Broadband Emission in Quantum-Dash Semiconductor Laser

Chee L. Tan¹, Hery S. Djie¹ and Boon S. Ooi¹,²
¹Lehigh University,
²King Abdullah University of Science & Technology,
¹United States
²Saudi Arabia

1. Introduction

A new type of semiconductor laser is studied, in which injected carriers in the active region are quantum mechanically confined in localized finite self-assembled wire-like quantum-dash (Qdash) structures that are varied in sizes and compositions. Effects of such carrier distribution and quasi three-dimensional density of states contribute to a quasi-supercontinuum interband lasing characteristics, which is a new laser design platform as compared to continuous broad emission spectrum generated by nonlinear media pumped with ultrashort laser pulse. The wavelength profile of quasi-supercontinuum emission is tunable at near-infrared wavelength spanning across several optical communication bands at around ~1500 nm in addition to the ability of operating condition at room temperature as opposed to that previously obtained only at operating temperature below 100 K. In this chapter, a thorough analysis of the Qdash material system, device physics and the establishment of ultrabroad stimulated emission behavior will be presented and discussed.

2. Background

The generation of white light by laser radiation was first reported by Alfano and Shapiro (Alfano & Shapiro, 1970) who observed a spectral broadening of a picosecond second-harmonic output of a neodymium garnet laser (400-700 nm) with an energy of about 5 mJ in the bulk of borosilicate glass. Experiments performed with these bulk samples were then followed by studies on waveguide white-light generation in air-silica microstructure optical fibers to date (Ranka, 2000). The generation of the artificial white light is mainly due to the effective nonlinear-optical transformations of ultrashort laser pulses. Owing to its broad and continuous output spectrum, such radiation is called supercontinuum. Supercontinuum generation is an interesting physical phenomenon and the relevant technology is gaining in practical implications – it offers novel solutions for optical communications and control of ultrashort laser pulses (Nisoli et al., 1996), helps to achieve an unprecedented precision in optical metrology (Lin & Stolen, 1976), serves to probe the atmosphere of the Earth (Zheltikov, 2003), and suggests new strategies for the creation of compact multiplex light sources (Morioka et al., 1993) for nonlinear spectroscopy, microscopy, and laser biomedicine.

The first mid-infrared broadband semiconductor laser was demonstrated in an intersubband structure by adopting a quantum cascade configuration (Gmachl et al., 2002). Laser action with a Fabry-Perot spectrum covering all wavelengths from 6 to 8 \( \mu m \) simultaneously is demonstrated with a number of dissimilar intersubband optical transitions. Recently, similar unique spectral properties in the form of quasi-supercontinuum lasing characteristics have been demonstrated on semiconductor quantum-dot (Qdot) and Qdash platforms in different near-infrared wavelength regime without the need of ultrashort pulse laser excitation or the engineering of the intersubband transition level. \(^{a}\)Djie et al., 2007; Kovsh et al., 2007; \(^{b}\)Djie et al., 2007; Tan et al., 2008). Most important, this unique feature of quasi-supercontinuum emission occurs at high temperature, i.e. room temperature in addition to identical operating conditions of a conventional semiconductor lasers. Owing to its broad and continuous spectrum emitted via only a single semiconductor laser diode, such device is called broadband laser. The broadband laser technology utilizes largely inhomogeneous quantum nanostructures active medium such as quantum-dot (Qdot) structures for wavelength emission in \( \sim 1200 \) nm \(^{a}\)Djie et al., 2007, Kovsh et al., 2007); and Qdash medium for emission in center wavelength of \( \sim 1600 \) nm \(^{a}\)Djie et al., 2007, Ooi et al., 2008). Bandgap tuning with emission width widening is possible and can be realized in Qdash materials via postgrowth lattice interdiffusion technique (Tan et al., 2008; Tan et al. 2009). Furthermore, interband optical transition in quantum confined heterostructures will contribute to a highly efficient broadband laser action as compared to other emitter technologies.

