Ultra-low frequency photocurrent self-oscillation in strained $In_xGa_{1-x}As$ quantum well diodes

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Abstract

Ultra-low frequency photocurrent (PC) self-oscillation has been investigated in a $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ quantum-well (QW) diode in details as a function of temperature, excitation power and wavelength. The PC oscillation frequency increases with increasing temperature and illumination power at excitation wavelengths below the leading n = 1 heavy-hole exciton resonance line under reverse bias conditions. The illumination wavelength dependence shows a clear evidence for beating due to two oscillators when photoexcitation by shorter wavelength below 1050 nm is used. These results suggest that the low-frequency PC self-oscillation with a characteristic frequency of about 0.01-0.1 Hz is caused by oscillating electric fields due to two-types of photogenerated charge carriers trapped at deep localized centers within the QW regions.

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1. Introduction

Fluorescence intermittency in self-assembled InP quantum dots and InGaN clusters embedded in InGaN quantum wells (QWs) [1, 2] has been receiving considerable interest recently. Blinking dots with a time interval of about several seconds are observed and the origin is attributed to a local electric field due to a carrier trapped at deep localized centers. Recently ultra-low frequency photocurrent (PC) self-oscillation has been observed in $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ quantum wells embedded in a *p*-*i*-*n* diode structure for $x \geq 0.1$ under reverse bias conditions at low temperatures [3, 4]. In this paper, frequency of the PC oscillation is investigated in details in a strained QW diode as a function of temperature, excitation power and wavelength. By illumination at wavelengths below the n = 1 heavy-hole exciton resonance line, beating of the PC oscillation is observed. At low temperatures and under reverse bias conditions the oscillation frequency strongly depends on the illumination power and wavelength. Possible origins for the low-frequency PC self-oscillation are discussed in terms of photogenerated carriers trapped at deep localized centers within the QW regions.

2. Experimental

A set of three samples with nominally undoped strained $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ QWs (x = 0.05, 0.10 and 0.15) embedded in a *p*-*i*-*n* diode structure were grown at 470 °C on n-GaAs (100) substrates by molecular beam epitaxy [5]. Well and barrier thicknesses of the $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ QWs are 10.0 and 25.0 nm, respectively, which are nearly the same for the three samples. The intrinsic strained QW layers with five-periods are clad by 0.1 μm *i*-$Al_{0.3}Ga_{0.7}As$

layers and further confined by 1 μm thick n- and 0.1 μm p-$Al_{0.3}Ga_{0.7}As$ layers that were grown at 520 °C to form a *p-i-n* diode structure. After the growth, each sample was processed to form 400 μm mesa diodes using standard photolithography. PC spectra were recorded as a function of bias voltage (-7 ~ 0 V) using a combination of a 100 W halogen lamp and a Jobin-Yvon HR320 monochromator for illumination and a dc computer-controlled pico ampere-meter for detection in a closed-cycle He cryostat at 12.6-300 K. PC intensity under monochromatic illumination was measured as a function of time using a monochromatized light from the halogen lamp at various wavelengths or a Nd: YVO_4 laser at 1064 nm (10mW power) with varying the illumination power by neutral density filters..

3. Results and discussion

PC spectra have been measured at room temperature for the QW diodes as a function of reverse bias voltage between 0 and –7 V [3]. Distinct PC peaks observed at 945 and 898 nm for the PC spectrum at 0 V of the QW diode ($x = 0.15$) are attributed to n = 1 heavy-hole (1HH) and light-hole (1LH) exciton resonances, respectively, indicating high sample qualities [3, 5]. When the reverse bias (applied electric field) is increased, these PC peaks evolve due to the well-known quantum confined Stark effect (QCSE) [5, 6]. However, when the sample temperature is decreased to low temperatures below 60 K, the PC spectra are significantly modified due to the PC intensity self-oscillations [3, 4]. When the reverse bias (field) is decreased, the efficient radiative recombination suppresses the PC intensity and the PC oscillation disappears. That is, the PC intensity oscillation is only observed under the higher reverse bias voltage at low temperatures. It is found that only the QW diode with higher In contents ($x \geq 0.10$) shows the photocurrent intensity self-oscillations as a function of time with a characteristic frequency of ~0.1 Hz [4]. On the other hand, no PC oscillation is observed for the QW diode with the smallest In content ($x = 0.05$). Therefore, the PC oscillation is associated with the QW layer. In this paper, we will concentrate on the QW diode with $x = 0.15$.

