Single photon interference between bidirectionally extracted photons originating from semiconductor quantum dots

Hirotaka Sasakura1, Shunichi Muto2, and Hidekazu Kumano3

1Creative Research Institute, Hokkaido University, Sapporo 001-0021, Japan
2Department of Applied Physics, Hokkaido University, Sapporo 060-8628, Japan
3Research Institute for Electronic Science, Hokkaido University, Sapporo 001-0021, Japan

Received August 13, 2015; accepted October 2, 2015; published online October 22, 2015

We report the experimental demonstration of the single-photon interference of bidirectionally extracted photons from epitaxially grown semiconductor quantum dots. The quantum dots were directly connected to single-mode optical fibers. Single-photon nature between transmission and reflection directions was confirmed through detection of antibunching in second-order photon correlation measurements. A Mach–Zehnder interferometer that was naturally formed by introducing the two outputs into a 2 × 2-fiber coupler was used to perform first-order photon correlation measurements.

Epitaxially grown semiconductor III–V quantum dots (QDs) generate bright, indistinguishable and entangled photons1–4 with long-term stability and wavelength tunability. Various efforts have been made to integrate a nanoscale photon source such as a QD into a single mode fiber (SMF) from the perspective of consistency with existing optical fiber infrastructures.5–8 Recently, we reported the detection of bidirectional single photons using an epitaxially grown InAs QD sandwiched by SMFs.9) This QD-in-fiber (QDinF) showed long-term stability in terms of emitted photon energy and number, which is one of the most important properties for a fiber-based nanoscale photon emitter from a scientific and engineering viewpoint.

In this paper, we present fiber-based bidirectional single-photon extraction from epitaxially grown In0.8Al0.2As QDs. The photons emitted from the single InAlAs QDs were extracted from both sides of the SMFs. Clear antibunching between the two outputs of two SMF patch cables was observed in second-order photon correlation measurements. To confirm bidirectional single-photon extraction, we performed first-order auto-correlation measurements between the two outputs of the SMFs under single-photon emission. Moreover, we discuss whether the QDinF structure has the possibility to work for a well-known dual-rail photon qubit device.10,11)

In0.8Al0.2As QDs were grown to a density of approximately 2.5 × 1010 cm−2 on a 600-nm-thick Al0.35Ga0.65As barrier layer on a non-doped GaAs(001) substrate using molecular-beam epitaxy (RIBER MBE32P). To bidirectionally extract the photons originating from QDs in both directions, the GaAs substrate and an 800-nm-thick Al0.8Ga0.2As were removed from the 150 nm AlGaAs/InAlAs-QDs/600 nm AlGaAs structure by chemical etching (HF), and the resulting emitting layer (H 0.75 µm × W 20 µm × L 40 µm) was sandwiched between two FC/PC SMF patch cables (Thorlabs SM600) with a φ900 µm jacket. This QDinF device was set in a liquid 4He reservoir at 4.2 K.

We used a fiber-pigtailed 637-nm laser diode (Thorlabs LP637-SF70) as an excitation source. To suppress the laser spectral noise, a bandpass filter (Edmund Optics #65-106) was inserted. To spatially separate the emissions in the reflection direction, a dichroic beam combiner (Edmund Optics #86-402) was used [Fig. 1(a)]. Figure 1(b) shows the time-integrated photoluminescence (PL) spectra of transmission (TO) and reflection (RO) configurations under barrier excitation at a power density of 6.6 W/cm2. The emission was dispersed by a monochrometer (HORIBA SPEX500m with 1800 g/mm) and detected with an Si-charge coupled device (Princeton Instruments PIXIS256E). The typical exposure time was 1 s to obtain a PL spectrum with a high signal-to-noise ratio. The emission X was centered at 791.6 nm with a full width at half maximum of 174.47 µeV obtained by the spectra fitting with a Lorentzian function. The observed X-shape was exactly identical between TO and RO, whereas the PL intensity was different because of the difference in the thickness of the QD-sandwiched AlGaAs barrier layer.

Both outputs of the QDinF were filtered with a 0.5-nm-wide band-pass filter (Optoquest custom-made product) to select the X, and two band-pass filters (Edmund Optics #86-
Second-order photon correlation is recorded using TAC employing two APDs connected to TO and RO of QDinF. Normalized histograms of the autocorrelation measurement of X at excitation powers of 1.6 (a), 2.9 (b), and 8.2 W/cm² (c). The excitation wavelength is 637 nm, and the time bins are 19.5 ps. The integration time and count rates are 11.9 h and 14.1 kHz (a), 12 h and 27.2 kHz (b), and 1.7 h and 51.5 kHz (c), respectively. The circles are the raw data, the black line is a fit taking the instrumental response function into account, and the blue line is the fit deconvolved. (d) Excitation power dependence of \(g^{(2)}(0)\) (red left axis) and \(\tau_{\text{rise}}\) (blue right axis). The solid (red) line is averaged \(g^{(2)}(0) = 0.39 \pm 0.02\). The dashed (blue) curve is a guide to the eyes.

