Modification of the Photoresponse by Energy Level Engineering in InAs Quantum Dot Nanostructures

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We design the energy structure and the absorption properties of infrared photodetectors based on the combination of quantum dots structures with a surrounding superlattice. By embedding vertically coupled or decoupled quantum dots in a two-dimensional superlattice, the advantages of self-organized growth and band structure engineering can be combined. The transition energies and the form of the transition peaks between the dot levels and the extended states of the superlattice can be adjusted by the period of the superlattice and the dot alignment. We use this scheme in photodetectors made of InAs quantum dots embedded in an AlAs/GaAs superlattice. Besides the reduced dark current compared to devices without a superlattice we can demonstrate clear advantages of vertically coupled dot stacks compared to uncoupled dots in this application.

Introduction

InAs and InGaAs quantum dot (QD) ensembles embedded in GaAs matrices or GaAs quantum well structures offer remarkable properties for fast and efficient optoelectronic devices such as NIR lasers [1]. The energy spacing of electronic states coupled with efficient electron capture capabilities into these discrete states predestine dots to be used as MIR photodetectors and emitters. In contrast to subband transitions in two-dimensional structures, the density of states is peaked at the transition energy, which reduces the phase space for scattering. Thus, QD structures are expected to provide higher photocurrents and lower dark currents than quantum well structures due to the longer lifetime of the excited states [2], [3].

The infrared photoresponse of InAs dots embedded in GaAs was investigated very recently [4] – [9], and transition energies between the dot ground state and the GaAs conduction band were found in the range of 80 to 400 meV. In some cases the existence of the first excited dot state [4] or even higher excited states [6] could be observed. It was also shown that the electronic states within the QD and thus the emission or absorption energies can be tuned by changing the InAs dot size [10]. Further methods to lift the energy levels of the InAs QDs is the incorporation of an AlAs layer close to the QDs [11] or the confinement in an $Al_xGa_{1-x}As$ matrix causing a higher conduction band offset to InAs [12].

In this paper we demonstrate that band gap engineering combined with vertical dot alignment allows tailoring of transition and ionization energies as well as absorption properties for mid-infrared (MIR) and far-infrared (FIR) photodetectors. Because the band structure of the minibands in the superlattice (SL) is not, or only slightly, altered by the embedded QDs, their properties can be tuned independently from each other. While the dot properties are modified by their growth conditions, the SL band structure can easily be estimated by solving the one dimensional Schrödinger equation numerically.

Experimental

The basic device structure and a band structure scheme in growth direction are given in Fig. 1 (a). The devices were grown at 485 °C on a semi-insulating GaAs(001) substrate by molecular beam epitaxy. Three multiple dot (MD) device structures – denoted as MD-A, MD-B and MD-C in the following – were designed, grown and characterized. Device MD-A consists of periodically arranged InAs QD layers, which are spaced by a 10 nm thick GaAs matrix. As shown in [8], this thickness is thin enough to cause a vertical alignment of the QDs due to their strain distribution. Device MD-B is additionally provided with 1 nm thick AlAs barriers at a distance of 1 nm from the QD layer resulting in a SL period of 11 nm and an increase of the absorption energy in comparison with device MD-A. The SL period of MD-C is 14 nm. Single dot (SD) and double dot (DD) devices were fabricated by growing one (SD) or two (DD) SL periods under the same conditions as device MD-B. These layers are followed by 2 SL periods without QD layers preventing the vertical alignment of the QDs. This sequence is repeated several times in such a way that the total number of QD layers in all devices is 20 or 30 (only MD-A).

