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InAs nanostructures were grown by molecular beam epitaxy on GaAs (211)B at temperatures between 400-530 ˚C and growth rates that were varied between 0.1 to 0.02 mono-layers (ML) per second. For temperatures up to 500 ˚C we obtain pyramidal-shaped InAs quantum dots with average heights between 3 and 7 nm while at 530 ˚C the dots become elongated, higher and are self organized into dashes along a specific crystallographic direction. Photoluminescence (PL) spectra taken at 18 K reveal in the QD samples grown at 500 ˚C a broad (55 meV FWHM) PL peak at 1.27 eV, associated with the QD layer. The PL peak blue shifts noticeably (~7 meV) upon increasing power of excitation, as a consequence of the strain induced electric field that exists in the (211)B direction.

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1 Introduction Quantum Dots (QDs) grown by the Stranski-Krastanov (SK) method [1] are interesting for the fabrication of novel optoelectronic devices like QD lasers with low threshold currents. While InAs QDs grown on GaAs(001) have been widely investigated for the realization of devices that emit in the near infra-red (IR) there are only few studies of InAs QDs on novel high index surfaces like for instance GaAs(311)B [2]. So far the growth of InAs QDs on GaAs(211)B, argued to be the optimum orientation for the fabrication of surface emitting photonic devices, has been investigated mainly by Guo *et al* [3] who showed that for growth temperatures above 500 ˚C quantum dashes (QDSHs) are self-organized and preferentially aligned in the [011] direction. A particularly important aspect of InAs QDs on GaAs(211)B is the strain induced electric field which is known to modify their optoelectronic properties [4]. Despite its importance, little is known about the role of the strain induced electric fields on the optoelectronic properties of these nanostructures, so as a precursor to further investigations we have grown InAs QDs on GaAs(211)B and measured their optical response in order to gain a deeper understanding of the fundamental processes involved and the magnitude of the strain induced field.

2 Experimental We have grown InAs QDs on GaAs(211)B by molecular beam epitaxy (MBE) under various growth conditions. After transfer to the MBE growth chamber the native oxide on the GaAs substrates was thermally desorbed by heating to ~580 ˚C under an As flux while the background pressure during growth was ≈ 8 x 10^{-8} mbar. The growth process was monitored *in situ* by means of reflection high energy electron diffraction (RHEED) and the growth rate was determined from RHEED oscillation measurements on GaAs(001). Initially a nominally undoped 0.5 μm GaAs buffer layer was grown at

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620 ˚C on an n^+GaAs (211)B substrate at a growth rate of 1.0 µm/h followed by a 40 period (15 Å AlAs)/(23 Å GaAs) superlattice (SL). The latter was included to achieve high purity InAs QDs and also provide confinement of the photoexcited electron-hole pairs in the near surface region. After completion of the AlAs/GaAs SL a thin 100 Å GaAs layer was grown and then the temperature was ramped down to 450, 500 and 530˚C for the growth of the InAs QDs. For the InAs QDs, a 0.1 µm/h growth rate was used in this series and, as in all cases in this work, the equivalent to a 2.5 ML InAs layer in the (100) orientation was deposited on the underlying GaAs. The respective sample numbers are 603, 601, and 607, where the QD layer was left uncapped for atomic force microscopy (AFM) characterization, or 604, 602, and 608, where the InAs QD layer was capped by a 300 Å-thick GaAs cap layer, grown at the same temperature as the InAs QDs, for the purpose of low temperature photoluminescence (PL) and time resolved photoluminescence (TRPL). Besides varying the temperature, we investigated the role of the growth rate on the properties of the InAs QDs grown at 500 ˚C. Three different growth rates were used, i.e. 0.1 ML/s, 0.0483 ML/s and 0.0261 ML/s in samples 601 (602), 612 (613), 619 (620) respectively, where sample numbers in parentheses correspond to capped QD samples. Finally, the PL spectra were taken using a He-Cd continuous wave (cw) laser at 325 nm and laser diodes at 650 nm and 850 nm between 18 and 300 K. At low temperatures the excitation power was varied by means of neutral density filters between 35 mW to 0.035 mW in order to investigate the screening of the strain induced electric field in the InAs QD nanostructures.

