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Quantum Dot Photonic Devices and Their Material Fabrications

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1. Introduction

Optical frequency resources with wide capacity are required for the construction of photonic transport systems exhibiting high performance and flexibility (Gnauck et al. 2007 & Sotobayashi et al. 2002). The use of ultra-broadbands such as the 1–2-μm wavelength band focuses on photonic communications (Yamamoto et al. 2009a). To utilize a wide wavelength band for photonic communications, novel photonic devices must be developed for each wavelength in the 1–2-μm band. Similar to the conventional wavelength division multiplexing (WDM) photonic transport system shown in Fig. 1, it is well known that several types of optical components of photonic devices such as infrared light sources, optical modulators, optical amplifiers, optical fiber transmission lines, photodetectors, arrayed waveguide gratings, and other passive optical devices are necessary for the construction of photonic transport systems. Photonic transport systems cannot be constructed, if any one component of those photonic devices is not available. Therefore, the development of novel photonic devices in the new waveband is important for the construction of photonic transport and optical communications systems in the all-photonic waveband between 1 and 2 μm. It is expected that ultra-broadband optical frequencies greater than 100 THz can be employed for optical communications. The researches of photonic devices and physics in the all-photonic waveband will help in expanding the usable optical frequency resources for photonic communications. Additionally, the novel photonic devices developed according to the use of the all-photonic waveband can be employed for not only photonic communications devices but also for several scientific applications such as bio-imaging (Yokoyama et al. 2008), environment sensing, and manufacturing.

Figure 2 shows a typical technology map in the all-photonic waveband between 1 and 2 μm (Yamamoto et al. 2009a). Semiconductor device technology is considered to be important for developing active devices in the all-photonic waveband. Generally, InP-based semiconductor devices have been produced for photonic transport systems because conventional photonic networks have been constructed in the C- and L-band (C-band: 1530–1565 nm, and L-band: 1565–1625 nm). The widening of an optical amplifier bandwidth has been intensively studied in the conventional photonic bands of the C- and L-band. However, GaAs-based, Si-based, and SiGe-based semiconductor photonic devices will

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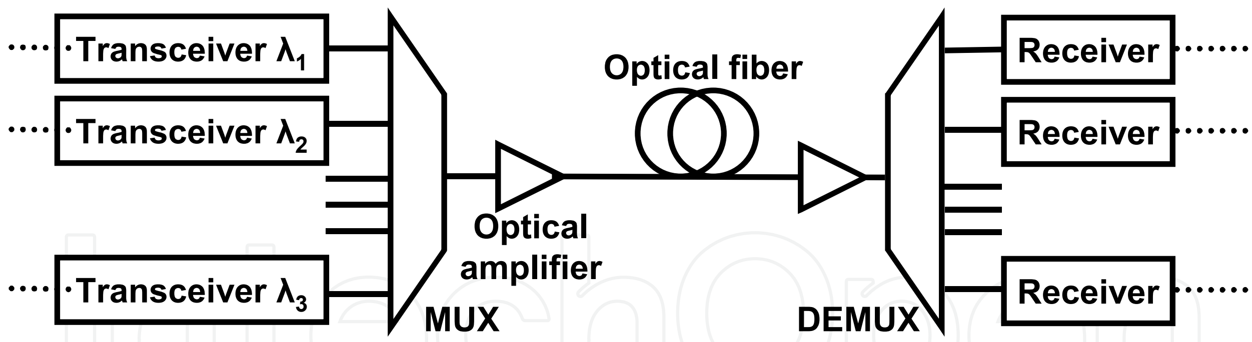

Fig. 1. Schematic image of wavelength division multiplexing (WDM) photonic transport system.

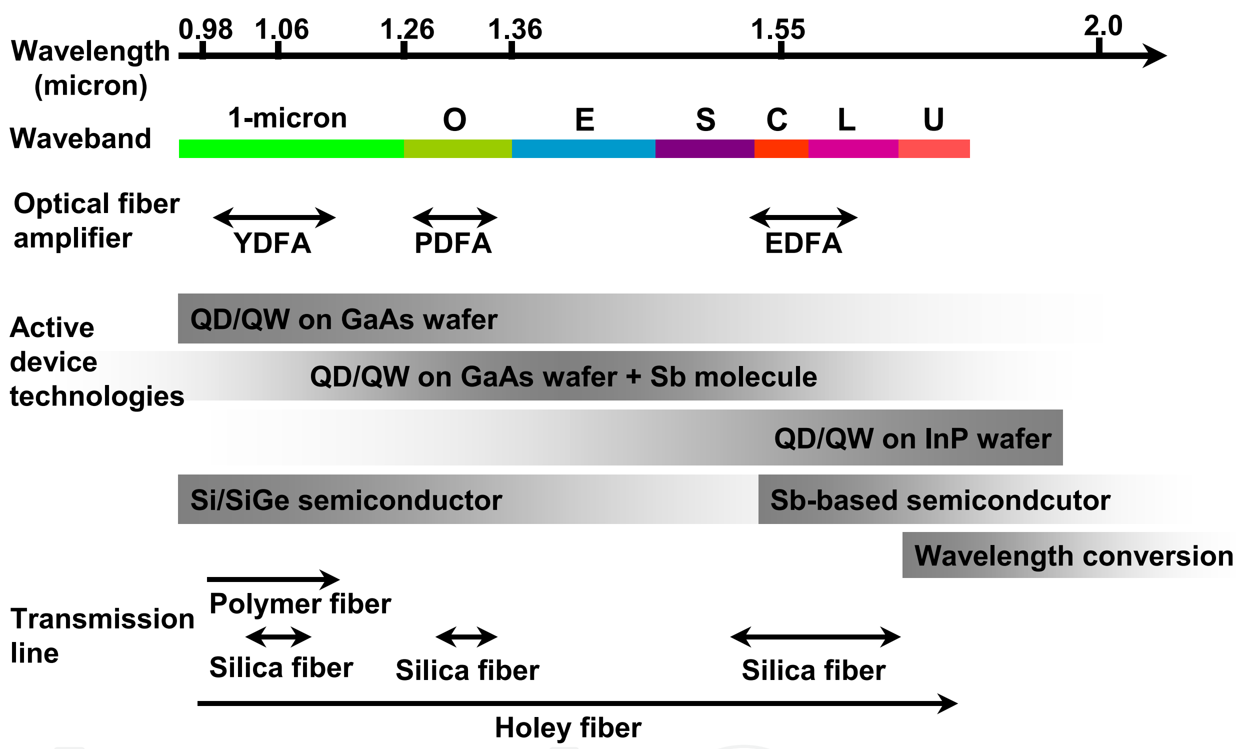

Fig. 2. Technology map and photonic waveband for optical communications. The abbreviations QD and QW denote the quantum dot and quantum well structures, respectively.

