Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.404-405

G-3-3

Development of Electrically Driven Single-Photon Emitter at Optical Fiber Bands

Toshiyuki Miyazawa[1], Jun Tatebayashi[1], Toshihiro Nakaoka[1], Motomu Takatsu[1], Satomi Ishida[1],
Satoshi Iwamoto[1,3,4], Kazuya Takemoto[2], Shinichi Hirose[2], Tatsuya Usuki[2], Naoki Yokoyama[2]
and Yasuhiko Arakawa[1,3,4]

[1] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
Phone: +81-3-5452-6291, E-mail: miyatosi@iis.u-tokyo.ac.jp
[2] Fujitsu Laboratories Ltd., 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197, Japan
[3] Nanoelectronics Collaborative Research Center, The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[4] Research Center for Advanced Science and Technology, The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

1. Introduction

Single-photon emitter (SPE) plays an important role in quantum key distribution (QKD). There are many candidates for SPEs. Especially, the quantum dot (QD) is one of the strongest ones, because of its quantum states that arise from three dimensional quantum confinements. Optically excited SPEs with QDs were demonstrated from visible to near infrared wavelength [1-5].

Electrically driven single-photon emitters (ED-SPE) with QDs are the final goal for SPE, because devices of QKD systems have to be small and controlled by electrical signals. Several groups focused on development of ED-SPEs [6-8]. The realization of QKD for telecommunication needs operation at longer wavelength which is called optical fiber bands ($\lambda > 1.26$ μm). ED-SPE with the longest wavelength has barely reached the optical fiber band [9], though optically excited SPE had already been demonstrated at the C-band (1.55 μm) [5]. For practical use, ED-SPE needs much longer wavelength and other requirements (for example: lower electric power, higher-speed operation etc.).

In this paper, we report on an ED-SPE operating at an optical fiber band. We succeeded in fabricating small ohmic contact area and observing the electroluminescence (EL) from single QD at the center of the O-band (1.32 μm). The small contact area reduced parallel current leak and heat generation.

2. Experiments and Results

The InAs/GaAs QDs were grown by metal organic chemical vapor deposition on an *n*-type substrate. In order to tune the wavelength of photons emitted from QDs to the optical fiber wavelengths, InAs QDs were capped with $In_xGa_{1-x}As$ strain-reducing layer (SRL) [10]. We used SRL with $x = 0.17$ for 1.3 μm EL at 7 K.
The device consist of six epi-layers. (Fig. 1 (a)) The *n*-type layers are a GaAs buffer layer and an $Al_{0.1}Ga_{0.9}As$ barrier layer with doping concentration of 1×10^{18} cm^{-3}. The intrinsic layers are a GaAs, an InAs QD layer, an $In_{0.17}Ga_{0.83}As$ SRL, and a GaAs layer. The *p*+-type layer is a GaAs with doping concentration of 1×10^{19} cm^{-3}. The QD density of this sample is about 8.0×10^9 QDs/cm^2 enume rated from the atomic force microscope image. (Fig. 1 (b))

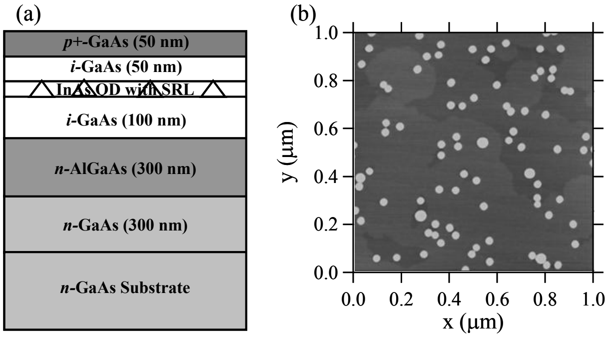

Fig. 1 (a) Schematic illustration of the epi-layers. (b) Atomic force microscope image of the QD.

In order to access single QDs, we fabricated nano-scale small apertures which had small ohmic contact area, on the top Au electrode. There were seven main steps in fabricating the device which was consisted of sputtering SiO_2, patterning by photolithography, etching an SiO_2, etching *p*+-GaAs, evaporating SiO_2, evaporating a Ti/Pt/Au electrode and removing the resist. In fabricating this device, only wet etching was used to minimize the damage that was caused in fabricating the device. The SEM images (Fig. 2 (a), (b)) show that the ohmic contact was limited only small area around an aperture (Fig. 2 (c)).

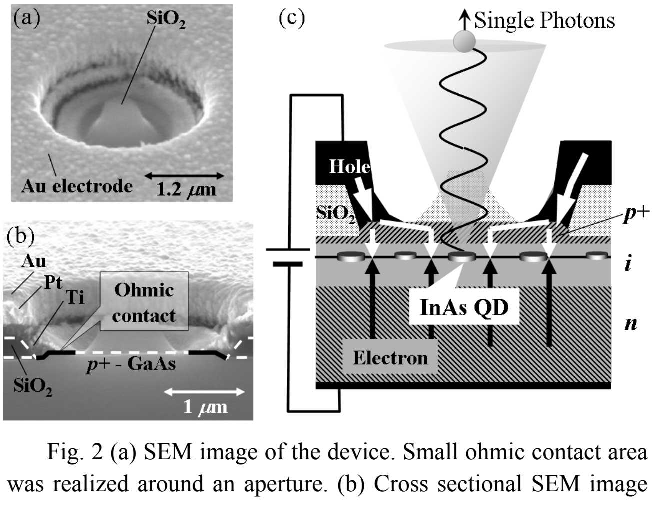

Fig. 2 (a) SEM image of the device. Small ohmic contact area was realized around an aperture. (b) Cross sectional SEM image of the device. (c) Schematic illustration of the device.