3 Results and discussion Representative images of InAs QDs on GaAs(211)B are shown in Fig. 1(a) and Fig. 1(b), respectively. The mean height (h_m) of the InAs QDs grown at 450 ˚C is 4 nm with a standard deviation $\sigma_h \approx 2$ nm and the corresponding statistical distribution is shown in Fig. 2(a). The mean height (h_m) of the InAs QDs increased with temperature which was accompanied by a broadening in the size distribution and a reduction in their surface density Ns^{QD} illustrated in Fig 2(b). For $T_G > 500$˚C the InAs QDs become elongated and form InAs QDSHs which are shown in Fig 1(b). A particularly interesting aspect from a device point of view is the fact that the InAs QDSHs are aligned and their mean height $h_m \approx 14$ nm is more than twice that of the InAs QDs grown at lower temperatures. Although the distribution of the InAs QDSH heights is centered about $h_m \approx 14$ nm, it is broader compared to the distribution of InAs QDs and their surface density Ns^{QD} is even lower. The reduction of Ns^{QD} occurs also as a consequence of decreasing growth rate. For example, $Ns^{QD} = 50$ µm^{-2} at 0.1 ML/s dropping to $Ns^{QD} = 16$ µm^{-2} at 0.022 ML/s for a growth temperature of T_G =500 ˚C. These findings are in good agreement with those of Guo *et al.* [3] who showed that self organized InAs QDSHs are aligned in the [011] direction for growth temperatures above 500 ˚C.

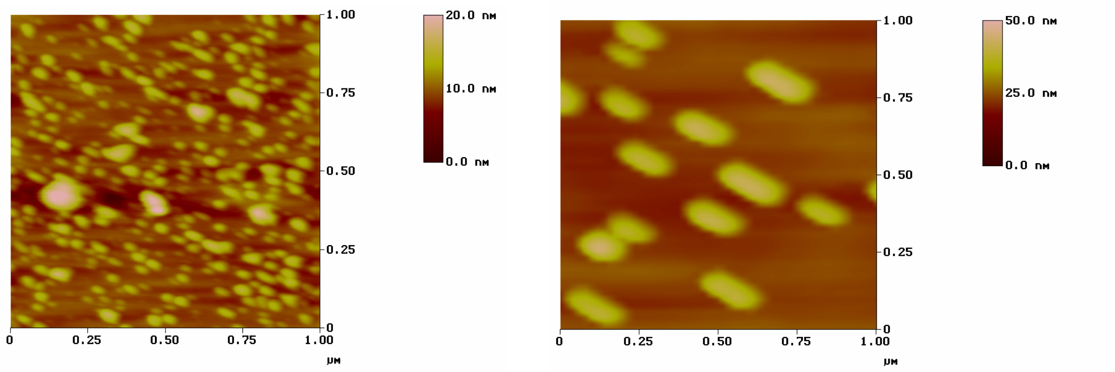

Fig. 1 Representative AFM image of InAs QDs (left, #603 T_G = 450 ˚C), and InAs QDSHs (right, #607 T_G = 530 ˚C) with average height to length ratio ≈ 1/20.

