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Selective optical doping to predict the performance and reveal the origin of photocurrent peaks in quantum dots-in-a-well infrared photodetectors

L. Höglund [a,*], P.O. Holtz [b], H. Pettersson [c,d], C. Asplund [e], Q. Wang [a], S. Almqvist [a], H. Malm [e], E. Petrini [a], J.Y. Andersson [a]

[a] Acreo AB, Electrum 236, S-16440 Kista, Sweden
[b] Department of Physics, Chemistry and Biology (IFM), Linköping University, S-58183 Linköping, Sweden
[c] Center for Applied Mathematics and Physics, Halmstad University, Box 823, S-30118 Halmstad, Sweden
[d] Solid State Physics and the Nanometer Structure Consortium, Lund University, Box 118, S-22100 Lund, Sweden
[e] IRnova, Electrum 236, S-16440 Kista, Sweden

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ABSTRACT

Resonant optical pumping across the band gap was used as artificial doping in $InAs/In_{0.15}Ga_{0.85}As/GaAs$ quantum dots-in-a-well infrared photodetectors. Through efficient filling of the quantum dot energy levels by simultaneous optical pumping into the ground states and the excited states of the quantum dots, the response was increased by a factor of 10. Low temperature photocurrent peaks observed at 120 and 148 meV were identified as intersubband transitions emanating from the quantum dot ground state and the quantum dot excited state, respectively by a selective increase of the electron population in the different quantum dot energy levels.

There is a growing market for cameras that detect infrared radiation, with applications in night vision, space, surveillance, search and rescue and medical diagnosis. Stringent requirements for the cameras, such as lower cost and higher operating temperature, create a demand for detectors that use more advanced materials. In recent years, quantum dots-in-a-well infrared photodetectors (DWELL IPs) have been suggested as a promising alternative to existing detector technologies [1,2]. The incorporation of quantum dots (QDs) in the detector is expected to enhance the detector performance due to the three dimensional (3D) confinement of charge carriers in the QDs [3]. The 3D confinement will give rise to a discrete energy level spectrum, which will limit the number of allowed dark current transitions and consequently the operation temperature could be increased. Furthermore, the 3D confinement will enable an increased sensitivity to light of all angles of incidence [3]. The detection mechanism in DWELL IPs is based on intersubband transitions between bound states in QDs and energy bands in a surrounding quantum well (QW). The photocurrent is generated by a subsequent tunneling of electrons from the QW into the matrix. This design offers an increased possibility to tailor the detection wavelength, partly by varying the size and composition of the QDs and partly by changing the width and composition of the surrounding QW layer [4,5].

Due to the complexity of the energy level structure which arises when including both QDs and QWs, there are several possible intersubband transitions which could give rise to a photocurrent. For example, dual colour detection has been enabled by utilizing two different intersubband transitions from the QD to the QW and to the continuum, respectively [6]. Even response in the far infrared region (>20 μm) has been reported by several groups, emanating from transitions between different bound QD states [7,8]. However, a detailed understanding of all relevant transitions occurring in the detector is not yet gained. This knowledge is essential in order to design and optimise a high performance infrared detector.

In this study, solid information about the intersubband transitions generating a photocurrent in an $InAs/In_{0.15}Ga_{0.85}As/GaAs$

* Corresponding author. Tel.: +46 8 632 78 43; fax: +46 8 750 54 30.
E-mail address: Linda.Hoglund@acreo.se (L. Höglund).

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DWELL IP was achieved by selective variation of the electron population in the different energy states in the QDs. The electron population was varied by pure optical means using interband optical pumping resonant with the QD ground state and the QD excited state, respectively. These interband transition energies were identified from photoluminescence (PL) and PL excitation (PLE) measurements. Furthermore, optical pumping with dual sources revealed that the additional photocurrent peak, appearing only at temperatures below 70 K, was due to an intersubband transition from a QD excited state to a QW excited state. In addition, the optical pump technique was used to evaluate the performance of the detector. The response of the detector could be increased by a factor of 10, when using resonant pumping with a laser power of 140 mW.

The DWELL IP structure employed in this study consisted of an active QD region sandwiched between an upper and a lower n-doped ($\sim 1 \times 10^{17}$ cm^{-3}) contact layer, with thicknesses of 300 and 500 nm, respectively. The active region in the DWELL IP structure was a 10-layer stack, where each period consisted of a 2 nm $In_{0.15}Ga_{0.85}As$ QW, an undoped InAs QD layer, a 6 nm $In_{0.15}Ga_{0.85}As$ QW and a 33 nm thick GaAs barrier layer. Details about the growth conditions were described in earlier publications [9,10]. From atomic force micrographs, the QD density and the average QD base diameter and height were estimated to 9.3×10^{10} cm^{-2}, 16 nm and 3.5 nm, respectively. The vertical DWELL IP structure was fabricated by standard optical lithography, etching and metallization techniques. A square 170×170 μm^2 single pixel component with alloyed AuGe/Ni/Au ohmic contacts was used for the photocurrent measurements.

