CThO59 Fig. 2. Pulsed light-current (L-I) characteristics of 1-mm-long, 120- μ m-wide broad area lasers with non-intermixed active region (sample TS112-012) and intermixed active region (sample TS112-116).

well GaInAs/GaInAsP lasers fabricated using photoabsorption induced disordering, Appl. Phys. Lett. 65, 2263–2265 (1994).

CThO60 Fig. 1. A schematic of nonidentical MQW structure with two different QWs.

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1:00 pm

Temperature-Induced Carrier Redistribution Among Nonidentical Multiple Quantum Wells

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1. Introduction

Nonidentical multiple quantum wells (MQWs) have been widely used for broadening gain bandwidth of semiconductor lasers and amplifiers.^{1–3} However, carrier distribution among those MQWs is not uniform and thus complicates actual gain profiles.⁴ In this work, we further explore the dependence of carrier distribution on temperature and discover that temperature characteristics of semiconductor lasers with nonidentical MQWs are very different from conventional ones with identical MQWs. The origin is due to the strongly temperature-dependent Fermi-Dirac distribution, which favors carriers in high-energy states at large temperature. As a result, carriers redistribute among those QWs as temperature varies. For laser diodes with nonidentical MQWs, the temperature-induced carrier redistribution could cause the lasing wavelength much less dependent on temperature, compared to the bandgap shrinkage. Theoretical reasons and experimental evidence are given.

2. Theoretical background

Theoretical explanation of carrier redistribution at different temperatures is as follows. Assume that the quantum-well (QW) structure has only two different QWs, as shown in Fig. 1. QW A has one quantized energy at E_1 and QW B has one quantized energy at E_2 , $E_1 < E_2$. Their densities of states are plotted in Figs. 2(a) and (b), respec-

CThO60 Fig. 2. external-cavity configuration and modified setup for widely-separated dual-wavelength operation.

tively. The Fermi-Dirac distribution is also plotted together at two temperatures. For a certain injection level of carriers, the Fermi level (E_F) is assumed to be slightly above energy E_2 . In general, the Fermi level varies with temperature. However, the variation is small. For the simplicity of explanation, this variation is neglected. As temperature

increases, carriers in QW A (Fig. 2(a)) and in QW B (Fig. 2(b)) change the number of $N_1(R_1-L_1)$ and $N_2(R_2-L_2)$, respectively. Because the shaded area R_1 is less than L_1 , the number of carriers in QW A decreases. On the contrary, the shaded area R_2 is larger than L_2 , so the number of carriers in QW B increases. For a fixed injected carrier level, the total amount of carriers in the QWs is approximately constant. Thus carriers flow from QW A to QW B as temperature increases and vice versa as temperature decreases.

3. Experiments

Laser diodes are fabricated on the substrate with nonidentical quantum wells for the experiments. The QW structure has two $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ QWs near the p-cladding layer and three $\text{In}_{0.67}\text{Ga}_{0.33}\text{As}_{0.72}\text{P}_{0.28}$ QWs near the n-cladding layer. The QWs are separated by $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ barriers. At room temperature, the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ QWs (QW A) and $\text{In}_{0.67}\text{Ga}_{0.33}\text{As}_{0.72}\text{P}_{0.28}$ QWs (QW B) have their first quantized transition energies of 0.8 eV and 0.954 eV, respectively. Because the bandgap shrinks with temperature, those transition energies decrease with temperature, as shown by the two solid curves in Fig. 3. In contrast, the measured wavelength of the above laser diode shows much less temperature dependence. For temperature varies from 33 K to 260 K, its corresponding energy changes less than 5 meV, while the bandgap energy changes more than 50 meV. As explained previously, because carriers flow from QW A to QW B when temperature increases, the lasing wavelength shifts toward the energy corresponding to QW B, leading to the significantly reduced temperature variation.

The temperature-induced carrier redistribution could also cause other novel characteristics that will be discussed in great depth.

References

1. Bor-Lin Lee and Ching-Fuh Lin, CLEO/QELS '97, Baltimore, USA, Paper CThA4, 1997.
2. H.S. Gingrich, D.R. Chumney, S.D. Hersee, L.F. Lester, and S.R. Brueck, *IEEE Photon. Technol. Lett.*, 9, 155 (1997).
3. X. Zhu, D.T. Cassidy, M.J. Hamp, D.A. Thompson, B.J. Robinson, Q.C. Zhao, and M. Davies, *IEEE Photon. Technol. Lett.*, 9 1202 (1997).

CThO60 Fig. 3. Variation of transition energy and lasing energy with temperature. (Top solid curve: $\text{In}_{0.67}\text{Ga}_{0.33}\text{As}_{0.72}\text{P}_{0.28}$ QWs (QW B); bottom solid curve: $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ QWs (QW A); middle: oscillation energy of the laser diode with both types of QWs.)

