Low-Threshold Ultrafast Surface-Passivated Photonic Crystal Nanocavity Lasers

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Abstract: Efficiency and speed of photonic crystal lasers are improved by passivating InGaAs/GaAs membranes using $(NH_4)S$ treatment. Lasers show five-fold reduction in nonradiative surface recombination rate, resulting in four-fold reduction in threshold and room-temperature operation with near THz response.

Photonic crystals (PCs) allow unprecedented control over the radiative properties of integrated emitters. By defining small mode-volume, high-quality factor (Q) cavities in PCs, enhanced light-matter becomes possible. This property has opened possibilities in fields including cavity quantum electrodynamics, detection, and light sources. Lasers in particular stand to gain through dramatically decreased lasing threshold, modulation rate, cost, and large-scale device integration. From their first demonstration [1], PC lasers have most commonly relied on QWs for optical gain. However, QWs limit PC laser performance in many material systems because of large nonradiative (NR) surface recombination. This problem is particularly damaging in PC structures where embedded QWs expose a large surface area. In this letter, we present our recent results on NR recombination problem addressed by surface passivation. We show that (NH4)S-mediated surface passivation of PC laser structures lowers the NR recombination rate by more than 5 times and leads to 4 times reduction of lasing threshold. The increased efficiency extends the operating range from cryogenic to room-temperature and enabled lasing at THz-modulation rates due to faster relaxation into the QWs as elevated temperatures. A three-level rate equations model fits our experimental data well and suggests that surface passivation is crucial for PC lasers in InGaAs/GaAs and other material systems with fast NR surface recombination both for lasing threshold and speed.

The PC nanocavity lasers consist of 172 nm-thick GaAs slabs patterned with 9x9 arrays of single-hole cavities defined in a square-lattice PC, similar to those described in Ref.[2]. A central stack of four 8-nm In0.2Ga0.8As QWs, spaced by 8-nm GaAs barriers, forms the gain medium. This sample is passivated using a solution of 7% (NH4)S in water following Ref.[3]. The treatment removes contamination and oxides from the GaAs and In0.2Ga0.8As surfaces and caps the fresh surface with sulfur atoms [3-4].

We measured the radiative and NR properties, as well as lasing characteristics, before and after surface passivation (Figure 1). The PL decay lifetime from the PC mirror region is extended to $\tau_{PC} \sim 142$ ps from $\tau_{PC} \sim 33.8$ ps before passivation, while the decay lifetime from the bulk QW has nearly unchanged lifetime $\tau_{bulk} \sim 571 - 614$ ps at 10μW pump power. Here we pump and collect only the PC membrane, away from the cavity. This data is analyzed using the three level rate equations, which include carrier populated above the GaAs-bandgap and at the QW lasing level. Since the pump is away from the cavity, Purcell enhancement is not applicable and the structure is not lasing such that F=1 and P=0, respectively. Total decay time is given by $1/\tau_{PC} = 1/\tau_{PC,nr} + F_{PC}/\tau_r$. Here, F_{PC} corresponds to the spontaneous emission quenching inside the PC bandgap compared to SE rate in the bulk. Its value is taken as 0.2 following simulation results. With this inputs, the lifetime data then lets us estimate the unpatterned bulk SE lifetime $\tau_r \sim 654$ (605) ps and NR lifetime $\tau_{PC,nr} \sim 35.5$ (188) ps in the PC mirrors before (after) passivation. The results indicate that non-radiative process is nearly five times slower. Fig.1b shows the lasing curves for the original and passivated structures. The lasing threshold is reduced nearly 75%. Suppression of non-radiative surface recombination reduces additional loss mechanisms, and therefore dramatically reduces lasing threshold. This reduction also agrees well with the value that we obtained by solving three level laser rate equation.

