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Response to "Comment on 'Tunnel injection $In_{0.4}Ga_{0.6}As$/GaAs quantum dot lasers with 15 GHz modulation bandwidth at room temperature'" [Appl. Phys. Lett. 81, 2659 (2002)]

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We thank Reidl and Hangleiter[1] for a critical reading of our recent letter.[2] In response we make the following comments. First, it is true that quantum dot (QD) lasers have not, hitherto, exhibited their full potential and the authors are right in pointing out that this is due to lack of carrier confinement at high temperatures. In fact, it may be noted that we have *measured* $f_{-3\,\mathrm{dB}}\sim 30$ GHz in InGaAs/GaAs QD lasers at 100 K,[3] where carrier heating is minimized. Another reason, of course, for QD lasers not exhibiting theoretically predicted performance is the inhomogeneity inherently introduced by self-organized epitaxy. The tunnel injection scheme was introduced to minimize carrier heating and even under high injection conditions at room temperature, the carrier distribution remains quasi-Fermi in these devices. Hence, dg/dn and T_0 are expected to be high in these devices as theoretically predicted by Luryi *et al.*[4]

Next, we turn to the formulation for dg/dn. In Eq. (1) in Ref. 1, substitution of $\alpha=\Gamma g^5$ leads to[5–8]

$$f_r^2=\frac{v_g^2\Gamma g}{4\pi^2}\frac{dg}{dn}S_0. \tag{1}$$

Also, since $\Gamma g v_g \cong 1/\tau_p$, and substituting from the rate equations, the relation[5]

$$S_0=\frac{\tau_p\eta_d\Gamma}{qV_{\mathrm{act}}}(I-I_{\mathrm{th}}) \tag{2}$$

one gets[9–12]

$$f_r=D(I-I_{\mathrm{th}})^{1/2}, \tag{3}$$

$$\text{where}\qquad D=\frac{1}{2\pi}\left(\frac{v_g\dfrac{dg}{dn}\Gamma\eta_d}{qV_{\mathrm{act}}}\right)^{1/2}. \tag{4}$$

We have used Eq. (4), which is found frequently in the literature, in addition to the references cited, to calculate the differential gain dg/dn. In our calculation of Γ, we have included the dot fill factor of 0.28 and we do not agree with Reidl and Hangleiter[1] in that the dot coverage has no influence. We might point out that Eq. (4) is used to calculate dg/dn in quantum well lasers, where also, Γ is small. Equation (4) also indicates that $D\,[=\Delta f_r/\Delta(I-I_{\mathrm{th}})^{1/2}]$ is proportional to the confinement factor Γ. This is indeed borne out by experiment.[13] Hence, dg/dn is inversely proportional to Γ.

We have recently determined the differential gain in our quantum dot lasers directly from the measured dependence of J_{th} on the cavity length and by measuring the modal gain as a function of injection current.[14] The data re shown in Fig. 1, which gives a value of $dg/dn\sim 2\times 10^{-14}$ cm^2. This is a factor of 4 lower than that reported in Ref. 2, but certainly an order of magnitude higher than that in quantum well lasers and in reasonable agreement with data reported by other groups.[15] Therefore, present day quantum dot lasers do exhibit high dg/dn at room temperature.

Finally, a comment on the measured and predicted small-signal modulation bandwidths in quantum dot lasers. In conventional separate confinement heterostructure QD lasers, the value of $f_{-3\,\mathrm{dB}}$ is low at 300 K because of significant hot-carrier problem and the resulting gain compression. However, by using techniques such as tunnel injection as demonstrated by us, or by reducing emission linewidth by *p*-type doping as demonstrated by Shchekin and Deppe,[16,17] bandwidths much larger than 10 GHz can be obtained at 300 K. We have recently reported[18] a measured $f_{-3\,\mathrm{dB}}\sim 22$ GHz in 3 μm$\times$400 μm tunnel injection $In_{0.4}Ga_{0.6}As$/GaAs QD lasers at 300 K.

