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Optical pumping as artificial doping in quantum dots-in-a-well infrared photodetectors

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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. A selective increase in the electron population in the different quantum dot energy levels enabled the low temperature photocurrent peaks observed at 120 and 148 meV to be identified as intersubband transitions emanating from the quantum dot ground state and the quantum dot excited state, respectively. The response was increased by a factor of 10 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. © 2009 American Institute of Physics. [DOI: [10.1063/1.3073048](https://doi.org/10.1063/1.3073048)]

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}

The complexity of the energy level structure, which arises when both QDs and QWs are included in the design, causes several intersubband transitions to be possible, each of which can give rise to a photocurrent. Dual color detection, for example, has been enabled by utilizing two different intersubband transitions from the QD to the QW and to the continuum, respectively.⁶ Several groups have even reported response in the far infrared region ($>20 \mu\text{m}$) emanating from transitions between different bound QD states.^{7,8} However, a detailed understanding of all relevant transitions oc-

curing in the detector has not yet been achieved. This knowledge is essential in order to design and optimize a high performance infrared detector.

More detailed information on the generation of photocurrents by intersubband transitions in an InAs/In_{0.15}Ga_{0.85}As/GaAs DWELL IP has been obtained in this study. This was achieved by selective variation in the electron population in the different energy states of the QDs. The electron population was varied by purely optical means using interband optical pumping⁹ 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, which appeared only at temperatures below 70 K, was due to an intersubband transition from a QD excited state to a QW excited state. The optical pump technique was also used to evaluate the performance of the detector. It was shown that 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 ($\sim 1 \times 10^{17} \text{ cm}^{-3}$) contact layer with thicknesses of 300 and 500 nm, respectively. The active region in the DWELL IP structure was a ten-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.^{10,11} The QD density and the average QD base diameter and height were estimated from atomic force micrographs to be $9.3 \times 10^{10} \text{ cm}^{-2}$ and 16 and 3.5 nm, respectively. The vertical DWELL IP structure was fabricated by standard optical lithography, etching, and metallization techniques. A square $170 \times 170 \mu\text{m}^2$ single pixel component with alloyed AuGe/Ni/Au Ohmic contacts was used for the photocurrent measurements.

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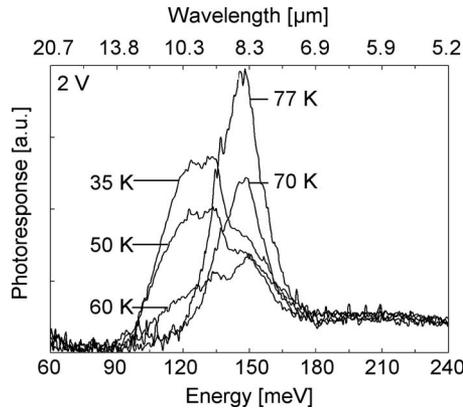


FIG. 1. Temperature dependence of the photoresponse of a DWELL IP at an applied bias of 2 V. Two peaks with different temperature dependences are observed at 120 and 148 meV, respectively.

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 analyzed 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 global 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°. The photocurrent measurements were carried out after applying a positive bias 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).

Two photocurrent peaks, situated at 120 and 148 meV, respectively, were observed while studying the temperature dependence of the intersubband photocurrent (Fig. 1). The intensity of the 148 meV peak is almost independent of temperature up to 60 K, after which it increases significantly with increasing temperature. We investigated the bias and temperature dependence of this peak in a recent study and clarified that the main escape mechanism corresponds to thermally assisted tunneling through the bias dependent triangular barrier between the QW and the matrix.¹² 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 ≥ 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). An average value of 1170 meV was deduced for the ground state transition energy from the PL peak. 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 in Fig. 2). A change in the detection energy causes one peak to shift (peak I, Fig. 2), while the other peaks (peaks II–IV, Fig. 2) remain at the same position. This dependence on the detection energy causes peak I to be assigned to QD excited state interband transitions, while peaks II and III are related to interband transi-

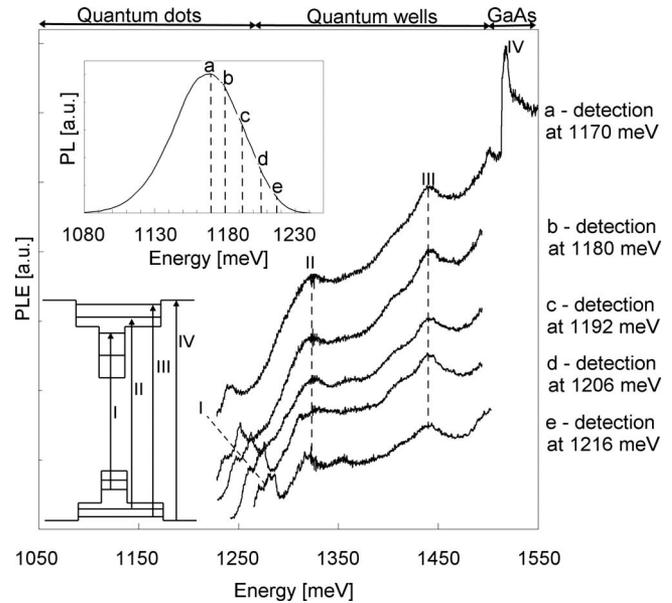


FIG. 2. PLE spectra at 2 K for five different detection intervals [(a)–(e)]. The detection intervals are indicated with dashed lines and labels in the PL spectrum in the upper inset. In the lower inset, the interband transitions corresponding to peaks I–IV are indicated.

