REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01-06-2003	**2. REPORT TYPE** Journal Article	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Improved Temperature Characteristics in Quantum Dot Lasers with Indirect-Bandgap Barriers	**5a. CONTRACT NUMBER** IN-HOUSE
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 61102F
6. AUTHOR(S) Richard A. Soref, Gregory Sun and Jacob B. Khurgin	**5d. PROJECT NUMBER** 2305
	5e. TASK NUMBER HC
	5f. WORK UNIT NUMBER 01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Electromagnetics Technology Division Source Code: 437890 Sensors Directorate Air Force Research Laboratory 80 Scott Drive Hanscom AFB MA 01731-2909	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL-SN-HS
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-SN-HS-TP-2002-1021

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED. CLEARANCE ESC-02-1021.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study demonstrates that a much high characteristic-temperature can be achieved with quantum dot lasers of indirect barrier compared to those of direct barrier. The temperature dependence of threshold current is reduced because the injected carriers residing in the barrier at “high” temperatures recombine slowly.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17.LIMITATION OF ABSTRACT**	**18.NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Richard Soref
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c.THIS PAGE** Unclassified	SAR	4	**19b. TELEPHONE NUMBER** *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Improved Temperature Characteristics in Quantum Dot Lasers with Indirect-Bandgap Barriers

Gregory Sun
Department of Physics, University of Massachusetts at Boston, Boston, Massachusetts 02125

Jacob B. Khurgin
Department of Electrical and Computer Engineering, The Johns Hopkins University, Baltimore, Maryland 21218

Richard A. Soref
Sensors Directorate, Air Force Research Laboratory, Hanscom AFB, Massachusetts 01731

Abstract: This study demonstrates that a much higher characteristic-temperature can be achieved with quantum dot lasers of indirect barrier compared to those of direct barrier. The temperature dependence of threshold current is reduced because the injected carriers residing in the barrier at "high" temperatures recombine slowly.

OCIS codes: (140.3380) Laser materials; (140.5960) Semiconductor lasers

The driving force behind the quantum dot (QD) studies was the possibility of reducing the laser threshold since the density of states in QDs is ideally much narrower than the density of states in bulk and quantum-well semiconductors. Although the progress in QD Lasers has been significant, they still have not fulfilled their promise because present QD lasers still exhibit strong exponential dependence of their threshold upon temperature due to carrier recombination in the barrier layers that "clad" the dots [1]. In this paper, we propose a new type of QD laser in which the direct-gap QDs are embedded in a semiconductor "matrix" material that has an indirect bandgap. We show that this technique reduces the dependence of threshold current on temperature. Specifically, we have studied InAs QDs in indirect $Al_xGa_{1-x}As$ barriers with x = 0.4. The choice of $Al_{0.4}Ga_{0.6}As$ barrier material with a lattice parameter almost equal to that of GaAs is made in anticipation of investigating similar InAs QDs in both GaAs and AlGaAs. Thereby, we can establish a fair comparison between QD lasers with direct GaAs barriers and those with indirect $Al_{0.4}Ga_{0.6}$ As barriers. In this paper, a significant reduction in temperature dependence (a much higher "characteristic temperature") is predicted for the QD lasers with indirect barriers. The reason is that a majority of the carriers reside in the barrier at higher temperatures. The longer effective carrier lifetime due to the indirect nature of the bandgap reduces the demand on the pumping current for maintaining those carriers in the barrier, a region that serves as a reservoir for carrier population in QDs.

The population dynamics is modeled with the theory of random population [2] based on the idea that carrier capture by the dots and recombination in the dots are essentially random processes. We further expand this theory to include the escape process that allows carriers to be thermally released from dots to their surrounding barrier before being recombined [3].

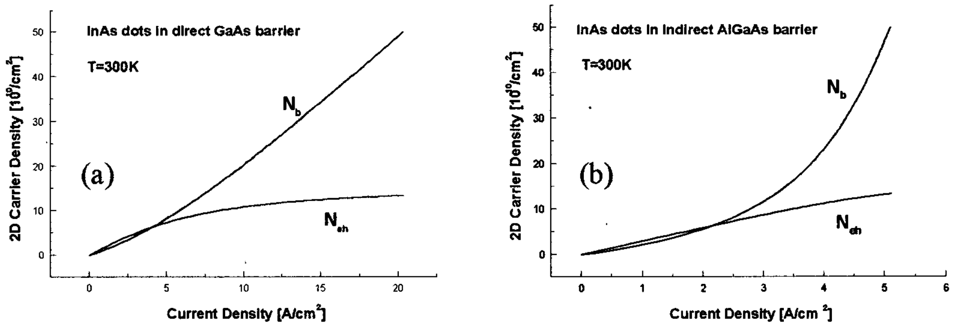

Fig. 1 Population distribution at 300K between dots N_{eh} and barrier N_b for InAs dots in barriers of (a) direct GaAs and (b) indirect AlGaAs.

Figure 1 shows the carrier distribution between the dots N_{eh} and barrier N_b as a function of the pumping current density at T=300K for dots with an area density of $4\times10^{10}\mathrm{cm}^{-2}$ embedded in either direct or indirect barriers. It can be seen from Figs.1(a) and 1(b) that carriers already starts to accumulate in the barrier before the dots are saturated. In order to maintain a steady-state distribution of carriers in the dots that is sufficient for threshold optical gain, it is necessary to maintain a certain level of carrier density in the barrier. As demonstrated in Fig.1, the barrier of indirect bandgap requires less pumping current density to inject a given density of carriers.

