Institute of Physics Publishing Journal of Physics: Conference Series **38** (2006) 140–143
doi:10.1088/1742-6596/38/1/034 NPMS-7/SIMD-5 (Maui 2005)

Single-photon generator for optical telecommunication wavelength

T. Usuki[1,4], Y. Sakuma[2], S. Hirose[1], K. Takemoto[1], N. Yokoyama[1], T. Miyazawa[3], M. Takatsu[1,3] and Y. Arakawa[3,5]

[1]Fujitsu Laboratories. Ltd., 10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan

[2]National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

[3]Institute of Industrial Science, the University of Tokyo, 4-6-1 Komaba, Tokyo 153-8505, Japan

E-mail: usuki.tatsuya@jp.fujitsu.com

Abstract. We report on the generation of single-photon pulses from a single InAs/InP quantum dot in telecommunication bands (1.3-1.55 μm: higher transmittance through an optical fiber). First we prepared InAs quantum dots on InP (0 0 1) substrates in a low-pressure MOCVD by using a so-called InP 'double-cap' procedure. The quantum dots have well-controlled photo emission wavelength in the telecommunication bands. We also developed a single-photon emitter in which quantum dots were embedded. Numerical simulation designed the emitter to realize efficient injection of the emitted photons into a single-mode optical fiber. Using a Hanbury-Brown and Twiss technique has proved that the photons through the fiber were single photons.

1. Introduction

Single-photon generator (SPG) attracts much attention for not only improving the performance of fiber-based quantum key distribution, but also quantum computing in future [1,2]. A nano-scale confinement of electrons and holes gives atomic-like quantized energy levels so that the Pauli's exclusive law prohibits the creation of the same electron–hole pair state. An optical structure, which has the nano-scale confinement, can provide an exclusive recombination process for each pulsed excitation. The optical structure is called a single-photon emitter (SPE). The SPEs have been studied by using various systems: single molecules [3], single nitrogen vacancy centers in diamond [4], impurity centers in semiconductors [5], and single quantum dots (QDs) [6–12]. Self-assembled single QDs offer advantages of a sharp luminescence line, optical stability, and controllability of wavelength.

[4] Present address: Institute of Industrial Science, the University of Tokyo, 4-6-1 Komaba, Tokyo 153-8505, Japan
[5] Research Center for Advanced Science and Technology, the University of Tokyo, 4-6-1 Komaba, Tokyo 153-8505, Japan

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2006	**N/A**	-

4. TITLE AND SUBTITLE
Single-Photon Generator for Optical Telecommunication Wavelength

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Fujitsu Laboratories. Ltd., 10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The Seventh International Conference on New Phenomena in Mesoscopic Structures & The Fifth International Conference on Surfaces and Interfaces of Mesoscopic Devices, November 27th - December 2nd, 2005, Maui, Hawaii, USA, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

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

In current optical telecommunications operating via single-mode fibers (SMFs), the wavelength range from 1.3 to 1.55 μm is a window of telecommunication network. For convenience, this range is divided into four bands: the O-band (1260–1360 nm), E-band (1360– 1460 nm), S-band (1460–1530 nm), and C-band (1530– 1565 nm). The C-band is especially important from a viewpoint of long-distance transmission, because it has the highest transmittance in all optical fiber bands. However, it is difficult to develop QDs for telecommunication purposes, and most single QD studies have used below 1 μm. The single photon emitters previously demonstrated are almost in this wavelength range. We are developing SPEs in telecommunication bands [13,14]. The development mainly has two difficulties. One is to obtain high-quality QDs, and the other is to inject single-photon pulses (SPP) into a SMF.

2. Experiments

Figure 1 shows a SPG setup that consists of a single photon emitter (SPE), an excitation pulse laser and a tunable band pass filter (BPF). The pulse laser controls generation timing of single photon pulses (SPP), and the BPF purifies SPP emitted from the SPE. The SPE obviously plays an important role in generating SPP.

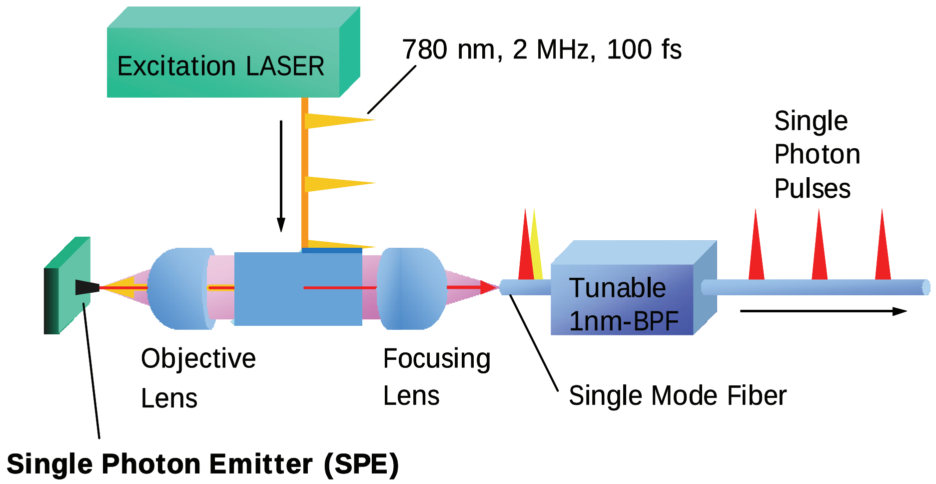

Figure 1. Schematic view of a single photon generator setup.

