Intraband Auger effect in InAs/InGaAlAs/InP quantum dot structures

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InAs quantum dot structures grown on InGaAlAs have been investigated for midinfrared photodetection. Intraband photocurrent and absorption measurements, together with a full three-dimensional theoretical modeling revealed that a bound-to-bound optical transition, where the final state is about 200 meV deep below the conduction band continuum, is responsible for the photogenerated current. The reported results strongly suggest that an Auger process plays a fundamental role in generating the observed intraband photocurrent. Photoluminescence and interband photocurrent spectra of the same structures further support the reached conclusions.
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Semiconductor quantum dot (QD) structures have raised much interest in the past years for midinfrared photodetection due to their potential for efficiently coupling normal incident light and for operating at higher temperatures as compared to quantum well structures.[1–7] In most cases, the QD structures for intraband optical transitions in the 4–20 μm range are designed in such a way that the photon absorption occurs between a QD bound state and the energy continuum or to an energy level close to the continuum, leading to efficient free carrier generation and collection at the contact layers. Structures based on bound-to-bound transitions, even though they produce more selective detectors, require a carrier transport mechanism to generate a photocurrent (PC). In many cases, the design relies on tunneling of carriers through thin barriers.[2] Another possibility is the excitation of the carriers from the final bound energy state to the continuum, where they can easily participate in the PC. Such excitation may take place either via thermal excitation[1,3–5] or via an Auger effect. The importance of intraband versus interband Auger processes in semiconductor QD structures has already been claimed in the 1990s in a detailed theoretical study.[8] More recently, interband PC spectra of InAs QDs embedded in an InP matrix were explained by the involvement of Auger processes[9] and Auger scattering in InGaAs QDs was theoretically investigated.[10] In this communication, we present results that demonstrate that Auger processes can indeed play a fundamental role in generating an intraband PC, broadening the possibilities for designing QD structures for highly selective midinfrared photodetectors.

In order to observe the Auger effect in intraband transitions in QDs, samples were designed in such a way that the final energy state of the strongest intraband absorption is relatively deep in the QD conduction band structure and several bound states are available at energies above this final energy state. This can be achieved by growing relatively large QDs. The reason for this choice will become clearer further below. Additionally, the barriers should be thick enough to prevent tunneling of the photoexcited carriers.

The samples were grown by metalorganic vapor phase epitaxy at 100 mbar. Growth starts with a 150 nm thick InP buffer layer deposition at 630 °C on a semi-insulating InP substrate followed by a 500 nm thick *n*-doped InGaAs layer lattice matched to InP. Then, a 109 nm thick layer of the quaternary material InGaAlAs is grown with 16% Al content and lattice matched to the substrate. The InAs QDs are then deposited for 5.5 s at 520 °C. The dots are annealed in an arsine atmosphere for 12 s. They are covered by a 16 nm thick InP layer while the temperature is ramped up to 600 °C. These three latter layers are repeated ten times. A last 109 nm thick layer of the quaternary material is then grown and finally a 250 nm *n*-doped InGaAs contact layer is deposited. The doping level at the contact layers is 1.0×10^{18} cm^{-3}. All ternary and quaternary layers are grown at 600 °C. The composition of the quaternary material was chosen so as to maximize the dot density.[11] Three samples were grown with this same structure but different doping levels: a nominally undoped sample and two others with estimated carrier concentrations of two and four electrons per dot. A QD density and height of 1.5×10^{10} cm^2 and 9 nm, respectively, were determined by atomic force microscopy measurements on control samples with uncapped QDs. Transmission electron microscopy (TEM) images showed lens shaped QDs with a base diameter of approximately 60 nm and confirmed the QD height average of 9 nm.

Fourier transform infrared spectroscopy (FTIR) was used for PC and absorption measurements. Conventional photoluminescence (PL), with the 514 nm Ar-ion laser line for excitation and an InGaAs *pin* diode for detection, was used as a complementary characterization technique.

Figure 1 shows the PC spectra at 5 K for the investigated samples measured with the FTIR with normal incident light and no external bias. An intrinsic electric field is revealed by PC measurements as a function of bias, which allows the detection of a PC. A narrow peak is observed around 190 meV for the undoped sample. Although the sample is nominally undoped, intraband absorption can occur due to

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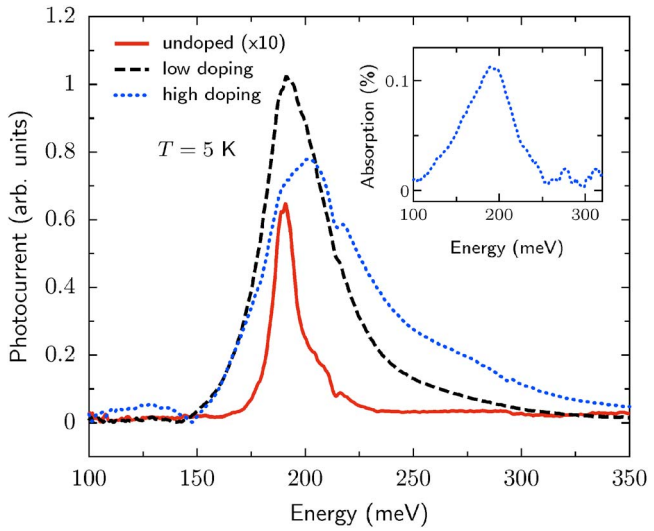

FIG. 1. (Color online) PC spectra for the three samples at 5 K without bias. Low doping and high doping mean around two and four electrons per dot, respectively. In the inset is the absorption spectrum for a sample with 20 QD layers equivalent to the one with the highest doping level.

