Temperature-Dependent Threshold Current in InP Quantum-Dot Lasers

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(Invited Paper)

***Abstract*—We explore the origins of the threshold current temperature dependence in InP quantum-dot (QD) lasers. While the internal optical mode loss does not change with temperature, the peak gain required to overcome the losses becomes more difficult to achieve at elevated temperature due to the thermal spreading of carriers among the available states. In 2-mm-long lasers with uncoated facets, this effect is responsible for 66% of the difference in threshold current density between 300 and 360 K. Spontaneous recombination current only makes up at most 10% of the total recombination current density over this temperature range, but the temperature dependence of the spontaneous recombination in the QD and quantum-well capping layers can be used, assuming only a simple proportional nonradiative recombination process, to explain the temperature dependence of the threshold current density.**

***Index Terms*—Nonradiative recombination, quantum-dot (QD) devices, semiconductor laser, short-wavelength lasers, threshold current density.**

I. INTRODUCTION

InGaAs self-assembled quantum-dot (QD) lasers, emitting in the 1–1.35-μm wavelength range, have been demonstrated with extremely low threshold current density, J_{th} (10.4 A·cm^{-2}) [1] and, in modulation p-doped structures, a threshold current that does not change with temperature (over the range 25–85 °C) [2]. These, coupled with the other advantageous characteristics of InGaAs QD lasers, have encouraged us to investigate the performance of lasers incorporating InP QDs grown on GaAs substrates that potentially cover the 650–780-nm wavelength range [3], [4]. Applications include more efficient high-power sources for photodynamic therapy (a cancer treatment), optical storage, sensing, and biophotonics, where operation in the red/near-infrared allows good tissue penetration and minimization of autofluorescence. For example, suitable light sources for fluorescence lifetime studies (using, e.g., Alexa Fluor Dye 647-749 or inorganic, QD reporters) for a range of life science applications could be accessed on an integrated chip fabricated from a single gain material due to the broad gain spectrum accessible in QD materials. These materials are also of interest as single photon sources [5]. Our previous work with InP dots has led to low threshold current density (e.g., 165 A·cm^{-2} at 300 K for 2-mm-long lasers with uncoated facets [6]) but the threshold current tends to increase superlinearly at higher temperatures, and in this paper, we want to identify the origin of this excess threshold current at elevated temperatures as it is the major factor limiting exploitation.

After describing the structures and our approach in Sections II and III, we begin with examples of the threshold current temperature dependence for typical InP QD lasers in Section IV, and then examine the role of gain and recombination processes in the temperature dependence of threshold current at elevated temperatures in Section V. We try to quantify the relative contributions of the relevant temperature-dependent processes in Section VI, and conclude in Section VII.

II. DEVICE STRUCTURES

The InP QD laser structures were grown by low-pressure metal organic vapor phase epitaxy (MOVPE) on n-GaAs (1 0 0) substrate oriented 10° off toward $\langle 1\,1\,1\rangle$ using trimethyl precursors for the group III elements and arsine $\mathrm{AsH_3}$ and phosphine $\mathrm{PH_3}$ as precursors of the group V elements. Self-assembled dots formed from the equivalent of 2.5 monolayers of InP material deposited on $(\mathrm{Al_{0.3}Ga_{0.7}})_{0.51}\mathrm{In_{0.49}P}$ were covered with 8-nm $\mathrm{Ga_{0.51}In_{0.49}P}$ quantum wells (QW). Structures contained five layers of dots in wells (D-WELL) grown in this way where each (D-WELL) layer was separated by 8-nm wide $(\mathrm{Al_{0.3}Ga_{0.7}})_{0.51}\mathrm{In_{0.49}P}$ barrier layers. Samples were grown at temperatures of 710 and 750 °C, which results in different numbers and distributions of dot states as observed in modal absorption spectra [6]. One-thousand-nanometer wide $\mathrm{Al_{0.51}In_{0.49}P}$ cladding layers, doped with Si and Zn for n- and p-type, respectively, form the rest of the waveguide structure. We use a standard 650-nm emitting QW laser as a comparator structure. This sample consists of three compressively strained, 55-nm wide coupled QWs with $(\mathrm{Al_{0.5}Ga_{0.5}})_{0.51}\mathrm{In_{0.49}P}$ waveguide core and $(\mathrm{Al_{0.7}Ga_{0.3}})_{0.51}\mathrm{In_{0.49}P}$ cladding layers.

The samples are fabricated into 50-μm-wide oxide-isolated stripe multisection test structures. All devices have as-cleaved, uncoated facets and are operated pulsed with a pulse length

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Manuscript received December 30, 2010; revised February 7, 2011; accepted February 9, 2011. Date of publication April 5, 2011; date of current version October 5, 2011. This work was supported by the U.K. Engineering and Physical Sciences Research Council under Grant EP/E056385.

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Digital Object Identifier 10.1109/JSTQE.2011.2115235