Design of Terahertz Quantum-Well Photodetectors

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Abstract—**Terahertz quantum-well photodetectors (QWPs) represent a new and emerging photon-type detector in terahertz region. We first discuss the many-particle effects on the accurate design of terahertz QWPs. Grating and metal-cavity light couplers for terahertz QWPs are introduced. At resonant coupling frequencies, the polarization of light field is effectively changed by the light couplers to fulfill the selection rule of intersubband transition. Meanwhile, the electric field intensities in the active multi-quantum-well region of terahertz QWPs are enhanced. The performance of terahertz QWPs with these light couplers is improved significantly.**

Keywords – terahertz; quantum-well photodetectors; grating; metal cavity

I. INTRODUCTION

Recently, terahertz QWPs have been realized [1]. In comparison with other terahertz detectors, intersubband-transition-based terahertz QWPs display some specific features [2]. Due to the intrinsic short lifetime of photon-excited electrons, terahertz QWPs can be operated with high response speed and therefore suited for high-frequency applications [2]. Terahertz QWPs are narrow band detectors because of the delta-function-like joint density of states of intersubband transitions. As a result, filters are not required in some laser-based concealed object imaging applications. The response peak frequency of a terahertz QWP is determined by the energy difference between the first and the second subbands of the quantum wells, which can be well designed and implemented with molecular beam epitaxy (MBE) growth technique. The mature semiconductor processing technique makes it possible to fabricate large-scale uniform, high resolution, and long-term stable focal plane array, which are important for realizing real-time terahertz imaging systems.

In this paper, we first discuss the design principle of GaAs/(Al,Ga)As terahertz QWPs. Two main many-particle interactions, the electron exchange-correlation potential and the depolarization effect are considered. Low intersubband absorption efficiency due to the low electron doping concentration in the quantum wells is a key factor in limiting the performance of terahertz QWPs. In order to improve the intersubband absorption efficiency, two light coupling schemes, metal diffractive grating couplers and metal-cavity couplers are investigated. High efficient light couplers are expected to effectively improve the responsivity and working temperature of terahertz QWPs.

II. BAND STRUCTURES AND PHOTOCURRENT OF TERAHERTZ QWPS

We calculate the band structures and the photocurrent spectra of two devices labeled as V266 and V267 reported in Ref. [1]. Numerical details are presented in Ref. [3].

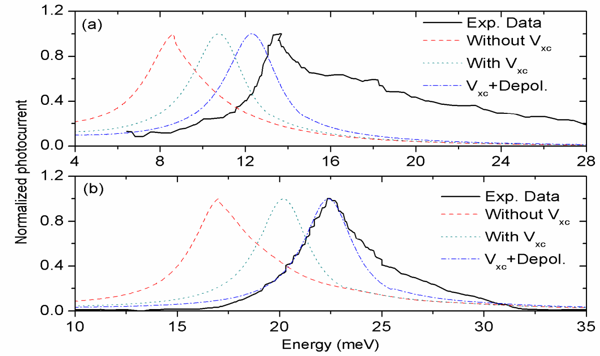

Fig. 1. Calculated and experimental photocurrent spectra of terahertz QWPs, (a) for V267 and (b) for V266. V_{xc} denotes the exchange-correlation potential.

The effects of the exchange-correlation potential and the depolarization interaction are explored [3]. For V266 and V267, when the electron Coulomb interaction is considered in Hartree approximation, only one localized subband exists in the quantum well, and the first excited subband is in alignment with the top of the barrier, which is coincidence with the design rule of bound-to-quasibound QWPs [2]. However, when the exchange-correlation potential is taken into account, the quantum well becomes deeper [4], which increases the energy difference between the ground subband and the first excited subband and pulls the first excited subband deep into the quantum well. The energy difference between the top of the barrier and the first excited subband ΔE is 3.2 meV for V266, and 3.0 meV for V267. The measured photocurrent spectra of the two devices indicate that the photon-excited electrons in the first excited subband can escape into the continuum states via scattering and electric-field-assisted tunneling mechanisms.

Theoretical and experimental photocurrent spectra for

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V266 and V267 are shown in Fig. 1 [3]. The deviations of response peaks between theory and experiment for V266 and V267 are 5.6 meV (24.8%) and 4.8 meV (36.0%) without including any many-particle interaction. When the exchange-correlation potentials are taken into account, the deviations decrease to 2.4 meV (10.6%) and 2.6 meV (19.4%), respectively. The further improvements of theoretical response peak positions are achieved by considering the depolarization effects, and the discrepancies are about 0.2 meV (0.9%) and 1.1 meV (8.2%) for V266 and V267. The large remaining discrepancy between theory and experiment for V267 may originate from the fluctuation of Al fraction in barriers due to the small Al mole fraction (1.5%).

