New optical coupling structure of high light absorption quantum well Infrared photodetectors

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Abstract

A new optical coupling structure of high optical absorption quantum well infrared photodetectors is reported, in which 4 periods of $Al_{0.15}Ga_{0.85}As$/GaAs QWs was integrated with double gold films and a sandwiched structure of metal-QWs-metal gratings has been adopted. Normal incident light can be coupled and trapped in the dielectric layer in the form of transverse electromagnetic waves, when the structure is optimized. Therefore, the light absorption of quantum wells is greatly enhanced when the light travels back and forth in the dielectric layer. Numerical simulations are made via 2D finite-difference time-domain (FDTD) method, yielding consistent results with experiments, which shows the photocurrent response increase of 21 times to the 45 degree mesa photodetector. At the same time, we observe the Rabi splitting.

I. INTRODUCTION

For quantum well infrared photodetector (QWIPs), normal incident light can not be absorbed by quantum wells due to the inter-subband transition rule, thus proper optical coupling schemes should be employed for normal incident light [1,2]. Now we propose and demonstrate efficient photo-couplers for QWIP by exploiting SPP resonance occurring metal gratings in the metal-QWs-metal gratings structure as shown in Fig. 1. It shows that light can be coupled into left-going and right-going waves in the dielectric layer, thus standing wave resonances can be formed between neighboring grooves. A series of Fabry-Perot-like standing-wave modes associated with the impedance mismatch of the entrance and exit apertures is supported by an open-ended slit[3]. These resonant states can be used to enhance the optical absorption of photodetectors. And the high coupling efficiency of the proposed scheme suggests that such a structure may have great significance for quantum well infrared detectors.

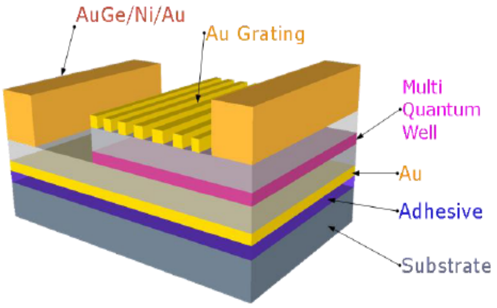

Fig. 1. (Color online) schematic diagram of the M-QWs-M structure of quantum well infrared photodetectors.

II. SIMULATION MODELS AND DEVICE STRUCTURE

The schematic view of unit structure is shown in figure 2. The contact/Quantum wells/contact (CQC) structure is located between a metal-reflection layer and a metal-grating layer. Grating period p, grating depth h and slit width d are marked in fig. 2. The thickness of between the top and bottom is h, and the thickness of both the Au-grating layer and the Au-reflection layer are h1. The contact /Quantum wells/ contact structure is regarded as a uniform medium with effective refractive index 3.34[4]. The frequency-dependent permittivity of Au is based on the Lorentz-Drude model [5].

In our simulation two-dimension finite-difference time-domain (FDTD) method is employed. Both periodic boundary conditions imposed on the left and right sides and finite structure are used. As many as 16-20 periods grating, for there is little difference between the two conditions, so periodic boundary conditions is used for convenience. And perfect matched layers are imposed at the front and back surfaces. To ensure the accuracy the grid size is carefully chosen.

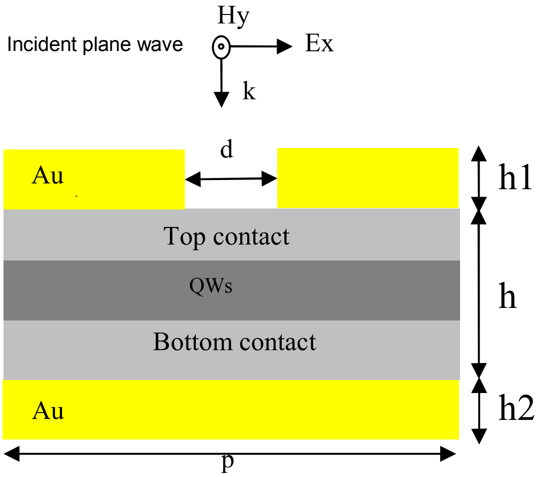

Fig. 2. (Color online) schematic diagram of the unit structure. The parameters are as shown.

