The Ultimate Cooling Temperature of Semiconductor Electroluminescent Refrigeration

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***Abstract*-We perform a self-consistent calculation, with the heat balance equation considered, to study the influence of heat transfer on the device temperature and also to investigate the ultimate cooling temperature of an EL refrigerator. We show that an EL cooler has to be thermally isolated carefully for the purpose of EL cooling. We also show that the lowest cooling temperature of an EL cooler with a GaAs active layer is ~ 112 K.**

I. INTRODUCTION

Recently, an important milestone has been reached in the area of semiconductor luminescent refrigeration. Researchers demonstrated that light-emitting diode (LED) can emit more optical power than its electrical input power at a small forward bias (~ μV) [1]. This is a direct evidence for the feasibility of electroluminescent (EL) refrigeration. However, in their work, cooling is not directly observed due to the extremely low cooling power (~ pW). Even if present, such a small cooling power is easily compensated by heat from the environment and hence obstructs the observation of EL refrigeration. Several theoretical studies have shown that cooling power of several Watts can be achieved if an EL cooler is properly biased at a voltage about E_g/q, where E_g is the bandgap energy of the active layer and q is the elementary charge [2, 3]. However, semiconductor EL cooling has still not been realized to date. It is generally believed that the realization of EL cooling relies on a well-designed device structure and an extremely high-quality post-processing technique. In this work, we will show that the heat transfer between devices and their environment also plays an important role in the observation of EL refrigeration, and the ultimate cooling temperature of an EL cooler will also be discussed.

II. NUMERICAL METHOD

The simulation approach used in this work is similar to that in our previous work [2], except we obtained the steady-state device temperature by incorporating the heat balance equation into our calculation,

$$P_{\rm rad} = P_{\rm in} + h(T_e - T) + \epsilon\sigma(T_e^4 - T^4), \qquad (1)$$

where $P_{\rm rad}$ and $P_{\rm in}$ are the light-output and electric-input powers, respectively, T_e and T are the environment and device temperatures, respectively, h is the heat transfer coefficient, ϵ is the emissivity of the device surface, and σ is the Stefan-Boltzmann constant. By solving this heat balance equation together with the Poisson and the continuity equations self-consistently, we can obtain the electrostatic potential, quasi-Fermi levels, and the device temperature for further analysis. Slightly different from our previous work, at the interfaces where current flows, not only the thermionic process but also the tunneling process [4] has to be taken into account due to its importance at a low temperature. Various recombinations are considered and detailed simulation approach can be found in Ref. [2]. Some parameters used in this work can also be found in Refs. [2] and [5].

Fig. 1 depicts the device structure used in this work and also shows the energy band profiles, E_c and E_v, and the quasi-Fermi levels, E_{Fc} and E_{Fv}, obtained from our simulation, under a forward voltage of 1.2 V for an ideal case of h=0, ϵ=1, and T_e=300 K. The calculated device temperature is 270.5 K.

III. RESULTS AND DISCUSSION

In this work, the light extraction efficiency and the surface emissivity ϵ are set to be unity for investigating the ultimate cooling temperature. The system is supposed to contact with a reservoir such that the environment temperature T_e is kept at 300 K.

Fig. 2 shows the steady-state temperature of an EL cooler as a function of applied voltage V for h=100, 10, 1, 0.1, and 0 W/cm^{2}K. As shown in this figure, the steady-state temperature basically decreases with an increasing V but with a decreasing h. This can be simply understood from (1) with the help of the cooling power density at 300 K, P_c=$P_{\rm rad}$–$P_{\rm in}$, as shown in the inset of Fig. 2. Fig. 2 indicates that a large heat transfer coefficient of 100 W/cm^{2}K leads to a nearly constant device temperature of 300 K, preventing EL cooling from being observed. For GaAs substrate with a thickness of 350 μm, which corresponds to h~10 W/cm^{2}K, an EL cooler can only achieve a minimum temperature of 296.6 K at V=1.44 V. Such a small temperature drop implies the difficulties in the demonstration of the EL refrigeration due to the heat transfer from the environment. If the heat transfer is reduced, the

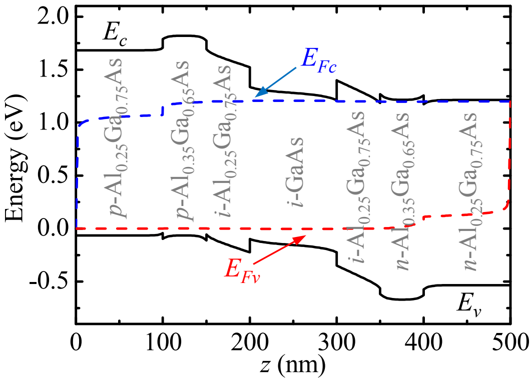

Figure 1. The device structure used in this work. It is composed of a 100 nm GaAs active layer symmetrically sandwiched by 50 nm Al$_{0.25}$Ga$_{0.75}$As spacers, followed by 50 nm Al$_{0.35}$Ga$_{0.65}$As carrier blocking layers, and the outermost are Al$_{0.25}$Ga$_{0.75}$As cladding layers. The whole structure is on GaAs substrate.

