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Ultra-low-frequency self-oscillation of photocurrent in $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ multiple-quantum-well *p–i–n* diodes

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We report an observation of ultra-low-frequency self-oscillation of photocurrent in $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ multiple-quantum-well *p–i–n* diodes. The photocurrent intensity shows self-oscillations with a characteristic frequency of ∼0.1 Hz at low temperatures under reverse bias voltages. The photocurrent self-oscillation depends on applied bias voltage, temperature, illumination power, and indium content of quantum-well layers. These dependences indicate that the photocurrent self-oscillation is attributed to photogenerated carriers trapped in localized centers within $In_xGa_{1-x}As$ quantum-well regions. © *2004 American Institute of Physics*.
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Recently, fluorescence intermittency, or random telegraph signal in luminescence from low-dimensional semiconductor systems such as CdSe nanocrystals,[1] InP self-assembled quantum dots,[2,3] and InGaN clusters[4] has been reported. This phenomenon is a blinking luminescence with a characteristic time scale of several seconds, that is, luminescence intensity switches between two or more discrete levels over time. The origin is ascribed to an intrinsic ionization-neutralization process,[1] a trapping-delocalization process,[2,3] or photoinduced many-carrier effects.[4] In this letter, we report an observation of ultra-low-frequency photocurrent (PC) self-oscillation in $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ multiple-quantum-well (MQW) *p–i–n* diodes. PC spectra of the MQW diodes show distinct exciton resonances associated with ground and excited subband states and redshifts due to the quantum-confined Stark effect (QCSE) under reverse bias voltages. At low temperatures below 60 K, the PC intensity shows self-oscillations with a characteristic frequency of ∼0.1 Hz under the reverse bias conditions. The PC self-oscillation depends on applied bias voltage, temperature, illumination power, and indium content of $In_xGa_{1-x}As$ QW layers. Based on the experimental observations, possible causes for the PC self-oscillation are discussed in terms of photogenerated carriers trapped in deep localized centers within $In_xGa_{1-x}As$ QW regions.

Three samples of $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ MQW with different In content x were grown on n^+-type GaAs (100) substrates by molecular-beam epitaxy.[5,6] Incorporation rates of In, Ga, and Al beam fluxes were precisely calibrated before a series of growth by observing intensity oscillations of zeroth-order reflection high-energy electron diffraction.[7] Five periods of nominally undoped 10-nm-thick $In_xGa_{1-x}As$ wells and 25-nm-thick $Al_{0.15}Ga_{0.85}As$ barriers in between were grown at 470 °C. The nominal values of x are 0.05, 0.10, and 0.15 for each sample. They are confined by undoped 50-nm-thick $Al_{0.15}Ga_{0.85}As$ and 0.1-μm-thick $Al_{0.3}Ga_{0.7}As$ layers. These layers are further clad by *n*- and *p*-type $Al_{0.3}Ga_{0.7}As$ layers to form a *p–i–n* structure. After the growth, the *p–i–n* diodes were processed into about 400 μm mesas and gold-ring electrodes as contact on the *p* material were formed by standard photolithography. The backside ohmic contact was formed with In-Ga alloy solders. PC spectra were measured using a lamp-monochromator system for illumination, in which the light of wavelength shorter than 700 nm is eliminated by a colored glass filter, and a dc picoampere meter for detection in a closed-cycle He cryostat at temperatures from 13 to 300 K.

Figure 1 shows PC spectra of the $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ MQW sample as a function of reverse bias voltage under illumination from the top of the epitaxial layer at 20 K. In the spectrum taken under the bias

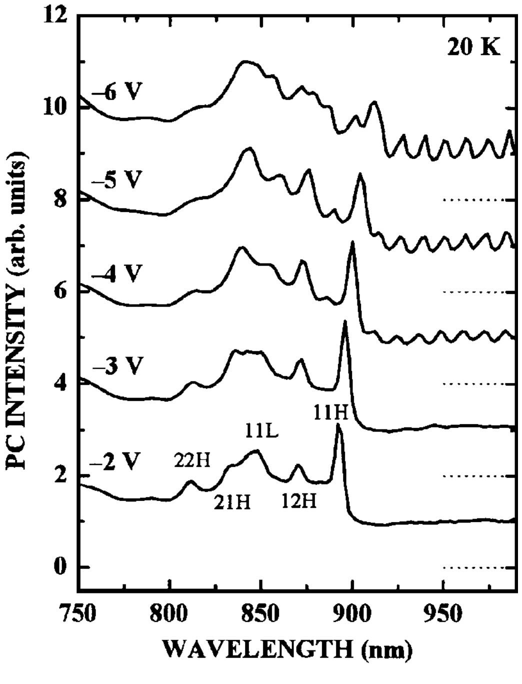

FIG. 1. PC spectra of the $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ MQW sample measured at 20 K under different bias voltages of −2, −3, −4, −5, and −6 V. The notation *ij*H (*ij*L) indicates the heavy-hole (light-hole) exciton transition between *i*th electron and *j*th heavy-hole (light-hole) subbands. The base lines of the PC spectra are vertically shifted for clarity.

