Strong enhancement of terahertz response in GaAs/AlGaAs quantum well photodetector by magnetic field

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A strong enhancement of terahertz (THz) response in a GaAs/AlGaAs quantum well photodetector (QWP) is observed under perpendicular magnetic field. Photocurrent spectra show that besides partial contribution from an increase in the detector differential resistance, improvement of photoconductive gain induced by electron localization and Landau quantization of the in-plane electron motion in quantum wells is the predominant underlying mechanism. This study sheds light on the transport mechanism in THz QWPs and provides a possible means for enhancing THz QWP's response. © *2010 American Institute of Physics*. [doi:10.1063/1.3462300]

Rapid advances in terahertz (THz) quantum-cascade laser (QCL) research in recent years have stimulated the development of THz semiconductor detectors.[1–3] Both QCL-like and conventional quantum well infrared photodetector (QWIP) structures are candidates for THz detection.[4–6] Though the former has advantages in working voltage and dark current,[7] QWIP structure is of special interest in reaching high performance THz detectors because of its well-known design and widely established application in the mid-infrared region.[8,9] A THz detector could be realized by extending the operating wavelength of a QWIP structure into the THz region through lowering the aluminum fraction of barrier layer of a properly designed GaAs/AlGaAs quantum well (QW). Liu *et al.*[10] have reported such a QW photodetector (QWP) with THz responsivity up to 1.0 A/W. However, for the low output power of THz sources coupled with the relatively high levels of thermal background radiation, it is desirable to further enhance the responsivity.[11] Practically we see limited room and avenue to pursue for improving the response by device design or materials improvement and other intrinsic methods. On the other hand, an appropriate external magnetic fields could tune the localization of photogenerated carriers and transportation of photocurrent (PC) and, consequently, the responsivity (R_p) in a QWP,[8,12] providing a possible means to improve the detection performance of THz QWPs. Based on this assumption, in this letter, we perform a PC spectral study of THz response of a GaAs/AlGaAs QWP detector in magnetic field perpendicular to the epitaxial layer and demonstrate that the THz responsivity could be strongly enhanced by sixfold to about 2.0 A/W.

The QWP structure consists of 30 periods of 15.5 nm GaAs and 70.2 nm $Al_{0.03}Ga_{0.97}As$ layers, with the center 10 nm of each well doped with Si to give rise to a two-dimensional electron density of around 6×10^{10} cm^{-2}.[13] The THz detector was processed into a mesa structure with a 45° facet and packaged in a double-pass back illuminated geometry shown in the right inset to Fig. 1(a). The PC spectral measurements were performed in a liquid helium cryostat with the sample mounted at the center of a superconducting solenoid capable of a maximum field of 10 T. The measurement setup included a Bruker IFS 113V fast-scan FTIR spectrometer equipped with an Hg lamp source, black poly filter, and a Ge/Mylar beam splitter.[14]

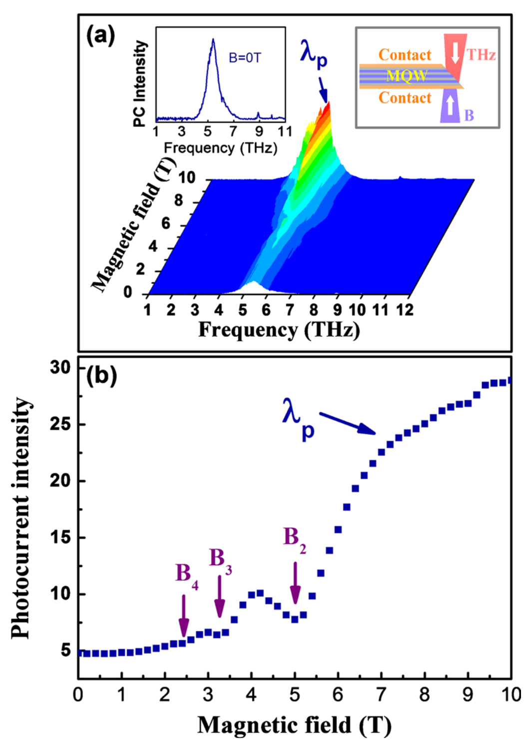

FIG. 1. (Color online) (a) PC spectrum for the GaAs/$Al_{0.03}Ga_{0.97}As$ QWP under magnetic field from 0 to 10 T at liquid helium temperature. The left inset shows the zero-magnetic-field PC spectrum. The right inset shows the measurement geometry. (b) Magnetic field dependence of PC intensity at peak response λ_p. Intensity resonance of λ_p are marked with arrow B_2, B_3, and B_4.

