I-6-05 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp645-646

Characterization of a surface plasmon antenna fabricated on a gate-defined lateral quantum dot

Rio Fukai[1], Yuji Sakai[1], Tomohiro Nakagawa[1], Takafumi Fujita[1,2], Haruki Kiyama[1,2], Arne Ludwig[3], Andreas Dirk Wieck[3], and Akira Oiwa[1,2]

[1] The Institute of Scientific and Industrial Research, Osaka University
8-1, Mihogaoka, Ibaraki, Osaka 567-0047, Japan
Phone: +81-6-6879-8409 E-mail: fukai21@sanken.osaka-u.ac.jp
[2] Center for Quantum Information and Quantum Biology, Institute for Open and Transdisciplinary Research Initiatives, Osaka University, Machikaneyama Osaka 560-8531, Japan
[3] Ruhr University Bochum
Universitätsstraße 150, Gebäude NB, D-44780, Bochum, Germany

Abstract

Quantum repeater composed of a quantum memory and an interface between photon qubits and memory qubits is indispensable for long distance quantum communication. Gate-defined lateral quantum dots (QDs) can be a suitable platform for quantum repeaters because of its aptitude for spin qubit and feasibility of quantum state transfer from photon polarization to electron spin. However, reported photoelectron excitation probability in the QD is not high enough to implement practical repeater protocols. To improve the photoexcitation probability, we combined a surface plasmon antenna with the QDs.

We fabricated a surface plasmon antenna designed to enhance optical transmission to QDs in a practical photoirradiation setup and characterized the fabricated antenna by measuring photocurrent at room temperature.

1. Introduction

Quantum communication provides secure communication based on non-cloning theorem but communication distance is about 100 km in an optical fiber network. To extend the communication distance, a quantum repeater is required [1]. A quantum repeater should have a quantum memory to store quantum information and an interface to transfer the information from photon qubits to the memory qubits [2].

Gate-defined lateral quantum dots (QDs) can be a suitable platform for the quantum repeater [2]. Electron spins in QDs have been exceedingly studied for spin qubits because of their relatively long coherence time and electrical controllability [3]. In addition, fundamental experiments for quantum interface using QDs such as single photoelectron and spin detection [4, 5] and angular momentum transfer from single photon polarization to single electron spin have been demonstrated [6, 7]. Quantum state transfer from single photon polarization to single electron spins in QDs is based on spin-selective optical transitions between light-hole (LH) state and electron state in a quantum well (QW) [8]. To achieve the quantum state transfer between single particles, gate-defined lateral QDs are suitable because of their ability for qubits.

The excitation efficiency of single photoelectrons in lateral QDs were less than 0.01 % [5, 6]. Small optical absorption in a QW layer, which is typically 1%, is a reason for the low efficiency. Additionally, the difference in size between the incident beam spot and an aperture of a metal mask on the QD reduces the efficiency. The metal mask is needed to avoid unnecessary irradiation around the outer area of the QD. To address the size-mismatch problem, we have proposed to combine surface plasmon antennas with QDs [10]. Surface plasmon antenna is a thin metal film with subwavelength aperture and concentric grooves. It enhances local electric field beneath the aperture and optical transmission though the aperture as a result of excitation and propagation of surface plasmons [11]. Increase of photocurrent in Si nano-photodiode with a surface plasmon antenna has been reported [12].

In this work, we fabricated a surface plasmon antenna on a lateral double QD to enhance optical transmission in a practical photoirradiation setup and characterized the transmission spectra by measuring photocurrent at room temperature.

2. Method

We designed a surface plasmon antenna on a GaAs/AlGaAs QW structure (Fig. 1(a)) using an FDTD method. In the

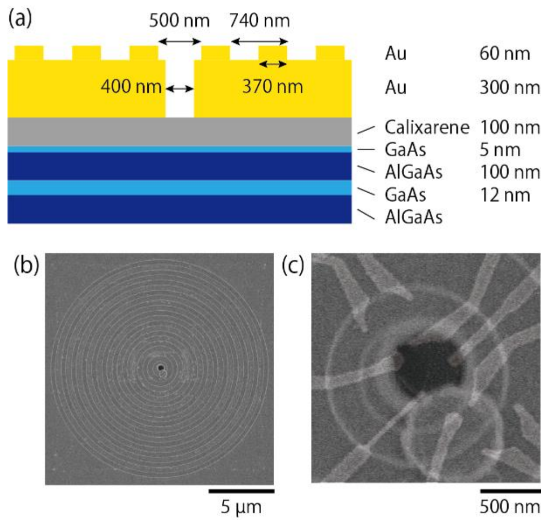

Fig. 1 (a) Cross sectional view of the device used for the simulation. (b) Scanning electron microscope (SEM) image of the fabricated surface plasmon antenna. (c) Combined SEM image of the fabricated surface plasmon antenna and gate electrodes to form a double QD.