A brief review of current state-of-art of Qdot/Qdash technology is necessary to comprehend the origin and progress of semiconductor broadband laser. To date, conventional self-assembled Qdot/Qdash semiconductor nanostructures have attracted considerable interest in the fabrication of semiconductor lasers and optical amplifiers due to the unprecedented potential offered by three-dimensional energy levels quantification that lead to vastly improved optoelectronic characteristics as compared to conventional quantum-well (QW) structures and bulk materials (Bimberg et al., 1997; Wang et al., 2001; Ooi et al., 2008). Apart from its predominant applications in optoelectronics industry, self assembled Qdot/Qdash demonstrate a number of unique features as compared to QW materials. In particular, self-assembled Qdot lasers have been shown to emit unique lasing spectral characteristics, where the laser emission spectra are broadened with modulated non-lasing spectral regions and the number of lasing modes increases above threshold (Harris et al., 1998). Furthermore, early experiments showed an extraordinary wideband lasing coverage of 50 nm, in the absence of modulated non-lasing spectral regions, but only at a cryogenic temperature (60 K) from Qdot gain medium (Shoji et al., 1997; Jiang & Singh, 1999). These phenomena have been attributed to the carrier localization in noninteracting or spatially isolated dot ensembles and nonequilibrium carrier distribution among highly inhomogeneous Qdots (Harris et al., 1998; Jiang & Singh, 1999). The most recent study reveals that a low-ripple (<3 dB) non-modulated broad interband lasing coverage of \( \sim 40-75 \) nm from GaAs-based Qdot lasers can be achieved at room temperature with center wavelength of \( \sim 1160-1240 \) nm by employing a highly inhomogeneous InGaAs Qdot structures (Djie et al., 2007) and chirp InGaAs Qdot structures (Kovsh et al., 2007). These novel semiconductor light emitters are particularly attractive for many practical imaging and sensor applications due to their compactness and relatively low energy requirement in comparison to other state-of-art broad spectrum light sources.
The effort of achieving this interesting broadband lasing action in a longer wavelength region (1.5-1.6 μm) will thus be critical for broader applications relevant to the important low-loss transmission window of fiber optic system such as multichannel optical communication system, fiber-based optical coherent tomography, interferometric fiber optic gyroscopes, optical measurement systems, etc. Intensive research in the advanced growth of InP-based self-assembled Qdash had enabled the realization of high quality lasers and optical amplifiers that potentially cover the wavelength operation on both 1.31 μm and 1.55 μm of optical communication bands (Wang et al., 2001). Qdash assembly is essentially comprised of isotropic Qdots and finite quantum-wires (Qwires), whose cross section is similar to that of a typical Qdot, 3-4 nm (height) × 10-20 nm (base), while its length is varied from tens to hundreds of nanometers, as pictured by scanning electron microscopy (Dery et al., 2004) and atomic force microscopy (Popescu & Malloy, 2006). Due to quasi-three-dimensional carrier confinement and intrinsic properties, Qdash enable several interesting laser diode characteristics such as improved temperature insensitivity, optical feedback resistance, wide spectral tunability, and broad stimulated emission (Sek et al., 2007; Lelarge et al. 2007; Djie et al., 2007). In addition, the gain properties of a Qdash amplifier bearing the distinct fingerprint of a quantum-wire-like density of states (Dery et al., 2004) while gain recovery characteristics and recovery time constants resembling Qdot characteristics (van der Poel et al., 2006). More so, it has been proposed that the role of optical gain broadening (Tan et al., 2007) that results in broadband emission from Qdot lasers is also inherent in Qdash lasers. These unique features will help to overcome the challenges in the nanoscaled epitaxial engineering of highly inhomogeneous Qdot for broadband laser applications.

All the interesting features of broad interband lasing actions from self-organized, spatially-isolated semiconductor nanostructure technology can be widely applied in optical telecommunications, various optical sensors detecting chemical agents, atmospheric or planetary gases, high-precision optical metrology and spectroscopy, and biomedical imaging (Ooi et al., 2008). In addition, it is natural to expect that narrow pulses can be generated by locking the phases of modes in this quasi-supercontinuum interband laser spectrum under mode-locked operation (Xing & Avrutin, 2005) due to the fast carrier dynamics and the broad optical gain bandwidth (Lelarge et al., 2007). Furthermore, the high power emission capability of ~1 W per device from these ultrabroadband Qdash lasers at room temperature (Tan et al., 2008) can be potentially employed as a high efficiency resonant pumping source (Garbuzov et al., 2005) for eye-safe Er-doped amplifiers and solid-state lasers.

In this chapter, we will present the generation of ultrabroad stimulated emission at room temperature operating condition in the InP-based broadband laser with wide wavelength coverage. For the first time, the InP-based unique dash quantum confined heterostructure properties is exploited to generate a broad lasing spectrum, following the prior success of short wavelength GaAs-based Qdot broadband laser. The fabricated Qdash laser diode emits at ~1.64 μm center wavelength with wide wavelength coverage of 76 nm. Unlike conventional diode lasers, the rule changing broadband lasing is obtained from the quasi-continuous interband transition by the inhomogeneous Qdash ensembles.

To further enhance the broad spectrum emission and fine tune the lasing wavelength coverage, we further engineer the bandgap energy of Qdash material with postgrowth lattice intermixing process utilizing impurity-free vacancy induced disordering (IFVD) technique. We successfully demonstrated a 100 nm wavelength blue-shifted Qdash lasers
exhibiting a room-temperature broad lasing spectral coverage of ~85 nm at a center wavelength of ~1.55 μm with enhanced total emission power of ~1 W from a single as-cleaved broad area laser structure (50 x 500 μm²). The peculiar broad lasing spectra from fabricated diodes with different cavity lengths related to the effect of nonequilibrium carrier distribution in these highly inhomogeneous dashes will also be discussed.

3. Experiments and theoretical modelling

3.1 Materials and laser structure

Fig. 1. (a) The plane-view AFM image (area of 0.5×0.5 μm²; height contrast of 8 nm) and the cross-sectional TEM images across [110] and [110] directions. (b) The illustration of carrier confinement in Qdash structure (top). Only the first two energy levels (E₁ and E₂) are shown for clarity. The height distribution profile of dash islands from AFM image (middle), that results in the density of states (DOS) spreading over the energy and forms the quasi-continuous interband transition (bottom).