Figure 1 shows PC intensity oscillation for the QW diode as a function of time at temperatures between 12.6 and 50 K under 1064 nm illumination (~10 μW) at a reverse bias voltage of -5 V. We note that the photoexcitation wavelength of 1064 nm is transparent to the QW layer, located below the 1HH exciton resonance line of ~905 nm (1.37 eV) at 15 K. Therefore, the PC oscillation is attributed to carrier trapping at deep localized states within the low-temperature grown, high In content QW layers. With increasing temperature from 12.6 to 50 K, the amplitude of the oscillations decreases and the oscillation frequency increases from 0.070 to 0.104 Hz. This result indicates that trapped charge carriers are thermally released with increasing temperature, thus accelerating the carrier movement.

In order to elucidate a relationship between the oscillatory PC behaviors and the amount of charges trapped at localized states, photoexcitation power dependence is investigated, using a Nd: YVO_4 laser (1064 nm wavelength) and neutral density filters. Figure 2 shows PC oscillations as a function of time at several different excitation powers for a reverse bias voltage of -5 V and at 15 K. An oscillation frequency at a 0.01 μW power is found to be 0.0027 Hz and increases to 0.4 Hz at 50 μW. This increase of the oscillation frequency with increasing the illumination power indicates that the PC oscillation strongly depends on the amount of photogenerated charges in the intrinsic layer. That is, the PC self-oscillation is a result of charging and discharging of localized carrier trap centers in the QW layer. When we further increase the illumination power and the PC intensity exceeds 10 mA, the PC intensity becomes to be unstable. If we further and further increase the power, then it suddenly starts to show an exponentially damping as a function of time. After this catastrophic behavior, the PC self-oscillation disappears, even if the illumination power goes back to a level of 10 μW. Therefore, by illuminating with the intense laser light at 1064 nm, the irreversible change of the deep trap states may occur like the DX centers in AlGaAs alloys [7]. However, an interesting fact is that the PC self-oscillation at low temperatures can be recovered repeatedly after the QW diode is annealed at room temperature. These results show that the PC oscillation is surely due to photogenerated carriers trapped at deep localized centers within the $In_xGa_{1-x}As$ QW layers.

The PC oscillation frequency has been measured over a wide range of excitation wavelength between 800 and 1150 nm at 15 K. When the illumination wavelength is set at 1026 nm (below ~1050 nm), a beat of the PC oscillations is observed (Fig. 3(a)) due to two oscillators at 0.074 and 0.086 Hz, which are determined by the Fourier transformation (Fig. 3(b)). However, the lower frequency PC oscillation dominates at excitation wavelengths longer than 1050 nm (1.18 eV), although faint higher frequency components might exist. This fact may be explained by assuming two types of charge generation processes in the conduction and valence subbands [8, 9] and a deep charge trapping state with an energy level ~0.2 eV below the conduction subband edge. This is because the occupation of the deep donor-like point defect can be changed optically depending on the excitation wavelength by the emission of an electron or a hole.

