Analysis of Electroluminescent Cooling in GaN-LEDs

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Abstract – **Recently, GaN-based light-emitting diodes (LEDs) were demonstrated to emit photons of higher energy than the injected electrons up to elevated currents, which is attributed to heat extraction from the crystal lattice. We investigate this electroluminescent cooling effect by advanced device simulation which is in good agreement with measurements on industry-grade blue LEDs. The built-in polarization is found to enhance the cooling process while Joule heating is negligible even at higher currents. Strategies for enhanced heat removal from the LED are evaluated.**

1. INTRODUCTION

While much attention is devoted to the efficiency droop of GaN-based light-emitting diodes (GaN-LEDs)[1] another phenomenon is hardly discussed in the literature: the surprisingly low turn-on bias of industry-grade devices. In a recent paper, Hurni et al. report that the emitted photons have a higher energy than the injected electrons up to 75 A/cm^2 injection current density, i.e., the electrical efficiency exceeds unity.[2] The authors attribute this to the absorption of thermal energy by injected electrons. We here reproduce this phenomenon by advanced numerical simulation and in good agreement with measurements on blue LEDs. Our analysis reveals the exact contribution of different heat transfer mechanisms and enables us to explore strategies for enhanced heat removal from GaN-LEDs. For the first time in 2012, such electroluminescent cooling of GaSb-based infrared LEDs was demonstrated to deliver wall-plug efficiencies above unity, but only at extremely low power and elevated temperature.[3]

2. MODELS AND PARAMETERS

We employ the advanced LED device simulation software APSYS[4] which self-consistently computes carrier transport, the wurtzite electron band structure of strained quantum wells (QWs), the photon emission spectrum, as well as heat generation and dissipation. Schrödinger and Poisson equations are solved iteratively in order to account for the quantum well deformation with changing device bias (quantum-confined Stark effect). The transport model includes drift and diffusion of electrons and holes, Fermi statistics, built-in polarization and thermionic emission at hetero-interfaces, as well as Shockley-Read-Hall (SRH) recombination and Auger recombination of carriers. All relevant heat generation mechanisms are considered self-consistently, i.e., calculated from the local carrier densities and current densities, including Joule heating, heat from non-radiative recombination, and partially negative Peltier heat.

Our study employs an industry-grade single-QW blue LED as practical example.[5] Crucial material parameters are obtained by simultaneously fitting measurements of light output power, bias, and emission wavelength vs. current at different temperatures. The QW interface polarization charge was extracted from reproducing the blue-shift of the emission wavelength with rising current. Carrier leakage from the QW is negligible and the LED efficiency droop is caused by QW Auger recombination only. Since heat removal is expected to be most effective at elevated temperatures, we refer to the case of T = 400K stage temperature in the following.

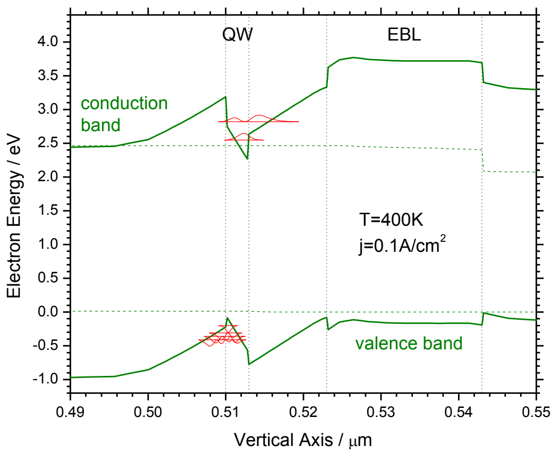

Fig. 1: Energy band diagram near the InGaN/GaN quantum well (QW; EBL – AlGaN electron blocking layer; dashed: quasi Fermi levels, red: quantum levels and wave functions).

3. RESULTS AND DISCUSSSION

Figure 1 shows the energy band diagram of the single-quantum-well structure at low current including the quantum well levels. Spontaneous and piezoelectric polarization cause a strong deformation of the QW and contribute to the triangular potential barrier which electrons and holes need to climb up before entering the active layer. This climbing process is enabled by thermal energy extracted from the crystal lattice (Peltier cooling, see below). Consequently, the carriers captured in the lowest QW level have a higher energy difference (2.745eV) than the quasi-Fermi levels (2.452eV at 0.1 A/cm^2, see Fig. 1). This results

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in the emission of blue photons while the applied bias is still substantially lower, as shown in Fig. 2. The energy of injected electrons exceeds the photon energy only at much higher current densities above 10 A/cm^2. Figure 2 shows the simulated bias, photon energy, and internal quantum efficiency (IQE) which are all in good agreement with the measurements.[5] The peak IQE is 0.56 but less than 20% of electrons are transformed into photons at low current density. The photon energy exhibits a typical blue-shift at high currents which is caused by partial screening of the QW polarization field.

