K-5-2
Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp1020-1021

Observation of enhanced exciton decay rate of single InAs quantum dots in nanoscale metal-semiconductor-metal plasmonic structures.

Takumi Yamamoto[1], Yasutomo Ota [1], Edmund Harbord [1],
Satomi Ishida [3], Naoto Kumagai [1], Satoshi Iwamoto [1, 2]
and
Yasuhiko Arakawa [1, 2]

[1] Institude for NanoQuantum information Electronics, University of Tokyo.
4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505, Japan
Phone: +81-3-5452-6920 E-mail：takuyama@iis.u-tokyo.ac.jp
[2] Institude of Industrial Science, University of Tokyo.
4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505, Japan
[3] Research Center for Advanced Science and technology, University of Tokyo.
4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505, Japan

Abstract

We observed exciton decay rates of single InAs quantum dots (QDs) in metal-semiconductor-metal (MSM) plasmonic structures for the first time. The decay rates were enhanced compared with that of as-grown QDs. Depending on the height position of the QDs in the MSM structures, we obtained enhancement factors in the decay rate ranging from 1.3 to 1.7. The field distribution of the surface plasmon polariton modes in the structures can explain the results qualitatively.

1. Introduction

Plasmonics is one of fascinating research fields because of their potential applications in various areas including optical interconnection, biological sensing, and so on. A nano-scale dielectric or semiconductor waveguide sandwiched by metals is a promising structure for realizing efficient nano-scale light sources. Light emitters embedded in dielectric or semiconductor material can interact with strongly confined surface plasmon polariton modes (SPPs), which can enhance the emission rate dramatically [1,2]. Furthermore, emitted photons can be guided to the next optical or plasmonic circuits. Towards efficient nano light sources, detail understanding on the SPP-matter interaction in such structures is crucial from the fundamental and technological points of view.

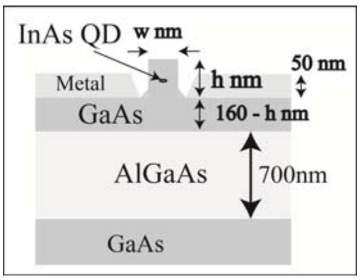
However, there are few experimental study on such structures [3,4]. In the previous reports, the emission dynamics was investigated for ensemble quantum dots (QDs) not for single QDs, which could smarted out the primitive interaction between a single QDs and SPPs.

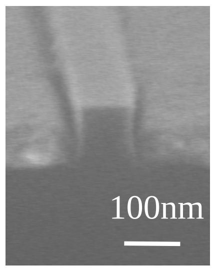
In this study, we successfully fabricated metal-sandwiched semiconductor nano-waveguides containing epitaxially grown InAs QDs and measured enhanced exciton decay rates from single InAs QDs embedded in such structures. We also found that the decay rate changed depending on the height position of the QD layer in the structure. This change can be attributed to the difference in field density of SPP modes at the position of QDs.

2. Sample structure and fabrication

A schematic illustration of the investigated structure is shown in Fig. 1 (a). Hereafter, we call the structure as metal-semiconductor-metal (MSM) structure. The width *w* and height *h* of the semiconductor waveguide, which consists of GaAs on AlGaAs, were smaller than the half of emission wavelength of embedded InAs QDs (~1μm). The waveguide is sandwiched by 50 nm thick gold plates as shown in Fig. 1. In this study, *w* was set to 80 nm and two different *h*'s (110 nm and 85 nm) were used.

We firstly grew a 700-nm-thcik AlGaAs layer followed by a 160-nm-thcik GaAs containing a single layer of InAs QDs on a GaAs substrate by using molecular beam epitaxy. The QD layer was located at 80 nm below from the GaAs surface. The waveguide structures were formed by using e-beam lithography and dry etching techniques. Then, gold film was deposited electron beam evaporation. Finally, metal film on the top of waveguides was removed by lift-off technique. Figure 1(b) shows a typical scanning electron microscope (SEM) image of the MSM structures.





(a) (b)

Fig. 1: Schematic of the investigated MSM structure (a) and a typical SEM image of the structures (b).

3. Experiments

We performed micro-photoluminescence (μ-PL) and time-resolved μ-PL measurements for single QDs in the structures at low temperature (<10K). In all measurements, QDs were excited from the top of the structures by an 840-nm wavelength pulsed laser (pulse width: 1ps, power: ~1μW, reputation rate: 76MHz). The time resolution of the system was 400ps. We measured more than four single QDs for each waveguide height *h*. Different *h* means that the QD layer is located at the vertical height position in the waveguide. Therefore, the interaction strength between QDs and SPP modes will be different in the structures with different *h*. This is expected to be reflected in the results of time-resolved μ-PL measurement.

