Polarization Dependence of Photocurrent in Quantum-Dot Infrared Photodetectors

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Through polarization dependence measurements of photocurrent together with theoretical calculations we were able to identify different intersubband transitions in InAs/InGaAs/InP quantum dot structures for infrared photodetectors and observe 2D/0D hybrid behavior of the dot structures.

Introduction

The technology to detect infrared photons is dominated by HgCdTe (MCT) photodetectors since about four decades. The major advantage of this material system is the tunability over a large detection range. Their high optical conversion efficiency and the wide-band response are hard to compete with. Despite that, there is still a need to improve handling, reliability, speed and reproducibility of state of the art infrared photodetectors. They are bulky due to cryogenic temperature operation, and the lack of uniformity of the grown material makes them only partially suitable for large focal plain arrays. The ripening process of the MCT technology was accompanied by intensive research efforts for alternative detector concepts for increased temperature operation, reliability and reproducibility. As a consequence of the highly advanced epitaxial growth techniques for III-V semiconductor materials, intersubband photo-detection via quantum wells (QW) showed great potential as a viable alternative. However, theoretical predictions show that quantum well infrared photo-detectors (QWIP) have problems as candidates to rival the MCT technology at higher temperatures, as the dark current in QWIP increases significantly due to inherent thermoionic emission. In addition, selection rules in QW prohibit light incoming parallel to the growth-direction to be absorbed in intersubband transitions. Gratings and random reflectors are needed to circumvent this physical limit. The evolution of quantum devices led to a further reduction of the confinement dimensionality and today self organized growth techniques made the growth of quantum dots (QD) possible for a variety of material systems. Quantum dot infrared photo-detectors (QDIP) are not only able to outperform QWIP [1], but they are also potential candidates to rival or outperform MCT photo-detectors [2]. The reduced phonon-electron interaction in QD results in a long lifetime of excited carriers. The photoconductive gain increases by magnitudes compared to QWIP and also the dark

current is theoretically reduced significantly due to suppressed thermoionic emission. The absorption coefficient is also much higher than in QW. QD show the inherent feature to absorb normal incident light [3].

The features of QDIP are very sensitively connected to the degree of control during the growth process, where many different uncertainties lead to reduced reproducibility. The self-organized growth process spreads the dots size inhomogenously, and this decreases the detectivity of the devices. This effect cannot be eliminated, but only minimized technologically. QDIP without blocking layer have still a much higher dark current than QWIP caused by interlayer-dot-tunneling through defects and thermally excited carriers from upper excited states and are therefore far away from theoretically predicted limits.

Hence, real QDs are quite different from ideal. The intraband absorption and the consequently generated photocurrent (PC) in these devices should be fully understood. In particular, there has been some controversy in the literature on the polarization dependence of the PC for QDIP structures [4] – [7]. In this work we investigate the photocurrent (PC) as a function of temperature and polarization produced by QD structures where InAs dots are nucleated on top of an InGaAs QW. The dots are covered with an InP barrier. The observed PC peaks are attributed to different intraband transitions based on the PC data together with theoretical calculations.

Experimental

A doped sample with 20 and an undoped one with 10 dot layers were grown by metalorganic vapor phase epitaxy on semiinsulating (100) InP substrate. The InAs dots were grown on a 8.5 nm thick InGaAs layer lattice matched with InP and capped by 18 nm InP layer. The Si doping density of the 0.4 µm thick InP contact layers is n = 4×10^{18} cm^{-3} for both samples. The nominal doping level of the QD in the doped sample provides 2 electrons in the ground state per dot. The dot sheet density of about 9×10^{9} cm^{-2} and the median dot height of 9 nm were estimated by atomic force microscopy.

The PC polarization QD samples were investigated by a Fourier transform spectrometer for normal and 45° light incidence. Choosing the TE polarization implies that the electric field is totally in the plane of the layers. However, for the TM polarization, the electric field will have a component perpendicular to the layers.

The measured spectra were corrected by the system response and by the Fresnel refraction coefficients for both polarizations.

Results

A PC signal was detected up to 50 K and 90 K for the doped and undoped sample, respectively. Polarization dependent PC measurements of the undoped sample show a signal around 5.3 µm. Figure 1 shows the PC spectra at 6 K for the undoped sample for different experimental configurations: normal incidence, 45 degrees incidence with TE polarization, 45 degrees incidence with TM polarization, and unpolarized light. Choosing the TE polarization implies that the electric field is totally in the plane of the layers. On the other hand, for the TM polarization, the electric field will have a component perpendicular to them. The same peak is observed for all configurations. However, for the TE polarization the PC signal was expected to be of the same order of magnitude as for the TM polarization, indicating that the energy levels involved have a 0D character.

For the undoped sample the transition around 5.3 µm should depart from the ground state, because only this state is populated due to non-intentional doping. The simple 1D calculation estimate the transition energy from the ground state to the first excited state of about 184 meV; this is a underestimation of about 20% in comparison to the experimental results. Electrons in the first excited state can contribute to the photocurrent due to sequential tunneling, as it has been already observed for these samples [10]. This transition has the highest oscillator strength, so other transitions to the excited states can be excluded.

