Observation of enhanced luminescence emitted from InAs quantum dots with direct contact to superconducting Niobium stripe

Makoto Takada[1], Yasuhiro Idutsu [*1,2], Yujiro Hayashi[1], Tatsushi Akazaki[2,3], Hirotaka Sasakura[1], Hidekazu Kumano[1,2] and Ikuo Suemune[1,2]

[1] Research Institute for Electronic Science, Hokkaido University, kita-21 nishi-10, Sapporo, Japan
[2] Japan Science and Techonology(JST)-CREST, Chiyoda-ku, Tokyo, Japan
[3] NTT Basic Research Laboratory, Atsugi, Kanagawa, Japan

Received ▰▰▰, revised ▰▰▰, accepted ▰▰▰
Published online ▰▰▰ (Dates will be provided by the publisher.)

PACS 00.00.Xx, 11.11.Yy, 22.22.Zz, 33.33.Aa (Please insert 4 to 6 PACS codes from the enclosed list or from www.aip.org/pacs)

* Corresponding author: e-mail y-idutsu@es.hokudai.ac.jp, Phone: +81 11 706 9332, Fax: +81 11 706 9332

Observation of the drastically enhanced luminescence emitted from InAs quantum dots (QDs) which were direct contact to superconducting Niobium (Nb) is reported. Although the PL intensity was essentially temperature independent without Nb effect, the drastically temperature dependence was observed with Nb effect. PL intensity was increased just below the Nb superconducting critical temperature (T_c). About 3-times enhancement was observed below T_c. Cooper pairs were penetrated from superconducting Nb stripe to InAs QDs by proximity effect and recombination were occur. This is experimental demonstration of Cooper pair superradiance effect predicted by Hanamura with QDs.

1 Introduction

Quantum information communication and processing are expected to form the next-generation highly secure quantum-information networks (QIN). Single photons generated from semiconductor quantum dots (QDs) are expected to play as messenger qubits in QIN. Superconducting qubits are actively studied and are strong candidates for processing qubits. However QD-based photonics and superconductors have been completely separate research fields and technological barriers remain for the qubits conversion. It is important to develop the key device to connect the two research fields. We have proposed superconductor-based QD-light-emitting diode (SQLED) [1] as the key device to connect the two research fields. Recently Hayashi et al. [2] reported the drastic enhancement of LED light output with superconducting effect with Nb electrode deposited n-type InGaAs/InGaAs/p-type InP quantum well (QW) structure. In this sample the luminescence with photo-excitation under zero bias and with current injection were enhanced below the critical temperature of Nb superconducting critical temperature. These observations of the drastic enhancement are the first demonstration that the Cooper pairs enhance the radiative recombination which was theoretically expected by Hanamura [3]. The superconductor LEDs employed in these works were based on QW structures. On the other hand, it is important to observe the enhancement effect with the LEDs based on QDs to realize the SQLED and QIN.

In this work we demonstrated the superconducting effect studied on InAs QDs. InAs QDs were left to air. The Nb stripes were directly contacted to InAs QDs. Although PL intensity of InAs QDs without Nb was essentially temperature independence, that with Nb electrode was drastic enhanced below the Nb critical temperature. This is the first demonstration that luminescence from QDs were enhanced due to the Cooper pair injection by proximity effect.

2 Experiments

In this work all QDs were prepared with metal-organic (MO) molecular-beam epitaxy (MBE) system. The MO sources used triethylgallium (TEGa), triethylindium (TEIn) and trisdimethylaminoarsenic (TDMAAs) for Ga, In and As. The epiready (001) semi-insulating GaAs substrates were thermally cleaned at 560°C with the simultaneous injection of 1.0×10^{-4}Pa TDMAAs beam equivalent pressure (BEP). A 100nm-thick GaAs buffer layer was grown with the TEGa and TDMAAs supplies at 510°C. For the growth of InAs QDs, the temperature was decreased to 480°C. With the TEIn and TDMAAs supplies the formation of InAs QDs was identified by the change of the reflection high-energy electron diffraction (RHEED) pattern from streaky to spotty ones. To increase the probability of QDs in contact with Nb QDs were over-growth about 5ML. After noticing the change, the growth was stopped and the substrate temperature was decreased to room temperature with the ramping rate of 30°C /min.