To confirm the single photon nature of QDinF, the coincidence between TO and RO of QDinF was recorded by a time-amplitude converter (TAC) board (Becker & Hickl SPC-130E). The second-order correlation curves were measured under continuous wave and Al0.35Ga0.65As barrier excitation. The detected total single count rate at SPCMs was approximately 4 W/cm², suggesting that observed X was PL originating from a single exciton state confined in the QDs.

The solid photon nature of QDinF, the coincidence between TO and RO of QDinF was recorded by a time-amplitude converter (TAC) board (Becker & Hickl SPC-130E). The second-order correlation curves were measured under continuous wave and Al0.35Ga0.65As barrier excitation. The detected total single count rate at SPCMs was approximately 4 W/cm², suggesting that observed X was PL originating from a single exciton state confined in the QDs.

The measured data (circles) were fitted with the convolution of Eqs. (1) and (2). The solid (red) and (blue) curves are fitting results of \(g_{\text{m}}^{(2)}\) and \(g_{\text{b}}^{(2)}\), respectively. Here \(B\) (=150 Hz) is fixed by the dark counts of the SPCM.

Figure 2(b) shows the excitation power dependence of \(g^{(2)}(0)\) and \(\tau_{\text{rise}}\). With increasing excitation power, \(\tau_{\text{rise}}\) gradually narrowed from approximately 1 ns, which is longer than \(\tau_{\text{s}}\) (~0.7 ns) measured by cross-correlation under pulsed photoexcitation using a ps mode-locked Ti:Sapphire laser with a center wavelength 720 nm for InAlAs WL excitation. This discrepancy is attributed to the elongation of the effective lifetime caused by the excess charge diffusion in the AlGaAs barrier layer under cw excitation. However, in the high-excitation power region, the lack of time resolution limited by the instrument response prevented us from determining \(\tau_{\text{rise}}\) and \(g^{(2)}(0)\); therefore, we imposed a restriction of \(\tau_{\text{rise}} > 439\) ps during the fitting process. The averaged \(g^{(2)}(0) = 0.39 \pm 0.02\) was lower than 0.5, which was the quantum limit in the measured excitation power range; however, an accidental coincidence remained because of the background photons originating from a large number of QDs weakly coupled with SMFs, as shown in Fig. 1(b).

To confirm the bidirectional extraction of a single photon originating from the QD, the coherence properties of X were investigated by a type of time-domain spectroscopy called single-photon Fourier spectroscopy. The two outputs (TO and RO) of QDinF sent photons to SPCMs through a 2 × 2-fiber coupler (Thorlabs FC780-50B-FC), with an optical delay line inserted into the transmission configuration, as shown in Fig. 3(a). All fiber components were mechanically fixed and installed in an isolated small darkroom in order to prevent environmental fluctuations. Rotating a thin glass plate in the optical delay line enabled fine-tuning of the relative phase \(\theta\) (approximately 0.2 fs) between the two outputs, and an interference fringe could be observed, indicating that a Mach–Zehnder (MZ) interferometer configu-
ration was naturally formed. Here the interference fringe was as follows:

\[ V(\tau, \theta) = \frac{PN_1(\tau, \theta) - PN_2(\tau, \theta)}{PN_1(\tau, \theta) + PN_2(\tau, \theta) - 2d} \]

where \( PN_{1,2} \) and \( d \) are the photon numbers detected by each SPCM and the averaged dark count of both SPCCMs, respectively. By varying the temporal delay \( \tau \) and \( \theta \), \( V(\tau, \theta) \) was recorded, as shown in Fig. 3(b). The detected photon number evolution of each SPCM as a function of \( \tau \) was as follows:

\[ PN_{1,2}(\tau) = \frac{PN_{12} - 2d}{2} [1 \pm V'(\tau) \cos(E_0\tau/h + \theta)] \]

