Supplementary Information: Ultrafast direct modulation of a single mode photonic crystal nanocavity light-emitting diode

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Supplementary Figure S1. (a) Lifetime measurements for a pre-annealed bulk sample at 45K. Data was renormalized into 3 nm bins for clarity. (b) Lifetime at 1,210 nm as indicated by the vertical dashed line in (a). (c) Lifetime measurements for a pre-annealed bulk sample at 300K. Data was renormalized into 3 nm bins for clarity. (d) Lifetime at 1,210 nm as indicated by the vertical dashed line in (c).
Supplementary Figure S2. (a) Photoluminescence lifetime measurements at 10K for the directly modulated cavity mode investigated in the main text. Dashed lines indicate wavelengths where on- and off-resonant lifetimes were taken. (b) Lifetime data and decay fits for both the cavity mode and nearby uncoupled QD emission from the photonic crystal. The dominant exponential lifetimes were found to be 40 ps and 120 ps for cavity and uncoupled emission, respectively. (c) Photoluminescence lifetime measurements at 10K for a regular cavity that was undoped and not annealed. Dashed lines indicate wavelengths where on- and off-resonant lifetimes were taken. (d) Lifetime data and decay fits for both the cavity mode and nearby uncoupled QD emission from the photonic crystal. The dominant exponential lifetimes were found to be 300 ps and 620 ps for cavity and uncoupled emission, respectively.
Supplementary Figure S3. (a) Photoluminescence lifetime measurements at 300K for a regular cavity that was undoped and not annealed. Dashed lines indicate wavelengths where lifetime data were taken. (b-d) Lifetime data and decay fits for the cavity mode (in (b)) and nearby uncoupled QD emission from the photonic crystal (in (c) and (d)). Purcell enhancement is not observed and the decay lifetime of 6 ps is seen for all points shown. The lifetime value increases slightly for longer wavelengths as seen in Figure 3 but Purcell enhancement is never observed at room temperature.
Supplementary Methods

Bulk lifetime measurements

Low temperature optically pumped lifetime measurements were performed on unpatterned regions of pre-annealed samples to determine the nominal quantum dot spontaneous emission lifetime. Supplementary Fig. S1a-b shows a spectrum of QD lifetime information at 45K, revealing that the quantum dot lifetime is over 1 ns for wavelengths greater than 1,210 nm. The lifetime decreases monotonically with wavelength as expected due to shallower carrier confinement and stronger dipole transition strength. Supplementary Fig. S1c-d shows a spectrum of QD lifetime for a room temperature sample that was not annealed. As described in the main text, the lifetime is 100-300 ps, limited by defect driven non-radiative recombination in bulk material.

Diode RC delay

The electrical bandwidth of the device is given by the inverse of the RC time constant:

\[ \frac{1}{2\pi \tau_{RC}} = \frac{1}{2\pi RC} \]

(S1)

Where \( \tau_{RC} \) is the time constant, \( R \) is the series resistance, and \( C \) is the junction capacitance. From measurement we know that \( R \) is 1.3 kΩ. The junction capacitance can be approximated using a simple electrostatic model for a 1D diode (neglecting fringing capacitance), given by:

\[ C = A \left\{ \frac{q\epsilon N_A N_D}{2V_{bi} (N_A + N_D)} \right\}^{1/2} \]

(S2)

The junction area, \( A \), is about 1 µm x 220 nm = 2.2x10^{-9} cm². The electrical permittivity of GaAs, \( \epsilon \), is 11.7x8.85x10^{-14} F/cm. The doping concentrations are found from our former study as \( N_A = 6x10^{17} \) cm^{-3} and \( N_D = 2.5x10^{19} \) cm^{-3}. The built in voltage, \( V_{bi} \), is approximately 1 V. Therefore we find \( C = 0.5 \) fF and \( 1/2\pi \tau_{RC} = 245 \) GHz which is well above the bandwidth tested for the experiments.
LED output power

The output power for the LED can be estimated by calculating optical losses in the experimental setup and by estimating the fraction of light collected by the objective lens using a Fourier analysis\textsuperscript{26}. When this is done, the output power for devices is estimated to be 10-32 pW at 2.5 µA, 63-200 pW at 6 µA, and 210-670 pW at 18 µA. These values are consistently lower than the reported lasing output power found previously\textsuperscript{6} as expected for an LED device.

