Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 760-761

E-5-3

Application of Surface-Plasmon Antenna to Near-Infrared Photodetectors for Optical Communication

Daisuke Okamoto, Junichi Fujikata, Kenichi Nishi, and Keishi Ohashi

Nano Electronics Research Laboratories, NEC Corporation
34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
Phone: +81-29-850-1589 E-mail: d-okamoto@ax.jp.nec.com

1. Introduction

High-speed and efficient photodetectors are key devices in high-bit-rate optical communication systems. Metal-semiconductor-metal photodiodes (MSM-PDs) with submicron finger spacing are promising because they have very fast response. However, a general trade-off between speed and quantum efficiency has been found. A thin absorption layer enables faster response but results in decreased efficiency. This trade-off can be reduced using an optical near-field enhanced by a surface plasmon (SP) antenna [1, 2] or using electromagnetic resonant modes of sub-wavelength gratings [3, 4].

This paper presents a study of MSM nano-photodiodes with one-dimensional SP antennas for optical communication systems. Fast response can be achieved by using narrow finger spacing and a thin absorption layer, and the SP antenna can enhance quantum efficiency.

2. Device Structure and Calculation Model

The structure of the nano-photodiode is illustrated in Fig. 1. A gold slit array acts as electrodes and also as SP antennas. The layer structure consists of a 100-nm thick InAlAs barrier layer, a 250-nm thick InGaAs absorption layer, and a 100-nm thick InAlAs buffer on an InP substrate.

The PD characteristics were numerically simulated using the finite difference time domain (FDTD) method. The quantum efficiency is defined as an absorbance in the InGaAs layer. The ohmic loss of surface plasmon polariton (SPP) on our gold antenna was very small at an optical communication wavelength. Light that is neither reflected nor absorbed was treated as the transmission component. A calculation was performed for a TM-polarized plane wave (defined by the E-field perpendicular to the slit array) with a periodic boundary condition. The wavelength, λ, was fixed at 1550 nm in this study.

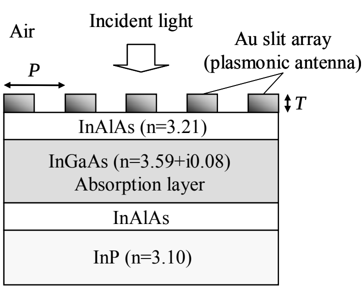

Fig. 1 Schematic cross-sectional view of MSM nano-photodiode with a gold SP antenna.

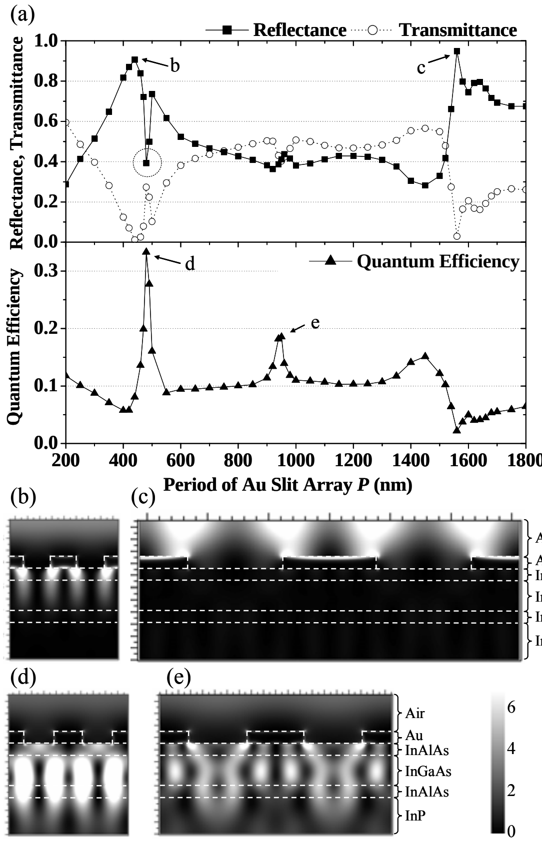

Fig. 2 (a) Reflectance, transmittance, and quantum efficiency vs. period of the gold slit array, P, at T=100 nm. (b), (c), (d), (e) Calculated contour maps of electric field intensity at P=440 nm, 1560 nm, 480 nm, and 950 nm, respectively.

3. Results and Discussion

A. Horizontal surface plasmon mode and Wood-Rayleigh anomaly mode

Figure 2(a) shows the calculated reflectance, transmittance, and quantum efficiency as a function of the slit period, P, at thickness, T=100 nm. Two peaks of reflectance at P=440 nm and 1560 nm were found, and the contour maps of electric field intensity for each case are shown in Fig. 2(b) and (c). The electric field was enhanced at the Au/InAlAs (P=440 nm) and Air/Au (P=1560 nm) interfaces by strong excitation of a horizontal surface plasmon (HSP) mode [3]. The two periods correspond to λ/n_{eff}, where n_{eff} is an effective refractive index on each interface, defined by $n_{eff}=\{\varepsilon_m\varepsilon_d/(\varepsilon_m+\varepsilon_d)\}^{1/2}$, where ε_m is the dielectric constant of gold, and ε_d is the constant of InAlAs or air. When HSPs were excited, the light transmission was inhibited due to their lateral momenta. These HSPs coupled with reflection light via a radiative mode by an inverse process, resulting in high reflectance.