The InAs/InAlGaAs Qdash material used in this study was grown by molecular beam epitaxy (MBE) on (1 0 0) oriented InP substrate. The laser is a p-i-n structure with active region consisting of four-sheet of InAs Qdashes, and each Qdash layer is embedded in an asymmetric InAlGaAs QW. The QWs are then sandwiched between two sets of SCHs. The Qdash-in-well structure consists of a 1.3 nm thick compressively strained In₀.₆₄Ga₀.₃₆Al₀.₂As layer, a five-monolayer (ML) thick InAs dash layer, and a 6.3 nm thick compressively strained In₀.₆₄Ga₀.₃₆Al₀.₂As layer. Each dash-in-well stack is separated by a 30 nm thick tensile strained layer of In₀.₅₀Ga₀.₃₂Al₀.₁₈As that acts as the strain compensating barrier. The lower cladding consists of a 200 nm thick In₀.₃₂Al₀.₄₈As layer doped with Si at 1 × 10¹⁸ cm⁻³, which is lattice matched to the InP substrate. The upper cladding and contact layers are 1700 nm thick In₀.₃₂Al₀.₄₈As and 150 nm thick In₀.₅₃Ga₀.₄₇As, respectively. Both layers are doped with Be at 2 × 10¹⁸ cm⁻³ (Djie et al., 2006; Wang et al., 2006). Fig. 1(a) shows the plane-view atomic force microscopy (AFM) of the surface Qdash and the cross-sectional transmission electron microscopy (TEM) images of the laser structure. The QDash structure comprises three-dimensional elongated nanostructure preferentially aligned along [110] direction with an average height of 3.2 nm, an average width of 18 nm, and the base or length varied.
from 20 to 75 nm. The individual Qdash provides strong carrier confinement along y- and z-
directions and weaker confinement along the x-direction [Fig. 1(b-top)]. The AFM image
reveals the nanostructure networks composed of dot-like and finite wire-like quantum
confined structures with a bimodal height distribution profile [Fig. 1(b-middle)]. The
isotropic, dot-like structure with a comparable width over the length have a relatively larger
height than the wire-like structure suggesting that the elongated islands are formed by the
coalescence of two or more dot-like islands. Considering the large dispersion in shape, size
and composition, the inhomogeneous Qdash gives a wide energy spreading in the confining
potentials. This effect leads to the broadened optical gain characteristics [Fig. 1(b-bottom)]
suitable for the wideband optical devices such as superluminescent diodes (SLD) (Djie et al.,
2006).

For the purpose of further enhancement of the broad spectrum emission and fine tune of
the lasing wavelength coverage, we performed the dielectric cap annealing technique to induce
selective intermixing using 475 nm thick SiO$_2$ layer as an vacancy source deposited using
plasma enhancing chemical vapor deposition system. During the annealing, the SiO$_2$ cap will
enhance the preferential atomic outdiffusion hence enhancing the group-III atomic
interdiffusion in the Qdash active region and resulting in the effective bandgap modification
of Qdash material (Tan et al., 2008; Wang et al., 2006). The dielectric cap also serves to
protect the surface quality during annealing from the thermal induced decomposition.
Following the dielectric cap removal, state-filling PL spectroscopy using a 980 nm diode
laser as an excitation source was performed at 77 K to assess the bandgap modification
from the interdiffusion effect on the laser structure. The IFVD process is performed by annealing
the SiO$_2$ capped sample in nitrogen ambient for one minute in a rapid thermal processor
(RTP). Fig. 2 gives the summary of PL peak shift and the linewidth as the annealing
temperature increases from 600ºC to 850ºC. At the temperature of 750ºC, the PL peak shifts
towards a shorter wavelength emission while the linewidth is the broadest. Further increase
in annealing temperature initiates more intermixing, and therefore improves the uniformity
in shape, size and composition of Qdash leading to reduction in PL linewidth. The result
points out the linewidth broadening at intermediate stage of intermixing due to non-
uniform interdiffusion, which will be further selected to broaden the Qdash laser emission.

![Fig. 2. The evolution of PL peak shift and linewidth measured at 77 K with varying
annealing temperature of rapid thermal processor from SiO$_2$ capped Qdash samples. The
inset depicts the normalized PL spectra for selected temperatures clearly showing the
broadening of PL linewidth at the intermediate degree of intermixing.](www.intechopen.com)
Broad area lasers with 50 μm wide oxide stripes with no facet coating were then fabricated from both the as-grown and intermixed Qdash samples (under annealing temperature of 750 °C) with SiO$_2$ capped layer. In order to maximize the gain (Ukhanov et al., 2002), the optical cavity of the laser is aligned along the [011] orientation and is perpendicular to the dash direction. Current injection was performed to the non-facet-coated Qdash lasers under pulsed operation at 0.2% duty cycle with a 2 μs pulse width.

### 3.2 Simulation model of group-III interdiffusion

The understanding of diffusion processes is important to the interpretation of interdiffusion induced compositional change and the band structure modification related to the experimental works and selected regrowth operating conditions presented in the previous sections. In IFVD process, majority vacancies are injected vertically from the dielectric cap during thermal treatment and therefore the interdiffusion will occur more effectively in the transverse direction that corresponds to the dash height (Tan et al., 2008; Wei & Chan, 2005). This diffusion effect becomes more pronounced at very thin Qdash layer when the dash height to base ratio is of ~ 0.1 or less (Wang et al., 2006). At intermediate stage of intermixing, the partial intermixing might occur, which the thick dash family will experience a larger degree of wavelength blue-shift due to the larger concentration (Crank, 1975) of active medium composition and hence its interdiffusion length is larger than the thin dash family. The solution of the diffusion problem (Crank, 1975) in the Qdash can be estimated by an equivalent one dimensional quantum-confined model (transverse direction of vacancies interdiffusion) by assuming a substance of concentration $C_0$ confined in a region of $n$ repeating well and barrier of width $w$ and $b$, respectively, centered at zero (Gontijo et al., 1994) that is given by

$$C_s = \frac{C_0}{2} \left[2 - \sum_{n=1}^{k} \left\{ \text{erf} \left( \frac{x-(n-1)(w+b)}{2L_D} \right) + \text{erf} \left( \frac{x-[nw+(n-1)b]}{2L_D} \right) \right\} \right]$$

(1)