The Nb stripes patterns were fabricated with widely used electron beam (EB) resist, PMMA950A (microchem CO.) by EB lithography method. 80nm-thick Nb was deposited on InAs QDs by NTT and lift-off process were done. After that Au electrodes were fabricated with photolithography and lift-off method. Photolithography resist was OFPR (TOKYO OHKA KOGYO CO.). Au electrodes thickness was 100nm.

The QDs heights were measured with tapping-mode atomic force microscopy (AFM). Scanning electron microscopy (SEM) was used to measure the QDs density, diameters and configuration of Nb stripes.

PL measurements were carried out using the CW-Ti:Sapphire laser at the wavelength of 770nm. The laser was focused with x50 objective lens and the laser spot size on the sample surface observed with CCD camera was about 3 um. PL signals were observed with same objective lens and dispersed with 50cm x 2 monochromator. A liquidd-nitrogen-cooled InGaAs detector was used to measure PL spectra. The samples were cooled down with L.He flow Oxford MicrostatHiResII cryostat.

3. Results and discussions

Figure 1(a) shows the SEM images of the InAs QDs. The bimodal QD were observed due to the over-growth.

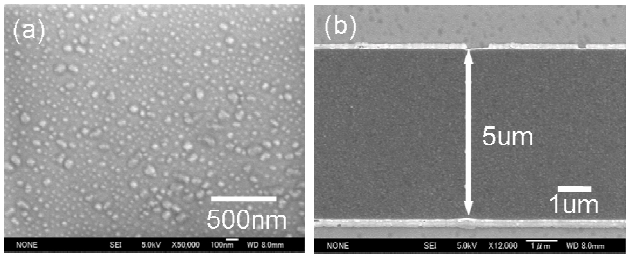

Figure 1 (a) shows the SEM image of InAs QDs and (b) is that of Nb stripe.

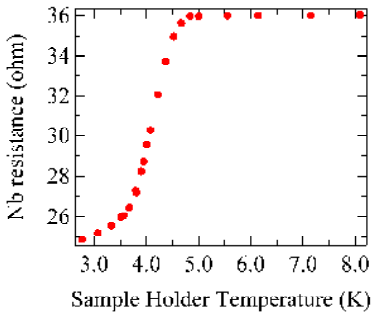

Figure 2 Temperature dependence of Nb stripe resistance.

Density for total QDs and large QDs was 1.4×10^{10}cm^{-2} and 1.0×10^{8}cm^{-2}, respectively. The typical height and diameter for small QDs was 8.1nm, 30nm and height for large QDs was 11.8nm. Because large QDs were combined with few QDs it was difficult to estimate the diameter, but it was from 60nm to 120nm. Figure 1(b) shows the SEM image of Nb stripe deposited on InAs QDs. Nb stripe width was about 5 um. PL spectra and intensities from InAs QDs remained unchanged after the lift-off process, showing no influence to InAs QDs.

Figure 2 shows the temperature dependence of Nb resistance. We observed the drastically reduction for Nb resistance when sample holder temperature (T_{SH}) was around 4.1K. Then we estimated that the Nb superconducting critical was 4.1K. It is known that the Nb critical temperature is about 8.3K. T_{SH} was 2 to 3 K higher.

Figure 3 shows the PL integrated intensity measured across 5-um Nb stripe at T_{SH}=2.8K, below Nb critical temperature. The excitation laser power was 100uW. Since the Nb metal surface reflects back the incident laser, PL intensities from InAs QDs was naturally reduced where laser position was close the Nb stripe. When the centre of the Nb stripe was excited, almost all the excitation laser should be reflected back. However the PL intensity remained to one-third of the other area. It was expected that PL signals measured centre of Nb stripe will include enhanced PL signals from QDs with direct contact to Nb. It was useful to

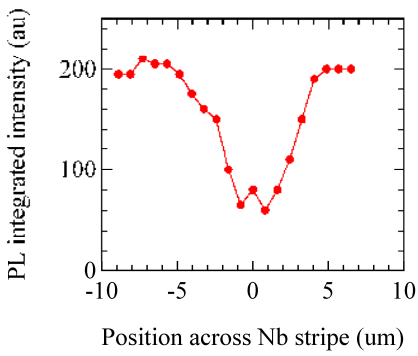

Figure 3 PL integrated intensity measured across 5-um-wide Nb stripe.