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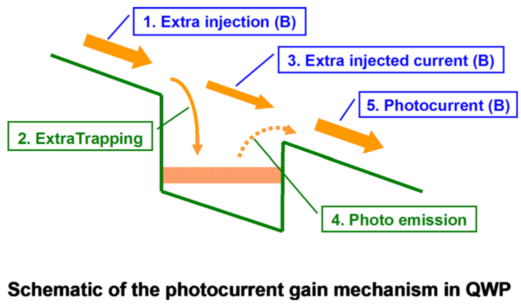

FIG. 2. (Color online) Schematic of the PC gain mechanism in QWP structures. The improvement of PC gain is a result of decreasing of balance probability through magnetic field effects on the process of extra injection. The influence of dark current is not considered.

The PC spectrum for the detector at a bias voltage of 0.15 V at liquid helium temperature under zero magnetic field is shown in the left inset to Fig. 1(a). The peak response (λ_p) of the detector is at around 5.4 THz. It originates from the intersubband transition from the ground state E_0 to the first excited state E_1 confined in the bound-to-quasi-bound QW structures of the detector, agreeing reasonably with expected value when many body effects are considered.[13] Detailed descriptions of zero-magnetic-field behaviors for the detector have been described elsewhere.[10] Here we focus on the magnetic-field effects on the PC characteristics. In the magnetic field measurements, THz radiation was adjusted to travel along the magnetic field direction (Faraday configuration) and normal to the epitaxial layers of the detector, shown in the right inset to Fig. 1(a). When magnetic field strength increased from 0 to 10 T with a step of 0.20 T, corresponding PC spectra were recorded and peak PC intensities at λ_p for different magnetic fields were obtained as shown in Fig. 1(a). The plot of magnetic field dependence of PC intensity at λ_p in Fig. 1(b) shows an approximately sixfold enhancement, from 4.8 to 28.9. Considering the linear relationship between PC intensity and responsivity (R_p), R_p of the detector was therefore, enhanced by about six times when magnetic field was applied. Knowing the R_p value of 0.33 A/W under zero magnetic field,[10] we can roughly estimate the highest R_p to be about 2.0 A/W.

The first common attribution to the enhancement of PC intensity of R_p at λ_p is the increase in the differential resistance (R_0) of the detector with magnetic fields because it helps to lower dark current and increase the ratio of PC to dark current in the detector.[8,15] We have also performed measurement of magnetic-field dependence of R_0 with same experimental geometry under illumination by THz radiation. The measurement result (not shown) indicates that R_0 and thus the product of differential resistance and area (R_0A, a figure of merit for photodetector) increase with magnetic field and contribute at most a twofold enhancement. This observation prompts us to further clarify the specific underlying mechanism for the remaining fourfold enhancement of PC intensity of R_p at λ_p under magnetic fields. Considering that the PC intensity and R_p of a photodetector is proportional to the product of PC gain (g_{photo}) and absorption quantum efficiency (η), the strong enhancement could be evaluated through analyzing magnetic-field effects on g_{photo} and η, respectively.

The simple physical process of g_{photo} mechanism in QWP structures under zero magnetic field is well known,[9,12] shown in Fig. 2. The collected total PC (5) flowing through

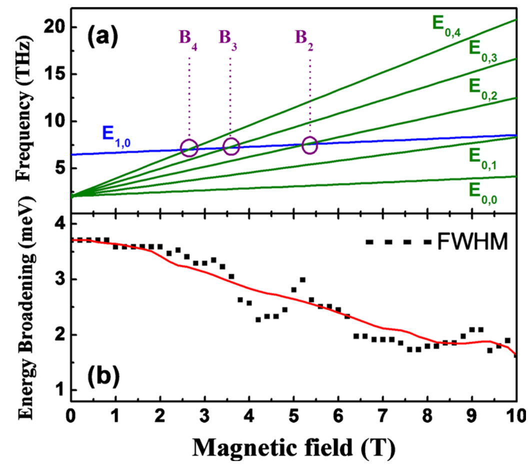

FIG. 3. (Color online) (a) Laudau levels in magnetic fields for the $GaAs/Al_{0.03}Ga_{0.97}As$ QWP. Intensity resonances at magnetic field of B_2, B_3, and B_4 satisfy condition of $\varepsilon_{1,k}-\varepsilon_{0,l}=n\hbar\omega_c$ (n=2, 3, and 4). (b) Magnetic field dependence on linewidth (FWHM) of PC spectrum for the $GaAs/Al_{0.03}Ga_{0.97}As$ QWP. Short-dashed line is used for visual aid only.

the detector includes direct photoemission of electrons (4) from QWs produced by absorption of the incident radiation and the extra injected current (3), which is the remainder of the extra injection (1) from the contact for balancing the "holes" in QWs (2, shortly named extra trapping) produced by photoemission of electrons. The amount of extra injection (1) should be sufficiently larger than the "holes" produced in the QWs so that such a balance process (2) could take effect. Extra injected current (3) that is collected by external circuit is indistinguishable from the direct photo emission (4) and will equally contribute to the total PC (5). Once a magnetic field is applied, the semiclassical localization of transport electron wave function will decrease the effective interplay range between extra injection (1) and holes in QWs, leading to a decrease in capture probability of electron traversing a QW with energy larger than the barrier height and an increase in a greater extra injection (1). Consequently, the extra injected current (3) will increase and a larger PC (5) directly collected by external circuit will occur. Briefly, we could attribute the improvement of g_{photo} in QWPs by magnetic field to the decreasing of capture probability induced by electron localization. It should be pointed out that, though lower dark current and higher R_0 will benefit the performance of the detector, we have not taken them into account in above discussions in Fig. 2.