Localized natures of the PC self-oscillation can be confirmed by measuring wavelength dependence of the frequency and the PC intensity, as shown in Fig. 4. A solid curve in Fig. 4 shows a time-averaged PC spectrum for 300 sec, measured at 15 K and a bias of -5 V. Below the leading absorption edge of the 1HH exciton line, significant PC signals are detected between ~900 and ~1050 nm. In this wavelength range two distinct PC oscillation frequencies, frequency 1 (circles) and frequency 2 (triangles), are determined by the Fourier transformation of the beats. The wavelength dependence of the PC oscillation indicates that the frequency becomes to be smaller, when the absorption strength decreases. This finding is consistent with the result in Fig. 2, revealing that the photogenerated carriers due to localized trap states play an important role for the PC oscillations.

The PC self-oscillation observed here is reminiscent of current self-oscillations at frequencies of 0.7-100 MHz generated in n-i-n superlattices [10] due to oscillating electric field domains. The frequency of the superlattice oscillators arising from the resonant tunneling is basically determined by tunneling time. But the oscillation frequency observed here is very different from those of the superlattice oscillators. Thus, the mechanism behind the electric field oscillation might be very different from the superlattice oscillators, but similar to the characteristic time behaviors observed for the luminescence blinking phenomena in InGaN QWs. Our observation of beats of the PC oscillations may be explained by assuming two types of charge generation processes in the conduction and valence subbands [9] and a deep charge trapping state with an energy level below the conduction subband edge. These results indicate that the ultra-low frequency PC self-oscillation is caused by slow tunneling from the localized trap states to the subband states, which leads to electric field oscillations due to photogenerated carriers trapped at deep localized centers within the high In content QW layers embedded in a *p-i-n* diode.

4. Conclusion

Frequency of self-sustained PC oscillations has been investigated in an $In_{0.15}Ga_{0.85}As$ quantum-well diode as a function of temperature, excitation power, and wavelength. The characteristic frequency of the PC oscillation is found to be strongly dependent on the illumination power and wavelength. A clear evidence for a beating is observed much for photoexcitation below the ground exciton resonance line. These results indicate that the PC self-oscillation is caused by oscillating electric fields due to two-types of photogenerated charge carriers trapped at deep localized centers within the high In content alloy wells.

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Captions to Figures

Fig. 1 PC intensity oscillation at several temperatures between 12.6 and 50 K at a reverse bias voltage of -5.0 V under 1064 nm (10 μW) illumination. Base lines of the PC intensity are shifted vertically for clarity.

Fig. 2 PC intensity oscillation at power levels of 0.1, 0.5, 1.0, 5.0, 10, and 50 μW under 1064 nm illumination at 15 K and a reverse bias voltage of -5.0 V.

Fig. 3 (a) Beat of PC intensity oscillation under 1026 nm illumination at 15 K and -5.0 V and (b) its Fourier transform.

Fig. 4 Frequency of the PC intensity oscillation as a function of illumination wavelength and a time-averaged PC spectrum for 300 sec. The temperature is 15 K and the bias -5.0 V. Note a significant enhancement of the PC intensity below the 1HH exciton resonance line, extending to ~1050 nm (~0.2 eV below the gap).

