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Enhancement of Electroluminescent Refrigeration by Inserting Carrier Blocking Layers

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1. Introduction

Compared with a conventional cooler with liquid refrigerant, a solid-state refrigerator has some benefits such as smaller in size, integrable with semiconductor devices, and potentially environmental friendly. One of the most interesting methods to cool the environment is by means of luminescence. It has been reported that optoelectronic materials, such as GaAs, could be cooled if the quantum efficiency is nearly unity [1]. This idea introduces two ways to perform refrigeration. One is by photoluminescence (PL) and the other is by electro-luminescence (EL). The optical refrigeration has been recognized as a great success of PL refrigeration [2]. Pumping the Yb-doped glass is capable of reducing a temperature of ~80 K below the room temperature. Recently, many researchers have been studying the cooling ability of optoelectronic semiconductors, especially for the EL purpose [3,4]. However, there has been little research addressing the effect of leakage current on the EL refrigeration. The leakage current reduces the internal quantum efficiency (IQE) of a light-emitting diode (LED) based device, and thus lowers the cooling power.

In this paper, we investigate the effect of the carrier blocking layers on the leakage current in bipolar LED-like devices by a self-consistent numerical simulation. The effect of leakage current on cooling power under different temperatures is also evaluated.

2. Numerical Method

The electrostatic potential is obtained by solving the coupled Poisson and continuity equations self-consistently. The Fermi-Dirac statistics and the thermionic current boundary condition are also taken into account. The device configuration is shown in the Fig. 1. The outer-most layers (I and VII) are cladding layers. Inside the cladding layers are the carrier blocking layers (II and VI), followed by spacers (III and V). Layer IV is the GaAs active layer. Regarding to the recombination process inside the device, both the Auger recombination and band-to-band radiative recombination are considered in the active layer, while only the Shockley-Read-Hall (SRH) recombination is considered in the other layers. Moreover, an infinite surface recombination velocity is assumed at the cladding layer surfaces.

3. Results and Discussions

The cooling power is defined as the emission photon power minus the input power. It can be expressed as follows:

$$P_{cool} = P_{ems} - P_{input} = P_{ems} - JV \,. \qquad (1)$$

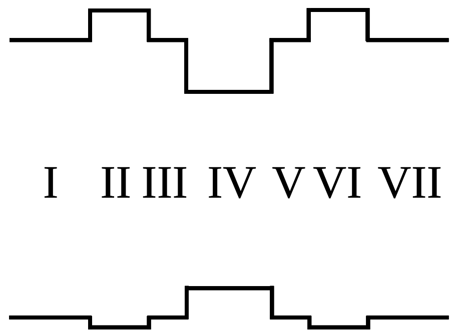

Fig. 1. The device structure. Layers I and VII are 100 nm $Al_{0.25}Ga_{0.75}As$ with doping concentration of 10^{18} cm^{-3}. Layers II and VI are 50 nm $Al_xGa_{1-x}As$ with doping concentration 10^{17} cm^{-3}. Layers III and V are 50 nm undoped $Al_{0.25}Ga_{0.75}As$. Layer IV is the 100 nm intrinsic GaAs active layer.

By an appropriate substitution, Eq. (1) could be re-written in terms of the individual current components as:

$$P_{cool} = \left(\frac{\alpha}{q} - V \right) J_{rad} - J_{heating} V \,. \qquad (2)$$

Where, α represents the average photon energy which is estimated to be about E_g+3kT. q is the elementary charge. J_{rad} is the radiative recombination current and $J_{heating}$ is the sum of the other current components that cause heating to the device. From Eq. (2), we see that the cooling power could be improved by inhibiting the leakage current.

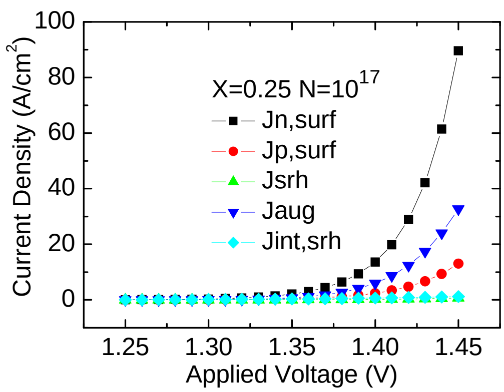

Fig. 2. The current components of a double heterojunction LED structures. $J_{n(p),surf}$ is the electron (hole) surface recombination current. J_{srh} is the SRH recombination current. J_{aug} is the Auger recombination current. $J_{int,srh}$ is the SRH recombination current at the interfaces.