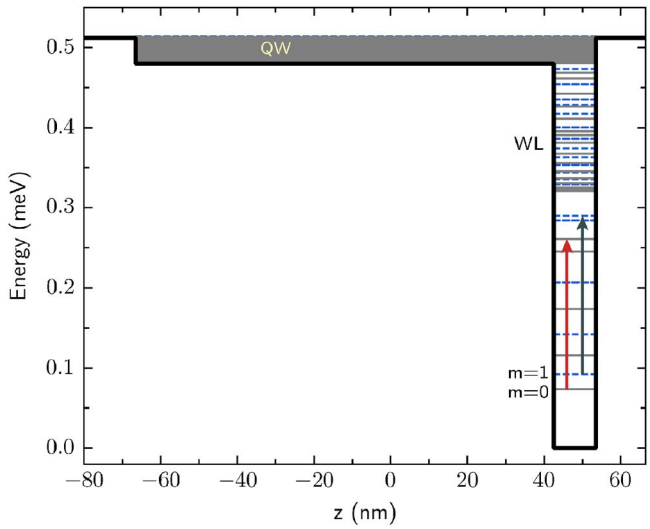

FIG. 2. (Color online) Calculated energy levels for the investigated samples for quantum numbers $m=0$ (solid lines) and $m=1$ (dashed lines) superimposed in the sample conduction band structure profile. The arrows show the optical transitions for which the oscillator strength is largest. The energy levels associated with the wetting layer (WL) and the InGaAs quantum well (QW) are also shown.

the presence of residual doping and carriers which are transferred from the contact layers to the QDs. For the samples with higher doping levels, the PC peak is more than ten times stronger and more than three times broader. In order to fully understand the PC spectra, it is fundamental to know if absorption occurs solely or, at least, mainly at the same energy range. To verify that, absorption measurements in waveguide geometry were performed in equivalent samples with 20 periods and without contact layers. A broad absorption band centered at 185–195 meV was observed for all samples, indicating that the optical transition responsible for the photogenerated current corresponds, indeed, to the energy at which the PC has a peak. The absorption spectrum for the highest doped sample is depicted in the inset of Fig. 1.

In trying to identify the optical transition involved in the PC and absorption spectra, theoretical calculations were performed using a three-dimensional effective mass approximation model and assuming a cylindrical symmetry,[12] given that our dots are lens-shaped. The relevant physical parameters were taken from Ref. 13. More details about the theoretical model can be found in Ref. 12. Figure 2 shows the results of the theoretical calculations for the angular momentum quantum numbers 0 and 1, superimposed on the QD structure potential profile. The oscillator strength for the different transitions was also calculated. The strongest absorption for normal incident radiation is expected to occur for the transition between the first and the fifth states at energies of 187 and 197 meV, depending on whether the angular momentum quantum number is 0 or 1, respectively, in full agreement with the PC and absorption spectra obtained. One notices in Fig. 2 that the final states of such transitions are about 200 meV from the continuum, meaning that they do not promptly produce free carriers to contribute to the detected current. This point will be addressed shortly. First the dependence of the PC spectra with doping will be discussed.

Based on the theoretical calculations, the broadening of the PC spectra with doping can be explained. For the undoped sample, carriers from the contact layers and from the residual doping will populate first the ground state of the larger dots and will participate in the observed absorption. As only a few dots with smaller size dispersion are populated, the detected PC is weak and narrow. Increasing the doping level will broaden the PC peak, as experimentally observed, due to two effects. First, there will be an increase in the size dispersion of the dots participating in the absorption. Second, even though on the average we expect two electrons per dot, there will be some dots which will have excited levels populated, allowing absorption to occur also between excited energy levels. As mentioned before, the transition between the first and fifth energy levels for $m=1$, predicted to occur at 197 meV, has very large oscillator strength and would be convoluted with the transition at 187 meV departing from the fundamental state, consequently leading to a broadening of the PC peak. Note that both effects mentioned lead to a broadening mainly towards higher energies, as experimentally observed (see Fig. 1).