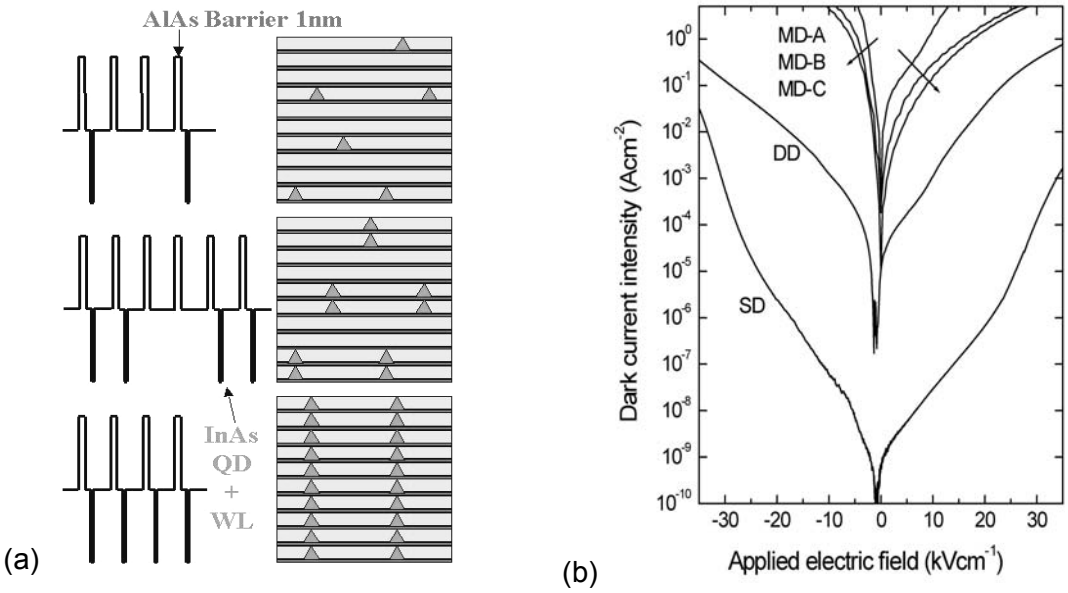

Fig. 1: (a) Device structure; (b) Comparison of dark current behavior.

For characterization of the devices, we performed photoluminescence (PL), photocurrent (PC), and current-voltage (IV) measurements in a LHe flow cryostat system. For the PC measurements, the devices were processed into mesas and provided with a back and front contact made of a thermally alloyed Ni/Ge/Au layer. The spectral photoresponse of the devices is measured in a standard FTIR spectrometer with a glow-bar infrared source.

Results and Discussion

The PL spectra of MD devices at 5 K shown in Fig. 2 are characterized by a PL peak at 1072, 1105, and 1100 meV for device MD-A, MD-B and MD-C, while there is a considerable and continuous shift of the PL peak energy to higher energies in the order of device MD-B, DD and SD in Fig. 2. In the first group, the peak is believed to be due to an electron-hole recombination between the heavy hole and electron ground state of

the QD. The second PL feature at higher energy, which is dominant in the second group, is attributed to higher excited states of the dot ensembles.

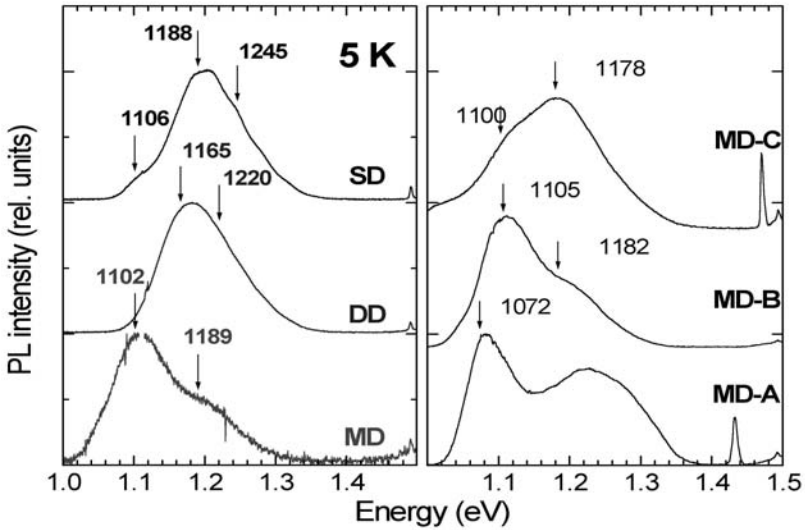

Fig. 2: Photoluminescence spectra of the different device structures.

PC spectra of MD devices at 4 K in Fig. 3 (a) are characterized by a single main peak at around 225 meV (device MD-A, MD-C) and at 247 meV (device MD-B). The full width at half maximum (FWHM) of these peaks amounts approximately to 13, 16 and 11 meV for device A, B and C, respectively. These peaks are assigned to the transition from the dot ground state to the continuum (device A) or to the first miniband of the SL (device B, C). Without vertical coupling of the QDs the situation becomes more complex and several PC peaks in the energy range between 170 and 320 meV can be observed (Fig. 3 (b)). It should be noted that the energy region between 190 and 200 meV is obscured by water absorption lines.

The IV characteristics of the devices at 4 K in Fig. 1 (b) show an asymmetric diode-like behavior. The dark current for the MD devices decreases by one order of magnitude from MD-A to MD-C. A larger decrease of the dark current is even seen in the order of MD-B, DD and SD.

The experimental results are used in the following to reconstruct the energy level scheme of the devices. In the following the heavy hole and electron ground state of the InAs QD are denoted as HH0 and E0, whereas the first excited electron state of the InAs QD and the first miniband of the AlAs SL is indicated with E1 and MB1, respectively.