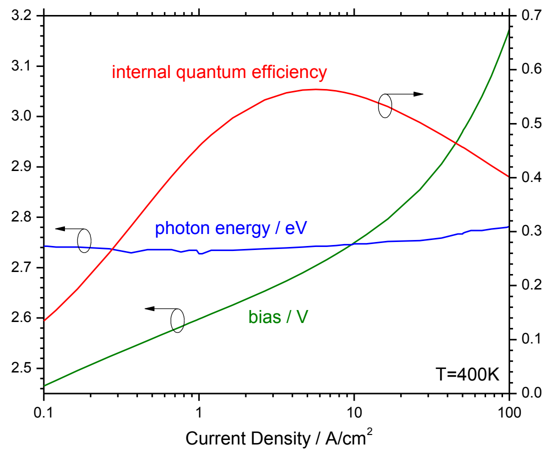

Fig. 2: Peak photon energy (blue), bias (green), and internal quantum efficiency (red) simulated at T=400K.

Carriers climbing up the energy hill towards the QW do so by acquiring thermal energy from the crystal lattice, which is often referred to as Peltier cooling. Subsequently, Peltier heating happens when carriers fall into the QW and transfer part of the thermal energy back to the lattice. Figure 3 shows the simulated Peltier heat profile near the QW. The cooling per carrier declines with higher current since the QW potential barrier is reduced with higher bias. However, the net Peltier heat is negative at all currents, as shown in Fig. 4 together with other contributions to the total LED power budget. Surprisingly, the Joule heat remains very small, it is mainly controlled by the free hole density (10^{18} cm^{-3}) and the hole mobility (10 cm^2/Vs). The strongest heat source is the non-radiative recombination inside the QW. Its rise is slightly depressed in Fig. 4 near the IQE peak when maximum energy is extracted by photon emission. At lower current, heat generation is dominated by SRH recombination and at higher current by Auger recombination. At the IQE peak, the Peltier cooling compensates for only about 20% of the other heat sources, assuming a photon extraction efficiency of EXE=1, neglecting heat from photon absorption. Net self-heating remains even in the ideal case of EQE=IQE*EXE=1.

After turning off the built-in polarization in our simulation, the Peltier cooling is reduced by about 30%, almost as much as with a GaN pn-homojunction. In both cases, the missing polarization charges reduce the potential barrier for carriers.

Considering the dominating heat production by non-radiative QW recombination, a simple strategy for enhanced heat removal at high current is the same as for efficiency droop suppression, namely the reduction of the QW carrier density at any given current. For example, our simulation with 18nm thick active layer results in 33% less heat generation while the Peltier cooling remains almost constant.

Further results and discussion will be presented at the conference, including the Peltier cooling effect on the efficiency droop.

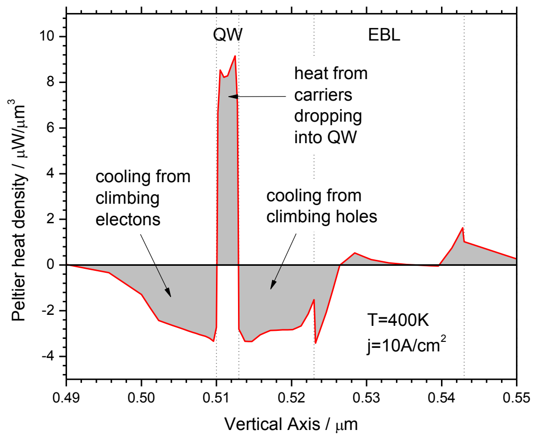

Fig. 3: Vertical Peltier heat profiles near the quantum well.

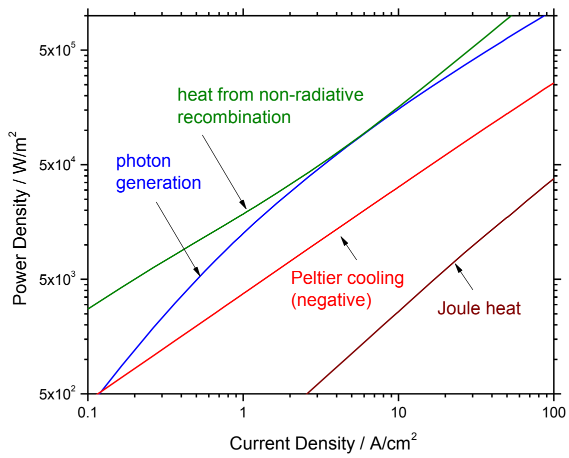

Fig. 4: Contributions to the total LED power budget vs. current.

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