Fig. 3. The blueshift of normalized transition wavelength when diffusion length increases in one-dimensional quantum confined structure with different well widths ($L_z$). The inset shows the corresponding change of the transition wavelength shift with normalized diffusion length to QW/Qdash.
The origin of the $x$ coordinate is at the left barrier of the first well. The one-dimensional quantum-confined structure of four repeating wells and barriers with arbitrary width are used in the simulation model to calculate the confined ground state energy level. The chosen material system is not critical because it serves only as a reference for the change of transition energy states with diffusion length ($L_d$) and well thickness. The quantum confined energy levels can be obtained by solving the one-dimensional time-independent Schrödinger equation and the results are shown in Fig. 3 and its inset. Different well widths (3, 4, 5 and 8 nm) with varied $L_d$ are used in the calculation model to represent the different dash heights in the real Qdash assembly. As $L_d$ increases, the wavelength shift to shorter wavelength due to group-III interdiffusion. The blue-shift rate is faster at same $L_d$ for thin nanostructure than the thick nanostructure, as stated in Fig. 3. At intermediate stage of intermixing, the disparity in wavelength blueshift is notable. As intermixing proceeds further, the variation rate in wavelength blueshift becomes less until the nanostructure becomes fully intermixed and the wavelength blueshift converges. Noting a high dispersion in Qdash structure used in the experiments [16], widened gain characteristics can be practically achieved by selecting suitable degree of intermixing to the Qdash structure. Thereafter, the broadened linewidth can be attributed to the different intermixing results from inhomogeneous nanostructure in Qdash assembly at a medium degree of intermixing. Experimentally, this can be obtained by a given dielectric film properties heat-treated under the suitable annealing temperature and/or duration. Furthermore, variation in transition energy state is more sensitive to the $L_d$ as compared to the well width. The thick dash family that tends to induce larger $L_d$ contribute to larger blueshift of peak emission is as shown in the inset of Fig. 3. Hence, there is a smaller peak emission blueshift in the intermixed samples as compared to the as-grown samples under high excitation.

4. Results and discussion

4.1 Optical properties of Qdash – As-Grown and intermixed materials
State-filling photoluminescence (PL) spectroscopy of as-grown Qdash samples were performed at 77 K by varying optical excitation density. As comparison, InAs Qdot embedded in InP matrix was grown and also characterized. The ground state PL peak emission is longer in Qdot as the InP matrix has a larger bandgap energy than InAlGaAs confining layers in the Qdash. Qdot structure shows well-resolved quantized states ($E_0$ to $E_4$) with a large energy separation between $E_0$ and $E_1$ ($\Delta E = 34$ meV) compared to Qdash characteristics (up to $E_4$ with $\Delta E = 30$ meV). At similar excitation density, more states are excited in Qdot than Qdashes as a manifestation of the enhanced DOS in Qdot subbands [Fig. 4]. At high excitation (1500 W/cm$^2$), a large number of minima in Qdash spectra are populated, resulting a broad emission line while in Qdot spectra, the individual minima is more apparent. These properties corroborate the quasi-continuous interband transition characteristics in Qdash over a wide wavelength range. The discrepancies between Qdot and Qdash are due to the shape of DOS [Fig. 1(b)]. Qdash with size and composition fluctuations have overlapping states with nearly identical transition energies in the high-energy portion that contributes to the gain broadening and thus produces less resolved confined state recombination in PL spectra. However, this is not the case in the Qdot assembly due to its delta function DOS leading to the atomic-line luminescence spectra.
Fig. 4. (a) PL spectra at 77 K with varying optical pumping level taken from InAs Qdots within InP matrix (above) and InAs Qdashes within InAlGaAs matrix (below). The confined energy subbands are indicated with the arrow, after the deconvolution with the multi-Gaussian spectra. (b) EL spectra at RT showing the spontaneous emission (top) at $J=0.8\times J_{th}$ from a 300 µm device and the lasing emission spectra (bottom) from $E_0$, $E_1$ and $E_2$ states. These individual lasing lines are obtained from laser with cavity length $L$ of 1000, 300, and 150 µm, respectively, at $1.1\times J_{th}$.

Broad area as-grown Qdash lasers with 50 µm wide oxide stripes without facet coating were fabricated and characterized. Fig. 4(b) shows the electroluminescence (EL) spectrum of the Qdash samples revealing fine structures of amplified spontaneous emission from different energy subbands in correlation to different lasing peaks. Up to three distinct laser emissions (1.65, 1.62, and 1.59 µm) from $E_0$, $E_1$ and $E_2$ energy transitions were obtained at $J= 1.1\times J_{th}$ from lasers with cavities $L$ of 1000, 300, and 150 µm, respectively. The distinct lasing wavelength peak is attributed to the finite modal gain of each quantized state in Qdash assembly.

Carriers localized in different dots/dashes, resulting in a system without a global Fermi function and exhibiting an inhomogeneously broadened gain spectrum, have shown an interesting phenomena of lasing spectra (Harris et al., 1998; Djie et al., 2007; Tan et al., 2007; Matthews et al., 2002). This unique feature of dot/dash can be well studied after postgrowth interdiffusion technique, from the evolution of state-filling spectroscopy from intermixed Qdash structures at 77 K, as shown in Fig. 5 and its inset. At low excitation below 3 W/cm², the ground state emissions of 1.57 µm and 1.50 µm are dominant in the as-grown and the intermixed samples, respectively. The PL spectra are gradually broadened in both samples with increasing optical excitation densities. An increase in the excitation power density leads to the filling of lower-energy states, allowing recombination from higher energy levels of Qdash structure. Under the same excitation density, the PL linewidth of intermixed sample is wider than the as-grown sample. At the power excitation density of 1500 W/cm², the PL linewidth increases by 11 nm (from 94 nm to 111 nm) after intermixing process. The phenomenon of carrier localization in Qdash becomes more evident when the intermixed
sample shows a larger variation of full-width-half-maximum (ΔFWHM up to 47 nm) than the as-grown sample (ΔFWHM up to 18 nm) under various power excitation densities relative to the FWHM obtained at the optical excitation of 3 W/cm², as shown in the inset of Fig. 3.