become powerful candidates for use in shorter wavelengths such as a 1-µm and O-bands (O-band: 1260–1360 nm) in photonic transport systems (Hasegawa et a. 2006; Yamamoto et al. 2008d; Ishikawa et al. 2009 & Koyama 2009). In particular, high-performance and wide optical frequency band fiber amplifiers (Ytterbium-doped fiber amplifier: YDFA, and Praseodymium-doped optical fiber amplifier: PDFA) can be employed in shorter wavebands (Paschotta et al. 1997). In the ultra-long wavelength band in the 1625–2000 nm and mid-infrared region (>2000 nm), Sb-based semiconductors such as GaSb and InGaSb are useful materials for the development of the photonic devices such as light-emitting diodes, semiconductor lasers, and detectors. Additionally, in this wavelength region, the wavelength conversion technique with an optical nonlinear effect is also employed for constructing light sources. Optical fiber transmission lines are important devices for the construction of photonic transport systems. Ultra-wideband and low-loss photonic transmission lines have been intensively investigated by using holey fiber, hole-assisted fiber, and photonic crystal fiber structures (Mukasa et al. 2007 & 2008). From Fig. 2, it is expected that photonic devices for the all-photonic waveband will be developed by combining GaAs-, InP-, GaSb-, SiGe-, and Si-based semiconductor device technologies. Additionally, implementing nanotechnology for these semiconductor materials is a powerful solution to enhance a usable waveband for semiconductor photonic devices. A quantum dot (QD) is a useful and simple structure for achieving a three-dimensional confinement of electrons and/or holes in the semiconductor (Arakawa et al., 1982). Therefore, the energy levels of the confined electrons and holes can be controlled artificially by controlling the size of the QD structure. It is well known that self-assembled semiconductor QDs exhibit interesting and excellent properties as compared to semiconductor bulk or quantum well structures. The typical properties are as follows: (1) quantum size effect, (2) high confinement efficiency of carriers, (3) desirable quantum levels, and (4) no restrictions on the crystal lattice constant. It is expected that these useful properties improve the device performance. For example, it is possible to fabricate low-threshold lasers (Shimizu et al. 2007), un-cooled lasers (Otsubo et al. 2004; Tanaka et al. 2009), long-wavelength lasers (Ledentsov et al. 2003; Yamamoto et al. 2005 & Akahane et al., 2008), high-power lasers (Tanguy et al. 2004) and ultra-broadband lasers by using QD structures (Rafailov et al. 2007). Additionally, the ultra-broadband semiconductor optical amplifier is also expected to be fabricated by using the QD structure. In this chapter, the development of a semiconductor QD laser and its photonic transport applications are described. The QD structure is considered to be suitable for the development of important devices for the all-photonic waveband.

2. Quantum dot photonic device and optical communications

2.1 Broadband quantum dot laser

The semiconductor QD structures are expected for broadband optical gain materials. Generally, the self-assembled semiconductor QD structure is formed on the GaAs or InP substrate under a S-K (Stranski-Krastanov) growth mode by using molecular beam epitaxy (MBE) and a metal-organic chemical vapor deposition (MOCVD) technique. Figure 3(a) shows an atomic force microscope (AFM) image of an InGaAs QD structure fabricated on a GaAs (001) wafer surface. The InGaAs/GaAs QD structure is fabricated by using solid source MBE. The typical height and dimensions of the InGaAs/GaAs QD structure is approximately 4 nm and 20 nm, respectively. It is well known that the density and structure of the QD hardly influence the surface condition before the growth of the QD structure. Therefore, the Sb-molecular irradiation technique (Yamamoto et al. 2008b), Si-atom irradiation technique, and sandwiched sub-nano-separator (SSNS) structure (Yamamoto et al. 2009c) are proposed to enhance the QD density and reduce the giant dot and crystal defect. Figure 3(b) shows a schematic image of the cross-sectional image of the InGaAs/GaAs QD structure embedded in the GaAs matrix with the surface controlling technique of Sb-irradiation. In other words, a high quality QD structure is obtained by using these surface controlling techniques. Therefore, it is expected that the surface controlling techniques employed during QD growth may improve the device performance. The density of the QD structure is estimated to be as high as $5.3 \times 10^{10}/cm^2$. The In composition and deposition amount of the QD structure are controlled in order to tune the emission wavelength. In this case, the In composition and deposition amounts are fixed as approximately 0.5 and 6.0 ML, respectively, in order to fabricate the InGaAs/GaAs QD structure emitting in the 1-μm waveband.

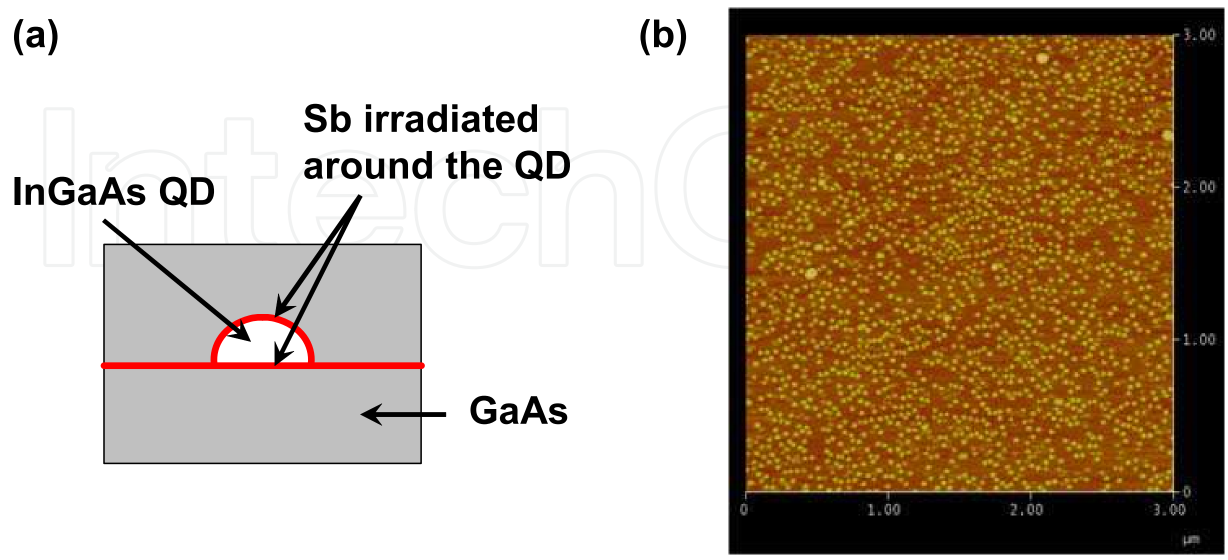

Fig. 3. (a) Schematic cross sectional structure of Sb-irradiated quantum dot structure, and (b) atomic force microscope (AFM) image of the InGaAs/GaAs quantum dot structure on a surface area of 3 μm².

Figure 4(a) shows a cross-sectional schematic image of a ridge-type QD laser structure. The fabrication technique employed for a GaAs-based laser device can be applied to QD laser devices on the GaAs wafer. In the core region, multi-stacked QD layers are generally fabricated with a 50-nm spacer GaAs layer. The QD core region is sandwiched by AlGaAs cladding layers with 1- or 2-μm thickness. A growth temperature of the top cladding layer is generally lower than a temperature for the conventional GaAs based laser, because a structure of the fabricated QD is influenced with the high growth temperature of the cladding layer. Figure 4(b) shows a cross-sectional scanning electron microscope (SEM) image of the fabricated QD laser structure. A buried polyimide process and a lift-off technique are carried out for fabricating the ridge-type QD laser diode. The width of the ridge waveguide structure is generally fixed from approximately 2 to 7 μm to achieve a single mode and low-threshold current operations. Naturally, the etching depth of the ridge structure depends on the width of the ridge. A mounted QD laser diode on a chip carrier is applied to photonic transport systems and bio-imaging, because a stable operation of the QD laser diode can be achieved by using the chip carriers. Figure 5(a) shows the mounted QD laser diode on the carrier. This mount technique is similar to the conventional technique used for the GaAs-based laser devices. In other words, wire-bonding and die-bonding techniques are used for the fabrication of the QD laser diode chip. It is important that a large number of fabrication technologies developed for GaAs-based devices are applied to the QD/GaAs device fabrication. Figure 5(b) shows the laser spectra obtained from two types of QD/GaAs lasers. The InGaAs QD/GaAs laser diode emission has a wavelength of 1.04 μm. Additionally, it is clearly observed that other laser emissions have a wavelength of 1.27 μm in the O-band. Laser emission with longer wavelengths can be achieved by using novel optical gain materials such as an Sb-irradiated QD in the well (Sb-DWELL) or InAs/InGaAs QD with SSNS structures (Liu et al. 2003; Yamamoto et al. 2008b, 2009a & 2009c). These emission wavelengths are matched to the ground state of the QD structure. It is well known that ground state lasing must be applied to achieve a low-threshold current density operation of the QD laser. These emission peaks such as 1.04 and 1.27 μm are suitable for the optical gain bandwidth of the YDFA and PDFA, respectively. Therefore, these QD laser devices are highly suitable for photonic transport systems in the 1-μm band and O-band. An emission wavelength of the conventional GaAs-based laser devices has a limitation of up to approximately 1.06 μm. Therefore, it is found that an expansion of the usable wavelength band of the GaAs-based laser diode can be achieved by using QD structures. It is clear that the fabrication of the long and ultra-broad wavelength band (1.0–1.3 μm) light sources can be achieved by combining a novel QD growth technology with the conventional GaAs-based device technology.

