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Ultrafast directly modulated single-mode photonic crystal nanocavity light-emitting diode

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1. Introduction

Optical interconnects have attracted much research attention in recent years owing to potential performance and power consumption improvements over traditional electrical connectivity. Unfortunately, previously demonstrated laser sources have µW to mW thresholds and the best external modulators consume 100 s of fJ to pJ per bit level energies [1-2]. Alternative to the standard approach of using a continuous wave laser and external modulator, direct modulation of a fast optical source can drastically reduce the energy consumption for the transmitter. Recently, we demonstrated an electrically driven photonic crystal (PC) quantum dot (QD) nanocavity laser with world record low threshold of 208 nW based on a lateral p-i-n junction defined by ion implantation in gallium arsenide [3]. In this work, we show that we are able to electrically switch such a single-mode photonic crystal nanocavity light-emitting diode (LED) at 10GHz speed and at room temperature with electrical injection power at the µW level. As a photonic crystal cavity has only a few unique modes in spectrally distant locations, our diode is effectively a single-mode light source and can be used as a fast, low-power transmitter for optical interconnects.

2. Fabrication and device characteristics

Fabrication

Fig. 1(a,b) shows a schematic of a fully fabricated photonic crystal cavity LED. A series of ion implant steps through a silicon nitride mask defined the lateral p-i-n junction in a 220 nm thick GaAs membrane with embedded high density quantum dots, as in our previous work [3,4]. After an activation anneal for the dopants, photonic crystals were patterned and transferred to the membrane through a dry etch step. Metal contacts were then deposited and the sacrificial AlGaAs layer beneath the GaAs membrane was wet etched to release the photonic crystal structures.

Device properties

The measured current-voltage characteristics for a device are shown in Fig. 1(c). Our LED has robust electrical properties with over three orders of magnitude on/off ratio and minimal leakage current. A spectrum of the emission for the LED is shown in Fig. 1(d) at a forward bias current of 10 µA and at room temperature. Bright and clearly defined cavity modes peak well above the background quantum dot emission with the fundamental mode centered at 1,260 nm. From pump power dependent studies, we find that our diode is non-lasing at room temperature due to the reduced gain of our annealed QDs at room temperature as well as our high cavity loss (Q ~ 1600).

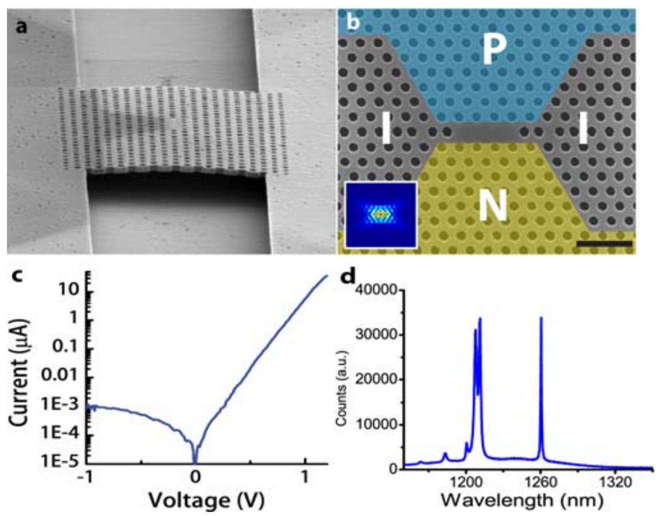

Fig. 1. (a) Tilted SEM of fully fabricated lateral PIN LED device. (b) Top-down SEM and doping layout schematic of an LED device. The inset shows a simulated field profile for the cavity mode and the scale bar is 1 µm. (c) Measured room temperature IV characteristic of the LED. (d) Output QD emission at 10 µA forward bias.

3. Ultrafast direct modulation

We first perform time resolved lifetime measurements using a Ti:Sapphire optical pump to examine the recombination rates in our system. We find that our rapid thermal anneal step substantially decreases the QD lifetime from 200 ps (pre-anneal) to 10 ps (post-anneal). Likely, the QD confinement potential is reduced due to dot size and composition modification, allowing carriers to escape much faster than ordinary spontaneous emission [5]. In addition, the fast (6 ps) non-radiative recombination from etched hole surfaces quenches the carriers, allowing QD emission to turn on and off within a duration of tens of picoseconds.