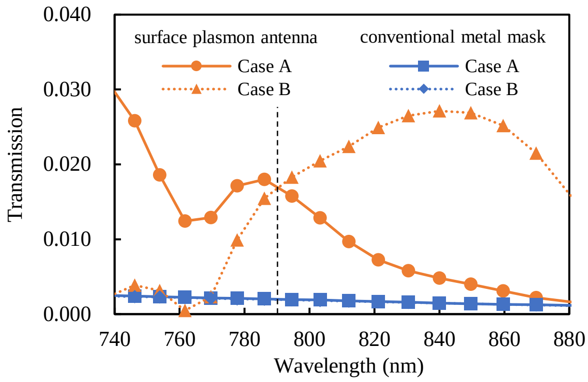

Fig. 2 Simulated transmission spectra of the designed surface plasmon antenna and conventional metal mask

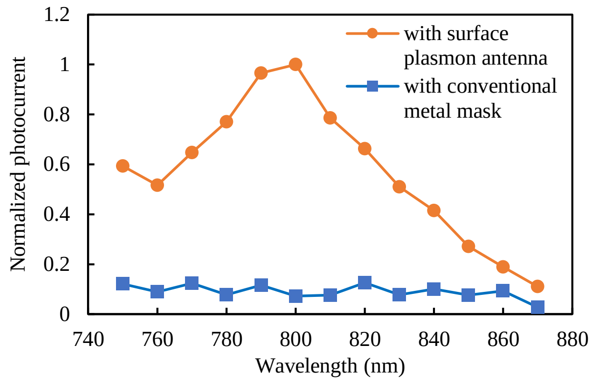

Fig. 3 Normalized photocurrent spectra of the samples with surface plasmon antenna and conventional metal mask

simulation, the incident beam was formed by collecting 1-mm collimated beam via aspheric lens (NA 0.55, diameter 3.6 mm). The sample surface in the simulation was slightly displaced from the focal point to scan the incident beam on the sample surface and recognize the aperture in practice, which resulted the spot size of 7 μm on the sample. The above conditions approximately reproduce the practical incident beam [6]. To compensate coarse positioning of the focal point relative to the sample position in our dilution refrigerator due to manual alignment of an aspheric lens, we designed single plasmonic antenna to enhance optical transmission both in front of (Case A) and behind the focal point (Case B) at the LH excitation wavelength in the QW of 790.1 nm. Figure 2 shows the simulated transmission spectra of the designed plasmonic antenna and conventional metal mask without concentric rings. In Fig. 2, we can see different transmission spectra of the designed antenna in Case A and B because opposite divergence angle of the incident beam varies the order of photon-plasmon coupling. We estimated the transmission enhancement at 790.1 nm as approximately 8 times.

We fabricated the designed surface plasmon antenna on a double QD with charge sensors as shown in Fig. 1 (b), (c). The sample with conventional metal mask was also prepared for a comparison. We measured the photocurrent flowing to one of the ohmic contacts at room temperature to characterize its wavelength dependence without resonant absorption peaks of the QW. Fabricated samples were attached to a sample holder with an aspheric lens in a dilution fridge for low temperature measurements afterward.

3. Results

Figure 3 shows the wavelength dependence of photocurrent normalized by the photocurrent measured by irradiating at the 2-dimensional electron gas out of the metal masks in each sample. Finally, we could place the samples in front of the focal point of the aspheric lens. The incident beam was linearly polarized. In Fig. 3, the measured photocurrent spectra are obviously different between the surface plasmon antenna and the conventional metal mask and show similar trend to the calculated transmissions, which implies that the fabricated structure works as a surface plasmon antenna. We estimated that the plasmonic antenna enhances the optical transmission by 8 times at 790.1 nm. This enhancement factor is consistent with the simulated result. We notice a 15-nm red-shift of the peak wavelength in the photocurrent spectrum with surface plasmon antenna compared to the calculated transmission spectrum. Possible reasons for this shift are incident angle, irradiation position, material parameter in FDTD simulation, imperfection of the fabricated structure. Their effects are subjects for future analysis.

4. Conclusions

We fabricated and characterized a surface plasmon antenna on a lateral QD structure at room temperature. Measured photocurrent and calculated transmission show similar trend and 8-times optical enhancement. This indicates that the FDTD simulation with taking practical optical setup parameters into account can predict the transmission enhancement of the surface plasmon antenna. In the next step, we will try to confirm the improvement of the photoelectron excitation efficiency in QD by surface plasmon antenna at low temperature. We can expect further enhancement with optimized design of plasmonic antenna by fixing the position of the focal point. We should also consider the polarization dependence, essential for quantum state transfer.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP17H06120, JP18J20764, and CREST JST (JPMJCR15N2). A.L. and A.D.W. acknowledge gratefully support of DFG-TRR160 and BMBF - Q.Link.X 16KIS0867.

References

[1] H. -J. Briegel *et al.*, Phys. Rev. Lett. **81**, (1998) 5932.
[2] L. Gaudreau *et al.*, Semicond. Sci. Technol. **32** (2017) 093001.
[3] R. Hanson *et al.*, Rev. Mod. Phys. **79** (2007) 1217.
[4] A. Pioda *et al.*, Phys. Rev. Lett. **106** (2011) 146804.
[5] K. Morimoto *et al.*, Phys. Rev. B **90** (2014) 085306.
[6] T. Fujita *et al.*, Nat Commun. **10** (2019) 2991.
[7] K. Kuroyama *et al.*, Phys. Rev. B **99** (2019) 085203.
[8] R. Vrijen and E. Yablonovitch, Physica E **10** (2001) 569.
[10] R. Fukai *et al.*, Jpn. J. Appl. Phys. **56** (2017) 04CK04.
[11] H. J. Lezec *et al.*, Science **297** (2002) 820.
[12] T. Ishi *et al.*, Jpn. J. Appl. Phys. **44** (2005) L364.