III. RESULT AND DISCUSSION

The normal incident light has been redirected and trapped into GaAs/Quantum wells/GaAs layer, which makes such a structure is a perfect candidate as optical coupling scheme for QWIPs. Cavity modes are formed in the dielectric layer due to interference between the left-going and the right-going waves from neighboring slits: $E = 2E_0\cos(k*p)$, as period condition is imposed, and the resonant

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978-1-4673-1604-0/12/$31.00 ©2012 IEEE

condition can be given by k*p = 2nπ, n = 1, 2, • • •, where n is the order of resonance and p is the grating period. The resonant frequency of the Fabry-Perot resonators can be exhibited as:

$$f_n = \frac{cn}{2n_r(p-d)},$$

Where c is the vacuum speed of light, n_r is the refractive index of dielectric of the CQC.

The black body photocurrent between the new M-CQC-M structure QWIP and standard 45° mesa detector with the same CQC material is compared. The black body response of the 45 degree mesa detector is 0.02(A/W) while that of the new structure can reach 0.15(A/W). The Fourier transform infrared spectroscopy (FTIR) method is used to characterize the photocurrent spectrum. Fig.3 displays the photocurrent spectrums of different structure. 45 degree mesa device (red), new M-CQC-M structure QWIP (black) with p=11.3um and d=2.9um and the yellow dots show the model transmission of the new structure. The resonance mode can be tell clearly when the new structure be used. The FWHM of the absorption of QWs is 7.5um while that of the resonance mode is about 1um. Between the spectrum of 13.8-14.6um, the response of the No.13 can be 22 time to the 45° mesa QWIP. And the numerical simulations show that the |Ez| field enhancements of at least 3.6 times.

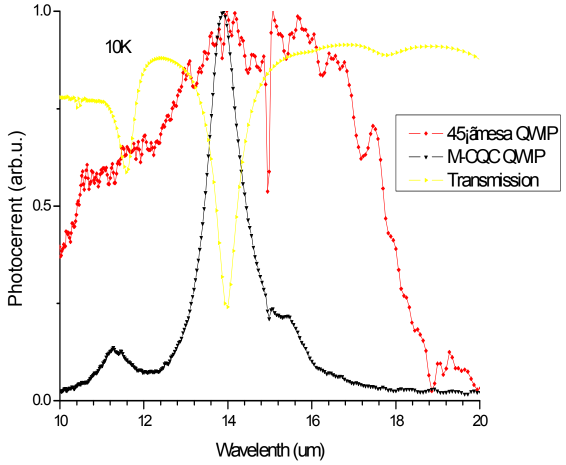

Fig. 3. (Color online) the photocurrent spectrums of different structure: 45 degree mesa device (red), new M-CQC-M structure QWIP (black) and the model transmission.

All the simulations above do not consider the absorption of the quantum wells. When cavity mode can not couple absorption, this influence can be ignored. When cavity mode and absorption are coupled, the Rabi splitting occurs [6], where the vacuum Rabi frequency can be expressed:

$$\Omega_R = \sqrt{\frac{e^2}{4\varepsilon_0 n_r{}^2 m^*} * \frac{f_{12}N_{2NEG}N}{h_2}} \text{ [7]},$$

in which e is the electron charge, m* is the electron effective, n_r is the effective refractive index here is 3.34, f_{12} is the oscillator strength 0.96 be used[8], N is 4 as the quantum wells number , N_{2NEG} is $16.5*10^{10}$ cm^{-2} as he population difference between the two subbands and h_2 is 0.326 um as the thickness of the 4 periods of quantum wells. The absorption is Ω_R/π = 1.1 THz in this CQC material. In sample 3 P is 11.5um and d is 6um. When we simulate taken the effective refractive index of CQC structure is 3.34, only crests at 10um, 13.4um and 14.7um can be seen. But there are two modes at 13.3um and 14um separated by 1.12 THz in the photocurrent spectrum, which is a good agreement with the Rabi frequency. To simulate this effect, the ISB absorption is add through a function of the electronic sheet density as a Drude-Lorentz dielectric tensor [9]. The simulation result is consistent to the experience.

IV. CONCLUSION

In conclusion, we experimentally demonstrate a new optical coupling structure of light absorption quantum well infrared photodetectors. The photocurrent response of such structure QWIP can increase 21 times to that of the 45 degree mesa QWIP. With an enhanced response, the new coupled QWIP can work at normal light incidence, at the same time, we observe the Rabi splitting. As far as we know, this is the first time to observe the Rabi splitting by the photocurrent spectrum, and the numerical simulations can consistent results with this effect. Introduction

ACKNOWLEDGEMENTS

This work was supported in part by the State Key Program for Basic Research of China (Grants No. 2007CB613206 and No. 2011CB922004).

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