Reduced heating effects in MBE grown nanowire array LEDs

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It has been theoretically demonstrated that junction temperature in nanowires can be significantly lower than that in bulk devices [1]. However, very little research has been reported on the thermal properties of nanowire LED devices. In this regards we have investigated the impact of the Joule heating of axial InGaN/GaN nanowire light-emitting diode (LED) grown by molecular beam epitaxy (MBE) on Si (111) and presented a systematic nanowire LED thermal theoretical model for the first time.

Four nanowire LED samples are spontaneous formatted under nitrogen rich conditions and nanowires with different geometries were obtained through different growth conditions. Figure 1 shows the measured peak wavelength of the samples at the same injection level. It can been seen that the peak wavelength shows a red shift of ~ 40 nm for sample with filling factor of 70% while only shows a red shift of ~ 20 nm for samples with filling factor of 10%. Since the red shift is commonly considered as the evidence of the LED self-heating effect [2], therefore the Joule heating effect of nanowires is significantly reduced for samples with low filling factors. Also observed is the large inhomogeneous broadening of the active region interplay with higher filling factors, which can be attributed to the increase of the junction temperature (shown in the inset). A significant improved EQE spectrum can also be observed in samples with low filling factors, as shown in Figure 2. These results indicate that nanowires with a low filling factor have much better thermal dissipation and conversion efficiency compared to nanowires with a high filling factor or conventional planar structures.

Based on the results in this work, a systematic simulation and theoretical model was presented for the first time to interpret the thermal transport process of the nanowire LEDs.

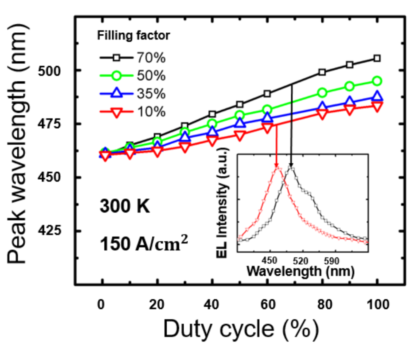

Figure 1 Peak wavelength of nanowire LEDs samples with different filling factor under different duty cycle at same injection level. The inset is the EL spectrum of nanowire LED samples under cw injection with filling factor of 10% and 70% respectively.

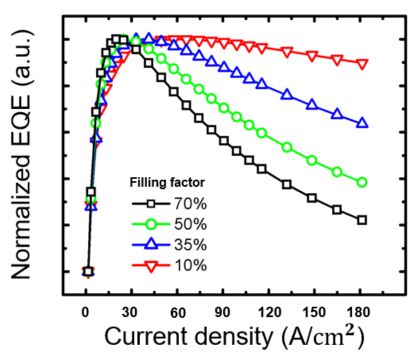

Figure 2 Measured EQE for samples with different filling factor.

Reference:

[1] Guthy, C. J, Appl. Phys, 103(6), 064319 (2008).

[2] Hong, C.C, Opt. Express, 17(20), 17227 (2009).

Supplementary Pages (Optional)

In order to investigate the thermal properties of nanowire LED devices, three-dimensional thermal simulations were performed using ANSYS Multiphysics, a commercial finite element analysis (FEA) software package.

The thermal transfer by conduction is determined by the first law of thermodynamics and Fourier's Law for heat transfer:

$$\frac{\partial Q}{\partial t} = -k \oiint \nabla T * dS$$

Where $\frac{\partial Q}{\partial t}$ is amount of heat transferred per unit time (in W) and ∇T is the temperature gradient (°C/m). k is the thermal conductivity (W/m·°C).

The boundary conditions described above are then solved and the steady-state temperatures throughout the structure are calculated, including at the junction region. From there, the thermal resistance of the device can be obtained.

We then simulate the nanowire structures. In this case, it is important to set up a comprehensive model which reflects the critical geometry of the real device. Since the nanowire geometry varies from one sample to another, we closely followed the geometry observed in TEM and SEM images of our experimental samples when creating the simulation model. The detailed geometry used in the simulation of the nanowire structures is shown in Figure 3. Each nanowire is separated into three parts: the n-type GaN (300 nm), p-type GaN (600 nm) and the active region (100 nm). The active region is at the center of the nanowire. In the simulation, we assume that heat is generated by the carrier recombination in the active region only. The nanowires are separated with a distance of 10 nm at the top. They are surrounded with a filling material (polyimide) and rest on a silicon substrate. Air can be found above the nanowires. This geometry matches closely to experimentally grown nanowires.

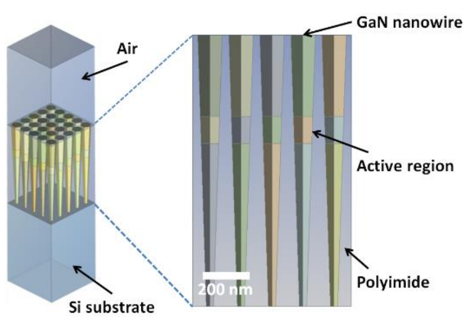

Figure 3 Illustration of nanowire LED structure used in the simulation.

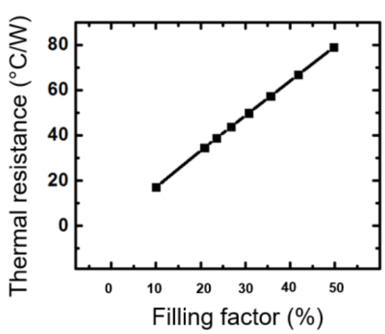

Figure 4 Calculated thermal resistance as a function of filling factor.

The calculated results are shown in Figure 4. From the figure, an increasing trend in thermal resistances can be clearly observed with increasing filling factors. This result is not surprising. Indeed, a nanowire array with a large filling factor has nanowires set very close to each other. Although nanowires have large surface area, there is much less in-plane heat transfer, due to limited material between each active region acting as a heat source. However, when the nanowires are far away from each other, the large surface area acts as an effective thermal conduction channel and it reduces the overall thermal resistance. If the distance between different nanowires equals 110 nm, which give a filling factor of ~ 10%, the thermal resistance is only ~18.7 °C/W.