4. Results and discussions

Figure 2 shows the results of the typical decay curves for single QDs in the structures with two different *h* and for an as-grown single QD. The results show that the decay rates of single QDs in MSM structures are enhanced compared with that of as-grown QDs. The change in decay rate depending on *h* (i. e. the height position of QDs) is also clearly observed. The average decay rates for four measured single QDs in each were 1.28ns^{-1} for the structure with *h*=85 nm, 1.08 ns^{-1} for *h*=110nm, and 0.78 ns^{-1} for as grown QDs. Form these results, the enhancement factors in decay rates for single QDs in MSM structures were 1.3 and 1.7 for the case of *h* = 110 nm and *h* = 85 nm, respectively, in average.

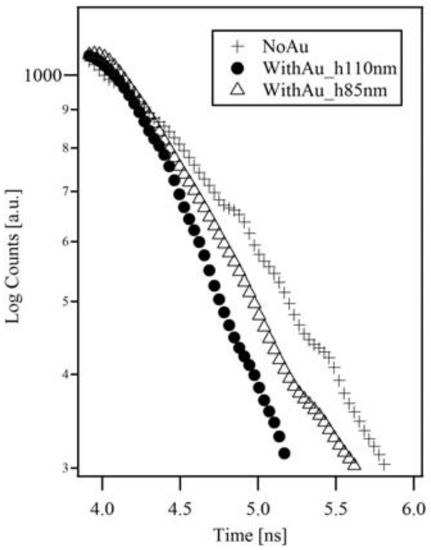
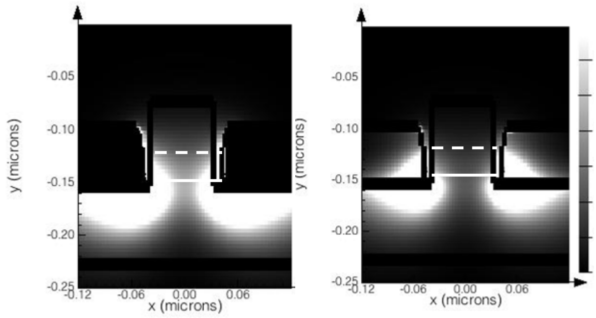


Fig. 2 Typical decay curves of excitons in single QDs in each structures. (crosses: for an as grown single QD, open triangles: for MSM structure with *h*=110 nm, solid circles: for MSM structure with *h*=85 nm).

The change in decay rate in different *h* can be attributed to the difference in the local field density of SSP modes supported in the structures. We calculated the field distributions of SPP modes by using two-dimensional finite difference frequency domain method. Figure 3 shows the distribution of field energy density for two SPP modes: symmetric SPP mode (a) and anti-symmetric SPP mode (b). Solid and dashed white lines show the positions of the QD layer for the structures with *h*=85 and 110 nm, respectively. The averaged field energy density at the QD position for *h*=85 nm is approximately three times higher than that for *h*=110 nm. If we assume that the density of state of non-SPP modes is not modified so dramatically even in the structures, the enhancement of decay rate due to the SPP modes is estimated ~0.3 (=1.3-1) for *h*=110 nm and 0.7(=1.7-1) for *h*=85 nm. The ratio of two values shows a good agreement with the ratio of average energy density at the QD plane in two structures. Although further detail investigations are necessary, this suggests that the observed enhancement of decay rate can be attributed to the interaction of QD with SPP modes.



(a) (b)

Fig.3 Energy density distributions of the two SPP modes of our MSM structure. (a) symmetric mode and (b) anti-symmetric mode. As the color becomes black, the density becomes low.

3. Conclusions

We succeeded in observing enhanced exciton decay rate of single InAs QDs in MSM structures. The decay rates for single QDs in MSM structure were enhanced compared with that of as-grown single QDs. The enhancement factor was ~1.3 in the structure with *h* = 110nm and ~1.7 in the structure with *h* = 85nm. This difference in enhancement mainly reflects the difference in field energy density of SPP modes at the height position of the QD layer,

Acknowledgements

This research was supported by JSPS through the FIRST Program and by MEXT Japan through the Special Coordination Funds for Promoting Science.

References

[1] Y.C.Jun, *et.al.*, Phys. Rev. B **78**, 153111 (2008)
[2] Georgios Veronis *et.al.*,J.Lightwave Tech., 25, 2511 (2007)
[3]Young Chul Jun et.al., J.Phys.Chem.C, 114 7269 (2010)
[4] R.J.Walters et.al., Nat.mat., **9**, 21, (2009)