Plasmonic enhanced optical coupling effect on the quantum well infrared photodetector

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***Abstract*—We propose a novel structure to couple quantum well infrared photodetectors (QWIPs) by inserting a gold disk array into the interface between gold and dielectric layers. The periodic plasmonic effect of the gold disks together with the cavity effect of the finite-thickness dielectric layer enables the incident light field to concentrate at the location of quantum wells, which is proved by the finite element simulation. This will largely facilitate the design and processing of the QWIPs to employ plasmonic enhancement effect where the near field effects are usually involved. We believe that this structure provide a new solution to improve the performance of QWIPs.**

I. INTRODUCTION

IN the past decade, surface plasmons (SPs) have attracted a lot of interests to improve performance of quantum well[1], quantum cascade [2] and quantum dot[3] detectors, as a result of the near filed enhancement characteristics of SPs. However, SPs coupled quantum well detector (SP-QWIP) must ensure the quantum well layer in the near field region[2], which limits its manufacturing. For multi-period quantum well (such as 50-period) detector focal plane array (QWIP-FPA), a thickness of 3 μm implies a weak SP-QW coupling due to the near field nature of SPs. In this paper, a novel plasmonic structure is designed to focus the most optical energy around the QW active layer, mitigating the processing difficulties brought by the near field effect that requires the QW layer to be very close to or even embedded in the metals in conventional SP schemes. A plasmonic structure is formed by inserting a gold disk array with the thickness of 0.6 μm and the period of 6 μm into the interface between the Au (0.2 μm) and the dielectric (6.2 μm) layers. An enhanced electric field within the QW active layer is demonstrated due to resonance effect of this plasmonic structure. Moreover, this scheme is completely compatible with the conventional manufacture processes of the QWIP focal plane arrays, no sub-micro lithography is required.

II. RESULTS

Figure 1 shows the schematic diagram of the unit cell of the plasmonic coupling structure, together with the sizes of different parts. The finite element method COMSOL software provides a platform to analysis reflectance spectra of the structure, and a reflectance dip occurs at 12.7 μm, as shown in Fig. 3. Also shown in Fig. 1 and Fig. 2 are the distribution of the square of electric field along *z* direction in the XOZ plane and XOY plane at the wavelength of resonance (the incident electric field is set as 1). The simulation is taken with n_{GaAs}=3.3, and the relative permittivity of gold obeys Drude model with the plasma frequency of 1.26×10^{14} rad/s and the damping rate of 0.76×10^{14} rad/s. It is obvious to see that the most of optical energy is localized within the QW layer (red rectangle area as shown in Fig. 1) and the enhancement of the average of square of electric field along *z* direction in QW layer by a factor of 10.5 is observed. The localization and enhancement of electric field are attributed to the total reflection at the interface between GaAs and air. Photons from air to GaAs cannot escape out of GaAs, leading to a photon capture by this novel plasmonic structure, implying that the most incident photons would be converted to photo-generated carriers, resulting in a performance improvement.

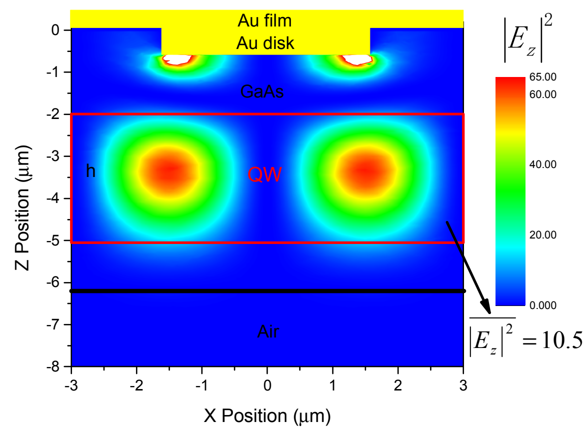

Fig. 1. Schematic diagram of the unit cell of plasmonic coupling structure and QWIPs. Also shown are the distributions of the square of electric field component along *z* direction in XOZ plane (y=0 μm).

