Modeling the anisotropic detection material in a quantum well infrared detector for critical coupling and high-discrimination polarization detection

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***Abstract*— The infrared detection material GaAs/AlGaAs quantum wells is modeled as an uniaxial effective medium during the simulation of quantum well infrared photodetectors (QWIPs). This approach helps us reveal new physics in QWIPs and design new QWIPs with high performances.**

Keywords—long wavelength infrared detection, quantum wells, effective medium, uniaxial, critical coupling, double polarization selection

I. Introduction

In the long wavelength infrared (LWIR) range, GaAs/AlGaAs quantum wells are regarded as a promising material for infrared photodetection due to low cost, high uniformity, easy design, controllable growth, and good compatibility with complex fabrication. Since the quantum wells (QWs) are only responsive to the light with an electric field component perpendicular to the GaAs/AlGaAs multiple layers and the efficiency of intersubband transition is fairly low, light coupling management is crucial for quantum well infrared photodetectors (QWIPs). Traditionally, during the design of the light coupling structures, the quantum wells are considered the same as GaAs [1], which is an isotropic dielectric without absorption in the LWIR range. We reveal that this type of modeling would leave out important physical effects, such as critical coupling and high-contrast polarization discrimination. These physical effects would fundamentally guide the design of the light coupling structures for high-performance QWIPs. In this presentation, we show that by modeling the QWs in a QWIP as an anisotropic absorptive material during the light coupling simulation, we could predict the light coupling properties more accurately and design new light coupling structures more efficiently. For light absorption enhancement, our model is able to capture the critical coupling effect and thus guide the design of the optimized light coupling structures. For polarization detection, our model captures the anisotropic absorption of the QWs and thus helps the design of high polarization-discrimination QWIPs.

National Key Research and Development Program of China (2022YFA1404602), the National Natural Science Foundation of China (61975223), the Program of Shanghai Academic/Technology Research Leader (22XD1424400), support of the SQDL.

II. Optical Modeling of QWs

A. *Treating QWs as an uniaxial effective medium*

The QWs for LWIR detection consist of periodic alternating AlGaAs/GaAs layers. Typically, the thickness of the barrier (AlGaAs) is several tens of nanometers and that of the well (GaAs) is several nanometers. Thus, the thickness of each layer is much smaller than the wavelength in the LWIR range, and hence the QWs can be treated as an effective medium. Due to the selection rule of the intersubband transition, the QWs only absorbs the light with an *z*-component electric field. Then, the QWs is regarded as an uniaxial effective medium with a permittivity tensor like ε_{QW} = diag (ε_x, ε_y, ε_z) [2-5]. Assuming that the AlGaAs/GaAs multilayers are parallel to the *x*-*y* plane, $\varepsilon_x = \varepsilon_y = \varepsilon_{GaAs}$ since the intersubband transition of the QWs cannot be excited by the light polarized within the *x*-*y* plane and thus the QWs behaves like GaAs in the LWIR range. For the light polarized along the *z*-axis, ε_z conforms to the Lorentz formula

$$\varepsilon_z = \varepsilon_{GaAs} + \frac{\varepsilon_{GaAs} f_{12} \omega_p^2}{\omega_{12}^2 - \omega^2 - i\omega\gamma} \tag{1}$$

where ε_{GaAs} is the refractive index of the GaAs, f_{12} the oscillator strength, ω_p the two-dimensional effective plasma frequency, ω_{12} the transition frequency in optics and γ the relaxation frequency [6]. In our practice, these parameters are determined by fitting the Lorentz formula to the photocurrent spectrum of the QWs. The QW together with the GaAs contact layers and the GaAs substrate are made into a standard 45° edge facet coupled device. Then, the photoresponse of this device reflects the properties of the QWs, so by measuring the photocurrent spectrum of this device and fitting the Lorentz formula to it, we obtain the wavelength dependent anisotropic dielectric constant of the QWs. In the following, we present the application of the optical modeling of QWs for the study of plasmonic cavity integrated QWIPs and chiral metamaterial integrated QWIPs.

B. *Exploring the critical coupling effect in the plasmonic cavity integrated QWIP for high sensitivity*

The optical modeling of QWs is applied to the study of the plasmonic cavity integrated QWIPs. Fig. 1 (a) shows a plasmonic cavity integrated QWIP pixel. Each of the two metal strips in the middle forms a plasmonic cavity with the GaAs/QWs/GaAs semiconductor layer and the Au reflector at the bottom.