Fig. 5. The PL spectra of both as-grown and intermixed samples, with varying optical pumping levels, show global blueshift after intermixing. The inset shows the corresponding changes of FWHM and PL peak wavelength as compared to those obtained under optical excitation of 3 W/cm².

These enormously large broadening of the PL spectra from both the as-grown and intermixed samples is attributed to the contribution of multiple transition states (Djie et al., 2007) or large inhomogeneous broadening of the non-interacting Qdash ensembles (Tan et al., 2007; Van der Poel et al., 2006). This observation is also clearly different from that of both conventional QW (Ooi et al., 1997) and Qdot structures (Wang et al., 2006). The IFVD technique is generally well-known to improve the size homogeneity of a highly inhomogeneous semiconductor nanostructure system and thus will contribute to smaller variation in energy transition after intermixing. For instance, at the power excitation density of 1500 W/cm², the PL linewidth decreases by 6 nm (from 94 nm to 88 nm) after the IFVD process is performed by annealing the SiO₂ capped sample at 750ºC for two minutes (Djie et al., 2008). However, the opposite observations in the Qdash, i.e. larger PL linewidth after intermediate intermixing, suggests the presence of different interdiffusion rates at a given intermixing degree in the Qdash nanostructures as a consequence of wide variation in surface to volume ratio in Qdash ensembles. The presence of more non-interacting Qdash with wider distribution of energy levels will contribute to radiative recombination emission over larger wavelength coverage and thus a larger FWHM in PL spectra. In other words, carrier localization is more prominent in an isolated Qdash, which affects the optical properties of these material systems. Nevertheless, both intermixed and as-grown Qdash samples showing saturation of ΔFWHM at excitation power over 400 W/cm² indicates that large degeneracy levels in highly confined energy states of Qdash is still preserved as can be seen in Qdot nanostructures (Hadass et al., 2004).

The nearly symmetric Qdash PL spectra in Fig. 5 are broadened with increasing optical excitation densities. Furthermore, an increase in integrated PL intensity after intermixing
occurs. All these observations are contrary to the conventional quantum-confined nanostructures. These can be attributed to the continuous PL wavelength blue-shift observed in both as-grown and intermixed samples, as shown in Fig. 5, with increasing optical excitation densities. The continuous blue-shift of the PL peak wavelength up to 88 nm in the as-grown sample and 61 nm in the intermixed sample at the optical excitation density of 1500 W/cm², relative to those obtained at the excitation of 3 W/cm², are shown in the inset of Fig. 5. The effect of band-filling is insufficient to explain the large degree of blue-shift observed from sample excited under high density excitation. Hence, it is reasonably ascribed this to the postulation of continuum states (Van der Poel et al., 2006) in the Qdash nanostructures, although spectral widening at a shorter wavelength is expected in an inhomogeneous Qdash structure (Hadass et al., 2004). Continuum states serve as an effective medium for exciton scattering and thus change the dephasing rate (Tan et al., 2007) at each energy level within the highly inhomogeneous ensembles and the radiative recombination profile will be different from that of conventional QW. The wide distribution of energy levels due to the nature of Qdash inhomogeneous (FWHM of 76 nm from PL measurement of as-grown sample at low excitation of 3 W/cm²) will further serve as the radiative recombination states or “sink” for the scattered excitons from the dense continuum states. Consequently, quasi-supercontinuum lasing spectra of the diode laser fabricated from these samples are observed, which will be discussed in the later section. Nevertheless, smaller blue-shift of PL peak wavelength in the intermixed sample, as depicted in the inset of Fig. 5, indicates that IFVD enhances the Qdash inhomogeneity more so in larger sizes of Qdashes, which emit at longer wavelengths. Assuming a uniform injection of group-III vacancies from the surface during the IFVD process, the interdiffusion in the vertical direction will affect the dash height more than other directions (Djie et al., 2008; Wei et al., 2005). At an intermediate stage of intermixing, the thick dash family, where the quantized energy level located closer to the conduction band minima, will experience a larger degree of intermixing as the effective height or thickness of the dash decreases, as depicted in the inset of Fig. 3. In addition, the local effective concentration for the thick dash family is higher than the thin dashes. Under uniform annealing temperature, the thick Qdash family that has larger interdiffusion length will yield larger degree of intermixing. As a result, largest degree of wavelength blue-shift (~65 nm) is observed at low excitation of 3 W/cm² (dominant emission from thick dashes) as compared to the smaller wavelength blue-shift (~38 nm) at high excitation of 1500 W/cm² (dominant emission from thin dashes).