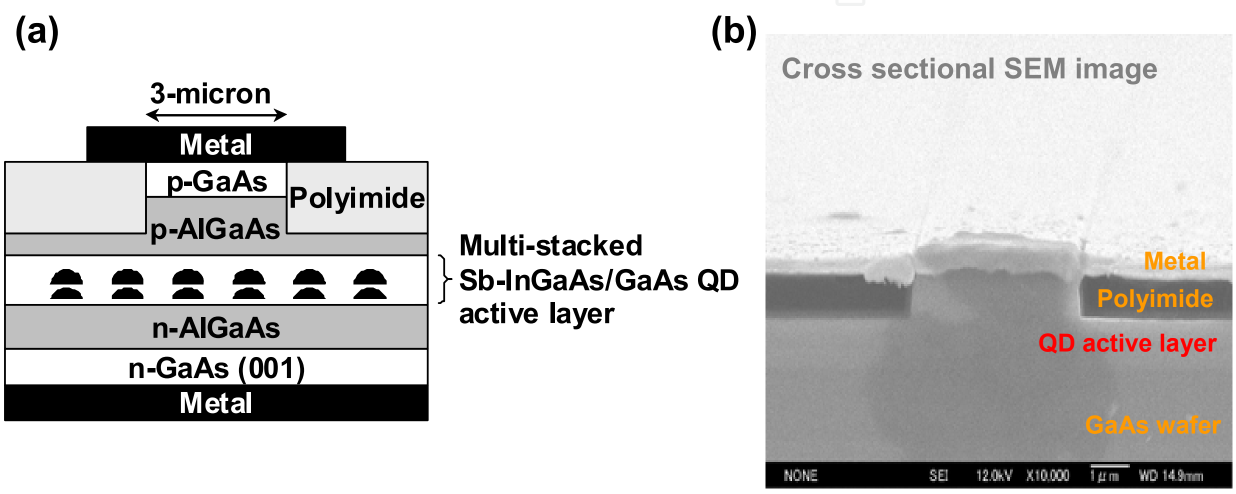

Fig. 4. (a) Schematic cross-sectional image of the InGaAs/GaAs quantum dot laser structure fabricated on a GaAs wafer. (b) Cross-sectional scanning electron microscope image of the ridge-type quantum dot laser.

2.2 Quantum dot wavelength tunable laser

It is expected that an ultra-broadband optical gain will be realized by using QD gain materials. Therefore, the broadband wavelength tunable laser is also achieved by using the QD structures. In this section, one of the QD wavelength tunable laser scheme is introduced. The InGaAs/GaAs QD structure is used to fabricate a wavelength tunable laser in the 1-μm waveband, because the ultra-broadband optical gain can be achieved by using the QD active media as compared to the conventional quantum well (QW) structure. An optical gain material of the InGaAs/GaAs QD laser diode is prepared by using solid-source MBE. A self-assembled QD structure is incorporated by using an Sb-molecule-irradiated InGaAs material on GaAs (001) surfaces together with AlGaAs cladding layers. Here, the emission wavelength corresponding to the QD ground state is tuned in to the 1-μm optical-waveband. Thus, from the MBE-grown QD layers, a 3-μm wide ridge-waveguide laser structure is formed through a standard sequence of GaAs-based semiconductor laser fabrication. The cavity length of the structure is 2 mm. The edge of the laser diode is a cleaved facet. Figure 6(a) shows a schematic configuration of the injection-seeding scheme with the operation wavelength tenability (Yamamoto et al. 2008c & Katouf 2009). A narrow-band optical wedge filter (0.6 nm) is incorporated between the QD laser chip and an external

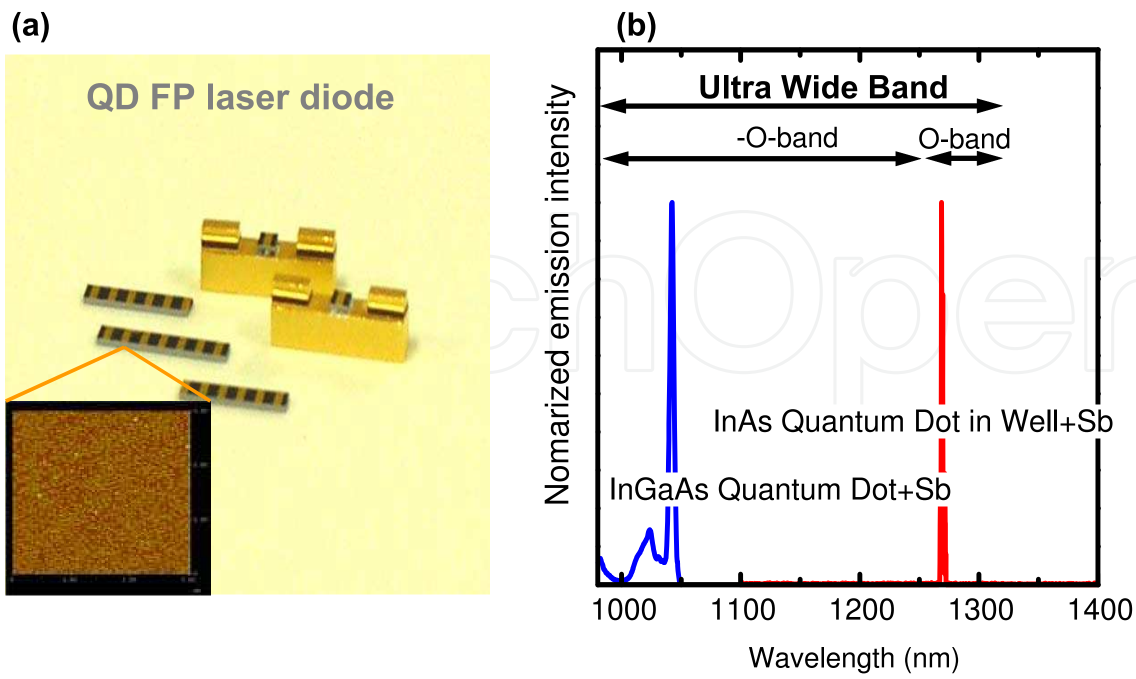

Fig. 5. (a) Photograph of the quantum dot laser diode chip. (b) Laser emission spectrum for the quantum dot laser diode in an ultra-wideband between the 1-μm and 1.3-μm wavelengths.