For our direct modulation experiment, we apply short voltage pulses to our LED device via high speed probes and monitor the output emission with a streak camera (Fig. 2(a)). As seen in Fig. 2(b,c) the cavity output replicates the input pump current pulse extremely well with only a slight turn on delay. The entire pulse duration (the time above 10% of the peak height) is less than 100 ps and therefore the LED switching speed for a non-return-to-zero signal is approximately 10 GHz. Compared to previously shown directly modulated photonic crystal single-mode LEDs at cryogenic temperatures [6], this speed is over an order of magnitude faster with three orders of magnitude lower power consumption (here only 2.5 μW). Next we directly modulate our diode with a pulse train to observe dynamic behavior with a multiple bit sequence. Figure 3 shows the light output for two different bit sequences, along with corresponding pump signal data. The diode replicates the bit sequences well and behaves very much like the single-shot measurement above. Fast electrical data is thereby effectively mapped onto the single mode carrier of the nanocavity LED, which can be used as the light source for an optical interconnect link.

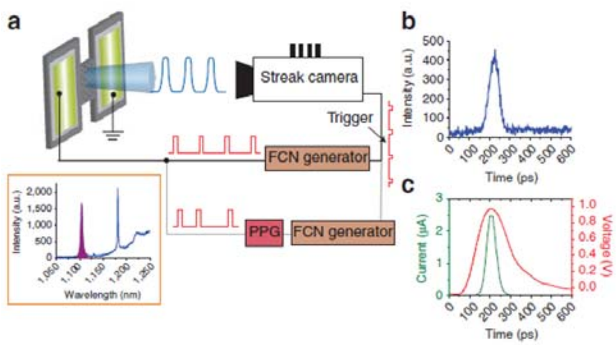

Fig. 2 (a) Schematic of the direct modulation experiment. PPG is pulse pattern generator and FCN is function generator. We use a higher order cavity mode (inset of (a) due to the increased sensitivity of our streak detector at short wavelengths. (b) The output optical pulse measured when the LED is driven by the pulse shown in (c). (c) Driving voltage and current pulses for the measurement in (b). The peak power is only 2.5 μW.

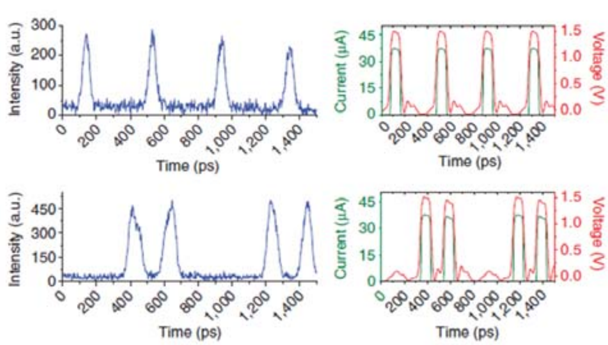

Fig. 3 Diode response for two different bit sequences in top and bottom panels. The applied electrical voltage and current are shown on the right and the LED optical output is on the left.

3. Conclusions

The results presented here show for the first time GHz speed direct electrical modulation of a single mode LED at ultra-low energies. In fact, the measured power consumption for the 10 GHz pulse in Figure 2 is only 2.5 μW, indicating an average energy per bit of only 0.25 fJ. This exceptionally low value indicates significant improvement over the standard approach of using slow, high threshold lasers and external modulator components. Information can just as easily be communicated over a directly modulated low power source, skipping the external modulator altogether. Our PC LED has one of the fastest switching speeds ever demonstrated for an LED device, either low power and single mode or high power and multimode. While we don't explicitly measure a -3 dB point, a single-pole analysis of the 10 ps turn-off time found above for QDs at 1,100 nm suggests a very large -3 dB bandwidth of 16 GHz. In summary we have demonstrated an ultrafast single mode nanocavity LED operating at room temperature with 10 GHz large signal direct modulation speed. The low energy per bit of these optical sources makes them promising for future energy efficient optical interconnect applications.

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