Extended Abstracts of the 2006 International Conference on Solid State Devices and Materials, Yokohama, 2006, pp. 36-37

B-1-3

Photonic Crystal Nanocavity Continuous-wave Laser Operation at Room Temperature

Masahiro Nomura, Satoshi Iwamoto, Katsuyuki Watanabe, Naoto Kumagai, Yoshiaki Nakata, Satomi Ishida, and Yasuhiko Arakawa

Institute of Industrial Science, Research Center for Advanced Science and Technology, and Nanoelectronics Collaborative Research Center, University of Tokyo, Tokyo 153-8505, Japan

Phone: +81-3-5452-6291, E-mail: nomura@iis.u-tokyo.ac.jp

1. Introduction

Photonic crystal (PhC) nanocavity lasers are considered one of the best candidates for ultra-low threshold lasers due to their small mode-volume of the order of cubic wavelength and high quality factor Q. The first PhC laser was reported on InGaAsP multi-quantum well (QW) structures by Painter *et al*. in 1999 [1]. PhC lasers with quantum dots (QDs) as the gain material have been more difficult devices to construct due to their inherently lower modal gain. Some groups have reported laser operation at certain conditions in PhC nanocavities with QDs: the first such lasing was reported at room temperature with pulsed excitation [2], and more recently, continuous-wave (cw) lasing at 4.5 K and up to 80 K using optical pumping has been reported [3]. However, in spite of the great importance, cw laser operation in PhC nanocavities at room temperature has been reported with neither QW nor QD as the gain materials so far due to its strict requirements for lasing.

In this paper, we demonstrate cw laser operation at room temperature in a PhC nanocavity with InAs self-assembled QDs as the gain material. The spontaneous emission coupling factor β was estimated by comparing experimental results with theoretical L-L curves calculated by a conventional coupled rate equation.

2. Sample Fabrication and Experimental Setup

We investigated PhC nanocavities fabricated in the sample grown on an undoped GaAs (100) substrate by molecular beam epitaxy. Firstly, a 300-nm-thick GaAs buffer layer was deposited on the substrate at 600°C. Then, a 700-nm-thick $Al_{0.7}Ga_{0.3}As$ sacrificial layer was grown at 600°C. Finally, a 250-nm-thick GaAs slab layer was grown including five-stacked self-assembled InAs QD layers as the active gain material. This slab layer consisted of five periods of structures grown on a 50-nm-thick GaAs layer grown at 600°C. Each 40-nm-thick period consisted of an InAs QD layer (~ 2 x 10^{10} cm^{-2}) grown at 445°C, a 4-nm-thick $In_{0.16}Ga_{0.84}As$ strain reducing layer grown at 445°C, and a 36-nm-thick GaAs inter-layer grown at 520°C.

The PhC nanocavity was fabricated by using electron beam lithography, with two dry etching processes and a wet etching process. The details of the processes and the architecture of the air-bridged sample can be found in ref. 4. We adopted an L3 defect structure, which consists of three missing air rods along the Γ-K direction of the triangular PhC lattice. In addition, the first and third nearest air rods at both edges of the cavity were shifted outside the cavity to obtain higher Q [5]. We fabricated a sample with a period of the lattice a = 353 nm and radius of the air rod $r = 0.27a$. In this structure, photons are confined by the photonic bandgap in lateral direction and by the refractive index contrast in vertical direction. Measurements were performed with a micro-photoluminescence setup at room temperature using a laser diode (λ = 785 nm) as the excitation source. The pump laser beam was focused to a 4 μm diameter spot on the sample surface by a microscope objective [50x, N.A. = 0.42]. The photoluminescence (PL) was collected by the same microscope objective.

3. Experimental Results and discussion

Figure 1 shows the lasing spectrum observed using cw pumping with an excitation power of 40 μW. The sharp peak observed at around 1.32 μm corresponds to the strong light emission from the cavity mode, which is located at the PL peak of the ground state of the InAs QD ensemble. The peak value of the lasing mode is greater than that of the PL peak by more than 20 dB. Single-mode operation was observed in a wide spectral range covering 60 nm, and lasing operation was observed for many PhC nanocavities fabricated in the same wafer. For an accurate evaluation, we used 100 μs-long quasi-cw pumping with a repetition rate of 1 kHz (10% duty cycle) to avoid thermal problems in the following experiments. We note that the pump duration of 100 μs is much longer than the timescales of any dynamics in the system except the heating. Therefore, the quasi-cw excitation condition is equivalent to the cw excitation condition.

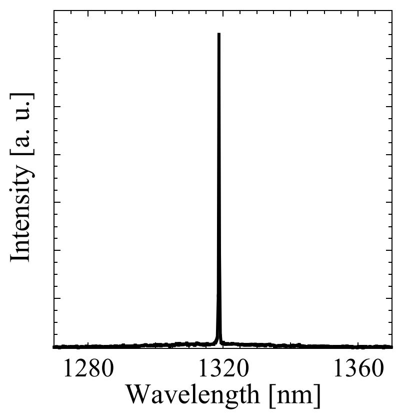

Fig. 1. Lasing spectrum observed using cw pumping with an excitation power of 40 μW at room temperature.

