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Interband and intersubband transitions of lateral $InAs/In_{0.15}Ga_{0.85}As$ dots-in-a-well quantum dot infrared photodetectors were studied in order to determine the origin of the photocurrent. The main intersubband transition contributing to the photocurrent (PC) was associated with the quantum dot ground state to the quantum well excited state transition. By a comparison between intersubband PC measurements and the energy level scheme of the structure, as deduced from Fourier transform photoluminescence (FTPL) and FTPL excitation spectroscopies, the main transition contributing to the PC was identified. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2207493]

Infrared photodetectors have been in focus for researchers for many years due to their applications in areas such as military night vision, surveillance, and medical diagnosis. The state-of-the-art detectors used today are quantum well infrared photodetectors (QWIPs),[1] indium antimonide (InSb) detectors,[2] and mercury-cadmium-telluride (HgCdTe) detectors.[2] In recent years a new kind of detector has been suggested for detection of infrared radiation, namely, a quantum dot infrared photodetector (QDIP). The QDIP utilizes intersubband transitions between different energy states of the electron in the quantum dot (QD), similar to a QWIP, to detect radiation in the infrared wavelength region. The major advantages of QDIPs, compared to QWIPs, are the possibility to detect light at normal incidence, which simplifies the fabrication of the detector, and that the dark current is reduced,[3] which makes it possible to operate the detector at temperatures higher than a QWIP.

Most work on GaAs-based QDIPs has been performed on InAs/GaAs QDs with detection wavelengths in the mid-wavelength infrared (MWIR, 3–5 μm) region,[4–6] while only a few groups have focused on the long-wavelength infrared (LWIR, 8–12 μm) region. One technique to reach the LWIR region is by using InGaAs/GaAs QDs,[7,8] whereas a more recent and advanced technique to achieve this is by embedding the InAs QD in an $In_xGa_{1-x}As$ quantum well, i.e., dots-in-a-well (DWELL), where the detected wavelength corresponds to a transition between a QD state and a quantum well (QW) state. This method can accordingly offer additional tuning possibilities: partly by varying the QD energy levels and partly by adjusting the width and composition of the QW.[9–12] For InAs/GaAs QDs, extensive experimental and theoretical studies have been made to map the electronic structure and their possible intersubband transitions.[13–15] Despite these prevailing studies, the identifications of the intersubband transitions responsible for the absorption and the photocurrent (PC) diverge in the literature. For InAs/InGaAs DWELL structures the identifications of the intersubband transitions are even less certain, although attempts have been made by some groups.[16] This knowledge is of great importance when designing the detector structure, since the intersubband transition with the desired wavelength should also have high oscillator strength and an effective electron transport to the contacts.

In this letter, the intersubband transitions responsible for the PC in a lateral InAs/InGaAs DWELL QDIP are identified. This identification of the responsible transition is derived by means of a comparison between intersubband and interband transitions in the structure. Optical measurements of interband transitions reveal the energy levels of the DWELL structures and from a comparison with this energy level scheme, the transitions contributing to the PC can be identified.

The QD structure used for interband and intersubband PC measurements was a ten-layer stack, where each period consisted of a Si doped InAs QD layer capped with a 30 Å $In_{0.15}Ga_{0.85}As$ QW and a 300 Å GaAs barrier. The structures were grown by metal-organic vapor phase epitaxy in a vertical Veeco reactor operating at 100 mbars, using triethylgallium, trimethylindium, and arsine as source materials. First a GaAs buffer layer of 3000 Å was grown at 710 °C. The temperature was lowered to 485 °C before the QD growth. The V/III-ratio (13), nominal thickness [1.8 ML (monolayer)] and growth rate (1.4 Å/s) of the InAs were optimized for a high QD density and the Si doping was calibrated to give a sheet concentration of 5×10^{10} cm^{-2}. After QD deposition a growth interruption of 30 s was applied, when all precursors were switched off. The InGaAs cap layer was grown at 485 °C with a growth rate of 1.8 Å/s. After that the temperature was increased slowly to 600 °C, simultaneously as the GaAs cap layer was grown at a growth rate of 1.5 Å/s. From atomic force micrographs, the QD density and the average QD width and height have been estimated to 2.5×10^{10} cm^{-2}, 230 Å, and 48 Å, respectively. The lateral

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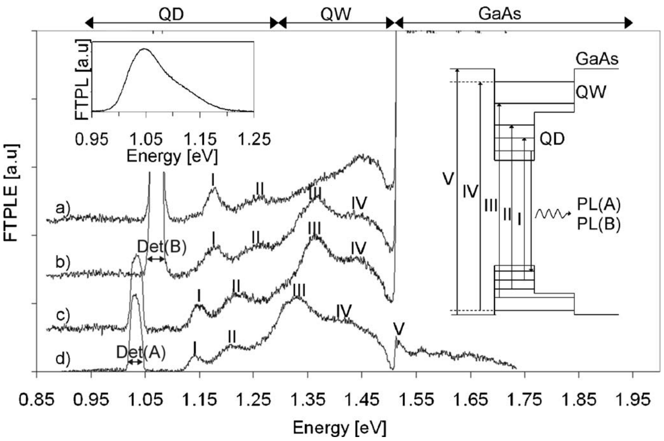