Room-temperature (RT) operation is more challenging because of heating problems associated with higher threshold, and was previously not possible with our structures. We achieved RT lasing after suppressing nonradiative surface recombination via surface passivation. RT operation allows remarkably fast full-signal

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laser modulation rates. In Fig.2, we present streak camera measurements of the lasing response to 3.4-ps-long pump pulses (13 ns repetition) at LT and RT. Both measurements were obtained with pump powers roughly 2× above threshold, corresponding to averaged pump powers of 13 µW and 136µW at LT and RT, respectively. We measured significantly faster lasing response at RT, with the lasing pulses roughly following the pump duration. This speed-up is due to faster phonon-mediated carrier relaxation at RT. The rise-time $\tau_{E,f}$ is streak-camera limited to less than 1 ps, which is significantly shorter than the LT rise-time of 6 ps. This behavior is captured well by the three-level rate equations model whose calculated response is convolved with a filter that takes into account the 3.2-ps response time (FWHM) of the streak camera [5]. Based on our model, lasing response should approach FWHM=1.2 ps at 2× threshold pump power when pumped with shorter 1-ps laser pulses, implying modulation rates in the THz regime. This is shown in the inset of Fig.2, where the lasing response is modeled for two values of the carrier relaxation time into the lasing level, $\tau_{E,f}$ = 0.8ps and $\tau_{E,f}$ = 0.2ps. The delay can be decreased with increasing pump power, but is ultimately limited by the carrier relaxation time $\tau_{E,f}$.

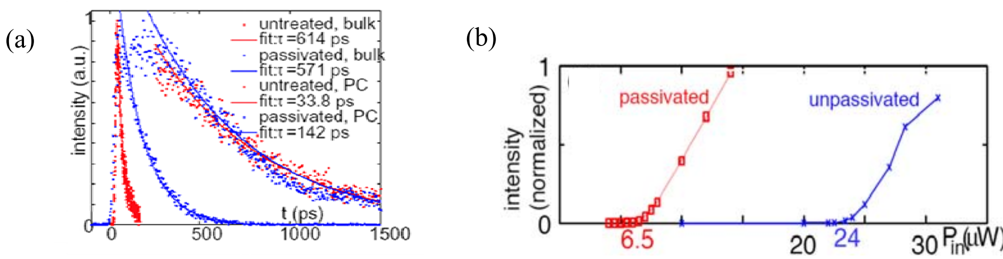

Figure 1 (a-b) PL measurements and lasing curve for the untreated (red) and passivated (blue) samples, from the PC and unpatterned regions at low temperature.

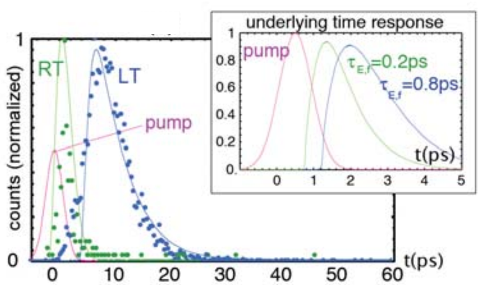

Figure 2 Photonic crystal laser time response. (a) At low temperature (blue curve), FWHM=14.1 ps at 2× above lasing threshold. At room-temperature (green), time response follows that of the pump laser with FWHM=3.5 ps. Inset: Calculated response to a shorter, 1-ps excitation pulse shows FWMH near 1 ps when pumped 2× above threshold; response is faster if we assume faster carrier relaxation time $\tau_{E,f}$.

In conclusion, we demonstrated that efficiency and speed of photonic crystal lasers are improved by passivating InGaAs/GaAs using $(NH_4)S$ treatment. Passivated lasers show five-fold-reduction in nonradiative surface recombination rate, resulting in four-fold reduction in threshold and room-temperature operation with near-THz response.

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References

[1] O. Painter, et. al., Science, **284** 1819–1821 (1999).
[2] H. Altug, D. Englund, and J. Vuckovic. Nature Physics, **2** 484–488 (2006).
[3] D. Y. Petrovykh, M.J. Yang, and L.J. Whitman. Surface Science, **523** 231–240 (2002).
[4] H. Oigawa, et. al., Japanese Journal of Applied Physics, **30 (3)** 322–325 (1991).
[5] D. Englund, Ilya Fushman, J. Vuckovic and H. Altug, to be published in Appl. Phys. Lett., 2007.