Fig. 2 shows the various current components of the double heterojunction LED structures without blocking layers (x=0.25) at 300 K. Remarkably, the electron surface recombination current dominates in the heating current. As a result, a low maximum cooling power is obtained, as the line with x=0.25 shows in Fig. 3. The leakage current can be reduced by increasing the barrier of the blocking layers. Fig. 4 shows the heating current components for the blocking layers with an Al fraction x=0.35. Comparing with Fig. 2, we find that the surface recombination current can significantly be reduced by inserting the blocking layers. Therefore, the cooling power can be enhanced through reducing the leakage current. The cooling power can reach a maximum of ~10 W/cm^2. There is no further improvement in the cooling power by further increasing x from 0.35 to 0.4 because the leakage current has been almost eliminated by the blocking layers with x=0.35. Instead, increasing the Al fraction introduces a higher barrier and reduces the majority carrier flowing into the active layer. This causes the lowering of the radiative current and the cooling power.

To further understand the effect of the current leakage on the cooling power, we also study the cooling capability

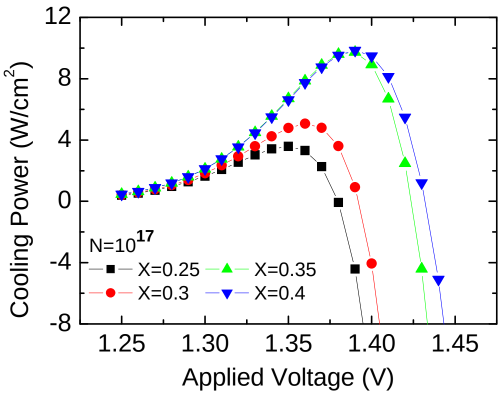

Fig. 3. The cooling power as a function of applied voltage for different Al fractions x in the blocking layer.

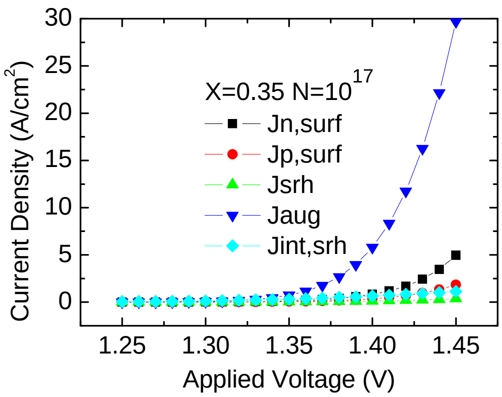

Fig. 4. The current components as a function of applied voltage for the blocking layers with an Al fraction x=0.35 and a doping concentration of 10^{17} cm^{-3}.

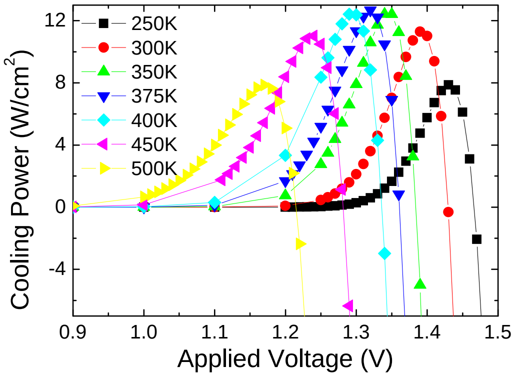

Fig. 5. The cooling power as a function of applied voltage for different temperatures. The blocking layers have an Al fraction x=0.4 and a doping concentration of 10^{18} cm^{-3}.

at different temperatures. We consider the blocking layers which have an Al fraction x=0.4 to block the leaking minority carriers at high temperature and a doping concentration of 10^{18} cm^{-3} to reduce the resistance of the layers. It seems that the cooling power would increase with the temperature because of increasing the average photon energy. However, the cooling power peak reaches the maximum at temperature about 375 K, but nor monotonically increases, as shown in the Fig. 5. A current analysis shows that the cooling power degradation at high temperature comes from the increase in the Auger recombination. On the other hand, the cooling power degradation at low temperature is a consequence of a low thermal energy.

4. Conclusions

In summary, we study the influence of the leakage current on the cooling power of electroluminescent refrigeration. The leakage current comes from the minority carrier flowing toward the opposite electrodes and leads to the heat inside the devices. By inserting the carrier blocking layers, the carriers could be confined in the active layer. Thus, this gives an improved internal quantum efficiency and higher cooling power. On the other hand, as the temperature increases, the increase in leakage current also lowers the cooling power. As a result, a maximum cooling power is obtained when temperature is 375K.

Acknowledgements

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