The question that remains is how a current can be produced even at 5 K since the electrons, after absorption, are transferred to energy levels which are quite deep (~200 meV) in the conduction band and tunneling has a very low probability of taking place due to the thick barriers. Further support for the fact that PC is produced as a consequence of absorption to a final deep bound state is found by comparing the spectra of interband PC and PL. Figure 3 shows the PL spectrum at 80 K for the nominally undoped sample. One observes a luminescence band around 700 meV which is due to recombination between the electron and hole ground states of the QDs. The onset of interband PC is observed at essentially the same energy, as shown in Fig. 3, implying that somehow electrons excited from the valence band to the electron ground state of the QD generate a current. As mentioned before, Landin *et al.*[9] have explained such effect by the mediation of an interband Auger effect, where the photoexcited electron receives additional energy from the recombination of another electron with the photogenerated hole. Such a process is depicted in the inset on the right side of Fig. 3. In the same figure, the PC spectra mea-

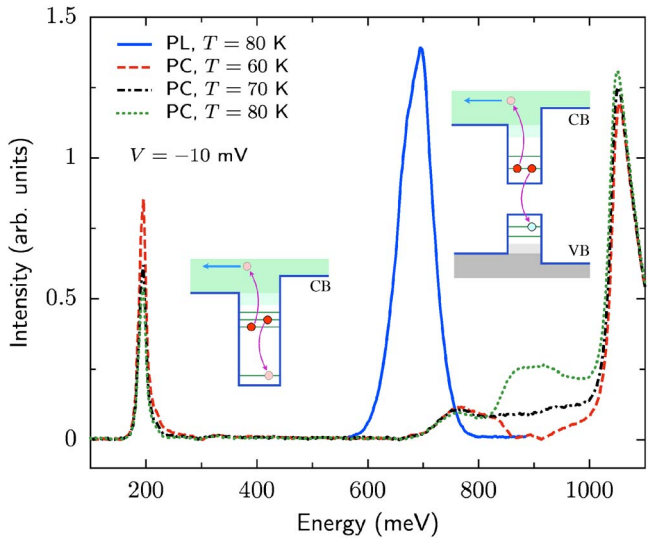

FIG. 3. (Color online) PL (solid line) and interband PC (dotted line) spectra for the undoped sample at 80 K. PC spectra at 70 K (dash-dotted line) and 60 K (dashed line) are also shown. The insets around 400 and 900 meV illustrate schematically the intraband and interband Auger effect, respectively.

sured at 60 K and 70 K are also shown. The PC generated by electrons promoted to the lowest lying conduction energy states (PC at energies below 800 meV) is essentially insensitive to the temperature, while those generated from electrons excited to higher energy levels (PC at energies between 800 and 1000 meV) are strongly temperature dependent. The strong peak above 1000 meV is due to interband PC in the InGaAlAs barrier layers. These results give further evidence that an Auger process mediates the current carried by electrons excited to deep energy levels with respect to the continuum. Electrons excited to shallow levels rely on thermal excitation to produce a PC and therefore the PC from dot states at higher energies strongly depends on temperature.

The generation of a current as a result of the intraband absorption of photons from the ground state to an excited state of the dots, which is about 200 meV below the conduction band, as seen in the presented experimental results, is attributed to an Auger process where one electron previously on a higher energy state relaxes to the ground state transferring its energy to the electron on the final state of the absorption. The latter is, in turn, promoted to energies above the quaternary barrier material, where it can be swept by the intrinsic electric field and contribute to the current. The inset placed on the left side of Fig. 3 shows the scheme illustrating the suggested intraband Auger mechanism. As one can see in Fig. 2, there are many possible states which can have electrons transferred to due to absorption and these carriers will then be available to mediate the Auger process. Even though one may at first think that the probability of having two electrons simultaneously in excited states is quite low, one should consider that the FTIR measurements are carried out with a broadband light source, implying that different optical transitions can occur essentially at the same time.

Additionally, dynamical processes in the device can raise the probability of finding more than one electron in excited states since they can produce a nonvanishing population of higher states. The dark current in the devices is a result of thermal emission and recapture of electrons. In time-resolved measurements it has already been observed that electron capture occurs very fast into high lying states and the relaxation to lower energy states is then slowed down.[14] As a consequence the QDs' higher lying energy states are expected to be populated. Thus an excited electron can be promoted to the continuum by an Auger scattering event in which a photoexcited electron and a captured electron take part. It should also be pointed out that thermal excitation of carriers is an efficient process in such structures,[15] increasing the probability of finding more than one electron in excited states.

Another possibility to explain the PC generation would be a polarization effect as discussed by Chen *et al.*[16] However, for the investigated experimental conditions, one can disregard this hypothesis since it would at best generate a displacement current of only a few picoamperes, three orders of magnitude lower than the detected PC.

In summary, a detailed study of the intraband optical response of QD structures for midinfrared photodetection was carried out in order to verify the possibility of carriers in a rather deep bound state generating a PC. The obtained PC and absorption results, together with a realistic theoretical calculation, strongly suggest that an Auger process can produce a significant current. PL together with interband PC further supports this attribution. The reported results indicate that QD photodetector structures could be designed to operate based on the more selective bound-to-bound transitions of QDs and still produce an efficient device.

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