Nanobeam photonic crystal cavity light-emitting diodes

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We present results on electrically driven nanobeam photonic crystal cavities formed out of a lateral p-i-n junction in gallium arsenide. Despite their small conducting dimensions, nanobeams have robust electrical properties with high current densities possible at low drive powers. Much like their two-dimensional counterparts, the nanobeam cavities exhibit bright electroluminescence at room temperature from embedded 1250 nm InAs quantum dots. A small room temperature differential gain is observed in the cavities with minor beam self-heating suggesting that lasing is possible. These results open the door for efficient electrical control of active nanobeam cavities for diverse nanophotonic applications. © 2011 American Institute of Physics. [doi:10.1063/1.3625432]
intrinsic region widths of 400 nm and 5 μm as well as for a control sample beam with no holes and an intrinsic region of 400 nm. As expected, the current is substantially reduced by two orders of magnitude when the intrinsic region is large due to the poor diffusion of carriers across the junction. Interestingly, the current magnitudes are very similar for both control and regular samples, with a current near 10 μA for a 1.2 V bias. Despite the reduced current cross sectional area of the beams with holes, the presence of additional etched surfaces creates a greater recombination current. Therefore, the narrow 100-200 nm conducting sidewalls of the beams are large enough for efficient carrier flow. The series resistance of 9000 Ω agrees well with the geometrical sheet resistance of our structure and is correspondingly larger than the 1150 Ω measured in 2D membranes. We perform 2D Poisson simulations of our devices using the Sentaurus package by incorporating measured doping densities, mobilities, and non-radiative recombination lifetime values. Full details of our method will be reported elsewhere. Figure 2(a) displays the simulation current data alongside the experimental data, where reasonable agreement is seen for all three structures. Recombination current accounts for approximately 95% of the total current with the remaining portion due to diffusion. The slightly lower simulation values are likely due to the exclusion of top and bottom device surfaces, for which extra recombination current would be observed. Also, the experimental intrinsic region width is slightly narrower than the simulated width due to dopant diffusion, giving rise to greater current. We find that the diffusion length of electrons (holes) is about 200 nm (40 nm) due to the fast non-radiative recombination in the structure. In Figure 2(b), we see the steady state carrier densities for a 1.2 V bias along the beam length with a 150 nm offset from the center axis. The injected electron and hole densities are only 4 × 10^{15} cm^{-3} due to the fast (6 ps) non-radiative recombination lifetime. Two-dimensional plots of the carrier densities for a 1.2 V bias are seen in Figures 2, where it is clear that the minority carriers are well localized to the cavity region. Finally, Figure 2(e) shows a map of the current density at 1.2 V for which high currents are observed in the beam sidewalls at values up to 10 kA/cm^2.

Electroluminescence (EL) data was taken at room temperature by forward biasing the nanobeam diodes and collecting the emission with a spectrometer and liquid nitrogen cooled InGaAs CCD array detector. Figure 3(a) displays the output spectrum for a nanobeam biased to 5 μA. Bright cavity mode emission is seen superimposed upon the weaker QD background, indicating successful carrier injection into the nanobeam cavity. The cavity mode has a quality factor of 2900 (Figure 3(b)), well below the theoretical value of 95 000. We believe the quality factor is limited both by fabrication imperfections as well as free carrier absorption by the nearby doping regions. As seen in Figure 3(c), the IR output emission is heavily concentrated to the nanobeam cavity center with a small amount of scattered emission visible at the nanobeam edges. We next investigate the properties of the nanobeams as we increase the injection current. For this experiment, a different cavity than the one seen in Figure 3(a) was used due to accidental device failure. The quality factor of the mode probed in this cavity is about 500. In Figure 3(d), the cavity output emission and Q-factor are plotted versus injection current. The cavity power output is linear for the entire range and therefore no lasing is observed. A small amount of room temperature linewidth narrowing was observed as the Q-factor increased with injection current. Therefore, we believe it is possible to obtain lasing in these important nanophotonic structures with much higher Q cavities. In order to characterize the heating effects of electrically pumped nanobeams, we examine the peak wavelength as a function of injection current. Figure 4(a) shows that the mode wavelength shifts by less than 1 nm for 5 μA of injection current. The thermal dependence of the refractive index of GaAs near 1.3 μm is given by \( dn = 2.7 \times 10^{-4} \Delta T \) K^{-1}, where \( \Delta T \) is the change in temperature and \( dn \) is the change...
in material refractive index.\textsuperscript{14} Hence the cavity wavelength is expected to shift via second order perturbation theory as $\frac{dk}{k} = \frac{dn}{n}$, where $dk$ is the change in mode wavelength, $k$ is the cavity peak wavelength, and $n$ is the nominal material refractive index. For a measured $dk$ of 0.6 nm, $k = 1266$ nm, and $n = 3.5$, the calculated temperature rise is only 6 K. For comparison, we calculate the lattice temperature from a hydrodynamic transport model in Sentaurus and find that the heating is 3.3 K at the cavity center. Therefore, our electrical design is very robust against self-heating despite the large injection current densities.

In summary, we have demonstrated efficient electrically driven photonic crystal nanobeam cavity LEDs at room temperature. The results here are an extension of our lateral p-i-n junction design in 2D PCs showing the versatility of the fabrication technique. Our nanobeams have excellent electrical properties even with their narrow conducting paths. Future designs could incorporate surface passivation techniques to slow down non-radiative recombination and hence increase the charge injection level. Other geometrical modifications such as beam width and hole size could further optimize the device performance. The electrical control of nanobeam cavities demonstrated here is an important step forward in developing practical on-chip devices for diverse applications such as lasers, sensors, and optomechanics.

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\begin{figure}[h]
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\caption{(Color online) (a) Plot of the cavity peak wavelength versus injection current. (b) 2D map of the change in temperature (in ÅK) of the nanobeam device for a bias voltage of 1.2 V. The cavity center only heats by about 3.3 K.}
\end{figure}

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