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InGaAs Nano-Photodiode enhanced by Polarization-Insensitive Surface-Plasmon Antenna

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1. Introduction

High-speed, highly efficient photodiode (PD) is one of the key components in high-bandwidth optical communication systems. However, conventional PDs have an inherent trade-off between speed and quantum efficiency. Several plasmonic structures have been suggested to overcome the trade-off.[1-4] In previous work, we investigated an InGaAs nano-scale metal-semiconductor-metal (MSM) PD with a surface plasmon (SP) antenna consisting of straight gold finger arrays.[3] Although a high efficiency of about 95% can be achieved by combining the straight-finger-type SP antenna with a distributed Bragg reflector (DBR), the antenna has strong dependency on polarization and narrow wavelength bandwidth due to sharp SP resonance. These characteristics are not suitable for optical communication applications.

In this paper, we propose a polarization-insensitive ring-type SP antenna to achieve efficient light coupling between an optical fiber and the InGaAs PD. Furthermore, we report the experimental results of the InGaAs nano-PD with the ring-type SP antenna.

2. Device Structure and Simulated Results

The ring-type SP antenna is composed of periodic concentric MSM electrodes as shown in Fig. 1(a). The cross section c-c in Fig. 1(a) of the InGaAs MSM nano-PD with the SP antenna is schematically illustrated in Fig. 1(c). In this work, the period, thickness, and ring width of the SP antenna are represented as *P*, *T*, and *W* respectively. A duty ratio *D* is defined as $D = W/P$. The InGaAs nano-PD consists of layered structure of a 80-nm-thick InAlAs barrier layer, a 250-nm-thick InGaAs absorption layer, a 160-nm-thick InAlAs phase-matching layer, and a multilayer DBR of 20 periods of quarter-wave InP/InGaAsP layers on an InP substrate. There is a SiN anti-reflection (AR) on top of the device. We applied a thin absorption layer to realize high-speed operation due to short carrier drift time. The InAlAs phase-matching layer enhances Fabry-Perot-like resonance between a top mirror of the SP antenna and a bottom mirror of the DBR.[3]

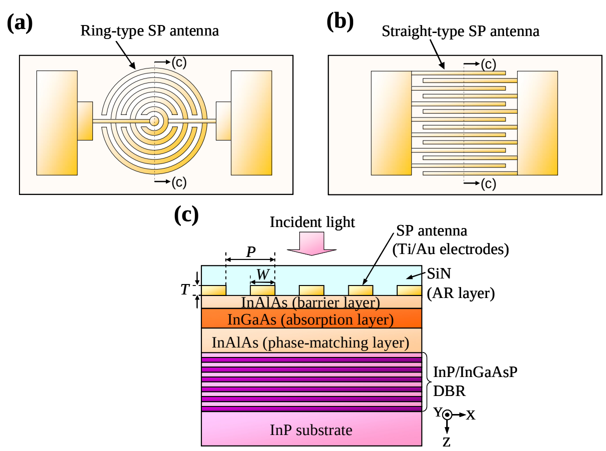

Fig. 1 (a) Schematic top view of a ring-type SP antenna. (b) Schematic top view of a straight-type SP antenna. (c) Schematic cross-sectional view of a nano-PD with a SP antenna.

In case of a straight-finger-type antenna described in Fig. 1(b), SP resonance can be efficiently excited by transverse magnetic (TM)-polarized light (defined by the electric field perpendicular to the finger array).[3] This polarization-sensitive characteristic is not desirable for optical communication applications. On the other hand, the ring-type antenna has such symmetric structure that it is insensitive to polarization of the incident light. As a result, the InGaAs nano-PD with the ring-type antenna has high efficiency for any polarization light.