4. Ching-Fuh Lin, Bing-Ruey Wu, Lih-Wen Lai, and Tien-Tsorn Shih, Opt. Lett. 26, 1099 (2001).

CTh061

1:00 pm

Immersion Optical Clearing of the Human Skin: *In vivo* Studies

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Controlling of skin optical properties related to the immersion of refractive indices of scatterers (keratinocytes components in epidermis, collagen and elastin fibers in dermis) and ground matter is a key technique for the structural and functional imaging.

CTh061 Fig. 1. Reflectance spectra measured before (1) and at 23 min (2) and 60 min (3) after intra dermis injection of 0.1 ml of 40%-glucose into internal side of the forearm of the male volunteer.

CTh061 Fig. 2. The OCT images from the normal human skin (a) of the male volunteer and at 13 min after intra dermis injection of 40% glucose (b).

For *in vivo* studies of clearing of the human skin two optical techniques were used: reflectance spectroscopy and OCT. The intra dermis injection of 40% glucose was applied as the immersion procedure. The fiber-optic grating-array spectrometer (LESA-6, 400–750 nm) was used. The mean distance between the irradiating and receiving fibers was close to 2 mm. Figure 1 shows the reflectance spectra of the human skin. Within one hour after glucose injection, the skin reflection coefficient decreases in average by a factor of 3.8 and then exhibits a slow increase, which indicates that glucose is eliminated from the observation area and the skin reflectance tends to restore itself to the initial level. Basing on the proposed skin clearing model, we may suggest that the main contribution to clearing in the first stage (first hour) is due to the refractive index matching between collagen fibrils of the dermis ($n = 1.46$) and the interstitial space (initially $n = 1.36$) to which glucose ($n = 1.39$) diffuses.

Estimated diffusion coefficient of glucose in dermis is $D_G = (2.56 \pm 0.13) \cdot 10^{-6} \text{ cm}^2/\text{s}$; this value is 3.6 folds less than for glucose diffusion in water at 37°C, $D_G = 9.2 \cdot 10^{-6} \text{ cm}^2/\text{s}$, and reflects the character of dermis permeability for glucose.

It is important that skin preserves transparency (low reflectance) for a few hours after injection, which is defined by glucose diffusion along the skin surface, because upper and lower layers of the skin—epidermis and fat—have much lower permeability than dermis.

These data well correlate with spectral measurements and also reflect the index matching induced by the glucose injection. The attenuation initially goes down and then goes up with the time course. The light beam attenuation in tissue $I/I_0 \propto \exp(-\mu_z)$, for normal skin (0 min) $I/I_0 = 0.139$, and for immersed skin at 13 min $I/I_0 = 0.298$, i.e. intensity of transmitted light increased 2.1 folds. This is a little bit less than for spectral

CTh061 Table 1. The total attenuation coefficients calculated for the OCT images captured from the arm

Time (min)	0	6	13	17	22	103
μ_z (1/mm)	1.97	1.63	1.21	1.39	1.54	1.47

measurements, and can be explained by a lower optical penetration depth of the OCT system.

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1:00 pm

A UV Fluorescence Lifetime Imaging Microscope to Probe Endogenous Cellular Fluorescence

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Background and Setup

Fluorescence lifetimes are sensitive to local physical conditions and insensitive to artifacts affecting intensity based measurements, providing a complementary source of contrast for fluorescence microscopy.¹ While lifetime microscopy is well-developed at visible wavelengths (e.g., fluorescence resonance energy transfer between exogenous fluorophores), FLIM of endogenous fluorophores is less developed with many potential uses (e.g., biomedical diagnostics).² Near UV wavelengths may become important in clinical applications because structural proteins and metabolic co-factors have excitation maxima in this wavelength region. This paper presents the construction of a FLIM system with the sensitivity to detect cellular autofluorescence.

The UV-FLIM system (Fig. 1) used a nitrogen laser (PTI, Lawrenceville, NJ) with a 600 ps pulse width and 1.5 mJ/pulse output. The microscope was a Zeiss Axiovert S100 using Fluor objectives in epi-illumination mode. The camera was a 200 ps gated intensified CCD (ICCD) camera (LaVision, Germany). A fiber introduced an optical delay needed for rough synchronization of the ICCD gate and optical signal, with a variable delay card providing fine control. The laser pulse width measured at the end of the fiber was 1.4 ns. Lifetimes were calculated using a two-point rapid lifetime determination (RLD) algorithm³ and lifetime maps were calculated on a pixel-by-pixel basis.

Results and Discussion

Fig. 2 shows lifetime maps of fluorescein in deionized water and ethanol in quartz cuvettes

CTh062 Fig. 1. System setup. ND neutral density filter; BS beam splitter; M mirror; QL quartz lens; DC dichroic.