Recombination, Transport and Loss Mechanisms in p-doped InAs/GaAs Quantum Dots

I. P. Marko, N. F. Massé, S. J. Sweeney, A. R. Adams, N. Hatori et al.

Citation: *AIP Conf. Proc.* **893**, 837 (2007); doi: 10.1063/1.2730151

View online: <http://dx.doi.org/10.1063/1.2730151>

View Table of Contents: <http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=893&Issue=1>

Published by the [American Institute of Physics](#).

Related Articles

Spontaneous emission control of single quantum dots by electromechanical tuning of a photonic crystal cavity
Appl. Phys. Lett. **101**, 091106 (2012)

Energy states and carrier transport processes in metamorphic InAs quantum dots
J. Appl. Phys. **112**, 034309 (2012)

High-frequency gate manipulation of a bilayer graphene quantum dot
Appl. Phys. Lett. **101**, 043107 (2012)

Magnetovoltaic effect in a quantum dot undergoing Jahn-Teller transition
Appl. Phys. Lett. **101**, 023120 (2012)

Fast detection of single-charge tunneling to a graphene quantum dot in a multi-level regime
Appl. Phys. Lett. **101**, 012104 (2012)

Additional information on AIP Conf. Proc.

Journal Homepage: <http://proceedings.aip.org/>

Journal Information: http://proceedings.aip.org/about/about_the_proceedings

Top downloads: http://proceedings.aip.org/dbt/most_downloaded.jsp?KEY=APCPCS

Information for Authors: http://proceedings.aip.org/authors/information_for_authors

ADVERTISEMENT

AIP Advances

Submit Now

**Explore AIP's new
open-access journal**

- **Article-level metrics
now available**
- **Join the conversation!
Rate & comment on articles**

Recombination, Transport and Loss Mechanisms in p-doped InAs/GaAs Quantum Dots

I. P. Marko¹, N. F. Massé¹, S. J. Sweeney¹, and A. R. Adams¹, N. Hatori²,
M. Sugawara²

¹*Advanced Technology Institute, School of Electronic and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, UK*

²*Optical Semiconductor Devices Lab. Fujitsu Laboratories LTD. 10-1 Morinosato-Wakamiya, Atsugi, 243-0197 Japan*

Abstract. The results on the temperature dependence of the radiative and non-radiative recombination processes in p-doped and undoped quantum dot (QD) lasers suggest that the observed characteristics of p-doped QDs are caused by an increase in the effective conduction band off-set due to Columbic attraction of the extra holes and so an increased localization of electrons in the dots. This leads to an increase in the temperature at which the carriers are able to establish thermal equilibrium from $T=200\text{K}$ in the undoped devices to $\geq 320\text{K}$ in the p-doped samples. Interestingly this can be used to advantage since, as the temperature increases, the improved efficiency associated with better transport between the dots can be exactly offset by the increasing rate of Auger recombination, thus leading to a temperature stable operation around room temperature.

Keywords: quantum dot laser, p-doping, recombination mechanisms, non-radiative recombination, carrier transport.

PACS: 72.20.Jv, 78.60.-b, 79.20.Fv, 85.35.Be

INTRODUCTION

The electronic and optical processes occurring in semiconductor quantum dots are extremely complex. Firstly, the carriers are isolated in the individual dots and therefore, depending on the temperature, they are unable to properly achieve a thermal equilibrium distribution. Secondly, QD size distribution leads to a distribution in optical transition energies that also inhibits interactions between the dots via photon emission and absorption. These properties are very important technologically because semiconductor quantum dot systems show great promise as single photon emitters or as lasers. It has been demonstrated recently that p-type modulation doping of InAs/GaAs quantum dots significantly improves the temperature performance of QD semiconductor lasers that might be used in optical fibre communications [1-2]. However the process is complex and is also accompanied by an increased threshold current density compared to undoped devices [3]. The results we present here are aimed to understand the specific influence of p-doping on temperature performance of $1.3\text{ }\mu\text{m}$ QD lasers.