Based on the analysis of population distribution, we have calculated the optical gain for the ground-state radiative transitions with the assumption that for a typical QD ensemble, the inhomogeneous broadening of the transition linewidth induced by the dot-size variation is much larger than the homogeneous broadening.

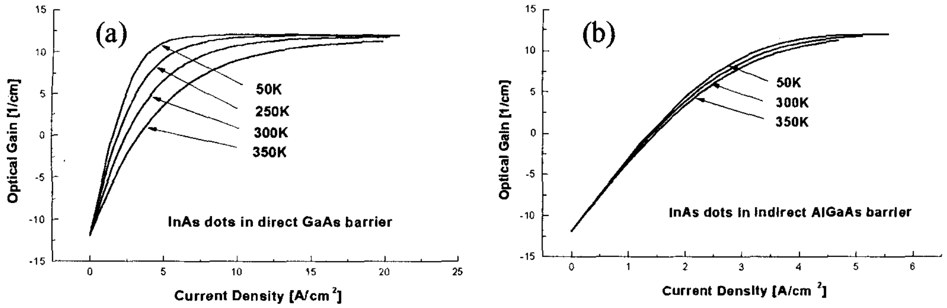

Fig.2 Optical gain as a function of pumping current density at various temperatures for InAs dots in barriers of (a) direct GaAs and (b) indirect AlGaAs.

The result of optical gain at the average transition photon energy is shown in Fig.2. The gain is calculated as a function of pumping current density for QDs with direct (Fig.2a) and indirect barriers (Fig.2b) for several temperatures ranging from 50K to 350K. It can be seen from Fig.2 that the optical gain increases with the pumping current density and reaches saturation value at approximately 12/cm. QD lasers with indirect barriers require less pumping current compared to those with direct barriers to reach the same level of optical gain. Comparing Figs.2(a) and 2(b), optical gain as a function of pumping current for QD lasers with indirect barriers shows rather insignificant temperature dependence, while that of direct barriers clearly indicates a strong temperature dependence. This conclusion is better illustrated with the assumption of a fixed value of optical gain that is required to compensate the typical losses (2 ~ 10/cm) found within QD laser cavities. Taking the value of threshold gain as g_{th}=8/cm, we have calculated the threshold current density J_{th} as a function of temperature. The result is shown in Fig.3 for QD lasers with direct and indirect barriers. Fig.3 reveals that QD lasers with indirect barriers require less pumping to reach J_{th} throughout the temperature range, and that J_{th} remains almost unchanged as the temperature increases. For QD lasers with direct barriers, even though their J_{th} can be low at "low" temperatures, J_{th} increases sharply as the temperature increases. The rather significant difference in J_{th} between the two cases at higher temperature is the direct result of the lifetime difference between the two types of barriers where there is an inevitable carrier buildup at elevated temperature. We have fitted our data to the standard threshold-temperature expression: $J_{th}=J_o\exp(T/T_o)$ where T_o is the characteristic temperature of the laser. For the temperature range of 50 ~ 350K, We obtain T_o=305K for the direct barrier and T_o=2857K for the indirect barrier. For the higher temperature range of 260 ~350K, we obtain T_o=153K for the direct barrier and T_o = 1152K for the indirect barrier, an enormous improvement. The T_o value that we obtained for QDs in direct barrier at higher temperature is consistent with the 161K value measured over the same temperature range in the InAs QD laser with GaAs barrier [4].

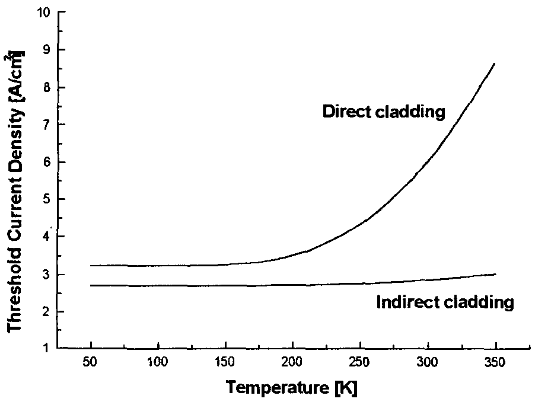

Fig.3 Pumping threshold current density as a function of temperature to maintain optical gain of 8/cm for InAs dots in direct and indirect AlGaAs barriers.

References

[1] O. G. Schmidt, N. Kirstaedter, N. N. Ledentsov, M.-H. Mao, D. Bimberg, V. M. Ustinov, A. Yu. Egorov, A. E. Zhukov, M. V. Maximov, P. S. Kop'ev, and Zh. I. Alferov, "Prevention of gain saturation by multi-layer quantum dot lasers", Electron. Lett. **32**, 1302-1303 (1996)

[2] L. V. Asryan and S. Luryi, "Tunneling-Injection Quantum-Dot Laser: Ultrahigh Temperature Stability", IEEE Journal of Quantum Electron. **37**, 905-910 (2001)

[3] G. Sun, J.B. Khurgin, and R.A. Soref, "Quantum dot lasers with indirect barriers", submitted to IEEE Journal of Quantum Electron. (2002)

[4] O. B. Shchekin and D. G. Deppe, "1.3μm InAs Quantum Dot Laser with T_o = 161 K *from* 0 to 80°C", Appl. Phys. Lett. **80**, 3277-3279 (2002)