III. LIGHT COUPLERS FOR TERAHERTZ QWPS

Light coupling is another key factor for better performance of terahertz QWPs [2]. Since light absorption in terahertz QWPs is due to intersubband transitions, the selection rule dictates that terahertz QWPs cannot respond to normally incident light. We study two types of metal-grating-based light couplers for terahertz QWPs. The metal grating period is in X direction, the length of metal strips is infinite in Y direction, and the quantum well growth direction is along Z axis. We define a quantity γ, the normalized coupling efficiency of a light coupler to that of a 45-degree facet coupling scheme,

$$\gamma = \frac{2\iiint_{MQWs} \left|E_Z\right|^2 dv}{\iiint_{MQWs} \left|E_0\right|^2 dv}, \qquad (1)$$

where E_0 is the electric field intensity in the multi-quantum-well (MQW) region of a terahertz QWP with a 45-degree facet coupling scheme.

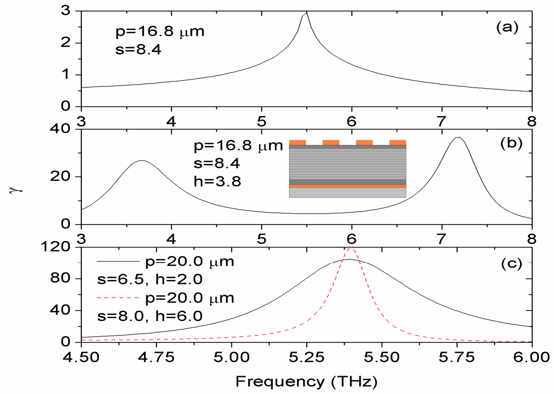

Fig. 2. Normalized coupling efficiencies of metal-grating couplers and metal-cavity couplers for terahertz QWPs, (a) metal-grating coupler, (b) metal-cavity coupler with the same grating parameters shown in (a), (c) optimal metal-cavity couplers for terahertz QWPs with the response peak frequency of 5.48 THz. The inset to (b) is a schematic of the cavity-coupled terahertz QWP.

The relative dielectric constant and the conductivity of gold, and the relative dielectric constant of GaAs are set to -1.80×10^4, 4.56×10^7 S/m, and 10.6, respectively in our calculations. The FEM [5] numerical resonant coupling peak of the metal grating is at 5.48 THz (Fig. 2(a)) [6]. However, in the metal-cavity-coupled terahertz QWPs, the original grating-determined resonant coupling peak at 5.48 THz disappears, and two other resonant coupling peaks with their maximum values at 3.65 THz and 7.20 THz emerge with the same grating parameters and the thickness of the cavity *h*=3.8 μm (Fig. 2(b)). In comparison with the case of metal-grating-coupled terahertz QWPs, the maximum coupling efficiency increases by about an order of magnitude [7]. The waveguide effects of the metal-cavity are responsible for the changes of the resonant coupling behaviors. A ray propagation method is successfully used to analyze the resonant behaviors in the metal-cavity-coupled terahertz QWPs qualitatively. The theoretical maximum value of normalized coupling efficiency γ is about 100 for the optimal metal cavity parameters (Fig. 2(c)).

IV. CONCLUSIONS

Due to the small barrier height and the energy difference between the ground subband and the first excited subband, many particle interactions play key roles in the band structure and the response peak frequency of a terahertz QWP. Because the exchange-correlation potential is minus, it increases the energy difference between the top of the barrier and the first excited subband ΔE. A blue shift of the response peak is introduced by both the exchange-correlation and depolarization interactions. Two types of light couplers are investigated. For the metal-cavity-based light couplers, at resonant coupling frequencies, the polarization of light field is effectively changed. Meanwhile, the electric field intensity in the active MQW regions of terahertz QWPs are substantially enhanced.

REFERENCES

[1] H. C. Liu, C. Y. Song, A. J. SpringThorpe and J. C. Cao, "Terahertz quantum-well photodetector," *Appl. Phys. Lett.*, vol. 84, pp. 4068-4070, May 2004.

[2] H. Schneider and H. C. Liu, "Quantum Well Infrared Photodetectors: Physics and Applications " (Springer, Berlin, 2007).

[3] X. G. Guo, Z. Y. Tan, J. C. Cao, and H. C. Liu, "Many-body effects on terahertz quantum well detectors," *Appl. Phys. Lett.*, vol. 94, pp. 201101-1—201101-3, Apr. 2009.

[4] X. G. Guo, R. Zhang, H. C. Liu, A. J. SpringThorpe, and J. C. Cao, "Photocurrent spectra of heavily doped terahertz quantum well photodetectors," *Appl. Phys. Lett.*, vol. 97, pp. 021114-1—021114-3, Jul. 2010.

[5] Multiphysics Modeling and Simulation Software-COMSOL: www.comsol.com.

[6] R. Zhang, X. G. Guo, C. Y. Song, M. Buchanan, Z. R. Wasilewski, J. C. Cao, and H. C. Liu, "Metal Grating Coupled Terahertz Quantum Well Photodetectors," *IEEE Electron Device Lett.*, vol. 32, pp. 659-661, May 2011.

[7] X. G. Guo, R. Zhang, J. C. Cao, and H. C. Liu, "Numerical Study on Metal Cavity Couplers for Terahertz Quantum Well Photodetectors," *IEEE J. Quantum Electron.* (2012, in press).