PL and PLE were performed at 2 K, using an Ar^+ laser pumped tunable Ti:Sapphire (Ti:Sp) laser as excitation source. The PL signals were analysed with a double-grating monochromator, together with a liquid nitrogen cooled Ge detector, using standard lock-in technique. The intersubband photocurrent measurements were performed with a Bomem DA8 Fourier Transform spectrometer equipped with a globar light source and a KBr beamsplitter, in combination with a Keithley 427 current amplifier. The sample was excited by unpolarized light at an angle of incidence of 45 degrees. In the photocurrent measurements, a positive bias was applied to the bottom contact of the DWELL IP. Two different laser sources were used to increase the electron population in the QDs during the photocurrent measurements: one laser diode pumped solid state laser with an emission wavelength at 1064 nm (1165 meV) and the Ti:Sp laser with emission at 980 nm (1265 meV).

When studying the temperature dependence of the intersubband photocurrent, two photocurrent peaks situated at 120 and 148 meV, respectively, were observed (peaks *i* and *ii*, Fig. 1). The intensity of the 148 meV peak is almost temperature independent up to 60 K, after which it increases significantly with increasing temperature. In a recent study, we investigated the bias and temperature dependence of this peak and clarified that the main escape mechanism corresponds to thermally assisted tunneling through the bias dependent triangular barrier between the QW and the matrix [11]. The temperature dependence of the 120 meV peak shows an opposite trend. The magnitude decreases with increasing temperature and is indistinguishable from the background at temperatures $\geqslant$70 K. In order to unravel the origin of this peak, resonant optical pumping experiments were performed.

The interband transition energies of interest for the optical pumping experiments were revealed utilizing PL and PLE measurements (Fig. 2). From the PL peak, an average ground state transition energy of 1170 meV was deduced. In order to unravel higher energy levels in the structure, five energy intervals within the PL spectrum, corresponding to different QD ensembles, were selected for PLE measurements (inset of Fig. 2). When changing the detection energy, one peak is shifting (peak I, Fig. 2) while the other peaks (peak II–IV, Fig. 2) remain at the same position. Due to this dependence on the detection energy, peak I is assigned to QD excited state interband transitions, while the peaks II and III are related to interband transitions associated with the QW. The energy difference between the ground state and excited state interband transitions in the QD, deduced from the PLE measurements, is approximately 60 meV. Consequently, the mean value of the interband transitions associated with the QD excited state is 1230 meV and the PLE spectra show a distribution of transitions associated with the dot excited state with an extension up to approximately 1290 meV.

The origin of the two intersubband photocurrent peaks was revealed by studying the dependence of the photocurrent on the electron population in the different energy states. Instead of fabricating many samples with different doping concentrations, we employed resonant interband excitation to tune the population in a specific QD energy state. During excitation resonant with the QD

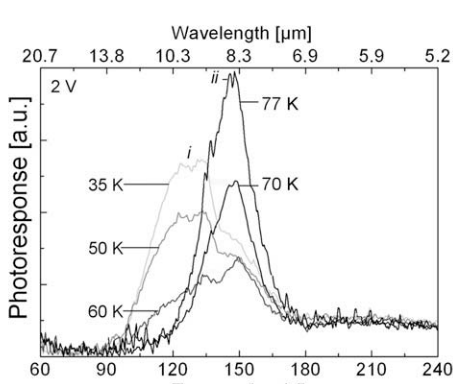

Fig. 1. Temperature dependence of the photoresponse of a DWELL IP at an applied bias of 2 V. Two peaks with different temperature dependence are observed at 120 and 148 meV (peak *i* and peak *ii*), respectively.

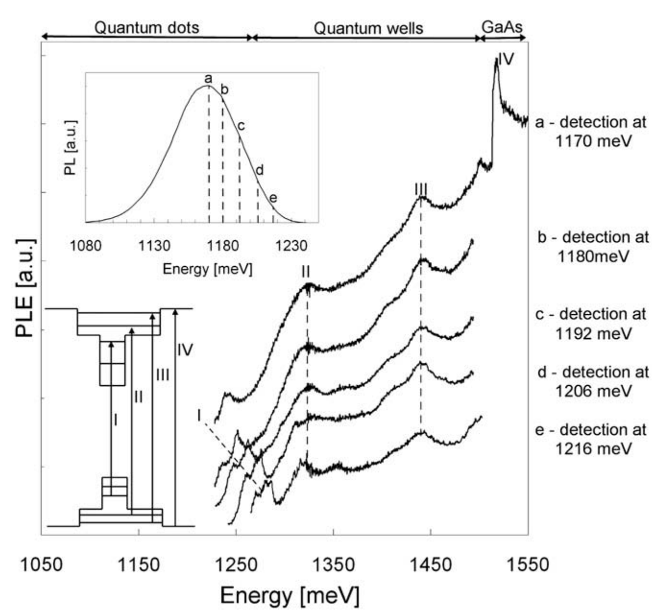

Fig. 2. Photoluminescence excitation spectra at 2 K for five different detection intervals (a–e). The detection intervals are indicated with dashed lines and labels in the PL spectrum in the upper inset. In the lower inset, the interband transitions corresponding to peak I–IV are indicated.