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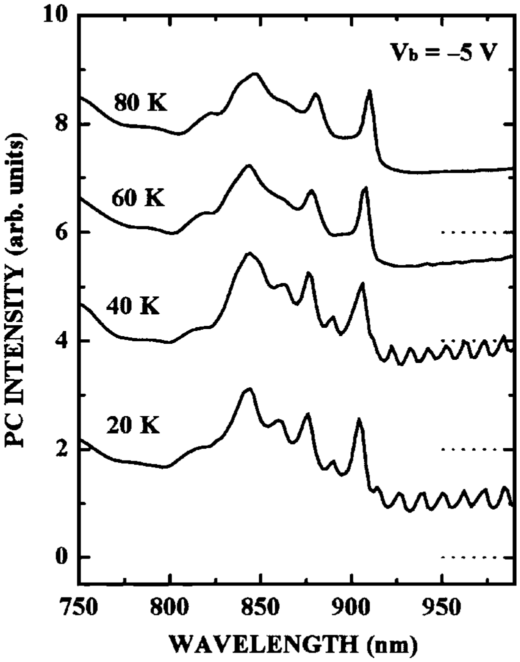

FIG. 2. PC spectra of the $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ MQW sample measured at 20, 40, 60, and 80 K under a fixed bias voltage of −5 V. The base lines of the PC spectra are vertically shifted for clarity.

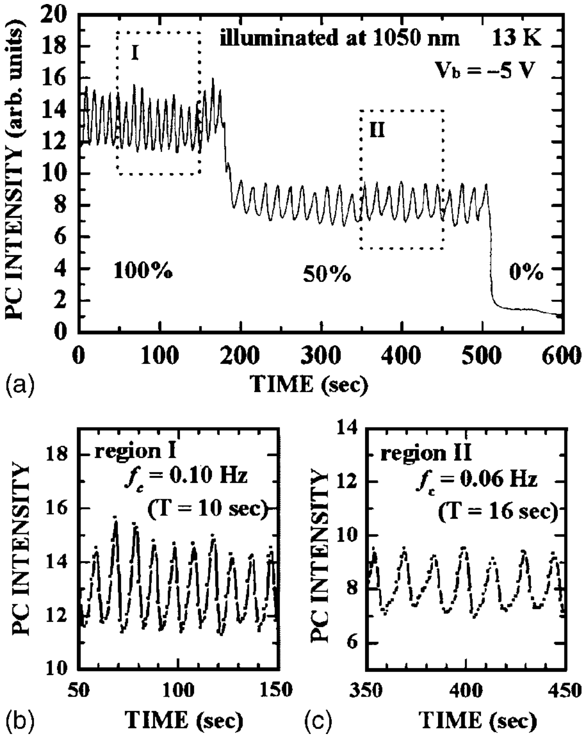

FIG. 3. (a) PC intensity of the $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ MQW sample as a function of time measured at 13 K under the bias voltage of −5 V. The illumination wavelength is 1050 nm and the maximum power is about 10 μW. The illumination power is instantaneously changed at 180 and 510 s. The PC intensity is temporally oscillating with a characteristic frequency (f_c) that depends on the illumination power. (b) Close-up of the region I, where the illumination power is maximum (100%). (c) Close-up of the region II, where the illumination power is reduced to 50%.