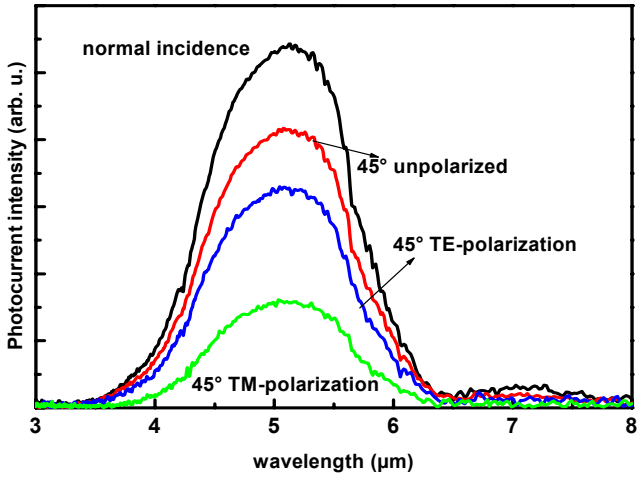

Fig. 1: Polarization dependence of the photocurrent at 6 K for the undoped sample.

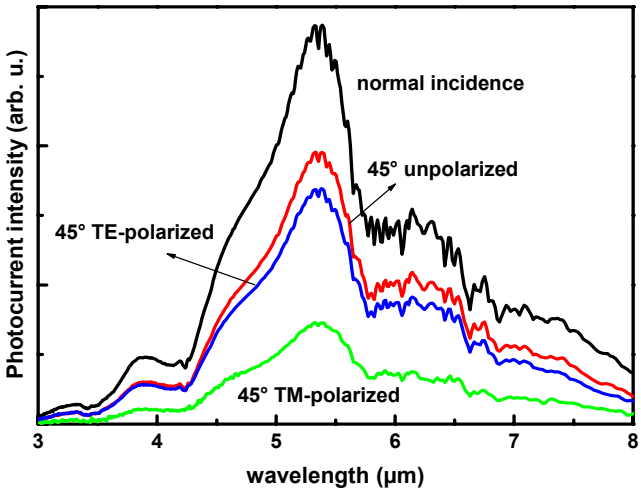

Fig. 2: Polarization dependence of the photocurrent at 6 K for the doped sample.

Equivalent polarization behavior, but noisier signal, is observed for the doped sample, as shown in Fig. 2. The doped sample contains twice as many layers as the undoped does. Even though one would expect a stronger signal, strain builds up more in such a thicker structure leading to more noise in the detected PC. Carefully looking in the spectra one observes that there are three peaks at 4 µm, 5.3 µm and 6.2 µm, corresponding to 310, 234 and 200 meV, in addition to a couple of shoulders. Using a simple 1D effective-mass model [8] for the InP/InGaAs/InAs/InP structure the band- con-

figuration shown in Fig. 3 is obtained assuming a dot height of 9 nm and an InGaAs QW thickness of 10 nm.

For the doped sample additional transitions can also occur from the first and second excited states to the third excited state or to the continuum. The oscillator strength to the continuum is small compared to these to the third excited state. The transitions E_1 – E_3 and E_2 – E_3 correspond to 5.8 and 8.9 µm, respectively. The theoretical and experimental transition energies are in fairly good agreement, considering that such a simple 1D model was used; the theoretical values being overestimated by about 15%. Results of photoluminescence give further support to these peak assignments [10].

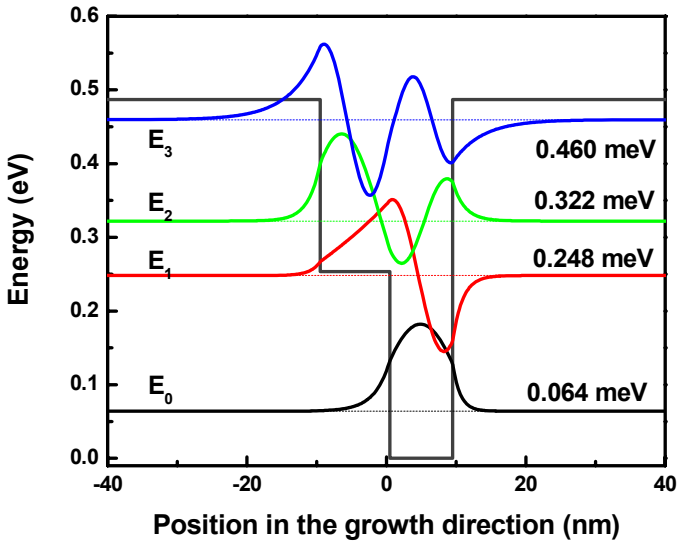

Fig. 3: Band configuration of the investigated samples.

Conclusion

We have performed polarization dependence measurements in InAs/InGaAs/InP quantum dot structures. Based on the difference between doped and undoped sample and the simple theoretical calculations, different transitions were identified. A strong PC-signal for s-polarization was observed as expected due to the 0D character of the QD. But surprisingly the PC for the p-polarization was rather weak showing little evidence 2D/0D hybrid behavior.

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