RESULTS AND DISCUSSION

The detailed analysis of the temperature dependence of the threshold current, I_{th} , and its radiative component, I_{rad} , determined as a value of integrated unamplified spontaneous emission (SE), L , (measured from a window milled in a substrate contact of p-doped and undoped devices) showed that their complex behaviour (see fig. 1) can be explained simply assuming that the radiative recombination and non-radiative Auger recombination rates are strongly modified by thermal redistribution of carriers between the dots [4]. The large differences between the devices at $T < 320\text{ K}$ arise due to the trapped holes in the p-doped devices. This is confirmed by measurements of temperature dependence of the full width at half maximum (FWHM) of SE line corresponding to the ground state (GS) optical transitions, which is given in fig. 2. The results demonstrate a broader carrier distribution at low T and lack of carrier thermalisation with increasing T in the p-doped device until about $T = 320\text{--}350\text{ K}$, where the difference between both devices almost disappears.

The measurements of the spontaneous and stimulated emission rates as a function of temperature and high hydrostatic pressure also show that Auger recombination is an extremely important process near room temperature (RT) and causes the same temperature dependence of I_{th} in both laser types above RT [3, 4]. This can be used to advantage since, as the T increases, the improved efficiency associated with better transport between the dots can be exactly offset by the increasing rate of Auger recombination, thus leading to a temperature stable operation around room temperature as shown in fig. 1.

FIGURE 1. Temperature dependence of I_{th} and I_{rad} for the p-doped and undoped QD devices.

FIGURE 2. FWHM of the GS spontaneous emission line for the p-doped and undoped QD lasers as a function of temperature.

The large differences between the devices below RT arise due to the trapped holes in the p-doped devices. These both greatly increase Auger recombination involving holes excitation at low temperatures and decrease electron thermal escape due to their Coulombic attraction which increases the barrier height for the electrons [4].

In order to explain fully the difference between the observed characteristics of the undoped and p-doped devices, we also studied the temperature dependence of gain [5] and external differential efficiency, η_d (see fig. 3). We observed smaller values of η_d in the p-doped devices and non-linear light-current (LI) characteristics at RT. The p-doped devices also

showed small increase of η_d and improved linearity of LIs with increasing T up to 350-370K supporting the idea of the improved carrier thermalisation. In contrast, η_d in the undoped devices was more temperature sensitive and decreased with increasing T.

FIGURE 3. External differential efficiency of the p-doped and undoped QD lasers as a function of temperature.

All these observations are in very good agreement with the measured values of optical loss, α_i , both at RT and 350 K, which showed that α_i is about 10 cm^{-1} in the p-doped devices at both temperatures. However, in the undoped devices α_i increased from $\sim 5 \text{ cm}^{-1}$ at 293K to $\sim 10 \text{ cm}^{-1}$ at 350K. Therefore, we think that further transitions involving the excitation of holes from the confined states to continuum states derived from the spin-split-off bands (inter-valence band absorption) must be taken into consideration.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the EPSRC (UK) and the Nuffield Foundation (NAL/00695/G) for supporting this work and Dr. A. Andreev for the helpful discussions.

REFERENCES

1. M.Sugawara, N.Hatori, M.Ishida, H. Ebe, Y.Arakawa, T.Akiyama, K.Otsubo, T.Yamamoto, Y.Nakata, J. Phys. D:Appl. Phys., 38, 2126 (2005).
2. I. I. Novikov, N.Y. Gordeev, L. Y. Karachinskii, M. V. Maksimov, Y. M. Shernyakov, A. R. Kovsh, I. L. Krestnikov, A. V. Kozhukhov, S. S. Mikhlin, N. N. Ledentsov, Semiconductors, 39, 477 (2005)
3. I. P. Marko, A. R. Adams, S. J. Sweeney, I. R. Sellers, D. J. Mowbray and M. S. Skolnick, H. Y. Liu and K. M. Groom, IEEE Select. Top. Quantum Electr., 11(5), 1041 (2005)
4. I. P. Marko, N. F. Massé, S. J. Sweeney, A. D. Andreev and A. R. Adams, N. Hatori, M. Sugawara, Appl. Phys. Lett., 87, 211114 (2005).
5. N. F. Massé, S. J. Sweeney, I. P. Marko, and A. R. Adams, N. Hatori, M. Sugawara, submitted to Appl. Phys. Lett. (2006).