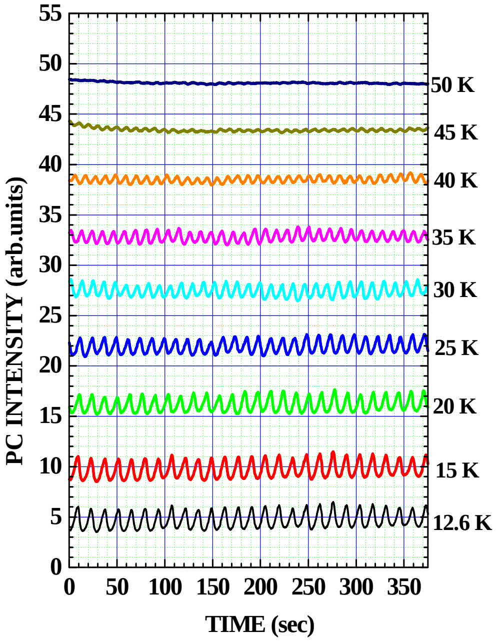

Fig. 1

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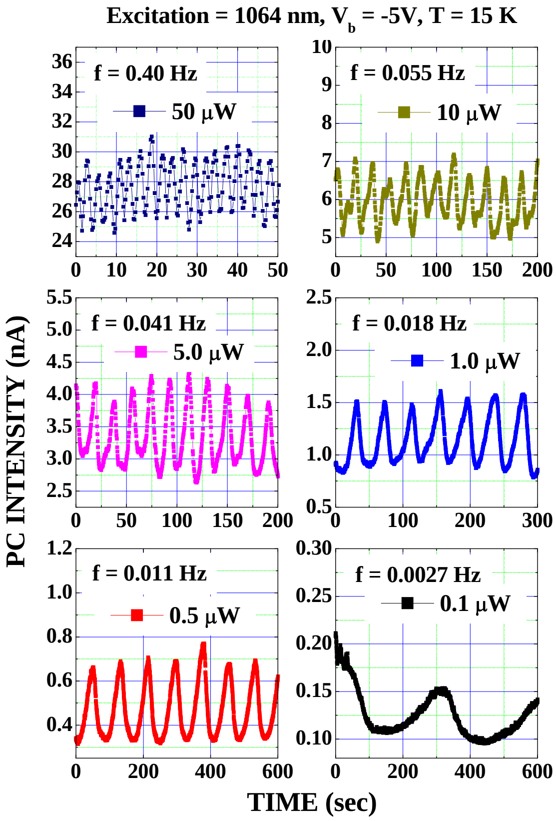

Fig. 2

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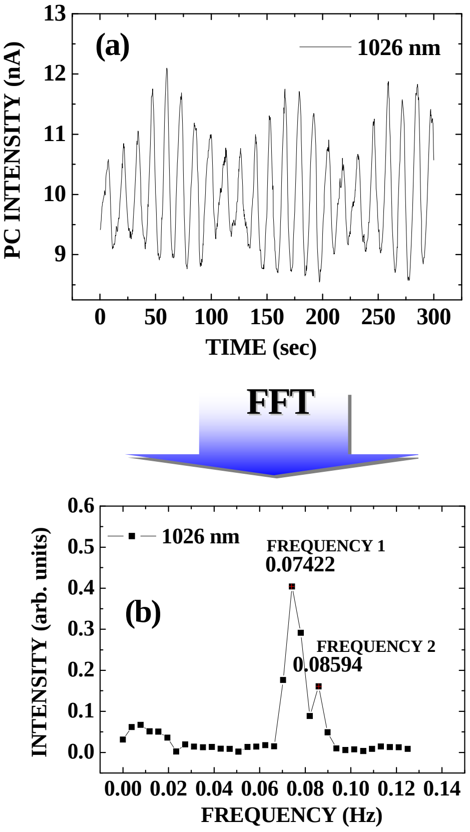

Fig. 3

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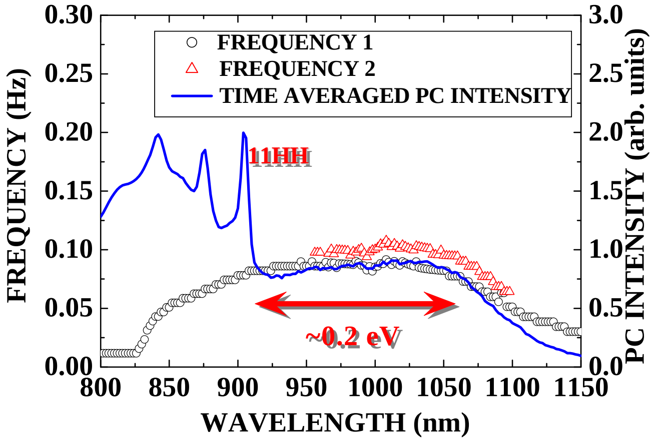

Fig. 4

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