voltage of −2 V, sharp exciton peaks are clearly seen and their assignments by the deformation potential theory and the confinement energy calculations[5,6] are indicated in Fig. 1. Here, we use the notation ijH (ijL) for the heavy-hole (light-hole) exciton transition between ith electron and jth heavy-hole (light-hole) subbands. As the reverse bias voltage is increased, the parity-allowed transitions (11H, 11L, and 22H) are redshifted with reduced oscillator strengths and the parity-forbidden transitions (12H and 21H) are enhanced. These features are attributed to a well-known QCSE.[8] The distinct exciton peaks and QCSE are observed even at room temperature, verifying high sample qualities. More detailed discussion about the transition energies of strained $In_xGa_{1-x}As/Al_yGa_{1-y}As$ quantum wells is given in previous studies.[6,9] The important point to note here is that the PC spectra under the reverse bias voltages over −4V reveal oscillatory behaviors, which are superposed on the photoabsorption spectral line shape. The amplitude of the PC oscillation becomes large with the increase of the reverse bias voltage. We also note in Fig. 1 that the PC oscillatory behaviors persist in a transparent wavelength range above 900 nm, which corresponds to the 11H exciton resonance at −4 V. The PC oscillation is not related with wavelength but it changes with time, as supported by the measurements of the PC intensity as a function of time (described later). That is, the PC intensity is temporally self-oscillating. The PC self-oscillation is observed for the samples with higher In content (x=0.10 and 0.15) at low temperatures under the reverse bias conditions. On the other hand, no PC oscillation can be observed for the sample with the smallest In content (x=0.05). These results suggest that the PC oscillation is due to photogenerated carriers trapped in deep localized centers within the $In_xGa_{1-x}As$ QW layers.

In order to investigate details of the PC characteristics, temperature dependence of PC spectra was measured. Figure 2 shows PC spectra of the $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ MQW sample at 20, 40, 60, and 80 K under a fixed bias voltage of −5 V. With increasing temperature, the amplitude of the PC oscillation is gradually reduced and then disappears at 80 K. That is, localized natures of the PC self-oscillation are confirmed by measuring the temperature dependence of PC spectra.

Furthermore, the PC characteristics are investigated by measuring the PC intensity as a function of time under a fixed wavelength illumination. Figure 3(a) shows a time trace of the PC intensity for the $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ MQW sample measured at 13 K under the bias voltage of −5 V. The illumination wavelength is fixed at 1050 nm and the maximum power is about 10 μW. The illumination power is instantaneously changed at 180 and 510 s in Fig. 3(a). The PC intensity is reduced with the decrease of the illumination power by 50%. The PC intensity is temporally self-oscillating, with a characteristic frequency that depends on the illumination power. Figures 3(b) and 3(c) show close-ups of regions I and II, respectively, indicated by dotted frames in Fig. 3(a). In the region I, where the illumination power is 100%, the frequency of the PC oscillation is 0.10 Hz (time interval of T=10 s). In the region II, where the illumination power is 50%, the frequency is 0.06 Hz (T =16 s). The amplitude of the PC oscillation in the region I is larger than that in the region II. These findings verify that the PC self-oscillation is actually induced by photogenerated charge carriers and suggest that deep localized centers exist.

Based on the experimental observations, possible causes may be proposed for the PC self-oscillation in the following. The ultra-low-frequency PC self-oscillation is caused by slow tunneling, which leads to electric field oscillations due to photogenerated carriers trapped in deep localized centers within the high-In-content $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ QW layers. Previously, current oscillations have been reported in GaAs/AlAs superlattices at frequencies between 0.7 and 100 MHz, which are attributed to oscillating electric field domains.[10] The frequency of the superlattice oscillators arising from the resonant tunneling is basically determined by tunneling time, which is fastest in the case of Bloch oscillators.[11] The PC self-oscillation observed here, however, has very different frequencies 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 blinking luminescence phenomena in low-dimensional semiconductors.[1–4] In the case of the quantum-dot system, the luminescence signal switches between two or more discrete levels (i.e., random telegraph signal) because the electric field in each dot is affected by only a few charged carriers around the dot. On the other hand, in the QW system, the PC signal is possible to vary continuously because the electric field in each well is affected by a large number of charged carriers. Therefore, the PC response in the QW system can be periodic if creation and annihilation of the charged carriers can occur periodically.

In summary, we have observed a phenomenon of ultra-low-frequency PC self-oscillation in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{Al}_{0.15}\mathrm{Ga}_{0.85}\mathrm{As}$ MQW $p-i-n$ diodes. The PC self-oscillation with frequencies (less than 0.1 Hz) is observed under reverse bias voltages at low temperatures. It is found that the appearance requirements for the PC self-oscillation depend on applied bias voltage, temperature, illumination power, and In content of the QW layers. It is also found that the frequency of the PC oscillation strongly depends on the illumination power. These results indicate that the PC self-oscillation is caused by local electric field oscillations due to photogenerated carriers trapped in localized centers within the $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ QW regions.

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