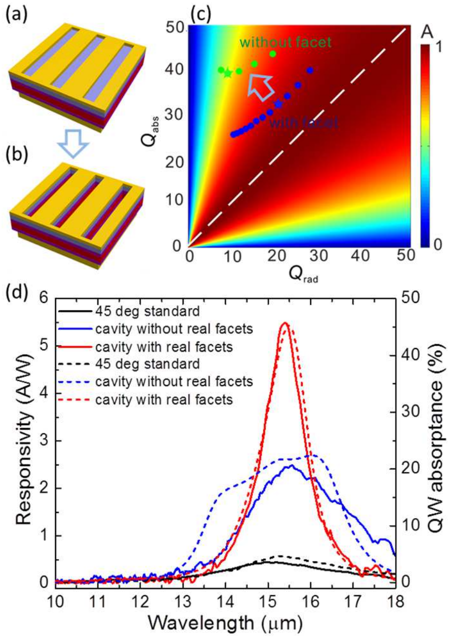

Fig. 1. (a,b) Sketch of the plasmonic cavity integrated QWIP pixel without (a) and with (b) high-reflection boundaries. (c) Contour of the on-resonance total absorption versus Q_{abs} and Q_{rad}. (d) Measured responsivity spectra of the 45° edge facet edge coupled device (black), the plasmonic cavity integrated QWIP without (blue) and that with high-reflection boundaries (red). And simulated absorptance spectra of the three devices.

Since the light absorption property of the QWs is taken into account in our modeling, it is revealed that the light coupling from free space to the plasmonic cavity mode is determined by the balance between the radiation Q factor (Q_{rad}) and the absorption Q factor (Q_{abs}). Q_{rad} is determined by the light confinement ability of the plasmonic cavity, and Q_{abs} by the absorptance of the QWs and that of the metal. As shown in Fig. 1 (c), the absorptance of the QWs reaches unity when $Q_{rad} = Q_{abs}$. The green dots correspond to the ordinary plasmonic cavity integrated QWIP, whose absorptances are not satisfied. The simulation indicates to increase Q_{rad} and decrease Q_{abs}. Then, we etched part of the semiconductor to form high-reflection boundaries of the plasmonic cavity and grew more QWs to increase light absorption (Fig. 1 (b)). As a result, the simulated absorptance of the QWs is markedly improved (blue dots in Fig. 1 (c)), and it is confirmed by experiment. As shown in Fig. 1 (d), the peak responsivity of the plasmonic cavity integrated QWIP with high-reflection boundaries is more than two times as high as that of the ordinary plasmonic cavity integrated QWIP [2,5].

C. *High circular polarization extinction ratio of the chiral metamaterial integrated QWIP*

Our optical modeling of QWs is also applied to the chiral metamaterial integrated QWIPs for circular polarization detection with high circular polarization extinction ratio (CPER). The device is depicted in Fig. 2 (a). The GaAs/QWs/GaAs semiconductor layer is sandwiched between the Au reflector at the bottom and the Z antenna at the top [3].

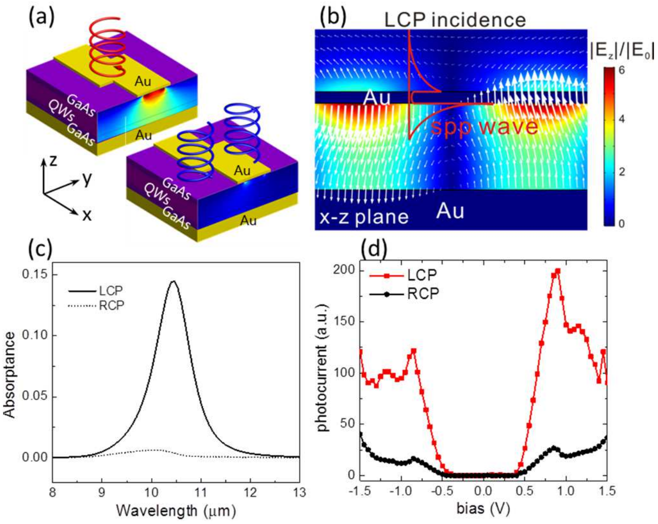

Fig. 2. (a) Sketch of the Z antenna integrated QWIP under LCP or RCP illumination. The cross section shows the simulated light field distribution. (b) $|E_z| / |E_0|$ distribution at the *x-z* cross section under LCP illumination. (c) Absorptance spectra of the device under LCP and RCP illumination. (d) Bias dependent photocurrent by LCP and RCP illumination.

For the left-handed Z antenna, the left circularly polarized (LCP) light can excite a surface plasmonic polariton (SPP) wave at the interface of the Z antenna and the semiconductor (Fig. 2 (b)). Thus, the intensified near field *Ez* of the SPP wave enhances the absorptance of the QWs. The absorptance peak due to the SPP resonance is shown in Fig. 2 (c). In comparison, the right circularly polarized (RCP) light is mostly reflected. In this way, a discrimination on the circular polarization of the incident light is created. By modeling the QWs as an uniaxial absorptive medium, we find that the anisotropy of the QWs provides another polarization selection in addition to the Z antenna, leading to a high CPER = I_{LCP} / I_{RCP}. I_{LCP} (I_{RCP}) denotes the photocurrent of the device illuminated by LCP (RCP) light. As confirmed by experiment (Fig. 2 (d)), at the bias about 0.9 V, the CPER reaches 10.2, which is more than two times as high as that of the ordinary plasmonic chiral metamaterial integrated photodetectors.

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