FIG. 1. FTPLE spectra (measured at 10 K) of single QD-layer structures with different indium contents in the surrounding QW and two different detection intervals (1.015–1.05 eV [Det(A)] and 1.05–1.085 eV [Det(B)]: (a) 0% indium, Det(B); (b) 15% indium, Det(B); (c) 15% indium, Det(A); (d) 20% indium, Det(A). FTPL spectrum of the QD structure in (b) and (c) is shown in the left inset. The origins of the interband transition peaks are shown in the right inset.

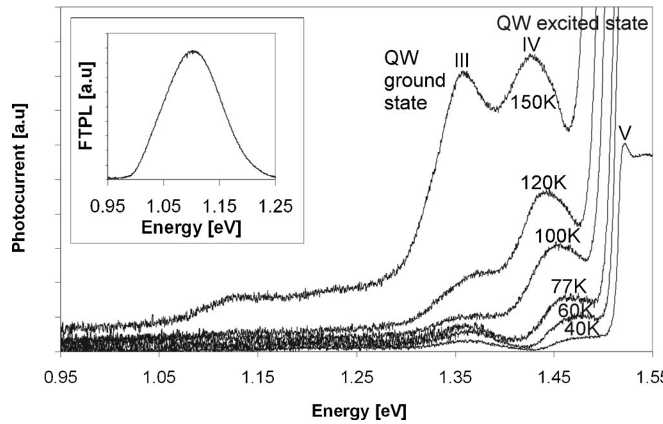

FIG. 2. Interband PC spectra of the lateral ten-layer QDIP structure at an applied voltage of 1 V. Peaks III and IV correspond to the QW ground state and excited state transitions, respectively, as illustrated in the right inset of Fig. 1. Peak V is the PC associated with the GaAs band edge transition. The inset shows the FTPL spectrum of this structure.

QDIP was fabricated by standard optical lithography and metallization techniques. Ohmic contacts (AuGe/Ni/Au) were formed on the surface of the structure, with a spatial separation of 40 μm, and were alloyed down through the structure, in order to employ the QWs as transport layers.

The QD structures examined by Fourier transform photoluminescence (FTPL) and FTPL excitation (FTPLE) spectroscopies,[17] in order to identify the origin of the interband transitions, were single QD-layer structures with different indium contents in the QW; 0%, 15%, and 20%, respectively.

FTPL and FTPLE measurements were carried out at a temperature of 10 K using a Bomem DA8 Fourier transform interferometer, a liquid nitrogen cooled Ge detector, a quartz beam splitter, and a continuous helium flow cryostat. During the FTPLE measurements, a quartz-halogen tungsten lamp was used as excitation source and the detection window was selected with a Spex monochromator. For the FTPL measurements, an argon ion laser ($\lambda = 514.5$ nm) was used as excitation source. The interband and intersubband PC measurements were performed in a Bomem DA8 Fourier transform interferometer, in combination with a Keithley 427 current amplifier. A quartz-halogen tungsten lamp and a quartz beam splitter were used when measuring interband PC, while a global light source and KBr beam splitter were used for intersubband PC. The sample was excited by unpolarized light of normal incidence at a sample temperature of 77 K.

Interband transition measurements were used to determine the energy levels of the DWELL structure. The ground state transition energies of the QD ensemble were determined by FTPL measurements (left inset, Fig. 1), where the width of the FTPL spectrum reveals a broad size distribution of the quantum dots. From this dot ensemble, QDs with their ground state transition energy within certain energy intervals [Det(A) and Det(B)] were selected, in order to study energy states above the QD ground states [Figs. 1(a)–1(d)] by FTPLE measurements. By comparing FTPLE spectra from different detection intervals in one sample [$InAs/In_{0.15}Ga_{0.85}As$, Figs. 1(b) and 1(c)], it can be seen that peaks I and II shift with the detection energy, but for another sample [InAs/GaAs, Fig. 1(a)] remain in the same position when the same detection interval is used [compare Figs. 1(a) and 1(b)]. Due to this dependence on the detection interval, peaks I and II are assigned to QD excited states. Peak III, on the other hand, is not influenced by a change of the detection interval for the same sample [Figs. 1(b) and 1(c)], but is shifted from 1.365 to 1.33 eV, when the indium content in the QW is decreased from 20% [Fig. 1(d)] to 15% [Fig. 1(c)] and disappears in the uppermost spectrum [Fig. 1(a)] in which the QW has been omitted. Based on these observations, peak III is assigned to the ground state transition in the QW. Additional structure in the FTPLE spectra above peak III (marked IV in Fig. 1) is interpreted as excited state related transitions in the QW, overlapping with wetting layer transitions close to the GaAs band edge.