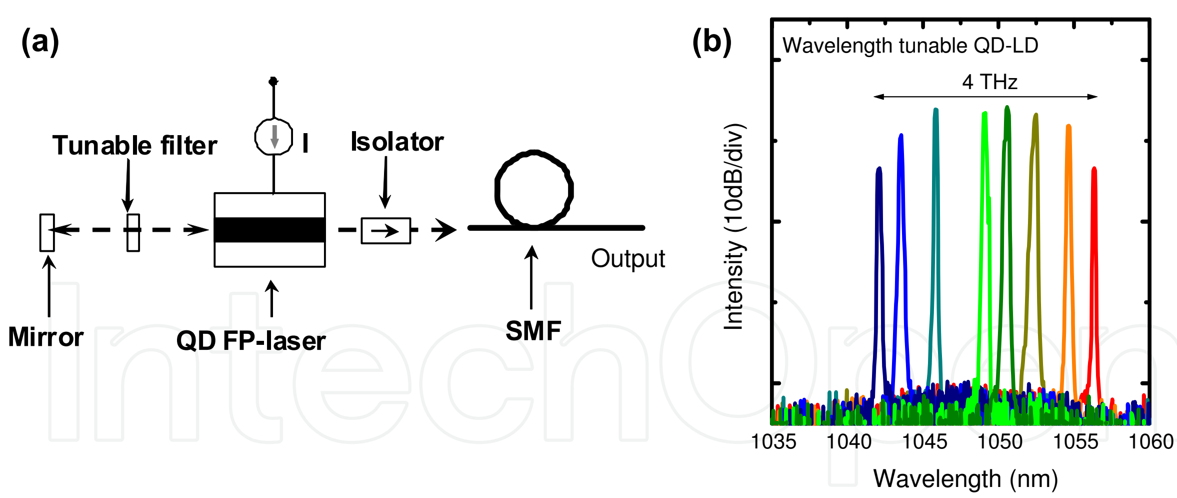

Fig. 6. (a) Wavelength tunable laser constructed with a self-injection seeded quantum dot Fabry-Perot laser. (b) 4-THz tuning range of the 1-μm wavelength tunable quantum dot laser.

mirror, which facilitates the tunability of the emission wavelength. The centre wavelength of the optical filter is controlled by adjusting the light-beam position on the filter. In other words, the wavelength selected by the filter is injected to the laser chip to lock the lasing wavelength of the QD laser diode. The temperature of the laser chip is maintained at 300 K by a thermoelectric cooler stage. The optical output from the laser is coupled to a single-mode optical fiber for the 1-µm optical waveband.

Figure 6(b) shows the typical experimental result of the injection-seeded operation of the QD wavelength tunable laser. The lasing operation is confirmed in a wavelength ranging from 1042 nm to 1057 nm, which corresponds to a broad optical frequency band with a 4-THz bandwidth and consequently to 40 WDM channels with a 100-GHz grid. The tunable frequency of the 4-THz bandwidth is similar to the bandwidth of the C-band. It should be noted that each laser emission peak in Fig. 6(b) is prominent and its optical power level is at least 25 dB higher than that of amplified spontaneous emission. Furthermore, it has been found out that the undulation of the optical output power in the wavelength ranging from 1045 to 1052 nm is 1.0 dB or less. Additionally, all the laser output in the injection-seeding bandwidth can be successfully amplified to up to 10 dBm by using the YDFA. This amplified output power level suggested that broadband WDM photonic transport systems can be feasible with the present devices. On the other hand, a photonic transmission experiment was performed using wavelength tunable QD laser devices. By using the wavelength tunable QD laser for the 1-µm waveband, a 2.54-Gbps error-free transmission with a clear eye opening was successfully demonstrated over the 1-km hole-assisted fiber.

Some wavelength tuning techniques of semiconductor lasers are already proposed, such as conventional techniques of an external cavity scheme and a multi-sectional electrode scheme. These techniques can be simply employed for achieving the broadband tunability width of the QD lasers.

2.3 1-µm waveband photonic transport system

To construct a WDM photonic transport system, the essential photonic devices required are a stable multiwavelength light source suitable for high-speed (>10 Gbps) data modulation, long-distance single-mode transmission optical fiber, wavelength multiplexer (MUX)/demultiplexer (DEMUX), and numerous passive devices. In this section, a 1-µm waveband photonic transport system is demonstrated to pioneer the novel waveband for optical communications (Yamamoto et al. 2008d & 2009b; Katouf et al. 2009). It is considered that a 1-µm waveband QD laser is useful for the optical signal source because a wide optical gain bandwidth can be realized by using the QD structure. Therefore, the QD light source and the photonic transport system are demonstrated. As the QD light source, the generation of a 1-µm waveband optical frequency comb from the fabricated QD optical frequency comb laser (QD-CML) and a method for an optical mode selection for a single-mode operation of the QD-CML are introduced. Additionally, to realize a WDM photonic transport in the 1-µm waveband, a long-distance single-mode holey fiber (HF) and an arrayed waveguide grating (AWG) are also introduced for the transmission line and MUX/DEMUX devices, respectively.

The Sb-molecular irradiated InGaAs/GaAs QD ridge type laser diode was used as the light source for the photonic transport system. The QD laser diode acts as a QD-CML in the 1-µm waveband under high current injection conditions. Figure 7(a) shows the optical frequency comb spectrum obtained from the QD-CML. The frequency bandwidth of the generated optical frequency comb is as wide as ~2.2 THz under a current of few hundred mA. The frequency bandwidth increased with the QD laser current. The free spectral range (FSR) of the optical frequency comb generated from the QD-CML is estimated to be approximately 20 GHz, which is close to the Fabry-Perot mode spacing corresponding to the cavity length.

It is expected that the QD-CML will emerge as an important light source and will have applications as a compact optical frequency comb generator in photonic networks, bio-imaging, etc (Gubenko et al. 2007).

The single- and discrete-mode selections of the QD-CML are important techniques for photonic communications. For applying the single-mode selection technique, an external mirror and a wavelength tunable filter were used for self-seeded optical injection. An optical discrete mode was selected by using the wavelength tunable filter. Figure 7(b) shows an optical spectrum of the single-mode selected QD laser. A sharp peak can be observed at 1047 nm. By using this technique, the side-mode suppression ratio (SMSR) and spectral line width were possibly >20 dB and <0.03 nm, respectively. Hence, the center wavelength of the lasing mode could be selected by controlling the wavelength tunable filter.

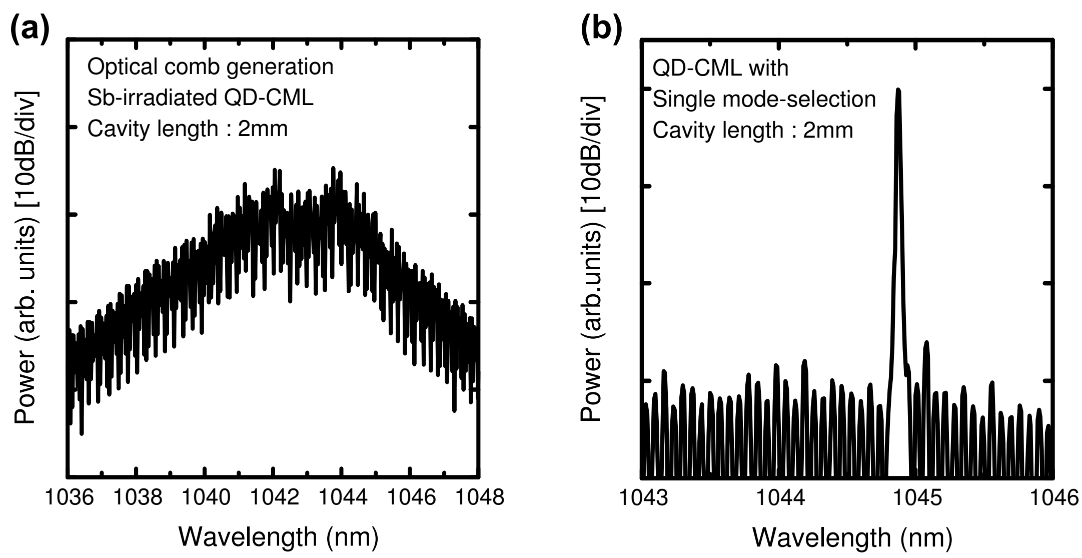

Fig. 7. (a) Optical frequency comb generation from the quantum dot optical frequency comb laser (QD-CML). (b) Optical spectrum of the single-mode selected quantum dot laser.