4.2 Effect of nonequilibrium carrier distribution from intermixed lasers

Broad area laser characterization of the intermixed samples further provides evidence of a multi-state emission as shown in Fig. 6. A spectral widening is apparent as the bias increases (Hadass et al., 2004). The emission spectra show multi-state lasing emission as injection increases to current density \( J \) of 1.5 \( J \) \( \text{th} \) (threshold current density) and above as opposed to a series of well-defined groups of longitudinal modes (Harris et al., 1998) emission above threshold in highly inhomogeneous Qdot. This implies the preservation of 3-dimensional energy confinement of the Qdash in addition to the emission from multiple sizes of Qdash ensembles as shown in Fig. 7 and Fig. 8 for fabricated lasers with different cavity lengths. The localized active region of the device can be treated as a large number of Qdot or Qdash, which can be further treated as a broad distribution of discrete energy levels (Shoji et al., 1997). This is owed to the inhomogeneous broadening nature of Qdash ensembles and the
dash variation from different dash stacks. The light-current ($L-I$) curve of the short cavity Qdash laser ($L = 300\mu$m) yields a $J_{th}$ and slope efficiency of 2.3 kA/cm$^2$ and 0.46 W/A, respectively, as depicted in Fig. 7(a). Measuring the temperature dependent $J_{th}$ over a range of 10-50 ºC, reveals the temperature characteristic ($T_o$) of 41.3 K. On the other hand, the long cavity Qdash laser ($L = 1000\mu$m) yields $J_{th} = 1.18$ kA/cm$^2$, slope efficiency of 0.215 W/A, and $T_o$ of 46.7 K over the same temperature range, as shown in Fig. 8(a).

Fig. 6. The lasing spectra show the changes of multi-state emission, from ground state (GS), first excited state (ES 1) and second excited state (ES 2) of the 50 x 500 µm$^2$ broad area Qdash intermixed laser, under different current injection of 1.1 x $I_{th}$, 1.5 x $I_{th}$ and 2.25 x $I_{th}$.

Fig. 7. (a) $L-I$ characteristics of the 50 x 300 µm$^2$ broad area intermixed Qdash laser at different temperatures. Up to ~450 mW total output power (from both facets) has been measured at $J= 4.0 \times J_{th}$ at 20ºC. (b) The progressive change of lasing spectra above threshold condition.

Compared to the laser with long cavity, the shorter cavity laser exhibits the progressive appearance of short wavelength emission line with an increase in injection level. The $L-I$ curve of the short cavity laser shows kinks as compared to the long cavity laser. The jagged $L-I$ curve below ~3 x $I_{th}$ implies that the lasing actions from different confined energy levels are not stable due to the occurrence of energy exchange between short and long wavelength.
Fig. 8. (a) L-I characteristics of the 50 x 1000 μm² broad area intermixed Qdash laser at different temperatures. Up to ~340 mW total output power (from both facets) has been measured at $J = 4.0 \times J_{th}$ at 20ºC. (b) The progressive change of lasing spectra above threshold condition.

Lasing modes (Hadass et al., 2004), as can be seen in the lasing spectra of Fig. 7(b). In addition, the observation of kink in the L-I curve for device tested at low temperature might also be a result of mode competition in the gain-guided, broad area cavity devices. The calculated Fabry-Perot mode spacing of ~1.1 nm is well resolved in the measurement across the lasing wavelength span at low injection before a quasi-supercontinuum lasing is achieved, where the spectral ripple is less than 1 dB.

Subsequent injections contribute to the stimulated emission from longer wavelength or lower order subband energies while suppressing higher order subbands as shown in Fig. 7(b). This Qdash laser behavior is fundamentally different from the experimental observation from Qdot lasers with short cavity length, where the gain of lower subband is too small to compensate for the total loss, and lasing proceeds via the higher order subbands (Markus et al., 2003; Markus et al., 2006). In short-cavity Qdash laser, the initial lasing peak at shorter wavelength (~1525 nm) is dominantly emitted from different groups of smaller size Qdash ensembles instead of higher order subbands of Qdash. Hence, the significant difference of ~11 meV as compared to the dominant lasing peak of ~1546 nm at high injection will contribute to photon reabsorption by larger size Qdash ensembles and seize the lasing actions at shorter wavelength. Regardless, a smooth L-I curve at the injection above $3 \times J_{th}$ due to the only dominant lasing modes at long wavelength demonstrates the high modal gain of the Qdash active core (Lelarge et al., 2007). These observations indicate that carriers are easily overflows to higher order subbands (Tan, et al., 2009) because of the large cavity loss and the small optical gain (Shoji et al., 1997) at moderate injection. At high injection, carrier emission time becomes shorter, when equilibrium carrier distribution is reached and lasing from multiple Qdash ensembles is seized (Jiang & Singh, 1999).

On the other hand, a relatively smooth L-I curve above the threshold is observed from the long cavity intermixed Qdash laser regardless of the injection levels. The corresponding electroluminescence spectra show only one dominant lasing emission at long wavelengths, unlike, the short cavity Qdash lasers. This observation can be attributed to the effect of long cavity parameter that results in smaller modal loss as compared to short cavity Qdash devices. The progressive red-shift (~10 nm) of lasing peak with increasing injection up to $J = 4 \times J_{th}$ and the insignificant observation of band filling effect indicates that photon
reabsorption occurs due to the photon-carrier coupling between different sizes of Qdash ensembles in addition to the high modal gain of the Qdash active core (Lelarge et al., 2007). Injection above $J = 4 \times J_{th}$ is expected to contribute to broader lasing span at long wavelength owing to the high modal gain characteristics (Tan et al., 2008) although the comparison scheme of the two devices with different cavity lengths may not be fair without applying threshold current density.

Distinctive lasing lines are observed from different cavity intermixed Qdash lasers at the near-threshold injection of $J = 1.1 \times J_{th}$. The similarity of lasing wavelength (inset of Fig. 9) from devices with different cavity lengths further shows promise that the Qdash structures have high modal gain characteristics (Lelarge et al., 2007). However, the Qdash laser with increasing cavity length shows progressive red-shift (total of ~20 nm up to $L = 1000 \mu$m) of peak emission. This may be ascribed to the wide distribution of energy levels because of highly inhomogeneous broadening and photon reabsorption among Qdash families. At the intermediate injection of $J = 2.25 \times J_{th}$, simultaneous two-state laser emission, which is attributed to two groups of Qdash ensembles as mentioned previously, is noticed from short cavity Qdash lasers. On the other hand, a broad linewidth laser emission from a single

Fig. 9. The presence of different lasing Qdash ensembles with cavity length at the injection of $J = 2.25 \times J_{th}$. The inset shows the progressive red-shift of lasing peak emission with cavity length at the injection of $J = 1.1 \times J_{th}$.