Figure 2 shows the contour maps of electric field intensity calculated at P = 480 nm by three dimensional FDTD method. In these simulations, the incident light was linearly-polarized Gaussian beam and its beam waist was 8 μm. The electric field was parallel to the X axis. In the simulation, the ring-type SP antenna was assumed to consist of simple concentric ring array. Figure 2(a) shows the contour map at the surface of the SP antenna (XY-plane). Figure 2(b) shows the contour map in the middle of the InGaAs absorption layer (XY-plane). It was shown that strong SP resonance occurred along the X axis and there was light absorption even in non-resonant region. This is because the SP antenna with thin metal thickness was designed to realize relatively high light transmission in the non-resonant region and Fabry-Perot-like resonance occurred between the SP antenna and the DBR in the whole region. Figure 2(c) shows the contour map in the cross section of the nano-PD across the center (XZ-plane). A strong field was found to be confined in the InGaAs absorption layer by a Wood-Rayleigh anomaly mode resulting in enhanced absorption. [3,4]

Then, we systematically calculated the dependencies of quan-

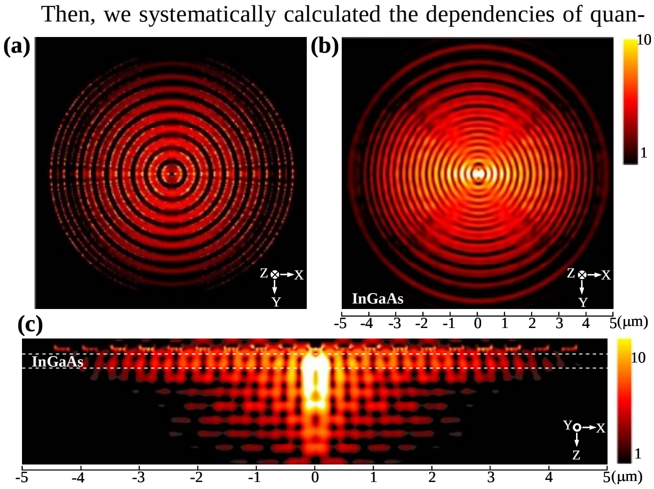

Fig. 2(a) Calculated contour maps of electric field intensity at the surface of the SP antenna, (b) in the middle of the InGaAs absorption layer, and (c) in the cross section of the nano-PD, respectively.

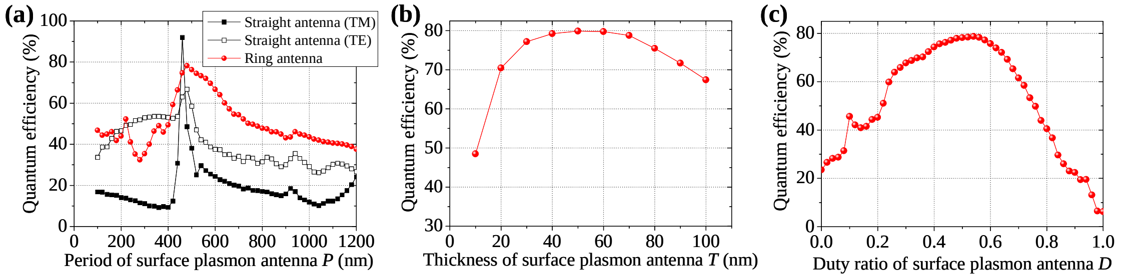

Fig. 3(a) Calculated quantum efficiency of the nano-PD as a function of antenna period *P*, (b) of antenna thickness *T*, and (c) antenna duty ratio *D*, respectively.

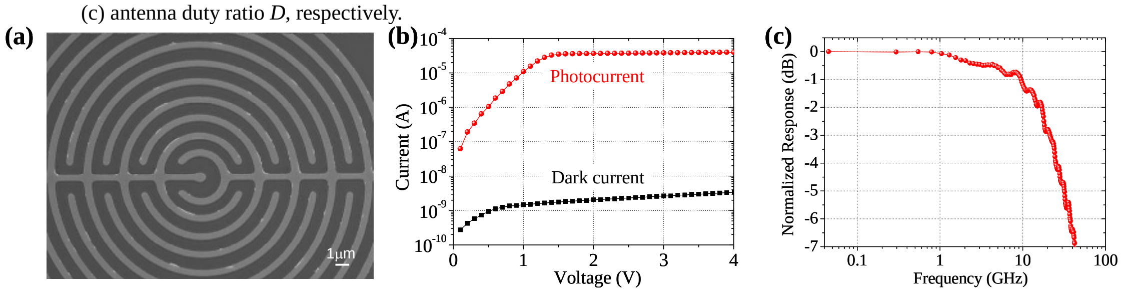

Fig. 4(a) Micrograph of a fabricated ring-type SP antenna. (b) Measured I-V characteristics of the fabricated nano-PD. (c) Measured I-V characteristics of the fabricated nano-PD.