Figure 8 shows the experimental setup for testing the WDM photonic transmission in the 1-µm waveband (Yamamoto et al. 2009a & 2009b) at 12.5 Gbps. The single-mode selected QD-CML was used as the wavelength tunable non-return to zero (NRZ) signal optical source. The lasing optical mode was selected by using the discrete single-mode selection technique. The selected mode was fitted to the channel spacing (100 GHz) of the AWG device in the 1-µm waveband. The optical signal was amplified by using a YDFA after a 12.5-Gbps and a 2^{15}–1 pseudorandom binary sequence (PRBS) data modulation. The optical signal was passed through the AWG pair. In other words, the AWG pair played the role of a DEMUX and MUX for the multiwavelength optical signal. A single-mode HF was developed for the transmission line in the 1-µm waveband. The dispersion characteristics of the HF were controlled by controlling the size of the holes and their distances from the fiber core (Mukasa et al. 2008 & 2009). The input power to the transmission line was approximately 0 dBm. The transmitted optical signal was amplified again by using a YDFA before the measurements. The optical filters positioned after the YDFAs were used for cutting off the amplified spontaneous emission (ASE) noise in the YDFAs. Figure 9(a) shows the optical spectra measured after a 1.5-km-long HF transmission at four different wavelengths (ch.1:

1042.71 nm–ch.4: 1043.85 nm). Each of the central wavelengths is selected for the 100-GHz channel spacing of the AWG by using the discrete single-mode selection method of the QD-CML. Figure 9(b) shows a typical eye diagram at ch. 2 after transmission. A clear eye opening at 12.5 Gbps is observed after the transmission. Therefore, the 1-μm waveband with a 12.5-Gbps transmission over a long-distance (1.5 km) single-mode HF is successfully

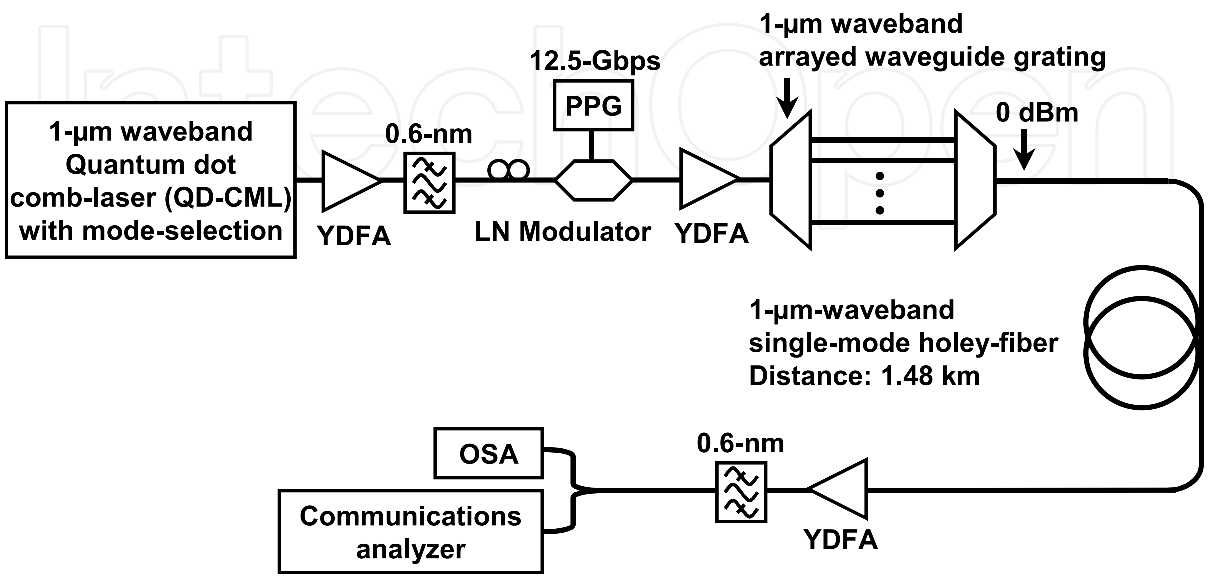

Fig. 8. Experimental set-up for testing the 1-μm WDM photonic transport system. A 1-μm waveband and single-mode selected quantum dot optical-frequency comb laser (QD-CML) was used for the light source.

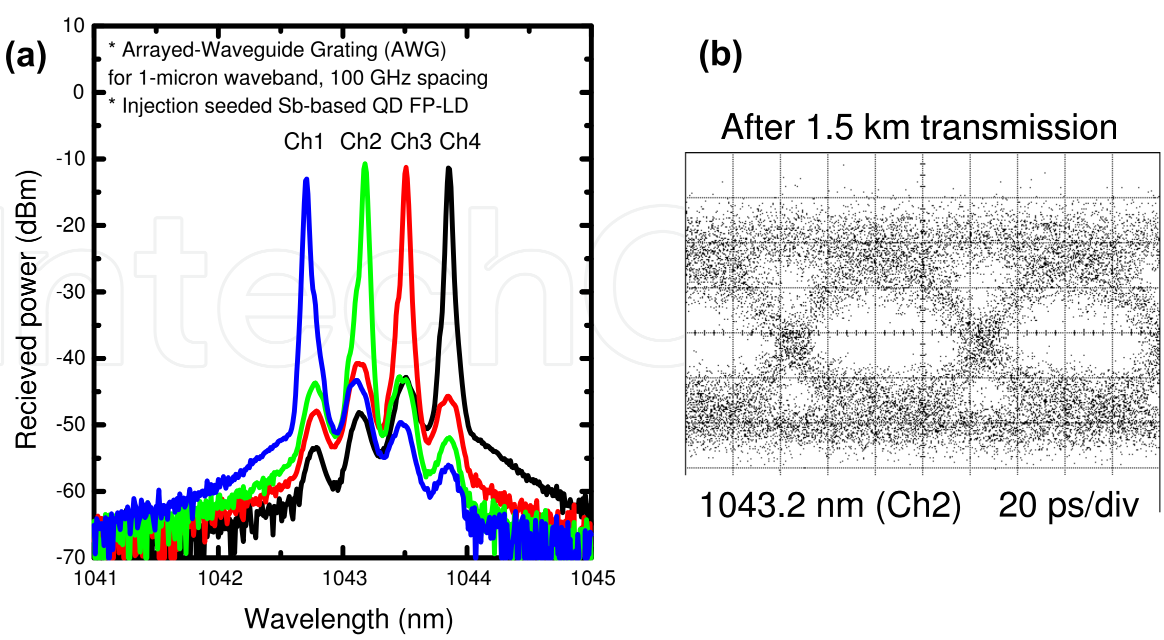

Fig. 9. (a) Optical spectrum of 12.5-Gbps and single-mode selected QD-CML after 1.5-km transmission of the holey fiber. (b) Eye opening of ch.2 after transmission.

achieved at four different wavelengths by using a wavelength-tunable discrete single-mode selected QD laser device. The 1-µm waveband AWG, YDFAs, and other passive devices are also important to construct the 1-µm waveband photonic transport system. From these results, a 12.5-Gbps-based WDM photonic transmission with a 100-GHz channel spacing can be realized in the 1-µm waveband by using the proposed methods. Additionally, it is expected that the QD photonic devices such as a semiconductor laser fabricated on the GaAs wafer will become a powerful candidate to realize an ultra-broadband 1- to 1.3-µm photonic transport system.