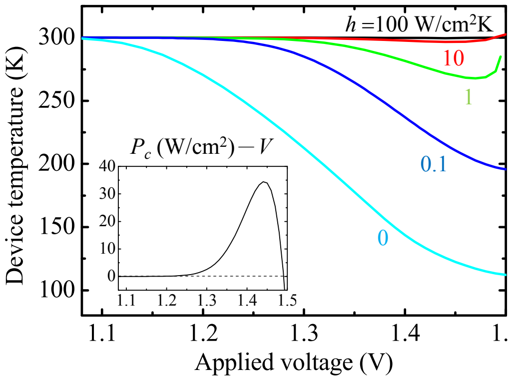

Figure 2. The steady-state temperature as a function of applied voltage V for h=100, 10, 1, 0.1, and 0. The inset shows the cooling power density P_c as a function of V for T=300 K.

situation becomes optimistic. For h=1 W/cm^{2}K, an EL cooler can be cooled down to a temperature of 267.7 K at a bias of 1.47 V and to an even lower temperature of 195 K for h=0.1 W/cm^{2}K. For an ideal case of h=0 W/cm^{2}K, i.e. when the heat transfer is only by thermal radiation, we can obtain the ultimate cooling temperature of 112 K for an EL cooler at 1.5 V.

It seems that 112 K is the lowest temperature that an EL cooler of a 100 nm active layer can achieve. To further reduce the cooling temperature, we try to improve the cooling power by increasing the active layer thickness [2]. The results are presented in Fig. 3, which shows the device temperature as a function of V for the active layer thickness L=100, 200, and 500 nm. As shown in this figure, the steady-state temperature first increases with the active layer thickness for V<1.1 V due to a lower internal quantum efficiency for a thicker active layer. After that, the steady-state temperature decreases with increasing L for V=1.1 to 1.46 V but increases again at even higher bias voltages. The improvement of the cooling temperature can be easily understood since the cooling power increases with L as a result of a larger radiative recombination current density, J_{rad}, and hence a higher emission power. For example, at V=1.2 V and T=270 K, J_{rad}=70.9, 140.3, and 358.9 mA/cm^2 for L=100, 200, and 500 nm, respectively, which is approximately proportional to L. However, such an enhancement is limited for a low T. Numerical results show that, at V=1.5 V and T=120 K, J_{rad}=4.7 A/cm^2 for L=500 nm, which is less than twice of J_{rad}=2.98 A/cm^2 for L=100 nm.

To understand the reason for this phenomenon, we plot the average electron density in Fig. 4 as a function of T for V=1.5 V. It is noticed that the carrier density decreases with T; in addition, it also decreases with an increasing L. Such a reduction of carrier density on L becomes worse especially for a low T. As shown in this figure, the ratio of the carrier density for L=100 nm to that for L=500 nm is less than 2 at 300 K, while it becomes approximately 3 at 100 K. This implies that the enhancement of the radiative recombination for a wide active layer is reduced. The reduction of the carrier density for a thick active layer also results in the decrease of the internal quantum efficiency and the average photon energy at a low T. Therefore a low cooling power and hence a high steady-state temperature are obtained for a thick active-layer device. Since the device structure is designed for maximizing the cooling power at 300 K [2], it is worthy of being further optimized for the purpose of achieving even lower cooling temperature.

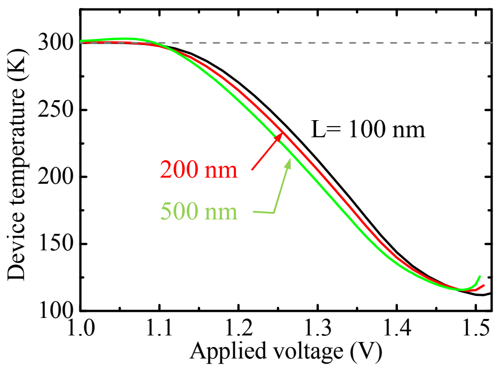

Figure 3. The steady-state temperature as a function of V for active layer thickness L=100, 200, and 500 nm.

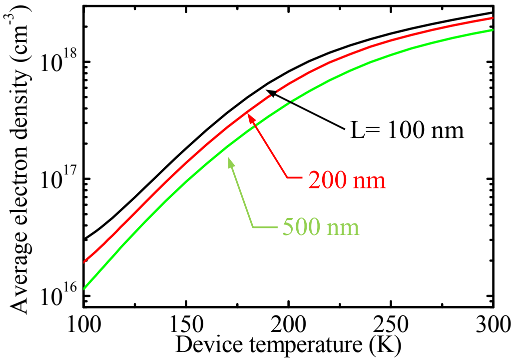

Figure 4. The average electron density in the active layer as a function of the device temperature T for L= 100, 200, and 500 nm at V=1.5 V.

IV. CONCLUSION

In summary, we studied the influence of the heat transfer on the cooling temperature of EL refrigerators. The ultimate cooling temperature is approximately 112 K and nearly independent on the active layer thickness. This is because the carrier density decreases with temperature and with an increasing active layer thickness. We also show that a well thermal isolation between a cooler and its environment is necessary for the observation of EL cooling.

ACKNOWLEDGMENT

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