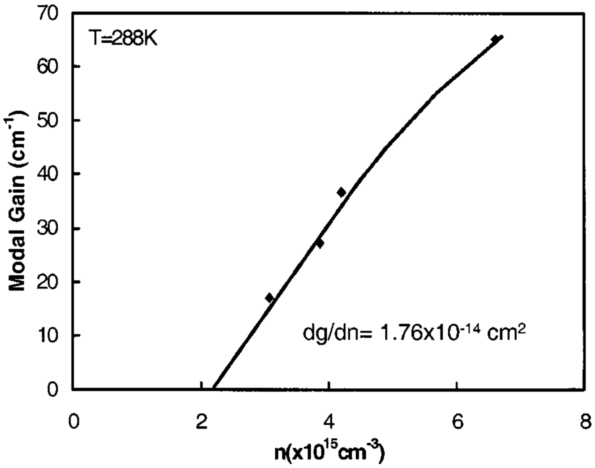

FIG. 1. Measured dependence of modal gain on injected carrier density in $In_{0.4}Ga_{0.6}As$/GaAs quantum dot single-mode ridge waveguide lasers at 288 K.

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0003-6951/2002/81(14)/2661/2/$19.00

[1] T. Reidl and A. Hangleiter, Appl. Phys. Lett. **81**, 2659 (2002), preceding paper.

[2] P. Bhattacharya and S. Ghosh, Appl. Phys. Lett. **80**, 3482 (2002).

[3] D. Klotzkin, K. Kamath, K. Vineberg, P. Bhattacharya, R. Murty, and J. Laskar, IEEE Photonics Technol. Lett. **10**, 932 (1998).

[4] L. V. Asryan and S. Luryi, IEEE J. Quantum Electron. **37**, 905 (2001).

[5] G. P. Agarwal and N. K. Dutta, *Semiconductor Lasers* (Van Nostrand Reinhold, New York, 1993).

[6] *Quantum Well Lasers*, edited by P. Zory, Jr. (Academic, Boston, 1993).

[7] L. A. Coldren, *Diode Lasers and Photonic Integrated Circuits* (Wiley, New York, 1995).

[8] J. Singh, *Semiconductor Optoelectronics: Physics and Technology* (McGraw-Hill, New York, 1995).

[9] S. Weisser, J. D. Ralston, E. C. Larkins, I. Esquivias, P. J. Tasker, J. Fleissner, and J. Rosezweig, Electron. Lett. **28**, 2141 (1992).

[10] H. Han, P. N. Freeman, W. S. Hobson, N. K. Dutta, J. Lopata, J. D. Wynn, and S. N. G. Chu, IEEE Photonics Technol. Lett. **8**, 1133 (1996).

[11] N. K. Dutta, J. Lopata, D. L. Sivco, and A. Y. Cho, J. Appl. Phys. **70**, 2476 (1991).

[12] R. Nagarajan, T. Fukushima, J. E. Bowers, R. S. Geels, and L. A. Coldren, Electron. Lett. **27**, 1058 (1991).

[13] M. C. Tatham, I. F. Lealman, C. P. Seltzer, L. D. Westbrook, and D. M. Cooper, IEEE J. Quantum Electron. **28**, 408 (1992).

[14] A. E. Zhukov, A. R. Kovsh, V. M. Ustinov, A. Yu. Egorov, N. N. Ledentsov, A. F. Tsatsul'nikov, M. V. Maksimov, S. V. Zaitsev, Yu. M. Shernyakov, A. V. Lunev, P. S. Kop'ev, Zh. I. Alferov, and D. Bimberg, Semiconductors **33**, 1013 (1999).

[15] D. Bimberg, N. Kirstaedter, N. N. Ledenstov, Z. I. Alferov, P. S. Kop'ev, and V. M. Ustinov, IEEE J. Sel. Top. Quantum Electron. **3**, 196 (1997).

[16] O. B. Shchekin and D. G. Deppe, Appl. Phys. Lett. **80**, 2758 (2002).

[17] D. G. Deppe and O. B. Shchekin, presented at the 60th Annual Device Research Conference, Santa Barbara, CA, June 2002.

[18] S. Ghosh, S. Pradhan, Z.-K. Wu, J. Singh, T. Norris, and P. Bhattacharya, presented at the 60th Annual Device Research Conference, Santa Barbara, CA, June 2002.