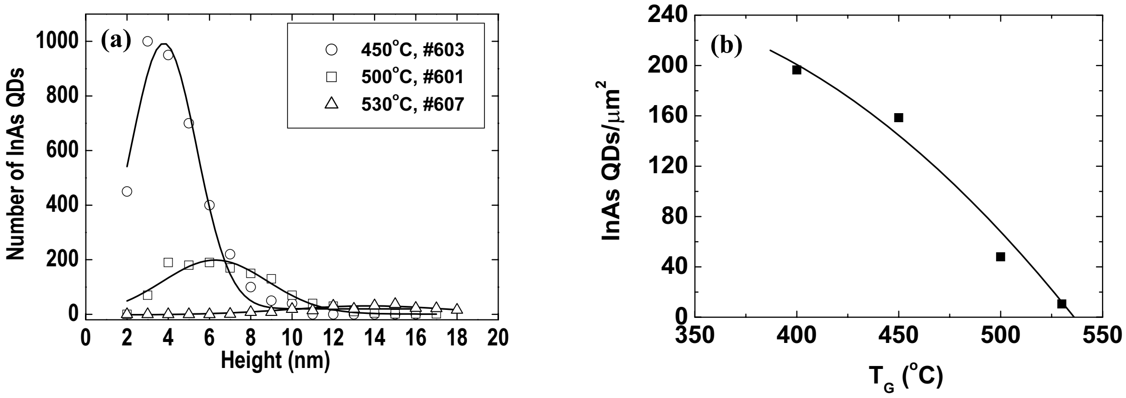

Fig 2 (a) Statistical distribution of heights and (b) InAs QD density for various samples grown at different temperatures on GaAs(211)B.

The difference between samples with InAs QDs and QDSHs is also seen in the PL spectra obtained at 18 K and shown in Fig. 3. The high energy peak at 1.75 eV is due to quantization in the AlAs/GaAs SL while the relatively weaker shoulder at 1.5 eV is clearly due to the GaAs substrate. This is substantiated by the PL spectrum of the reference sample (#599), which is a sample having no InAs QDs and whose growth was interrupted right after the GaAs/AlAs SL. The peak at 1.25 eV is due to electron hole recombination within InAs QDs obtained at lower growth temperatures. Interestingly the QD PL peak blue shifts by about 7meV upon increasing power of excitation, which is attributed to the screening of the strain induced piezoelectric (PZ) field that exists in the (211)B direction.

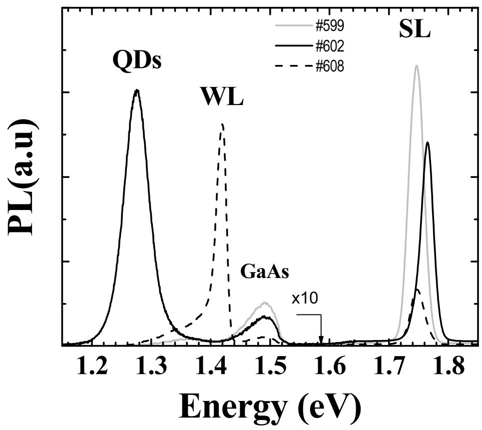

Fig. 3 PL spectra measured at 18 K from InAs QD (solid line), InAs QDSH (dashed line), and reference (light gray line) samples.

Further indication of the PZ field in the (211)B QDs was found in preliminary T = 10 K TRPL experiments, where a decay time of 1.1 ns was measured, as compared to 0.86ns measured in (100) QDs of comparable size. Please note that in the absence of PZ field, the oscillator strength in the (211)B orientation is higher than in the (100), and shorter decay times are expected. Therefore, the longer decay time in the (211)B case is very likely due to the PZ field. Nevertheless, we found no significant change in the time decay under different excitation power levels, suggesting that small changes in the PZ field due to screening do not influence significantly the electron-hole wave function overlap. This is understandable based on the fact that the PZ field acts over a very short distance (~3 nm) and the wavefunctions are practically 'squeezed' into the narrow InAs WL and QDs. Finally, the InAs QDSHs which have large base lengths and significantly larger heights compared to the InAs QDs exhibit a prominent peak in Fig. 3 at approximately 1.37 eV. This peak however is not attributed to emission from the dashes, but rather to emission from the InAs wetting layer (WL), which becomes here visible since the dash-density is quite low (~10/μm^2).

4 Conclusions As a precursor to further investigations we have grown InAs nanostructures on GaAs(211)B by MBE and obtained InAs QDs with heights of 3-7 nm for growth temperatures up to 500 ˚C and InAs QDSHs at 530 ˚C with heights of 14 nm. The latter are self organized on the surface along a specific direction and the surface density was shown that could be varied by a factor of four through adjustment of the growth rate. The PL peak from InAs QDs, shows up at 1.27 eV and is consistent with emission from QD heights of ~3 nm. The PL peak blue shifts noticeably upon increasing power of excitation, as a consequence of the PZ field that exists in the (211)B direction. Additional indication of the PZ field is found in TRPL experiments, but further investigations are required to quantify its magnitude.

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