where \( PN_{12} \), \( E_0 \), and \( V'(\tau) = \max(|V(\tau, \theta)|, \theta = 0, \ldots, 2\pi) \) are the total photon number of both SPCCMs, the center selected photon energy, and the visibility (interference fringe contrast), respectively. Figure 3(c) shows \( V'(\tau) \) as a function of the time delay \( \tau \) between TO and RO. The visibility of the interference fringes decayed almost with an simple exponential function (solid line) \( V'(0)e^{-\gamma/\tau} \), implying that the spectrally selected line had a Lorentzian shape. The obtained dephasing time \( T_2 \) of 8.3 (±0.3) ps was longer than the 1.3 ps deduced by the spectral window of the 0.5-nm-wide band-pass filter, corresponding to FWHM of the X of 2\( h/T_2 \approx 157.2 \text{meV} \) [Fig. 1(a)]. The observed value of \( T_2 \) is more than a few order of magnitude shorter under resonant excitation using various different experimental methods and materials.\(^{13,15-17}\) This short \( T_2 \) is attributed to fluctuations of environmental excess charges in InAlAIW and comparable to the neutral exciton spin relaxation time under non-resonant excitation.\(^{18}\) This means that the single photon state \( |\phi\rangle \) generated by the QD was directly spatially separated and extracted to TO and RO via bidirectionally located SMFs in the QD: \( |\alpha \rangle_{\text{TO}}|\beta\rangle_{\text{RO}} + |\beta \rangle_{\text{TO}}|\alpha\rangle_{\text{RO}} \), which is similar to the well-known dual rail photon qubit state. In the case of \( |\alpha|^2 = |\beta|^2 = 0.5 \), the visibility at zero delay time \( V'(0) = 1 \) (ideal) is larger than the observed value of 0.316 (±0.005) due to the unbalanced optical coupling between the QD and the edge faces of the SMFs and the throughputs of the free space modules such as temporal delay and spectral filtering [Fig. 1(b)]. To attain a balance between \( \alpha \) and \( \beta \), a variable attenuator was inserted before the 2×2-fiber coupler. Figure 3(d) shows the time-averaged photon-number ratio \( R = PN_{12}^{\text{TO}}/PN_{12}^{\text{RO}} \) dependence of \( V'(0) \), where \( PN_{12}^{\text{TO/RO}} \) is the total photon number of TO/RO detected by both SPCCMs. We obtained \( V'(0) \) values in the \( R \)-range of 0.01 to 4, corresponding to the input ratio for the 2×2-fiber coupler. The measured \( V'(0) \) attained a maximum value under a condition of \( R = 1 \) and recovered from 0.20 up to 0.62. This maximum value was still lower than the expected ideal value of 1.0 mainly because of the polarization mismatch at the 2×2-fiber coupler caused by the incomplete optical coupling between the QD and SMF and the cross-polarization coupling inside the SMF.

Here we discuss the deviation of \( V'(0) \) by the assumption that all optical loss mechanisms are equivalent to inserting beam splitters into the optical paths [inset of Fig. 3(d)]. Initially, we assume that a single photon state originating from the QD is split into spatially separated components by a 50/50 beam splitter, and \( |\phi\rangle = 1/\sqrt{2}(|\alpha\rangle_{\text{TO}}|\beta\rangle_{\text{RO}} + |\beta\rangle_{\text{TO}}|\alpha\rangle_{\text{RO}}) \), which corresponds to an ideal QDinF situation. After passing through the unbalanced TO and RO arms with optical losses including incomplete spatial coupling at the interface between the QD and the edge faces of the SMFs and free space modules, the single photon state transforms...
to $1/\sqrt{2}(\sqrt{1 - \Gamma_{\text{TO}}} |\psi\rangle_\text{TO}|0\rangle_\text{RO} + \sqrt{1 - \Gamma_{\text{RO}}} |\psi\rangle_\text{RO}|0\rangle_\text{TO})$, where $\Gamma_{\text{TO/RO}}$ is the reflectance of a hypothetically inserted beam splitter, corresponding to the total optical losses in the TO/RO arm. Combining with a $2 \times 2$-fiber coupler, the single photon state transforms to

$$\rho\rightarrow \frac{1}{2} \left[ |\psi\rangle_\text{PN} \langle 0|_\text{PN} \left\{ -\sqrt{1 - \Gamma_{\text{TO}}} + e^{-i\theta} \sqrt{1 - \Gamma_{\text{RO}}} \right\} + |0\rangle_\text{PN} \langle 1|_\text{PN} \left\{ \sqrt{1 - \Gamma_{\text{TO}}} + e^{-i\theta} \sqrt{1 - \Gamma_{\text{RO}}} \right\} \right].$$ (5)

The measured $V'(0)$ can be reproduced (black curve) as follows:

$$V'(0) = 2\gamma \sqrt{(1 - \Gamma_{\text{TO}})(1 - \Gamma_{\text{RO}})} = 2\gamma \sqrt{R} \frac{1}{1 + R},$$ (6)

where $\gamma = 0.64 (\pm 0.01)$ is a fitting parameter related to the degree of polarization mismatch. This fact provides evidence that a single photon in the modes of two optical paths (TO and RO) can serve as the basis of a dual-rail qubit and that $\alpha/\beta$ can be encoded from 0.2 to 4.