tum efficiency on the period *P*, thickness *T*, and duty ratio *D* of the SP antenna, as shown in Figs. 3(a), 3(b), and 3(c) respectively. Figure 3(a) shows the calculated quantum efficiency of the nano-PD with the ring-type antenna and with the straight-finger-type antenna,[3] at *T* = 40 nm and *D* = 0.5. Each-type SP antenna was incorporated on the same semiconductor layer structure. In case of the straight antenna, very high efficiency of more than 90 % was obtained for TM-polarized light due to strong SP resonance. This high efficiency peak, however, is so sharp that it is difficult for practically fabricated antennas to always meet the resonance conditions. For transverse electric (TE)-polarized light (defined by the electric field parallel to the finger array), the maximum efficiency was less than 70 %.

On the other hand, the ring-type antenna had a broader peak and achieved a quantum efficiency of more than 60 % for the wide period range. The maximum efficiency was about 80 % at *P* = 480 nm. It indicates that the ring-type antenna enables a high efficiency for a wide wavelength range at a fixed period of the SP antenna. Figure 3(b) shows the calculated quantum efficiency as a function of the thickness of the SP antenna *T*, at *P* = 480 nm and *D* = 0.5. A quantum efficiency of more than 70 % was obtained at *T* = 20-90 nm. At *T* < 20 nm, the quantum efficiency decreases since efficient SP resonance doesn't occur. When the thickness *T* is more than about 100 nm, the reflection by the SP antenna reduces the quantum efficiency. Figure 3(c) shows the calculated quantum efficiency as a function of the duty ratio *D* of the SP antenna, at *P* = 480 nm and *T* = 40 nm. The peak was found to be broad and a quantum efficiency of more than 70 % was obtained at *D* = 0.36-0.64.

3. Experimental Results

We fabricated an InGaAs nano-PD with a gold-based ring-type SP antenna to investigate its photoresponsivity as shown in Fig. 4(a). The periodical SP antenna was designed to have 1.4 μm period with 0.6 μm of ring and 0.8 μm of spacing. Figure 4(b) shows the measured photocurrent and dark current of the fabricated nano-PD without DBR under 100 μW illumination at 1.55 μm wavelength. The diameter of the active area was 28 μm and the spot size of the incident light was about 18 μm. The photocurrent was found to be saturated around at 1.5 V bias voltage. A responsivity of 0.39 A/W and a low dark current of 3.4 nA were obtained at 4.0 V bias voltage. Figure 4(c) shows the frequency response. A 3-dB bandwidth of 21 GHz was obtained at 4.0 V. Since the junction capacitance and carrier drift time were estimated to be less than 30 fF and 10 ps respectively, the 3-dB bandwidth of the nano-PD has the potential of over 40GHz bandwidth with a load resistance of 50 Ω by improving the device. Therefore, both higher responsivity and bandwidth can be obtained by an optimized SP antenna of MSM electrodes with DBR. These characteristics indicate that the nano-PD can be potentially applied to high-bandwidth optical communication systems.

4. Conclusions

We developed an InGaAs nano-PD incorporated with a polarization-insensitive SP antenna which consists of concentric-ring gratings for optical communication systems. The ring-type antenna induces SP resonance for any polarization of incident light and enhances light absorption in a thin InGaAs layer due to its symmetric structure. FDTD simulations suggest that the ring-type SP antenna is capable of achieving a quantum efficiency of more than 60 % for wide wavelength range and the maximum efficiency is about 80 %. We fabricated the InGaAs nano-PD and experimentally demonstrated a 3-dB bandwidth of 21 GHz and an external responsivity of 0.39 A/W at 1.55 μm wavelength.

Acknowledgement

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References

[1] T. Ishi et al.: Jpn. J. Appl. Phys. **44** (2005) L364.
[2] J. Fujikata et al.: Appl. Phys. Express **1** (2008) 022001.
[3] D. Okamoto et al.: Jpn. J. Appl. Phys. **47** (2008) 2921.
[4] D. Crouse: IEEE Trans. Electron Devices, **52** (2005) 2365.