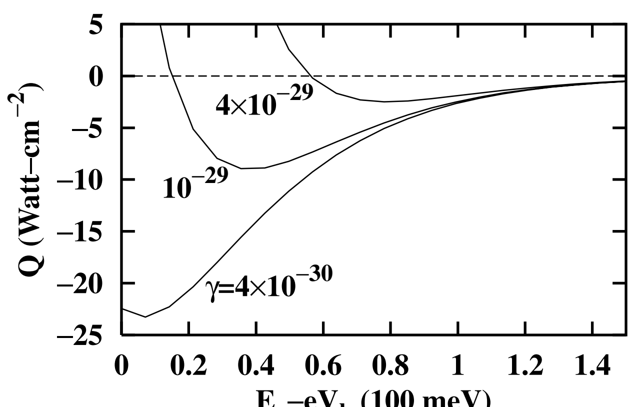

FIG. 2. Heat released from the system, Q, as a function of E_g-eV_b, for various Auger coefficient $\gamma = 4 \times 10^{-29}$, 10^{-29}, and 4×10^{-30} cm^6/sec.

In our above calculations we have assumed that the current J is much less than the Richardson current $I_{R,n}^{\leftarrow} = A^*T^2 \exp(-U_b/k_BT)$. This imposes a condition on the barrier height U_b and/or the carrier density in the QW. We will perform a quantitative check on this condition. Under a bias to yield E_g-$eV_b = 50$ meV, the recombination current J is about 100 A/cm^2. In an n-doped AlGaAs, the Richardson constant A^* 8 A/K cm^2. Hence, for a barrier height $U_b \simeq 0.2$ eV, at room temperature the Richardson current $I_{R,n}^{\leftarrow}$ is about 350 A/cm^2, which is more than three times J.

So far we have studied the photon system under thermal equilibrium, for which the second term in (2) does not contribute to the cooling power Q. When U_b increases to a sufficiently large value, the difference between V_b-V_b^* becomes comparable with k_BT, and we can reach the situation $eV_b > E_g > eV_b^*$. For those photons with energies $\hbar\omega_{\mathbf{q}}^{\lambda}$ between eV_b and E_g, the second term in (2) will make Q more negative if $\Delta N_{\mathbf{q}}^{\lambda}$ is finite. Therefore, nonequilibrium photons can provide additional cooling power, which increases with the nonequilibrium photon occupation number $\Delta N_{\mathbf{q}}^{\lambda}$. This number can be enhanced by the use of a properly designed microcavity which reflects the light with frequencies in the range $eV_b/\hbar < \omega_{\mathbf{q}} < eV_b^*/\hbar$. The photons with energies $\hbar\omega_{\mathbf{q}}^{\lambda} > eV_b$ will be released from the microcavity. In this Letter, we will not study such processes.

To close this Letter, we should mention that the nonradiative Auger recombination can be suppressed by the special design of a heterojunction, such as a QW with type-II band offset [12]. It would be interesting to find out the cooling power of such heterostructures.

We thank Professor Hermann Grimmeiss for helpful discussions. A. G. M. acknowledges the support from the Royal Swedish Academy of Sciences.

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