In summary, we have demonstrated single-photon extraction from epitaxially grown InAlAs QDs sandwiched by single-mode fibers. The photon antibunching behavior was confirmed by second-order photon correlation measurements. The first-order autocorrelation function was measured between bidirectional outputs of a SMF. These experimental results suggest that the single photon state generated by the QD was directly spatially separated and extracted via bidirectionally located SMFs in the QD, signifying that the QDinF structure can naturally form a dual-rail photon qubit without any additional passive fiber components. Moreover, in the naturally formed MZ interferometer, the visibility at zero delay time could be improved nearly three times by the control of the throughput ratio between the two arms. Our results suggest that QDinF devices have significant potential as photon sources and qubits that can be operated at cost with high durability on a maintenance-free basis over a long period for the inspection and development of quantum information protocols.

Acknowledgment

This work was supported by the Strategic Information and Communications R&D Promotion Programme (SCOPE).

References

1. A. J. Bennett, D. C. Unitt, P. Atkinson, D. A. Ritchie, and A. J. Shields, Opt. Express 13, 50 (2005).
2. Y.-M. He, Y. He, Y.-J. Wei, D. Wu, M. Ataüre, C. Schneider, S. Höfling, M. Kamp, C.-Y. Lu, and J.-W. Pan, Nat. Nanotechnol. 8, 213 (2013).
3. R. M. Stevenson, C. L. Sailer, J. Nilsson, A. J. Bennett, M. B. Ward, I. Farrer, D. A. Ritchie, and A. J. Shields, Phys. Rev. Lett. 108, 040503 (2012).
4. K. Takemoto, M. Takatsu, S. Hirokawa, Y. Sakuma, T. Suzuki, T. Miyazawa, and Y. Arakawa, J. Appl. Phys. 101, 081720 (2007).
5. M. Fujiwara, K. Touban, T. Noda, H.-Q. Zhao, and S. Takeuchi, Nano Lett. 11, 4362 (2011).
6. M. Davanco, M. T. Rakher, W. Wegscheider, D. Schuh, A. Badolato, and K. Srinivasan, Appl. Phys. Lett. 99, 121101 (2011).
7. T. Schroder, A. W. Schell, G. Kewes, T. Aichele, and O. Benson, Nano Lett. 11, 198 (2011).
8. G. Shambat, J. Provine, K. Rivoire, T. Sarmiento, J. Harris, and J. Vlčková, Appl. Phys. Lett. 99, 191102 (2011).
9. H. Sasakura, X. Liu, S. Odashima, H. Kumano, S. Muto, and I. Suemune, Appl. Phys. Express 6, 065203 (2013).
10. M. Nielsen and I. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, Cambridge, U.K., 2000).
11. L.-A. Wu, P. Walther, and D. A. Lidar, Sci. Rep. 3, 1394 (2013).
12. C. Becher, A. Kiraz, P. Michler, A. Imamoglu, W. V. Schoenfeld, P. M. Petroff, L. Zhang, and E. Hu, Phys. Rev. B 63, 121312(R) (2001).
13. C. Santori, D. Fattal, J. Vlčková, G. S. Solomon, E. Waks, and Y. Yamamoto, Phys. Rev. B 69, 205324 (2004).
14. C. Kammrath, G. Gassabois, C. Voisin, M. Perrin, C. Delalande, Ph. Roussignol, and J. M. Gérard, Appl. Phys. Lett. 81, 2737 (2002).
15. K. Kuroda, T. Kuroda, K. Sakoda, G. Kido, and N. Koguchi, Appl. Phys. Lett. 90, 051909 (2007).
16. C. Matthiesen, A. N. Vamivakas, and M. Atatüre, Phys. Rev. Lett. 108, 093602 (2012).
17. M. E. Reimer, G. Bulgarini, R. W. Heeres, B. J. Witte, M. A. M. Versteegh, D. Dalacu, J. Lapointe, P. J. Poole, and V. Zwiller, arXiv:1407.2833.
18. S. Adachi, N. Yatsu, R. Kaji, S. Muto, and H. Sasakura, Appl. Phys. Lett. 91, 161910 (2007).