A sharp dip in reflectance minima appeared at a *P* of 480 nm close to the HSP resonant peak, as shown in Fig. 2(a). At this period, a high quantum efficiency was obtained. The electric field intensity is illustrated in Fig. 2(d). The field has a similar profile to that of HSP resonance, but a stronger field was found in the InGaAs absorption layer because of a Wood-Rayleigh (WR) anomaly resonant mode [3]. The slit array evanescently coupled diffracted waves to the InGaAs absorption layer in this WR anomaly mode because the InGaAs layer had a higher refractive index than that of the InAlAs layer. As a result, incident light was efficiently absorbed, and a quantum efficiency of more than 30% was obtained even with a 250-nm thick absorption layer. The efficiency was enhanced by a factor of about five compared to that at longer periods (P>λ). Additionally, the other peak of quantum efficiency (P=950 nm) came from a second-order diffraction, as illustrated in Fig. 2(e).

B. SPP Vertical cavity mode

The slit thickness, *T*, is also an important factor for the SP antenna. Figure 3(a) shows the calculated reflectance and transmittance as a function of *T* at P=800 nm. The plotted curves have clear periodic dependencies. This behavior can be attributed to the standing waves in Fabry-Perot like cavities between the inlet and the outlet of the slit array, which is called a vertical cavity mode [3]. The calculated cross-sectional contour maps of electric field intensity for cases where high transmittances were obtained are shown in Fig. 3(b), (c). Transmission was enhanced via vertical cavity modes when an antinode was formed at the inlet edge of the slit array. By utilizing this resonant mode, reflection by opaque metals can be suppressed and the incident light can be efficiently guided into the semiconductor layers. For instance, a reflectance of less than 5% was calculated at T=300 nm.

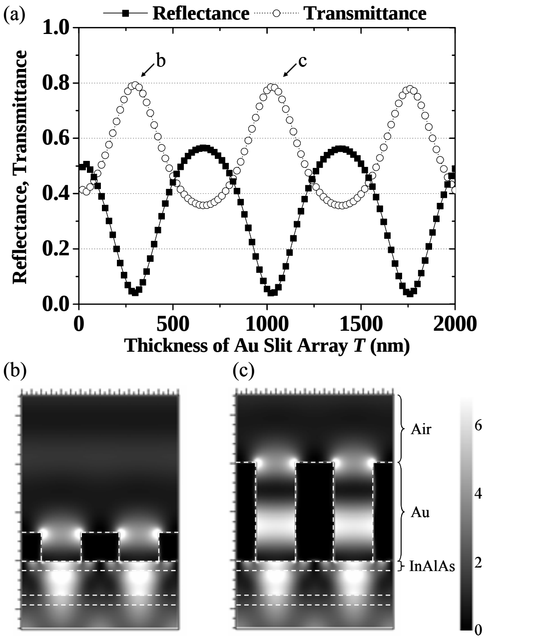

Fig. 3 (a) Reflectance and transmittance vs. thickness of the gold slit array *T*. (b), (c) Calculated contour maps of electric field intensity at T=300 nm and 1020 nm, respectively.

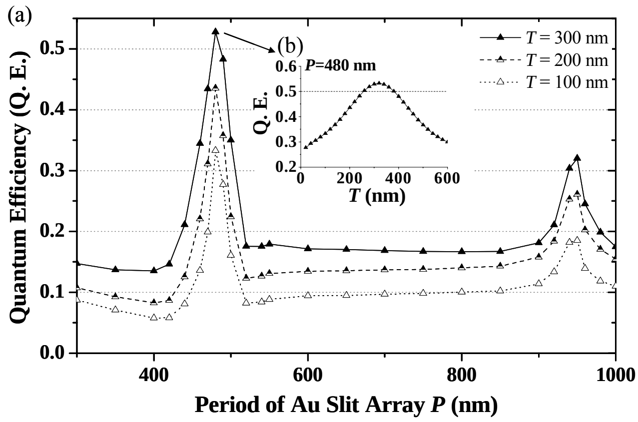

Fig. 4 (a) Quantum efficiency vs. the slit period, *P*, at T=100 nm, 200 nm, and 300 nm. (b) Quantum efficiency vs. the slit thickness, *T*, at P=480 nm.

C. Hybrid mode of WR anomaly and vertical cavity

Finally, we systematically calculated the dependencies on *P* and *T*, as shown in Fig. 4 (a) and (b), to investigate the coupling effects between the WR anomaly mode and the vertical cavity mode. A slit thickness of around T=300 nm produced the highest efficiency at any period for the gold slit array because the vertical cavity mode has weak dependency on *P*. However, the position of the WR anomaly resonant peak does not depend much on *T*. These results show that we can produce a hybrid mode of a WR anomaly and vertical cavity by optimizing the slit period and thickness. This hybrid mode enables a very high quantum efficiency of more than 50% using the nano-structured SP antenna, as shown in Fig. 4 (b).

4. Conclusions

We tested an MSM nano-photodiode with an SP antenna having high efficiency and fast response for optical communication systems. FDTD simulations showed that the hybrid mode of a WR anomaly and vertical cavity enables a quantum efficiency of more than 50% even with a 250-nm thick InGaAs absorption layer. These SP antennas are useful for enhancing nano-structured photodiodes.

Acknowledgement

This work was supported by the Ministry of Internal Affairs and Communications (MIC).

References

[1] J. Fujikata, T. Ishi, D. Okamoto, K. Nishi, and K. Ohashi, 2006 IEEE LEOS Ann. Meeting Proc. (2006) 476.

[2] T. Ishi, J. Fujikata, K. Makita, T.Baba and K. Ohashi, Jpn. J. Appl. Phys. **44** (2005) L364.

[3] D. Crouse, IEEE Trans. Electron Devices, **52** (2005) 2365.

[4] S. Collin, F. Pardo, and J. L. Pelouard, Appl. Phys. Lett. **83** (2003) 1521.