tions 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. As an alternative to fabricating many samples with different doping concentrations,¹³ we employed resonant interband excitation to tune the population in a specific QD energy state. A major increase in the height of the 148 meV peak was observed during excitation resonant with the QD ground state (at 1165 meV), accompanied by a minor increase in the 120 meV peak height [Fig. 3(a)]. The intensity of the 120 meV peak saturates at a pumping power of 30 mW, while the magnitude of the 148 meV peak increases continuously with increasing excitation power (up to 13 W/cm²). There is a simultaneous increase in the 148 meV and the 120 meV peaks while pumping resonantly with the QD excited state (at 1265 meV), [Fig. 3(b)]. The magnitude of the 120 meV peak in this case is larger than that obtained when the QD ground state was selectively excited. This is consistent with the QD excited state occupancy having a major influence on the 120 meV peak. The different behaviors of the photocurrent peaks when increasing the electron population in the QD ground state and the QD excited state, respectively, lead to the 148 meV peak being attributed to an intersubband transition emanating from the QD ground state, while the 120 meV peak is interpreted as a transition from the QD excited state. Relaxation and thermal excitation of carriers occur between the QD states during optical pumping, which can explain the simultaneous increase in the two photocurrent peaks. The gradual increase in the 120 meV peak with de-

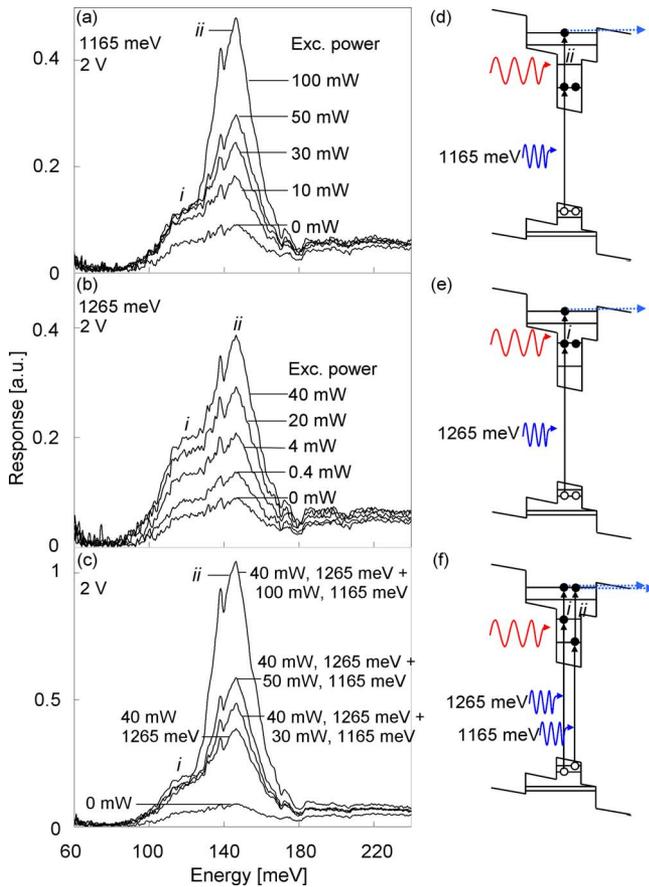


FIG. 3. (Color online) Photoresponse of a DWELL infrared detector with varying electron population in the QDs. Optical pumping is performed resonantly with (a) the QD ground state interband transition using a 1165 meV laser (1064 nm) and (b) the QD excited state interband transition using a 1265 meV laser (980 nm). The main interband and intersubband transitions influenced by the photoexcitation in (a) and (b) are indicated in (d) and (e), respectively. In (c) the two different laser sources are used simultaneously as indicated in (f), resulting in an increase in the response by a factor of 10. The arbitrary units of the response are the same for the three graphs in (a)–(c).

creasing temperature (Fig. 1) is somewhat unexpected since the electron population in the QDs is fairly low and most of the electrons should occupy the QD ground states at low temperatures. However, application of a high electric field may further reduce the occupation probability of the QD excited state at higher temperatures since the probability of electron thermal excitation to the QW energy bands increases. Electrons that are thermally excited to the QW could in a subsequent step be removed from the proximity of the QD by the electric field and escape from the QW via tunneling or thermal excitation.

The optical pumping technique was also used for artificial doping of the structure in order to predict the possible performance of the detector for varying carrier population. It was observed from single source optical pumping experiments [Figs. 3(a) and 3(b)] that the intensity of the 148 meV peak could be increased by a factor of 4 or 5 when pumping with 40 mW to the excited state (followed by relaxation to the ground state) or with 100 mW to the ground state, re-

spectively. Dual source optical pumping was employed in order to increase the total number of electrons supplied to the QD ground state. Simultaneous pumping of electrons to the QD ground state and to the QD excited state will provide a more efficient filling of the ground states since the number of QD interband transitions (corresponding to QDs with various sizes), which will be resonant with the pumping energy of the lasers, will increase. The additional number of electrons supplied to the QD ground state, when using pumping powers of 40 and 100 mW to the excited state and the ground state, respectively, enabled an enhancement in the response by a factor 10 [Fig. 3(c)]. We reported a peak responsivity of 15 mA/W (Ref. 12) in a previous paper, so this value could in principle be increased to 150 mA/W (Ref. 14) if sufficient doping is supplied.

In conclusion, optical pumping has been used as artificial doping in DWELL IPs instead of conventional doping in order to predict the achievable response of the detector. The response was increased by up to a factor of 10 when using optical pumping. The origins of the two dominant photocurrent peaks, at 120 and 148 meV, in a DWELL IP have been identified as transitions originating from the QD ground state and the QD excited state, respectively, by means of resonant optical pumping into these states.

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