More detailed analysis of the intensity resonances as marked with B_2, B_3, and B_4 in Fig. 1(b) will provide further insight into the understanding of magnetic field effects on g_{photo} and η. A perpendicular magnetic field to the epilayer of the detector will break the free-electron in-plane two dimensional parabolic energy into a set of equidistant Landau levels (LLs) identified with $\varepsilon_{i,n}=E_i+(n+(1/2))\hbar\omega_c$, where i=0, 1 is the subband index, n=0, 1, 2,... is the Landau index, and $\hbar\omega_c$ is the cyclotron energy. This physical process is also named as Landau quantization of the in-plane electron motion.[1,16,17] When the lowest LL, $E_{1,0}$, of the upper subband crosses $E_{0,2}$, $E_{0,3}$, and $E_{0,4}$ of the ground state subband as shown in Fig. 3(a), an enhancement in mixing of the two subbands and therefore, in capture probability occur. Excited electrons on the upper subband could more readily transfer to the ground state subband,[7,17–20] leading to the intensity resonances at λ_p. Short-range disorder caused by interface roughness or impurities is responsible for the mediation of momentum transfer required for inter LL scattering. Yet, at other nonresonant magnetic fields, electron transitions from upper subband will be suppressed. Since Auger scattering is the governing intersubband nonradiative process and its rate scales inversely with the separation between neighboring equidistant LLs, the nonradiative relaxation channel will be more suppressed with increasing of magnetic field. This suppression will lead to increase in the value of η, which is defined as the radiative transition rate over the sum of radiative and nonradiative transition rates.[8,18] Meanwhile, it contributes to the improvement of g_{photo} as a result of increase in the lifetime of excited electrons on upper subband.[20,21]

The effect of electron localization and Landau quantization of the in-plane electron motion could be further appreciated by the magnetic field dependence on the linewidth of the PC spectrum. The LL scattering rate is found to decrease with the electron localization induced by the magnetic field. This will lead to a narrowing of the intersubband transition and to a transition from a homogeneously broadened system to an inhomogeneously broadened one resulting from a zero-confinement dimension.[1,22] In experiment, we observe that the measured linewidth shows a strong monotonic decrease with some oscillations when applied magnetic field increases as shown in Fig. 3(b). The field-free full width at half maximum (FWHM) of PC spectrum for the detector is about 3.0 meV, slightly larger than the typical values of intersubband absorption linewidth in THz QWs,[10,12] indicating the characteristic of transition from bound ground state to quasibound excited states. It decreases by 60% down to 1.5 meV at a magnetic field of 10 T. This phenomenon agrees well with previous reports on THz QWs,[19,21,23] supporting our reasoning and argument of the underlying mechanism for the strong enhancement of THz response in the GaAs/AlGaAs QWP. The origin of linewidth oscillations should be connected with PC intensity resonances. More discussions on linewidth will be given in future study.

It should also be noted that the spacing between neighboring resonance such as B_2, B_3, and B_4 as shown in Fig. 1(b) and Fig. 3(a) tends to decrease with increasing of Landau index of crossing LLs of ground state subband. This should be the main reason for the absence such a strong PC intensity and response enhancement in midinfrared QWIPs. The energy separation of intersubbands in midinfrared QWIPs is much larger than in THz QWPs. Under same intensity of magnetic field as this experiment, only very high index LLs of ground state subband could cross upper subband. The spacing between resonances associated with these high index LLs will be so small that the transition of excited electrons to ground state subband can take place quasicontinuously with magnetic field. Therefore, the suppression of nonradiative relaxation channel will be negligible and improvement of g_{photo} and η will not be observable.

In summary, we have shown that the application of a perpendicular magnetic field strongly enhances the PC intensity and THz response of a GaAs/AlGaAs QWP. The THz responsivity is increased by six times to about 2.0 A/W at a magnetic field of 10 T. Magnetic field decreases the capture probability of an electron traversing QWs with energy larger than the barrier height as a result of electron localization. Landau quantization of in-plane electron motion in quantum wells improves the PC gain and absorption quantum efficiency. These effects, together with increase in the differential resistance of the detector, contribute to the observed strong enhancement of THz response. This study reveals the transport mechanism in THz QWPs under magnetic field and provides a possible means for enhancing THz response of QWP.

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