A practical quantum network through optical fibers requires a SPE at telecommunication wavelength. Then we grew self-assembled InAs QDs on InP (0 0 1) [15] with the use of the double-cap method [16,17] in an MOCVD. We can tune the growth of InAs/InP QDs to telecom wavelength range, and we set the thickness of the first cap layer over QDs at 1 nm to obtain well-isolated QDs at 1.55 μm. By using the QDs, we fabricated a small mesa structure as shown in figure 2(a). The QDs as shown in figure 2(b) are embedded at 300 nm below the top of the mesa. In order to achieve high optical efficiency, the structure with a tapered rectangular column shape was designed by a finite-difference-time-domain (FDTD) simulator. Figure 3 shows column's diameter dependence of photon extraction efficiency from a QD to an upward space in which numerical aperture 0.55 is matched to the objective lens in figure 1. From FDTD simulation, we estimated that extraction efficiency of the SPE is about 6%.

3. Results and Discussion

Figure 4(a) shows resolution-limited sharp exciton line from a single QD at 1.546 μm at 10 K. The tunable BPF could select the exciton line from the luminescent spectrum. To confirm the non-classical photon emission, we used a Hanbury-Brown and Twiss setup which includes single-photon detection modules (id 200, id Quantique). These modules were Peltier-cooled InGaAs avalanche photodiodes

(APDs) operated in the gated mode. The gate time and the dead time of the APDs were set to 5 ns and 10 μs, respectively; these values have been found to efficiently suppress dark counts and after pulses of the detectors. The gate timing of photon detection was well synchronized to the excitation pulse with 2MHz repetition rate (corresponding to the time period of 0.5 μs). The photon pulses were split by a 50:50 fiber coupler with each arm connected to the detection modules. The start and stop signals from the two APDs were input into a time-correlated single-photon counting board (TimeHarp 200, PicoQuant). Then we obtained the second-order correlation function $g^{(2)}$ for the exciton emission. (see figure 4(b)) The correlation function clearly shows an anti-bunching property of generated SPP.

4. Summary

We developed SPE, and we studied generating SPP in the C-band from a single InAs/InP QD through an SMF. The SPP at 1.546 μm was realized by optimizing the growth conditions and the optical structure. Then we proved the SPP emission by photon correlation measurements. The results confirm that the QDs can be applied to the SPP emitter at telecommunication wavelengths. We are now improving the SPE and a whole system with a cryostat to realize practical quantum telecommunication.

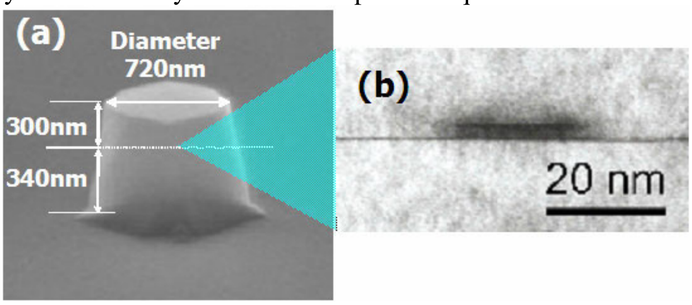

Figure 2(a). SEM image of a single photon emitter. (b) InAs/InP QDs were embedded in a mesa structure of the single photon emitter.

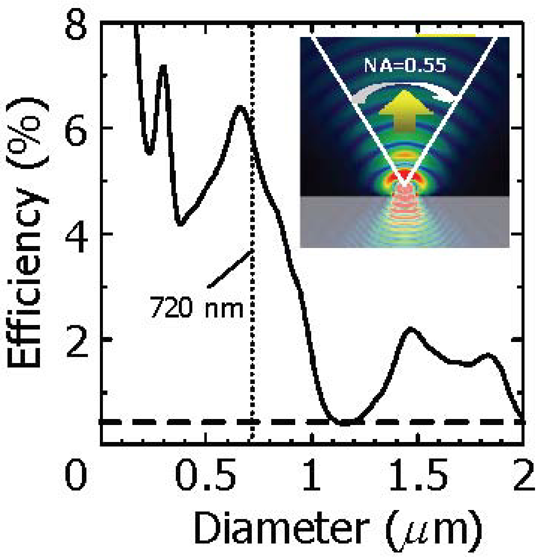

Figure 3. Numerical results of photon extraction efficiency from a quantum dot to an upward space (numerical aperture 0.55). Inset: electric field distribution from a single photon emitter.