The electronic transport properties play a major role for the PC spectrum, since the electrons in the final state of the intersubband transition have to be transported to the contacts in order to be monitored as a PC. The transport properties were first investigated by interband PC measurements at different temperatures (Fig. 2). At 150 K, interband transitions corresponding to the QW ground state as well as the QW excited states (peaks III and IV in Fig. 2 and in the inset of Fig. 1) give high intensity PC peaks. As the temperature was successively decreased from 150 to 40 K, the relative intensity of the peak corresponding to the QW ground state transitions decreased. This behavior demonstrates that thermal energy is needed in order to excite electrons from the final state in the QW to the GaAs band edge. Accordingly, the main electron transport takes place in the GaAs matrix and not in the QW itself. The poor conduction in the QW compared to the GaAs matrix is probably due to a high recapture rate into the QDs at low temperatures. Consequently, the PC will be dominated by transitions to the QW excited state for measurements performed at temperatures below 150 K.

The identification of the intersubband transitions responsible for the PC in the DWELL QDIPs is based on a comparison between, on the one hand, the different interband transition measurements made (PC, FTPL, and FTPLE in Figs. 1 and 2) and, on the other hand, the intersubband PC spectrum in Fig. 3. From the assignment of the peaks in the FTPLE spectra (right inset in Fig. 1), it can be concluded that there are five different energy states available for intersubband transitions (inset in Fig. 3). The total subband energy

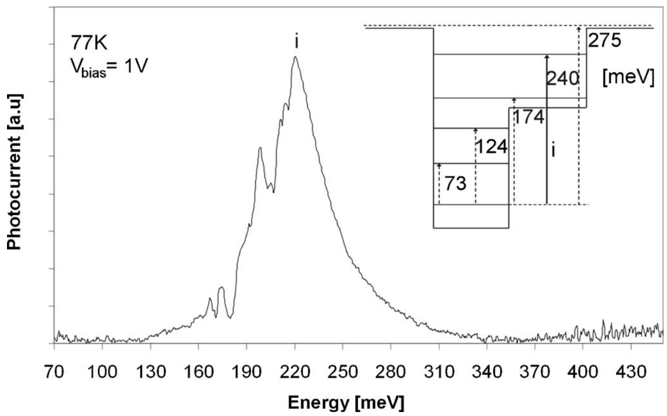

FIG. 3. Intersubband PC spectrum for the lateral ten-layer QDIP structure, measured at 77 K and an applied bias of 1 V. The possible transitions from the QD ground state, with the expected transition energies derived from the interband measurements, are illustrated in the inset. The transition from the QD ground state to the QD excited state (marked i) corresponds to the dominating peak in the PC spectrum. The other possible transitions (marked with dotted lines) are less pronounced in the PC spectrum.

separation (for the electron *and* the hole) between the QD ground state and the available final states can be derived from the separation between the peak of the QD ground state emission (FTPL in Figs. 1 and 2) and the peaks of the interband absorption (peaks I and II in Fig. 1; peaks III and IV in Fig. 2). In order to obtain the corresponding energy separation for the electron solely, the total energy separation is multiplied by the relation between conduction band energy separation and the total energy separation ($\sim$67%).[18] The evaluated energy separations are presented in the inset of Fig. 3. The best correspondence to the PC spectrum is found for the transition from the QD ground state to the QW excited state. The discrepancy between the evaluated transition energy (240 meV) and the PC peak (220 meV) can be due to the widths of the optical bands (i.e., the inhomogeneous size distribution of the QDs) observed and the uncertainty in the factor used to extract the conduction band energy separation. The expected transition energy from the QD ground state to the ground state of the QW (174 meV) is significantly lower (by about 45 meV) than the peak of the PC, but still above the onset of the PC spectrum. Consequently, this transition could also give a contribution to the PC, but with considerably lower amplitude than the contribution from the excited state. The explanation for this can be found in comparison with the interband PC measurements, which showed that the probability for contribution to the PC signal for electrons situated in the excited states of the QW is significantly higher than for the electrons excited to the QW ground state at low temperatures. At higher temperatures the contribution to the PC from the QD ground state to the QW ground state should increase and cause a redshift of the PC peak. Transitions between the QD ground state and the GaAs barrier are evaluated to occur at energies >275 meV. However, at these energies the measured PC signal is low, which could be due to lower transition probability to the GaAs matrix, compared to the QW excited state.

In conclusion, a comparison of interband and intersubband transitions has been used to identify the principal intersubband transition responsible for the photocurrent in a lateral DWELL QDIP. The main contribution to the PC was found to be the transition from the QD ground state to an excited state of the QW. This knowledge enhances the possibility to tune the detection wavelength, either by varying the size and composition of the QD or by adjusting the width and composition of the quantum well.

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