Supplementary Discussion

Studies on the cavity spontaneous emission lifetime reduction were performed in order to determine the feasibility of Purcell enhancement as a fast switching mechanism. The same cavity investigated in Figure 4 was cooled to 10K and optically pumped for time resolved PL measurements. We utilize optical pumping and not electrical pumping at low temperature because our cryostat has a limited electrical bandwidth of 100 MHz\textsuperscript{27}; however the results should be identical since our device is not limited by RC delay. Supplementary Fig. S2 shows that at cryogenic temperatures, there is indeed a reduction in quantum dot PL lifetime at the cavity mode wavelength (relative to QD's uncoupled to the cavity). We find a Purcell-enhanced cavity lifetime of 40 ps at 1,100 nm and a non-resonant QD lifetime of 120 ps. In order to calculate the Purcell factor we note that our lifetimes can be expressed as follows:

\[
\frac{1}{\tau_{\text{cav}}} = \frac{F_C}{\tau_{SP,QD}} + \frac{1}{\tau_{\text{leak}}}
\]

(S3)

\[
\frac{1}{\tau_{\text{un}}} = \frac{1}{\tau_{SP,QD}} + \frac{1}{\tau_{\text{leak}}}
\]

(S4)

Here \(\tau_{\text{cav}}\) is the lifetime of emission coupled to the cavity (40 ps in this case), \(\tau_{\text{un}}\) is the lifetime of QD's not coupled to the cavity (120 ps here), and \(1/\tau_{\text{leak}}\) accounts for all other carrier decay rates including non-radiative recombination and carrier escape. By subtracting these two equations, we can find that the Purcell factor is given by \(F_C = \tau_{SP,QD}(1/\tau_{\text{cav}} - 1/\tau_{\text{un}}) + 1\). For a measured bulk QD SE lifetime, \(\tau_{SP,QD}\), of 270 ps at 1,100 nm, we calculate a Purcell factor of 5.5 for the cavity mode. This value agrees well with
a similar result obtained in reference 17 and suggests that Purcell enhanced single-mode diodes with fast modulation speeds may be possible at cryogenic temperatures for this material system. Optimization of the spatial and spectral overlap of the quantum dots with the cavity mode could lead to higher enhancement factors as well. Purcell enhancement as a mechanism for fast switching, however, is limited to only cryogenic temperatures for these particular InAs quantum dots. As discussed in the main text, elevated temperatures cause carriers to escape from their confining potentials and relax non-radiatively at a rate much faster than any Purcell enhanced spontaneous emission. For the room temperature emission of the directly modulated device, we see identical QD lifetimes both on and off resonance from the cavity mode with the emission tracking the current pulse in both cases.

We repeat PL lifetime measurements for undoped QD samples with pre-annealed quantum dots to verify that this effect is not due to the fabrication of the electrically driven sample. Supplementary Fig. S2c-d shows lifetime data for a similar cavity that is not electrically contacted at 10K. Indeed, the cavity emission shows a reduced spontaneous emission lifetime compared to non-resonant QD emission with a calculated Purcell factor of 2.5. The lifetime values for this sample are longer than those found in Supplementary Fig. S2a-b primarily because of the longer wavelength cavity used here, but Purcell enhancement is observed in both cases. Meanwhile, in Supplementary Fig. S3, we see that at room temperature, the carrier lifetime is short due to non-radiative recombination and is flat across the wavelength range. Purcell enhancement is not seen for the cavity modes at room temperature, in contrast to low temperature, confirming the prediction. Therefore, the demonstration of a Purcell enhanced nano-LED would require quantum dot material improvements, which is outside the scope of our work. Still, the presence of the nano-cavity in our LED has several great benefits, including the improvement of the device efficiency (increased light emission into the cavity mode and channeling in the desired, collection direction), reduction in the modulation energy per bit, and single mode operation.

Supplementary References