3. Quantum dot structure for advanced photonic devices

In this section, novel material systems of a QD structure are introduced for advanced photonic devices. The novel materials of the QD are expected to be used in laser device fabrication, silicon photonics, visible light-emitting devices, etc.

3.1 Long-wavelength quantum dot structure

Sb-based III-V semiconductor materials have very narrow-band gap properties. Therefore, the use of Sb-based III-V semiconductor QD structures (the Sb atoms are included in the QD structure) are expected for producing long-wavelength-emitting devices (Yamamoto et al. 2005 & 2006b). In this section, the Sb-based QD structure fabricated on a GaAs substrate is introduced. However, the fabrication of the Sb-based QD such as an InGaSb QD is difficult under conventional QD growth conditions with the MBE method. To form the high-quality Sb-based QD structure, a Si atom irradiation technique is proposed as one of the methods for surface treatment. Figure 10(a) shows a schematic image of the Si atom irradiation

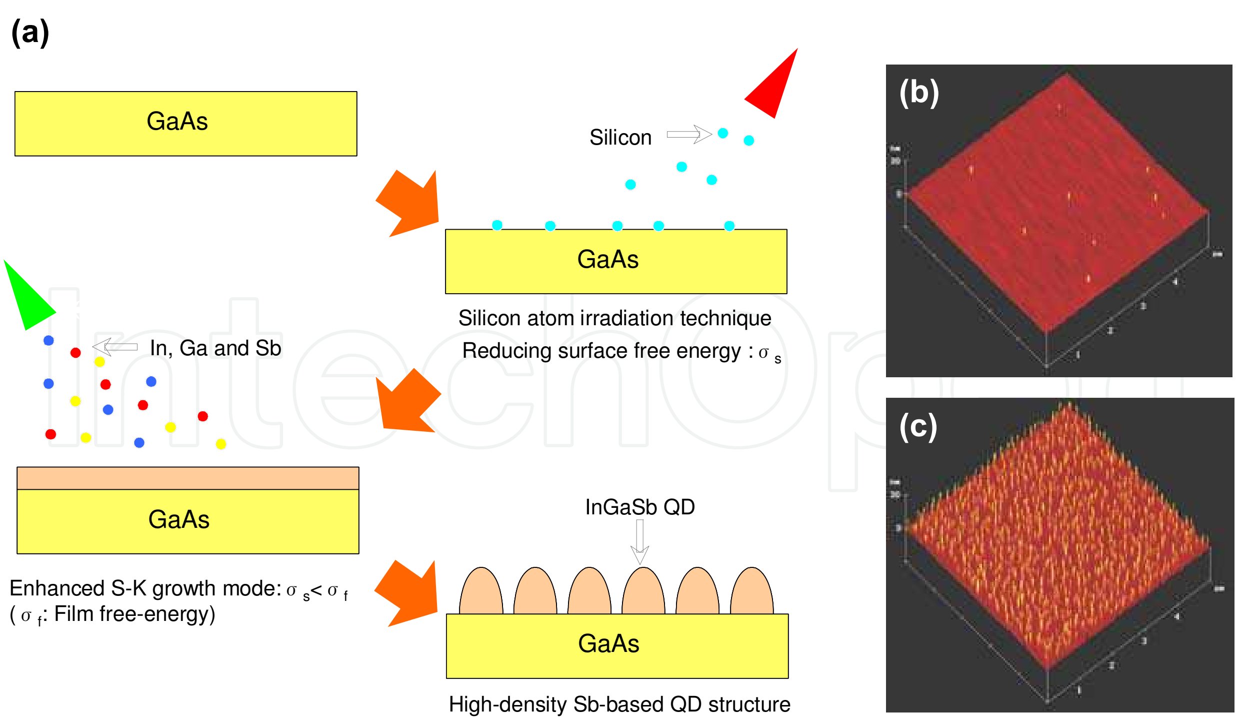

Fig. 10. (a) Schematic image of silicon atom irradiation technique for the fabrication of the high-quality QD structure. AFM images of InGaSb QD structure in a 5 × 5 -µm² region on GaAs substrate without (b) and with (c) the Si atom irradiation technique.

technique. Low density Si atoms are irradiated on to the GaAs surface immediately before the Sb-based QD structure growth. It is expected that the surface free-energy may be reduced with the irradiation of Si atoms. Therefore, the density of the Sb-based QD structure is enhanced by using this atom-irradiation technique. Figures 10(b) and (c) show the AFM images of the Sb-based QD structure without and with the Si atom irradiation, respectively. It is found that the QD density with Si atoms is approximately 100 times higher than that without Si atoms. Generally, the QD density as high as $10^{10}/cm^2$ is necessary if the QD structure is used for developing a laser or other photonic devices. Therefore, the optimization of the QD growth conditions such as growth-rate, As-flux intensity, and temperature is also important to obtain the high-quality QD structure. Figure 11(a) shows an AFM image of the Sb-based QD/GaAs structure under the optimized growth conditions. The height, dimension, and density of the Sb-based QD are approximately 7.5 nm, 25 nm, and $2 \times 10^{10}/cm^2$, respectively.

An ultra-wideband emission between wavelengths of 1.08- and 1.48-μm can be successfully realized by using the Sb-based QD/GaAs structure, as shown in Fig. 11(b). The long-wavelength and ultra-broadband emission is also obtained from a light-emitting diode (LED) that contained the Sb-based QD in active regions. From this result, it is expected that ultra-broadband wavelength (>350 nm) light sources may be achieved with the QD structure for the O-, E-, S-, and C-band (Yamamoto et al. 2009a).

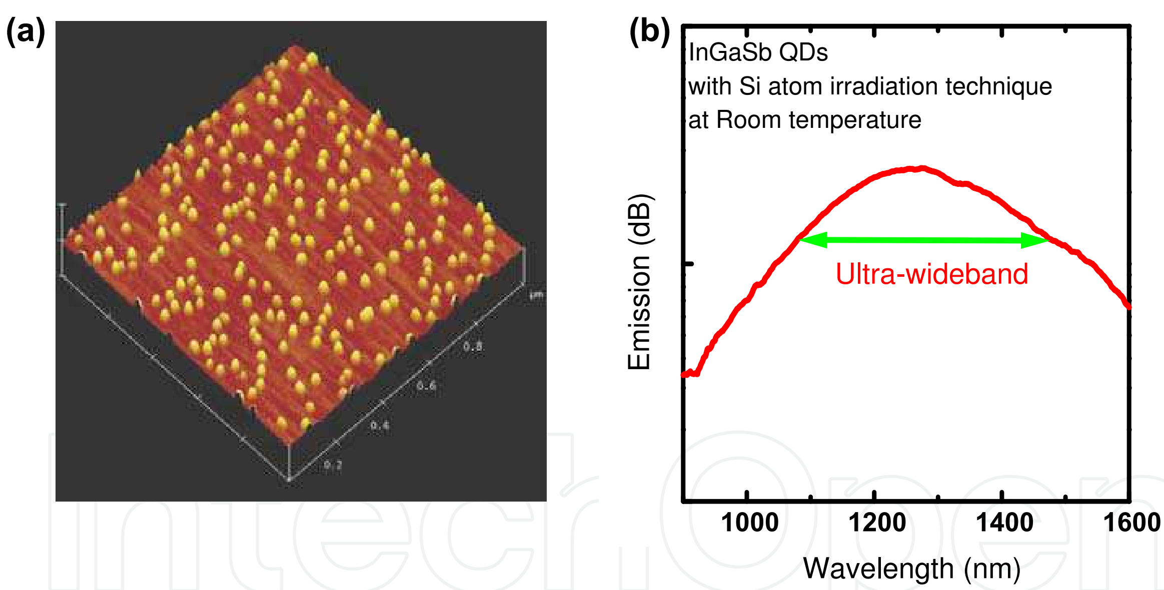

Fig. 11. (a) Atomic force microscope image of high-quality Sb-based QD (InGaSb QD) structure on GaAs surface. (b) Ultra broadband and long-wavelength emission from the Sb-based QD/GaAs structure.