According to the measurements an energy spacing of 1072 meV between HH0 and E0 and of 224 meV between E0 and the GaAs conduction band (CB) has been found for device MD-A. Although the dot growth conditions are the same for all devices, an enhanced energy spacing of 1105 meV between HH0 and E0 is observed for device MD-B in the PL measurement.

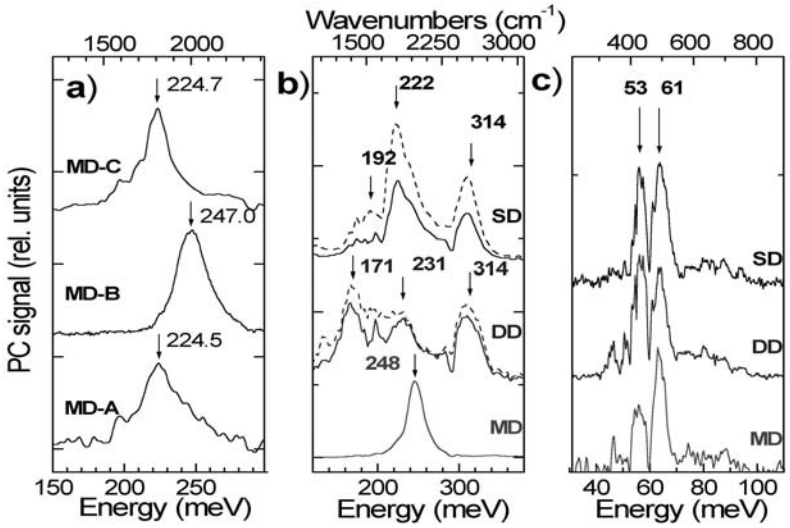

Fig. 3**:** Photocurrent spectra for the MIR region (a) and (b): (c) PC in the FIR region.

In [13], the calculated energy spacing for this transition is blue shifted if the dots are grown close to an AlAs barrier. As a result, the HH0→E0 transition energy increases by 33 meV in our sample. Because of the considerably heavier hole mass, we suppose in a first rough approximation, that the HH0 state remains nearly unchanged, and that the E0 state is lifted by the whole amount of 33 meV [14]. The energy of 247 meV obtained from PC measurements for the E0→MB1 transition can be now split into an energy of 191 meV for the distance E0→CB and an energy of 56 meV for the distance CB→MB1. The position of MB1 was calculated to expand between 48.6 and 53.2 meV above the CB.

The larger SL period of device MD-C lowers and narrows MB1, which now extends between 30.1 and 32.3 meV above the CB. The PC peak at 225 meV leads directly to the experimental value of 29 meV for the CB→MB1 transition. This value and the decrease of the width of the PC peak are in good correspondence with our theoretical prediction. Because of the SL the dark current in MD-C has been decreased by more than one order of magnitude (Fig. 1 (b)) compared to MD-A.

Without or with reduced vertical alignment the description becomes more complicated. Now three different cases have to be distinguished: a SL period without an InAs wetting layer, a SL period with a wetting layer, and a SL period with QD and wetting layer. Additionally to the MB1 in the first case, the wetting layer introduces a ground and first excited state WL0 and WL1. The split up of the former MB1 position in the case of DD and SD devices now enables several transitions to become likely, in good agreement with Figs. 3 (b) and (c). Unfortunately, the rough approximation to describe the QDs by thin quantum wells in our calculation does not allow a quantitative prediction of the PC peak energies in these devices.

The decrease of the dark current can easily be explained by the tunneling behavior of the electrons within the CB or MBs of the materials. Introducing AlAs barriers, the electrons have now to tunnel through the SL structure. Increasing the SL period leads to a decrease of the MB1 energy; thus, the relative barrier height for the electron is increased and the dark current decreases.

The suitability of the various device architectures for infrared photodetectors should be briefly discussed. In comparison with SD and DD devices, there is a clear preference for MD devices. Although SD and DD devices feature an extremely low dark current, their PC spectrum is complex, difficult to predict and of comparatively low intensity. In

contrast, the PC spectra of MD devices are characterized by an intense single peak, whose position can be designed by changing the SL parameters. Even with the crude approximation of a one-dimensional structure and the neglect of strain influences, this peak position can be calculated quite well.

Conclusion

In summary, we present an advanced method to design QD based devices by combining the self-organized growth of QD with band gap engineering. The spectral response was modified by changing the transition energy from the QD ground state to the lowest miniband of the SL. In comparison with isolated QDs, QD stacks are preferable concerning the PC intensity and the possibility to design the spectral dependence of the infrared absorption.

Acknowledgements

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