Model for a semiconductor quantum-dot nanolaser

W. W. Chow,[1] F. Jahnke[2] and C. Gies[2]

[1]*Sandia National Laboratories, Albuquerque, NM 87185-1086, wwchow@sandia.gov*

[2] *Institut für Theoretische Physik, Universität Bremen, 28334 Bremen, Germany,* jahnke@itp.uni-bremen.de, gies@itp.uni-bremen.de

Abstract: A quantum-electrodynamics model is developed for a nanolaser with a semiconductor quantum-dot gain region. Intensity, coherence time and photon autocorrelation function are calculated, especially during transition from below to above lasing threshold.

Advances in nanofabrication techniques enable development of optical cavities extending optical-mode confinement from one-dimensional to three-dimensional. Interesting and potentially useful is the possibility of only one cavity mode overlapping with the spontaneous emission spectrum. Among the cavity-quantum-electrodynamics phenomena is thresholdless lasing.

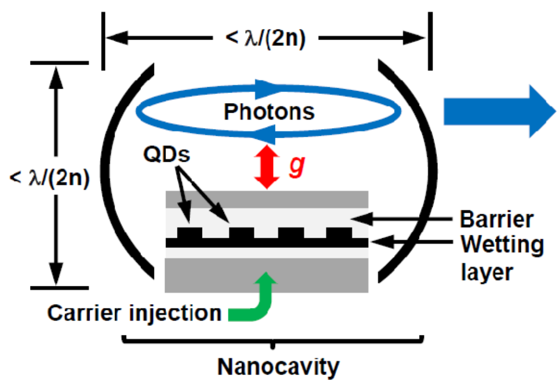

Figure 1. Sketch of quantum-electrodynamics nanolaser model.

A model is developed to investigate the emission properties of a nanolaser operating with a semiconductor active medium consisting of inhomogeneously-broadened semiconductor quantum dots embedded in a quantum well, where carriers are introduced via current injection. Figure 1 is a sketch of the generic nanolaser used in developing the quantum-electrodynamics model, which allows examination of emission properties during transition from thermal (chaotic) to laser (coherent) operation. [1] Basic features are an active medium inside optical cavity with each dimension less than $\lambda/2n$, where λ is lasing wavelength and n is background refractive index. Central to the physics is treatment of light-matter correlations (see red double arrow), characterized by coupling coefficient g.

The model is applied to address ongoing discussions relating to criteria for lasing and lasing threshold, in particular for thresholdless lasing when intensity jump, customarily used to indicate transition to lasing, vanishes (see dashed curve, Fig. 2). The computations are performed for an active medium consisting of $In_{0.3}Ga_{0.7}As$ quantum dots and wetting layer embedded in a GaAs quantum well. By assuming a cylindrical QD shape of 2nm height and 18nm diameter, the electronic structure calculation predicts only one electron bound state and one hole bound state because of the shallow quantum confinement. This simple electronic structure is well suited for illustrating the nanolaser behaviors of interest. In the active region, we assume 50 quantum dots giving an inhomogeneous broadening of 20meV. Other input parameters are: dephasing rate = $10^{13}s^{-1}$, nonradiative carrier loss rate = $10^{9}s^{-1}$, carrier-carrier scattering rate = $10^{13}s^{-1}$, carrier-phonon scattering rate = $10^{12}s^{-1}$ and cavity loss rate = $10^{10}s^{-1}$.

This talk will illustrate that combinations of intensity and coherence time, photon autocorrelation function or carrier spectral hole burning can provide a unique and consistent picture for nanolasers in the new regimes of laser operation. The solid curve in Fig. 2 shows the example of the combination of intensity and equal-time 2nd order intensity correlation versus current.

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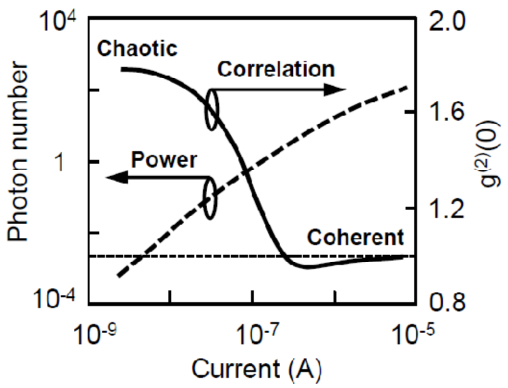

Figure 2. Combination of intensity (dashed curve) and 2nd order intensity correlation (solid curve) providing information on transition to lasing in a nanolaser, where there is complete channeling of spontaneous emission into lasing mode (β = 1).

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References

[1] W. W. Chow and F. Jahnke, 'On the physics of semiconductor quantum dots for applications in lasers and quantum optics,' Prog. Quant. Electron. vol. 37, pp. 109-184, 2013.