Fig. 10. The effect of cavity dependent on quasi-supercontinuum broadband emission from intermixed Qdash laser at an injection of $J = 4 \times J_{th}$.
dominant wavelength is shown in longer cavity Qdash lasers of 850 µm and 1000 µm, as depicted in Fig. 9. As a result, a quasi-supercontinuum broad laser emission could be achieved at high injection, as shown in Fig. 7. An ultrabroad quasi-supercontinuum lasing coverage from Qdash devices with \( L = 500 \mu m \) (Tan et al., 2008) results from emission in different order of energy subbands and groups of ensemble, which will be discussed in the following section.

The broad lasing spectra from devices with different \( L \) suggest there is collective lasing from Qdashes with different geometries. However, the broad laser spectra of Qdash lasers obtained at room temperature are different from that of Qdot lasers which shows similar phenomenon but occur at low temperature below 100 K (Shoji et al., 1997; Jiang & Singh, 1999). In Qdot lasers, with increasing temperature, carriers can be thermally activated outside the dot into the well and/or barrier and then relax into a different dot (Tan et al., 2007). Carrier hopping between Qdot states can favor a drift of carriers towards the dots where the lasing action preferentially takes place, thus resulting in a narrowing of the laser mode distribution. However, in Qdash lasers, carriers will be more easily trapped in the dash ensembles due to the elongated dimension in addition to random height distribution in each ensemble. These profiles of energy potential will support more carriers, thus retarding the emission of carriers (Jiang & Singh, 1999) and resulting in a smaller homogeneous broadening at each transition energy level (Tan et al., 2007). Hence, the actual carrier distribution in Qdash nanostructures will be at high nonequilibrium and lead to broadband lasing even at room temperature.

4.3 Ultrabroadband lasers - as-grown and bandgap tuned devices

Fig. 11(a) shows the light-current (\( L-I \)) characteristics of the as-grown Qdash laser (\( L = 600 \mu m \)). The corresponding \( J_{th} \) and slope efficiency are 2.6 kA/cm\(^2\) and 0.165 W/A. Up to 400 mW total output power has been measured at \( J = 4.5 \times J_{th} \) at 20°C, which is significantly higher than the SLED fabricated from the same wafer (Djie et al., 2006). From the dependence of \( J_{th} \) on temperature, the temperature characteristic \( T_0 \) of 43.6 K in the range of 10 to 70°C has been obtained. At \( J < 1.5 \times J_{th} \), there is only ground state lasing \( E_0 \) with the wavelength coverage of ~10 nm [Fig. 11(b)]. The broad \( E_0 \) lasing spectrum suggests the collective lasing from Qdashes with different geometries. At \( J > 1.5 \times J_{th} \), the bi-state lasing is noted. The simultaneous lasing from both \( E_0 \) and \( E_1 \) is attributed to the relatively slow carrier relaxation rate and population saturation in the ground state in low-dimensional quantum heterostructures (Zhukov et al., 1999). The transition from mono-state to bi-state lasing is marked with a slight kink in the \( L-I \) characteristics. The bi-state lasing spectrum is progressively broadened with increasing carrier injection up to a wavelength coverage of 54 nm at \( J = 4.5 \times J_{th} \). The corresponding side-mode suppression ratio is over 25 dB and a ripple measured from the wavelength peak fluctuation within 10 nm span is less than 3 dB.

Bangap-tuned broad area lasers with optimum cavity length (\( L = 500 \mu m \)) that gives largest quasi-supercontinuum coverage of lasing emission, as presented in Fig. 10, are fabricated. The \( L-I \) curve of the Qdash laser yields an improved \( J_{th} \) and slope efficiency of 2.1 kA/cm\(^2\) and 0.423 W/A, which is depicted in Fig. 12(a), as compared to that of as-grown laser with 2.6 kA/cm\(^2\) and 0.165 W/A, respectively (Djie et al., 2007). The \( L-I \) curve of the intermixed laser shows kinks, which is similar to that of short cavity \( L = 300 \mu m \) Qdash lasers. The energy-state-hopping instead of mode-hopping occurs due to the wide distribution of the energy levels across the highly inhomogeneous Qdash active medium, as derived from the...
Fig. 11. (a) The L-I characteristics of the 50×600 µm² broad area Qdash laser at different temperatures. The inset shows the schematic illustration of oxide stripe lasers with [110] cavity orientated perpendicular to the dash direction. (b) The lasing spectrum above the threshold condition at 20ºC (curves shifted vertically for clarity). The lines are as the guide to the eyes indicating the confined state lasing lines, $E_0$ and $E_1$ (dashed lines) and the wavelength coverage of laser emission (dotted lines). The spectra are acquired using an optical spectrum analyzer with wavelength resolution of 0.05 nm.

PL results. In spite of that, a smooth $L-I$ curve above 6 kA/cm² yields a total high power of ~1 W per device at room temperature before any sign of thermal roll-over. This shows that injection above 6 kA/cm² provides enough carriers for population inversion in all the available or possible radiative recombination energy states and thus the energy-state-hopping is absent.