Figure 3 (a) shows current *I* of this device as a function of external bias voltage *V* at 7K. The current was increased rapidly over threshold voltage V_{th} = 1.2 V. The EL started to appear above V_{th}. The small ohmic contact (Fig. 2(c)) realized clear diode behavior without parallel leak current.

Figure 3 (b) shows the current dependence of the EL spectra from a large aperture whose diameter is 20 μm. The current dependence of the EL spectra showed that the ground state (the first excitated state) of exciton concentrated around the 1.32 μm (1.24 μm).

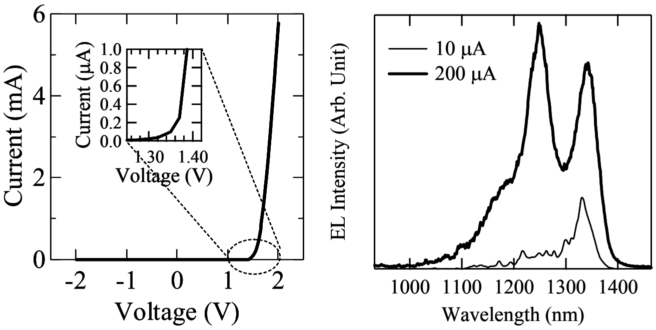

Fig. 3 (a) *I-V* characteristic. (b) EL spectra from the large aperture.

We measured the micro-EL with conventional micro-PL setup at 7 K. The emitted photons were collected through an objective lens (Numerical Aperture is 0.5). Photons were dispersed by 0.6 m triple grating monochromator and detected with a liquid-nitrogen-cooled InGaAs multi-channel detector. The energy resolution of this setup was about 60 μeV in micro-EL measurements.

Figure 4 shows typical micro-EL spectra for various injected current over an aperture with 650 nm in diameter. Narrow emission lines were observed from 1319.9 to 1324.9 nm in the region of the ground state (Fig. 3 (b)) assigned by the EL measurements from the large aperture.

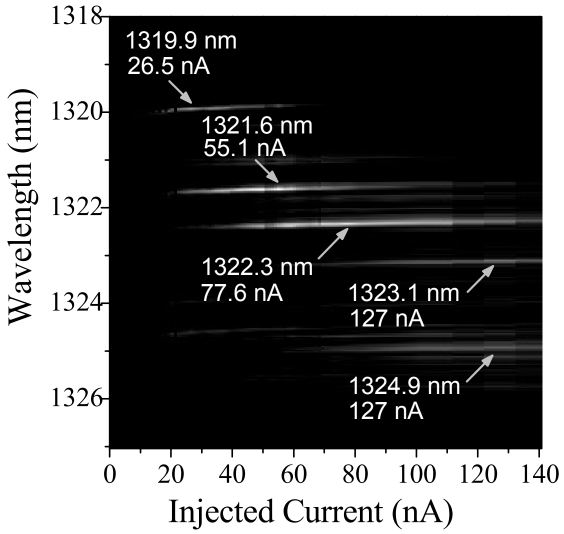

Fig. 4 EL spectra from single QDs. Arrows indicate wavelength and I_{max} of the single exciton emission.

With increasing the current, the EL intensities from single exciton emission increased linearly, then showed saturation behavior. The current I_{max} for each single exciton, which is at maximum intensity of the EL, was distributed in the rage from 26 to 127 nA. They were lower than the former report [5-7]. These results showed that our device has advantages in realizing ED-SPE in the point of a low electrical power.

On the other hand, due to the low damage device fabrication, the maximum count rate of these lines (20 cps) was about five times larger than that of the previous device [11].

3. Conclusions

In summary, we succeeded in fabricating single InAs QD LED which has small ohmic contact area. Due to the reduction of ohmic contact area, the device showed clear diode behavior without parallel leak current. The EL lines of single exciton were clearly observed around the center of the O-Band (λ = 1319.9 to 1324.9 nm) at 7 K from the aperture. The current I_{max} for each single exciton was distributed in the range from 26 to 127 nA. These results were expected low power ED-SPE. Comparing with the previous device, the count rate of this device was increased due to the low damage fabrication. Further improvements of the photon collection efficiency to realize a QKD system using an ideal SPE at optical fiber bands is now going on.

Acknowledgements

This work was partly supported by the MEXT. The authors would like to thank Dr. N. Hatori and Dr. S. Kako at the University of Tokyo as well as Dr. H. Z. Song at Fujitsu laboratories for helpful discussion and continuous support.

References

[1] C. Santori *et al.*, Nature **419**, 594 (2002).
[2] J. Hours *et al.*, Appl. Phys. Lett. **82**, 2206 (2003).
[3] V. Zwiller *et al.*, Appl. Phys. Lett. 82,509 (2003).
[4] K. Takamoto *et al.*, Jpn. J. of Appl. Phys. **43**, 7B, L993, (2004).
[5] T. Miyazawa *et al.*, Jpn. J. of Appl. Phys. **44**, 7B, L620, (2005).
[6] Z. Yuan *et al.*, Science **295**, 102 (2002).
[7] Xiulai Xu *et al.*, Appl. Phys. Lett. **85**, 3238 (2004).
[8] A. J. Bennett *et al.*, Appl. Phys. Lett. **86**, 181102 (2004).
[9] M. B. Ward *et al.*, Physica E, **21**, 390 (2004).
[10] J. Tatebayashi *et al.*, Appl. Phys. Lett. **78**, 3469 (2001).
[11] T. Miyazawa *et al.*, CLEO/QELS 2005, QTuH5 (2005).