The combination of a micro-cavity structure and the QD structure is a very interesting device structure for the investigation of cavity quantum-electrodynamics (QED). Study on the QED of the QD structure is important for constructing a quantum communications system (Ishi-Hayase et al. 2007 & Kujiraoka et al. 2009). A vertical cavity structure and a photonic crystal structure as an optical resonator are useful for confining the photons (Nomura et al. 2009). Figure 12(a) presents a cross-sectional image of a fabricated vertical cavity structure, which include the Sb-based QD in the cavity. A high-performance diffractive Bragg reflector (DBR) for accomplishing the vertical cavity structure can be simply produced by using an AlGaAs material system. From the Sb-based QD structure in the vertical cavity, a 1.55-μm sharp emission peak, as shown in Fig. 12(b), is successfully observed under the optically pumped condition (Yamamoto et al. 2006a). It is also found that a long-wavelength emission with a 1.52-μm peak can be obtained from the similar QD in the cavity structure at room temperature with a current injection. Therefore, it is expected that the use of the long wavelength QD active media in the semiconductor micro-cavity structure is a very useful and important way for fabricating long-wavelength and multiwavelength vertical cavity surface emitting lasers (VCSELs), resonant cavity light-emitting diodes (RCLEDs), single photon sources, etc.

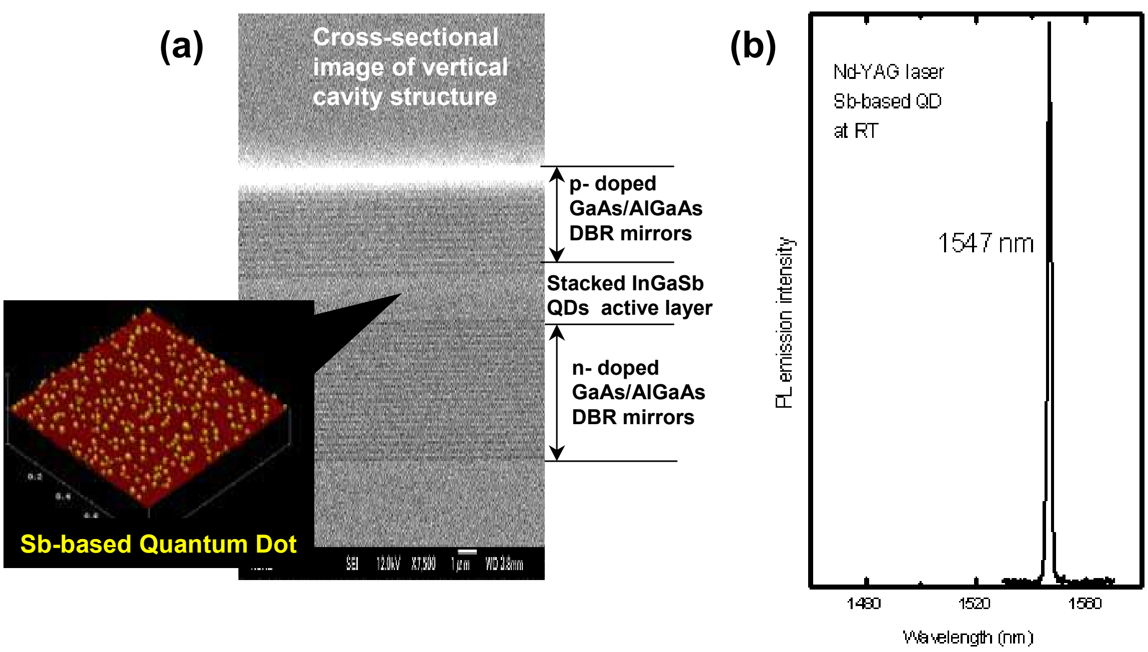

Fig. 12. (a) Sb-based QD in micro cavity structure and (b) 1.55-μm wavelength emission spectrum from optically pumped vertical cavity structure.

3.2 Quantum dot and related materials for silicon photonics

Silicon photonics technology has been conventionally used to fabricate high performance photonic circuits, which have low-power-consumption, are compact, and are relatively inexpensive to fabricate (Liu et al. 2004 & Yamamoto et al. 2007b). Poly-, amorphous-, and crystalline-Si waveguide devices have been developed and their properties have been investigated. An optical gain region must be provided for silicon waveguide structures to enable the fabrication of active devices such as light emitters and optical amplifiers on silicon platforms (Balakrishnan et al. 2006). As one of the candidates of the optical gain media, a III-V semiconductor QD structure on a Si wafer has been investigated. Figure 13 shows the schematic image of the Sb-based QD/Si structure and AFM images of the Sb-based QD structures grown between 400°C and 450°C on Si substrates (Yamamoto et al. 2007a). From the AFM image, it is found that the high-quality and high-density Sb-based QD structure can be obtained under the optimal growth conditions by MBE. Therefore, a high-density (>10^{10} /cm^2) and small-sized (<10 nm) QD structure can be obtained by growing the QDs below 400°C. From this result, it is expected that the nanostructured Sb-based semiconductors with a low-temperature process (<400°C) should become useful materials for complementary metal oxide semiconductor (CMOS) devices compatible with silicon photonics technology (Yamamoto et al. 2008a). Additionally, it is also expected that the nanostructured Sb-based semiconductor will be used for high-speed electro-devices, because the III-Sb compound semiconductor has high-mobility characteristics (Ashley et al., 2007).

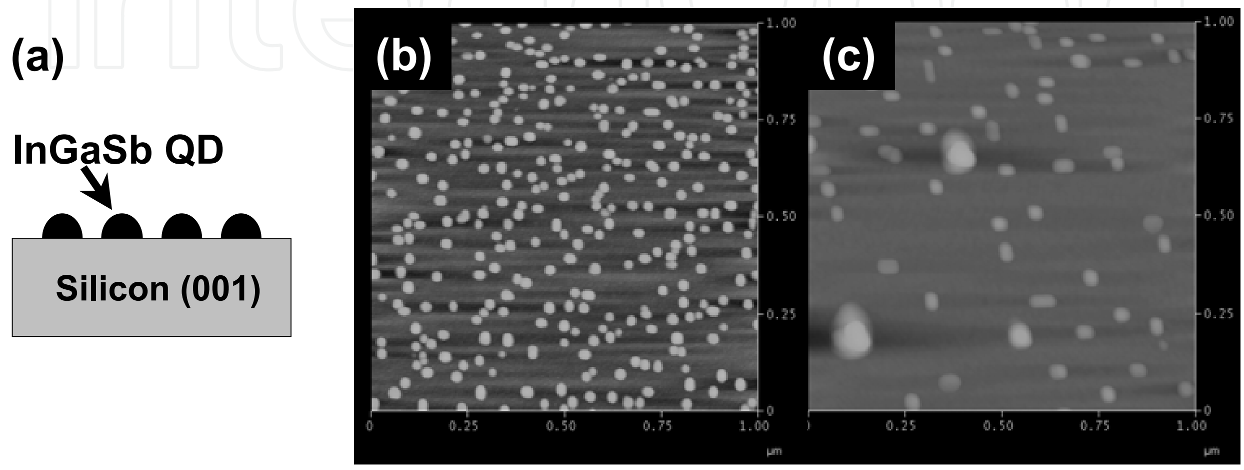

Fig. 13. (a) Schematic image of Sb-based QD structure on Si wafer, and AFM images of the Sb-based QD on Si at (b) 400°C and (c) 450°C.