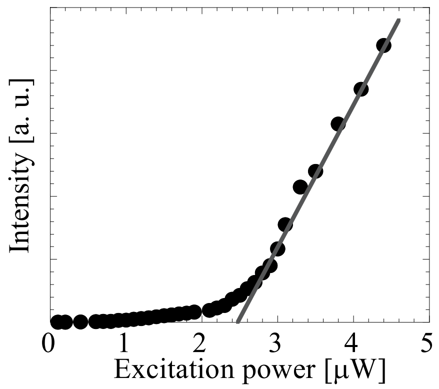

Fig. 2. Excitation power dependence of the output power.

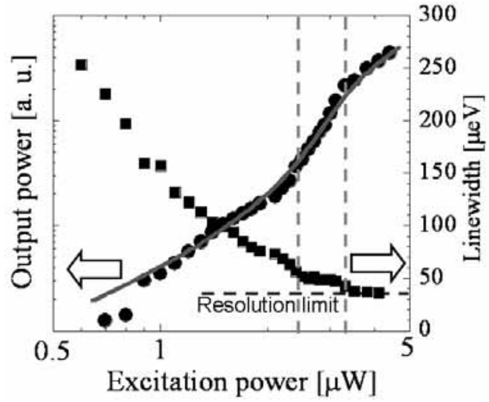

Fig. 3. Output power and linewidth measured at various excitation powers.

The excitation power dependence of the output power is shown in Fig. 2. The averaged threshold excitation power is ~ 2.5 μW at 10% duty cycle, corresponding to 25 μW for cw operation. The ratio of the absorbed power in the GaAs slab layer to the incident pump power is estimated to be 15%. Consequently, the actual threshold excitation power is ~ 4 μW for cw operation. Above the threshold excitation power, linear increase of the output power is observed as indicated by the gray line.

Figure 3 shows the L-L curve on a logarithmic scale and linewidths of the lasing mode on a linear scale, at various excitation powers. In order to evaluate the β of the PhC nanocavity laser, the experimental L-L plot is compared with theoretical L-L curves calculated using rate equations. A conventional coupled rate equation model [6] in a nanocavity was used. The value of $\beta = 0.22$ was obtained with parameters of the confinement factor = 0.01, transparent carrier density = 5 x 10^{14} cm^{-3}, radiative recombination time = 3 ns, non-radiative recombination time = 150 ps, and gain coefficient = 1 x 10^5 cm^{-1}.

Another important characteristic of the lasing operation is the narrowing of the emission linewidth. The linewidths measured below 0.2 μW have a constant value of ~ 380 μeV. This relatively wide linewidth corresponds to Q = 3,300, which is probably limited by the absorption of the InAs QDs. Below the threshold, the linewidth is decreased as the excitation power is increased, because the absorption by QDs is saturated. Around the threshold, the phase transition from spontaneous radiation into lasing results in a pronounced kink both in the output power and linewidth. The linewidth decreases above the threshold, reaching the energy resolution limit of 35 μeV, which corresponds to a Q factor of 27,000. The redshift of the lasing mode can be attributed to the change of the refractive index due to the sample heating.

We point out that three-dimensional carrier confinement, which is one of the important characteristics of a QD system, plays an important role in the cw laser operation at room temperature. The PhC nanocavity consists of air rod arrays, thus any photo-carriers diffuse and easily be captured at surface states at the material-air boundaries especially at room temperature. However, the diffusion of the captured carriers in QDs is suppressed in the QD system compared with other systems. We also point out the small volume effect of the QD system probably has an advantage in the laser operation in air-bridge-type PhC nanocavity structure. A remarkably low transparent carrier density of a PhC nanocavity laser with QDs requires much less excitation power, which avoids excessive sample heating.

4. Conclusions

We have experimentally demonstrated cw laser operation at 1.3 μm in a PhC nanocavity with InAs self-assembled QDs by optical pumping. The L-L curve shows a soft turn-on of lasing resulting in a relatively high spontaneous emission coupling factor of 0.22. The averaged lasing threshold power is ~ 2.5 μW at 10% duty cycle, corresponding to actual absorbed power of ~ 4 μW for cw operation. The linewidth of the lasing mode decreases by more than a factor of ten and reaches the measurable resolution limit of ~ 35 μeV. Two important characteristics of QD system of three-dimensional carrier confinement and small volume effect contribute to the cw laser operation at room temperature, but also critical is a high quality factor PhC nanocavity. This PhC nanocavity cw laser has, to the best of our knowledge, the smallest mode volume among the cw lasers operating at room temperature.

Acknowledgements

This work was supported by the Focused Research and Development Project for the Realization of the World's Most Advanced IT Nation, MEXT.

References

[1] O. Painter, R.K. Lee, A. Scherer, A. Yariv, J.D. O'Brien, and P. D. Dapkus, Science **284** (1999) 1819.

[2] T. Yoshie, O.B. Shchekin, H. Chen, D.G. Deppe, and A. Scherer, Electron. Lett. **38** (2002) 967.

[3] S. Strauf, K. Hennessy, M.T. Rakher, Y.-S. Choi, A. Badolato, L.C. Andreani, E.L. Hu, P.M. Petroff, and D. Bouwmeester, Phys. Rev. Lett. **96** (2006) 127404.

[4] M. Nomura, S. Iwamoto, T. Nakaoka, S. Ishida, and Y. Arakawa, Appl. Phys. Lett. **88** (2006) 141108.

[5] Y. Akahane, T. Asano, B. -S. Song, and S. Noda, Nature **425** (2003) 944.

[6] H. Altug and J. Vučković, Opt. Express **13** (2005) 8819.