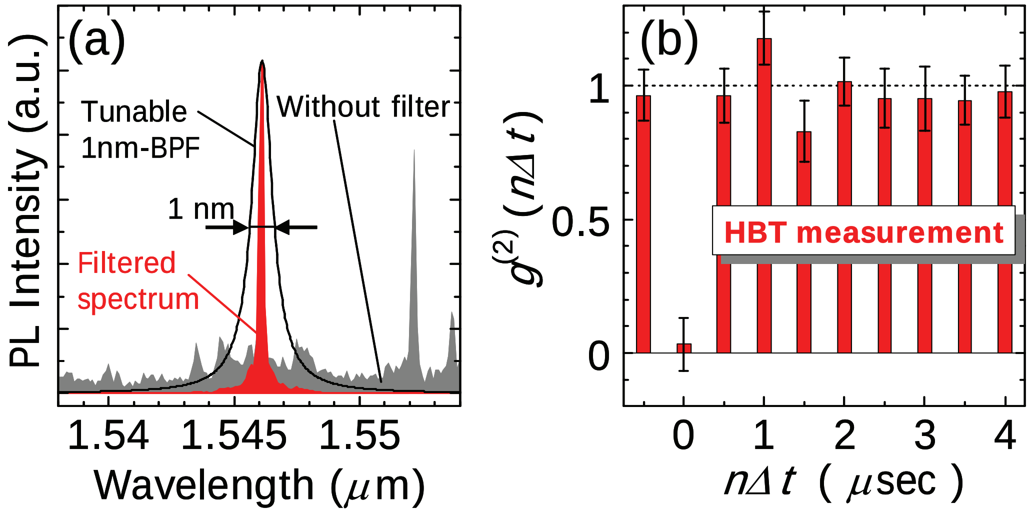

Figure 4. (a) PL spectrum from the single photon emitter. (b) Photon correlation function of filtered spectrum at 1.546 μm.

A part of this work has been supported by the Focused Research and Development Project for the Realization of the World's Most Advanced IT Nation, IT Program, MEXT.

References

[1] Knill E, Laflamme R and Milburn G J 2001 *nature* **409** 46
[2] Li X, Wu Y, Steel D, Gammon D, Stievater T H, Katzer D S, Park D, Piermarocchi C and Sham L J 2003 *Science* **301** 809
[3] Brunel C, Lounis B, Tamarat P and Orrit M 1999 *Phys. Rev. Lett.* **83** 2722
[4] Kurtsiefer C, Mayer S, Zarda P and Weinfurter H 2000 *Phys. Rev. Lett.* **85** 290
[5] Strauf S, Michler P, Klude M, Hommel D, Bacher G and Forchel A 2002 *Phys. Rev. Lett.* **89** 177403
[6] Baier M H, Pelucchi E, Kapon E, Varoutsis S, Gallart M, Robert-Philip I and Abram I 2004 *Appl. Phys. Lett.* **84** 648
[7] Hours J, Varoutsis S, Gallart M, Bloch J, Robert-Philip I, Cavanna A, Abram I, Laruelle F and Ge´rard J M 2003 *Appl. Phys. Lett.* **82** 2206
[8] Zwiller V, Aichele T, Seifert W, Persson J and Benson O 2003 *Appl. Phys. Lett.* **82** 1509
[9] Santori C, Fattal D, Vucˇkovic´ J, Solomon G S and Yamamoto Y 2002 *nature* **419** 594
[10] Kim J, Benson O, Kan H and Yamamoto Y 1999 *nature* **397** 500
[11] Yuan Z, Kardynal B E, Stevenson R M, Shields A J, Lobo C J, Cooper K, Beattie N S, Ritchie D A and Pepper M 2002 *Science* **295** 102
[12] Michler P, Imamoğlu A, Mason M D, Carson P J, Strouse G F and Buratto S K 2000 *nature* **406** 968
[13] Miyazawa T, Takemoto K, Sakuma Y, Hirose S, Usuki T, Yokoyama N, Takatsu M and Arakawa Y 2005 *Jpn. J. Appl. Phys.* **44** L620
[14] Takemoto K, Sakuma Y, Hirose S, Usuki T, Yokoyama N, Miyazawa T, Takatsu M and Arakawa Y 2004 *Jpn. J. Appl. Phys.* **43** L993
[15] Sakuma Y, Takemoto K, Hirose S, Usuki T and Yokoyama N 2005 *Physica E* **26** 81
[16] Paranthoen C, Bertru N, Dehaese O, Corre A L, Loualiche S, Lambert B and Patriarche G 2001 *Appl. Phys. Lett.* **78** 1751
[17] Poole P J, Williams R L, Lefebvre J, Moisa S 2003 *J. Crystal Growth* **257** 89