Compound semiconductors are widely studied for the fabrication of the QD structure because they exhibit an observable quantum size effect in the quantum confinement structure of a relatively large size (approximately few tens of nanometers). On the other hand, a carrier confined structure several nanometers in size, which is generally called a nanoparticle, is necessary when using a silicon semiconductor material. Several techniques have been proposed for the fabrication of the Si nanoparticle as a Si-QD structure (Canham et al. 1990). An anodization method and a photochemical etching method of a Si wafer are proposed for producing the Si nanoparticles (Yamamoto et al. 2001 & Hadjersi et al. 2004). It is known that the Si nanoparticle exhibits a bright visible light emission of red or blue color, and it is considered that this light emission is caused by the quantum size effect of the Si-QD. Figure 14(a) shows a visible emission spectrum from the photochemically etched layers, such as Si nanoparticles (Yamamoto et al. 1999). In addition, electroluminescence devices on a Si wafer are also demonstrated using Si nanoparticles, as shown in Figure 14(b). It is expected that the Si nanoparticle as the Si-QD structure will become a useful material for the visible light-emitting devices with Si-based electric devices (Yamamoto et al. 2000).

4. Conclusion

The quantum dot (QD) structures are intensively investigated as the three-dimensional carrier confined structure. It is expected that the QD structure can act likely as an atom, which has a controllable characteristic of energy levels. The semiconductor QD structure is a very important material for developing novel photonic devices. In this chapter, fabrication techniques and characteristics of novel QD photonic devices such as a broadband QD light

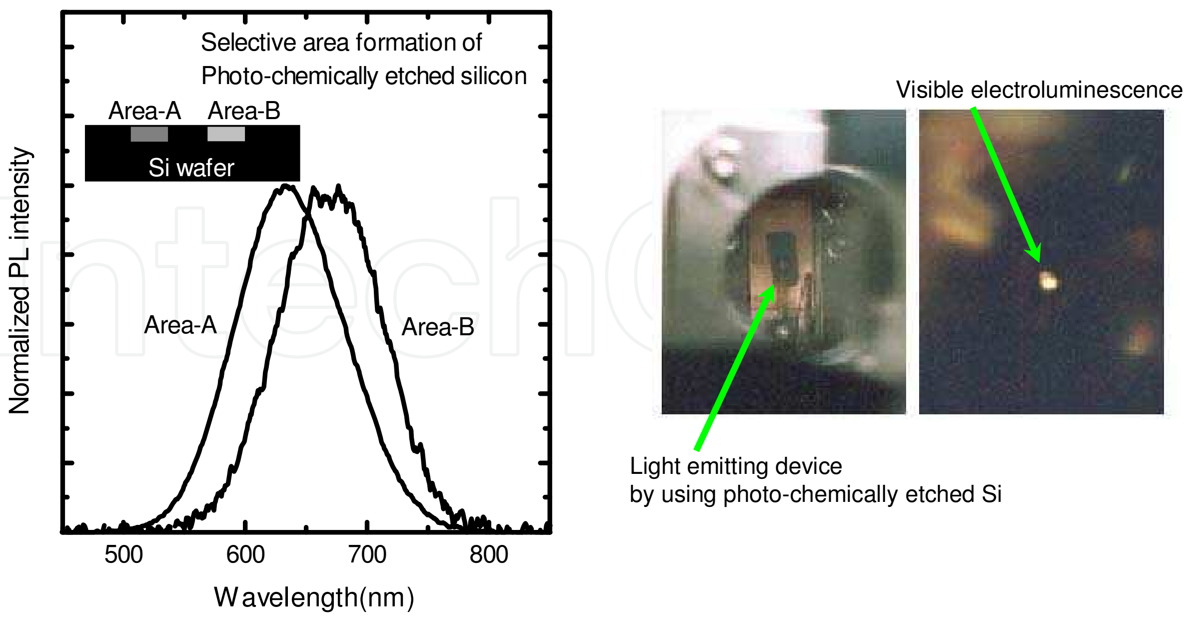

Fig. 14. (a) Emission spectra of photochemically etched layers as Si nanoparticles. The emission colors in areas A and B are observed as yellow and red, respectively. Each layer is formed on the same Si substrate using a selective area formation technique. (b) Visible electroluminescence devices on Si wafer by using the Si-particle as the Si-QD.

source and a wavelength tunable QD laser were explained. The QD light source act in a broad wavelength band between 1-μm and 1.3-μm can be fabricated on the GaAs substrate as a low cost and large-sized wafer by using InAs QD and InGaAs QD structures as an active media. In addition, a fabrication technique of the Sb-based QD structures on the GaAs substrate was demonstrated for the ultra-broadband light source between 1 and 1.55 μm, and the novel photonic devices using the cavity-QED. In other words, by using the QD structure, ultra-broadband optical gain media can be achieved for broadband light-emitting diodes, wavelength tunable laser diodes, semiconductor optical amplifiers, etc. Additionally, the QD structures have interesting opto-electric characteristics compared to the conventional quantum well and bulk materials. It is expected that the QD optical frequency comb laser (QD-CML) can be realized by using the useful characteristics of the QD structure.

Ultra-broadband optical frequency resources in the short wavelength band such as the 1-μm waveband can be used for optical communications. As the 1-μm waveband photonic transport system, over 10 Gbps and a long distance transmission were successfully demonstrated by using high-performance key components such as single-mode QD light sources, long-distance holey fibers, and YDFAs. Therefore, it is expected that the uses of the QD photonic devices enhance the usable waveband for optical communications.

For the silicon photonics, a fabrication technique for the high-quality Sb-based QD structure on a Si wafer was demonstrated clearly. As the other QD structure for the silicon photonics, it is also demonstrated that Si nanoparticles as the Si-QD become candidates for the light-emitting devices on the Si wafer.

It is expected that a fabrication and application of the QD structure will provide a breakthrough technology for the creation of novel photonic devices, improvement in the existing photonic devices, and enhancement of usable optical frequency resources in the all-photonic waveband.

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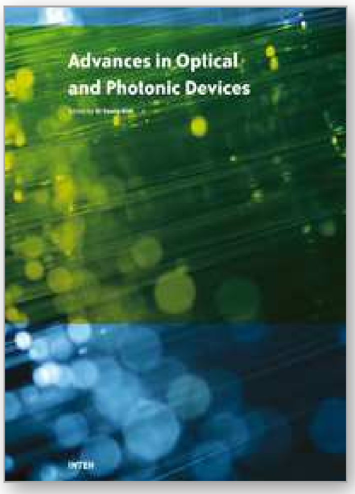

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The title of this book, Advances in Optical and Photonic Devices, encompasses a broad range of theory and applications which are of interest for diverse classes of optical and photonic devices. Unquestionably, recent successful achievements in modern 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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