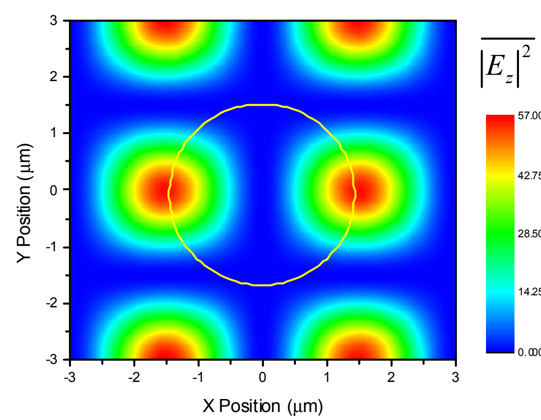

Fig. 2. Distributions of the square of electric field component along *z* direction in XOY plane (z=-3.7 μm)

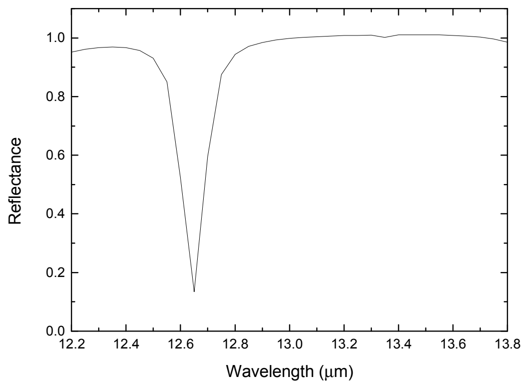

Fig. 3. Reflectance spectrum of the plasmonic coupling structure.

We can use metal-dielectric (MD) waveguide periodic resonance to explain this resonance. The COMSOL software demonstrates that metal/finite-thick dielectric layer structure can support the MD waveguide mode, and its distribution of the square of electric field component along z direction is shown in Fig. 4. It is found that electric field of the MD waveguide mode is concentrated in QW layer, in agreement with the distribution along z direction of electric field in Fig. 1. Fig. 5 shows the effective index of the MD waveguide mode, and the effective index decreases as the wavelength getting longer, which indicates that light confinement capability of dielectric layer become weaker at longer wavelengths. Note that this plasmonic structure have a thin Au disk array (*h*=0.6 µm), which is tenth of the dielectric layer thickness, thus Au disk array can be considered as a perturbation to the MD waveguide in order to provide grating wavevector to form resonance. Resonance of this plasmonic structure occurs when the wavevector of the MD waveguide mode matches that of the grating wavevector of the period structure as follows:

$$k_0 n_{\mathrm{MD}} = \mathrm{m}G_{\mathrm{x}} + \mathrm{n}G_{\mathrm{y}}$$

where k_0 is the wavevector in vacuum, n_{MD} is the effective index, m and n are integers indicating the order of the coupling, $G_x = G_y = 2\pi/p$ are the grating momentum wavevectors for the square array. As expected, a period of 6 µm is chosen for Au disk array corresponding to the (1, 1) resonance of 12.7 µm, which is indicated by the distribution of electric field in Fig. 2.

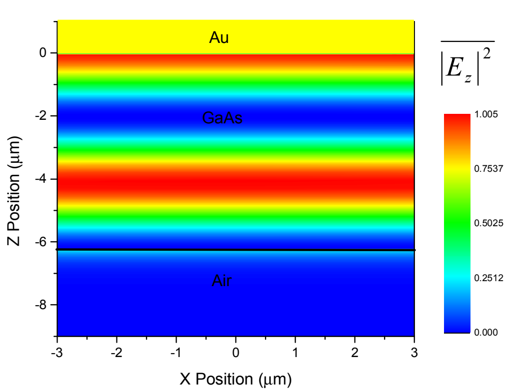

Fig. 4. Distribution of the square of electric field component along *z* direction in the MD waveguide mode.

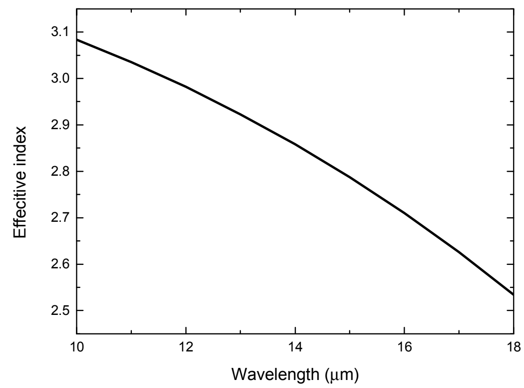

Fig. 5. Effective index of the MD waveguide mode at 12.7 µm.

III. Summary

In conclusion we demonstrate the design of a novel plasmonic coupling structure for QWIPs by inserting gold disk arrays into the interface between the Au reflection film and the finite-thick dielectric layer. The simulated electric field distribution shows that the resonant mode squeezes most of the optical energy into the QW layer, leading to a 10.5-fold enhancement of the average of electric field in *z* direction in QW layer. Moreover, we use MD waveguide resonance to explain this structure resonance. We believe that this plasmonic structure opens a new way to improve performance of photoelectric devices.

References

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