Fig. 12. (a) $L-I$ characteristics of the 50 x 500 µm² broad area Qdash laser at different temperatures. Up to ~1 W total output power has been measured at $J = 5.5 \times J_\text{th}$ at 20ºC before showing sign of thermal roll-off. (b) The lasing spectra above threshold condition that are acquired by an optical spectrum analyzer with wavelength resolution of 0.05 nm.

Measuring the temperature dependence $J_\text{th}$ over a range of 10-60 ºC reveals the improved $T_\text{o}$ of 56.5 K as compared to the as-grown laser of 43.6 K (Djie et al., 2007). This result is
comparable to the $T_0$ range (50-70 K) of the equivalent QW structure. In Fig. 12(b), only a distinctive ground state lasing with the wavelength coverage of $\sim$15 nm is observed below injection of $1.5 \times J_{th}$. This broad lasing linewidth, again suggests collective lasing actions from Qdashes with different geometries. In addition, the quasi-supercontinuum lasing spectrum at high current injection ($4 \times J_{th}$) without distinctive gain modulation (Harris et al., 1997) further validates the postulation of uniform distribution of dash electronic states in a highly inhomogeneous active medium. At $J > 1.5 \times J_{th}$, the bistate lasing is evident. The simultaneous lasing from both transition states (Hadass et al., 2004) is attributed to the relatively slow carrier relaxation rate and population saturation in the ground state in low-dimensional quantum heterostructures. The bistate lasing spectrum is progressively broadened with increasing carrier injection up to a wavelength coverage of 85 nm at $J = 4 \times J_{th}$, which is larger than that of the as-grown laser ($\sim$76 nm), as shown in Fig. 11 and Fig. 13. A center wavelength shift of 100 nm and an enhancement of the broadband linewidth, which is attributed to the different interdiffusion rates on the large height distribution of noninteracting Qdashes at an intermediate intermixing, are achieved after the intermixing. The inset of Fig. 13, showing the changes of FWHM of the broadband laser with injection depicts that energy-state-hopping and multi-state lasing emission from Qdashes with

![Fig. 13](image13.png)

Fig. 13. The wavelength tune quasi-supercontinuum quantum dash laser from 1.64 $\mu$m to 1.54 $\mu$m center wavelength. The lasing coverage increases from 76 nm to 85 nm after intermixing process. The inset shows the FWHM of the broadband laser in accordance to injection above threshold up to $J = 4 \times J_{th}$.

![Fig. 14](image14.png)

Fig. 14. (a) Spaced and quantized energy states from ideal Qdot samples. (b) Large broadening of each individual quantized energy state contributes to laser action across the resonantly activated large energy distribution. (c) Variation in each individual quantized energy state owing to inhomogeneous noninteracting quantum confined nanostructures in addition to self broadening effect demonstrate a broad and continuous emission spectrum.
different geometries occur before a quasi-supercontinuum broad lasing bandwidth with a ripple of wavelength peak fluctuation that is less than 1 dB is achieved. This idea can be illustrated clearly in Fig. 14, when a peculiarly broad and continuous spectrum is demonstrated from a conventional quantum confined heterostructures utilizing only interband optical transitions. The effect of variation in each individual quantized energy state owing to large ensembles of noninteracting nanostructures with different sizes and compositions, in addition to self inhomogeneity broadening within each Qdot/Qdash ensemble, will contribute to active recombination and thus quasi-supercontinuum emission.

5. Conclusion

In conclusion, the unprecedented broadband laser emission at room temperature up to 76 nm wavelength coverage has been demonstrated using the naturally occurring size dispersion in self-assembled Qdash structure. The unique DOS of quasi-zero dimensional behavior from Qdash with wide spread in dash length, that gives different quantization effect in the longitudinal direction and band-filling effect, are shown as an important role in broadened lasing spectrum as injection level increases. After an intermediate degree of postgrowth interdiffusion technique, laser emission from multiple groups of Qdash ensembles in addition to multiple orders of subband energy levels within a single Qdash ensemble has been experimentally demonstrated. The suppression of laser emission in short wavelength and the progressive red-shift of peak emission with injection from devices with short cavity length indicate the occurrence of photon reabsorption or energy exchange among different sizes of localized Qdash ensembles. These results lead to the fabrication of the wavelength tuned quasi-supercontinuum interband laser diodes via the process of IFVD to promote group-III intermixing in InAs/InAlGaAs quantum-dash structure. Our results show that monolithically integration of different gain sections with different bandgaps for ultra-broadband laser is feasible via the intermixing technique.

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7. References


The title of this book, Advances in Optical and Photonic Devices, encompasses a broad range of theory and applications which are of interest for diverse classes of optical and photonic devices. Unquestionably, recent successful achievements in modern optical communications and multifunctional systems have been accomplished based on composing “building blocks” of a variety of optical and photonic devices. Thus, the grasp of current trends and needs in device technology would be useful for further development of such a range of relative applications. The book is going to be a collection of contemporary researches and developments of various devices and structures in the area of optics and photonics. It is composed of 17 excellent chapters covering fundamental theory, physical operation mechanisms, fabrication and measurement techniques, and application examples. Besides, it contains comprehensive reviews of recent trends and advancements in the field. First six chapters are especially focused on diverse aspects of recent developments of lasers and related technologies, while the later chapters deal with various optical and photonic devices including waveguides, filters, oscillators, isolators, photodiodes, photomultipliers, microcavities, and so on. Although the book is a collected edition of specific technological issues, I strongly believe that the readers can obtain generous and overall ideas and knowledge of the state-of-the-art technologies in optical and photonic devices. Lastly, special words of thanks should go to all the scientists and engineers who have devoted a great deal of time to writing excellent chapters in this book.

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University Campus STeP Ri
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51000 Rijeka, Croatia
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No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
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