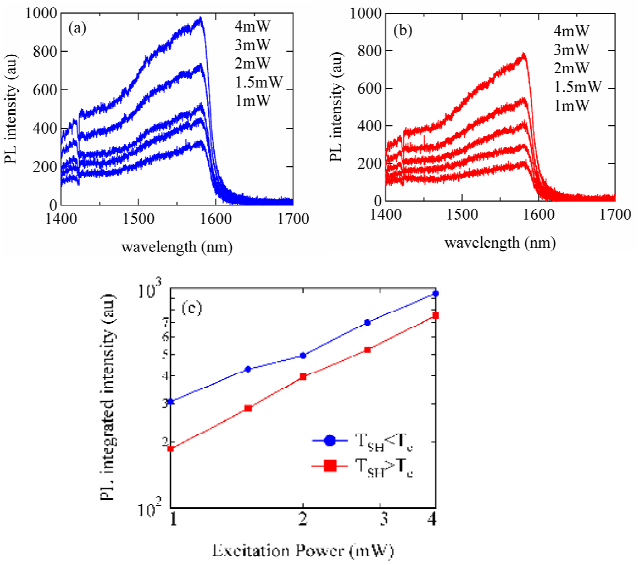

Figure 4 (a) and (b) show the PL spectra measured below Tc and above Tc, respectively. 4(c) shows the excitation power dependence of PL integrated intensity.

observe the Nb superconducting effect to InAs QDs. Then we fixed the excitation laser position at centre of Nb strip.

Figures 4(a) and 4(b) shows the PL spectra measured below and above the T_c. The excitation laser powers were 1, 1.5, 2, 3, and 4mW. The observed spectra showed the apparent peak at 1580nm, but this is due to the detection limit of the used InGaAs detector. Because of the QDs size distribution due to the over-growth, the PL spectra have wide emission wavelength. Although temperature and excitation power
were changed, PL spectral shape remained unchanged. It was expected that the origin of luminescence was same for all measurements. The observed PL intensity was higher at the lower temperature. Figure 4(c) shows the summary of the excitation power dependence of the PL integrated intensity. Measurements below the T_c systematically show the higher PL intensities. It was expected that the Cooper pairs penetrating from superconducting Nb stripe to InAs QDs relate to recombination process.

Figure 5 shows the temperature dependence of the QDs luminescence intensities measured at the centre of the Nb stripe (red circle) and the without Nb area (blue square). The intensity showed clear enhancement at the lower temperature. About 3-times enhancement was observed. The upper-limit temperature of observed luminescence enhancement was start at 4.1K. This corresponds to the Nb critical temperature, as shown Figure2. On the other hand without the Nb effect, the intensity was essentially temperature independent. This is due to only the normal carrier recombination occurred. This comparison demonstrates that the superconducting Nb enhances the luminescence. This will be due to the Cooper pair penetration into InAs QDs by the penetration effect. This result is the first demonstration for enhancement of luminescence from QDs due to the Cooper pair injection.

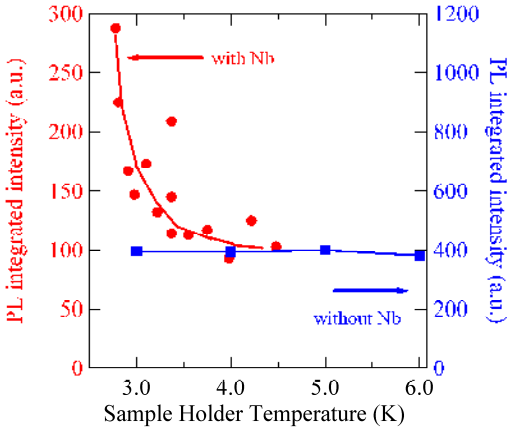

Figure 5 Temperature dependence of PL integrated intensity measured at the center of the Nb stripe (red circles) and without Nb (blue squares).

4. Summary

In summary, we demonstrated the drastic enhancement of luminescence intensity from InAs QDs with Nb direct contact to InAs QDs structures. The upper-limit temperature observed the enhancement corresponds to the Nb critical temperature. PL intensity measured without Nb area shows essentially temperature independence. This is the first demonstration of enhancement of QDs luminescence with Cooper pair injection.

Acknowledgements This work is supported in part by Hokkaido Univ. and Hokkaido Innovation through NanoTechnology Support (HINTS).

References

[1] I. Suemune, et al., Jpn. J. Appl. Phys. **45**, 9264 (2006).
[2] Y. Hayashi et al. Appl. Phy. Exp **1**, 011701 (2008)
[3] E. Hanamura Phys. Status Solidi B **234**, 166 (2002)