HL 44: Quantum dots: Preparation and characterization

Time: Wednesday 9:30–13:00 Location: EW 203

HL 44.1 Wed 9:30 EW 203

Recent advances in growth of high- density InP based InAs/InGaAlAs quantum dots with reduced size inhomogeneity — •Saddam Banyoudeh and Johann Peter Reithmaier — Technische Physik, Institute of Nanostructure Technologies and Analytics (INA), University of Kassel

High-density 1.55 μm emitting quantum dot (QD) layers with a narrow spectral gain are requested for high-performance optoelectronic devices, like high-speed directly modulated communication lasers. We report about the influence of different growth parameters on the formation of 1.5 μm emitting InAs/InGaAlAs quantum dots (QDs) based on InP substrate. The InAs/InGaAlAs QDs were grown in a solid source molecular beam epitaxy system. The photoluminescence spectroscopy (PL) and atomic force microscope (AFM) were used to investigate the impact of the growth parameters, like V/III ratio, growth temperature of the InGaAlAs nucleation layer and growth rate of QD layers, on optical and structural properties of the formed QDs. The improved QD materials with dot densities up to 6 x 10^{10} cm^{-2} show a new record-low linewidth of 17 meV for a single QD layer and of 26 meV for multi QD layers, respectively (measurments performed at 10 K).

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Growth and structure of $In_{0.50}Ga_{0.50}Sb$ quantum dots on GaP — •Elisa Maddalena Sala, Gernot Stracke, Andre' Strittmatter, and Dieter Bimberg — Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany

III-V self-assembled QDs on GaP have recently attracted great interest for application in nano memory cells. As demonstrated by Marent, Geller and Bimberg et al, such QDs can be employed as storage units in a novel type of non-volatile nano memory, the QD-Flash. In this context, a proper choice of QD material is of decisive importance: by embedding $In_{0.50}Ga_{0.50}Sb$ QDs in a GaP matrix, storage times of more than 10 years can be obtained. Here we demonstrate the Stranski-Krastanov (S-K) growth of $In_{0.50}Ga_{0.50}Sb$ QDs on GaP(001) in metalorganic vapor phase epitaxy (MOVPE) environment for the first time. As reported in our previous works on InGaAs/GaP, a thin GaAs interlayer prior to QD deposition plays a decisive role in the surface energetics. $In_{0.50}Ga_{0.50}Sb$ QD growth is partially suppressed for GaAs coverage of less than 5 ML. Utilizing a 5 ML- thick GaAs layer, the transition from 2D to 3D growth is determined to about 0.20 ML and the QD density shows a logarithmic dependence on initial layer thickness, revealing a typical S-K growth mode. Prior to QD material deposition, a short Sb-flush is used to initiate antimony incorporation. Experimental results show that Sb apparently modifies the growth kinetics by reducing the surface diffusion length of gallium and indium atoms.

HL 44.3 Wed 10:00 EW 203

Atomic structure of InAs(Sb)/GaAs submonolayer stacks — •Zeno Diemer, Andrea Lenz, Christopher Prohl, David Quandt, Udo W. Pohl, André Strittmatter, Dieter Bimberg, Mario Dähne, and Holger Eisele — Technische Universität Berlin, Institut für Festkörperphysik, 10623 Berlin, Germany

Submonolayer-grown semiconductor nanostructures are promising for high power and high speed laser devices. Recent cross-sectional scanning tunneling microscopy (XSTM) studies of InAs/GaAs submonolayer stacks have shown the formation of InAs agglomerations with lateral sizes of about 5 nm, heights of about 2 nm, and a high density above $10^{12}/cm^2$. In this work, the structural changes upon additional supply of Sb, shown by cathodoluminescence to result in a stronger localization of charge carriers, are studied on the atomic scale using XSTM. The InAs(Sb) agglomerations show slightly smaller sizes than equivalent submonolayer structures grown without Sb. From atomically resolved filled-state XSTM images the Sb incorporation could be determined simply by counting the Sb atoms. The Sb atoms are mostly incorporated in the submonolayer structures. From an analysis of the local lattice parameter the In content could be determined, being considerably smaller than the nominally deposited amount of In. Also the distance of the submonolayer stacks along growth direction is reduced by about 30% with additional Sb. These reductions from the nominal values are due to a reduced growth rate of InGaAs and GaAs on Sb-containing growth surfaces.

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HL 44.4 Wed 10:15 EW 203

Localization of charge carriers in MOCVD-grown InAs(Sb)/GaAs sub-monolayer stacks — •D. Quandt, J.-H. Schulze, A. Schliwa, M. Gschrey, S. Rodt, Z. Diemer, C. Prohl, A. Lenz, H. Eisele, A. Strittmatter, U. W. Pohl, S. Reitzenstein, and D. Bimberg — Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstraße 36, D-10623 Berlin

Conventional growth of InAs/GaAs sub-monolayer stacks results in the formation of high density InAs islands with strong vertical electronic coupling. Additionally, lateral electronic coupling is possible for sufficiently large densities, resulting in weakened three-dimensional confinement of electrons and holes. The addition of Sb to the growth sequence results in a stronger localization of charge carriers, as shown by cathodoluminescence measurements, in which individual emission lines appear in the luminescence spectrum, and temperature-dependent photoluminescence measurements revealing an S-shape in the temperature-dependent peak energy position. 8-band k·p simulations have been utilized to investigate the influence of Sb on the wavefunctions of electrons and holes. The structural properties of the sub-monolayers have been investigated by cross-sectional scanning tunneling microscopy, showing a smaller size of the In agglomerations as compared to sub-monolayers grown without Sb as well as a slight clustering tendency of the Sb atoms.

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Cross-sectional Scanning Tunneling Microscopy Analysis of InGaAs/GaP Quantum Dots — •Christopher Prohl[1], Andrea Lenz[1], Holger Eisele[1], Gernot Stracke[1], André Strittmatter[1], Udo W. Pohl[1], Dieter Bimberg[1], Mario Dähne[1], Yuncheng Song[2], and Minjoo Larry Lee[2] — [1]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstr. 36, 10623 Berlin, Germany — [2]Department of Electrical Engineering, Yale University, New Haven, Connecticut 06520-8284, USA

GaP with its particular low lattice mismatch to Si offers the possibility to monolithically integrate III-V nanotechnology into Si. Recently, the topic of self-assembled InGaAs/GaP quantum dots (QDs) came more into focus because of their possible applications in new nanomemory cells. Furthermore, the first light emitting diode based on epitaxially grown InGaAs QDs on a monolithic GaP/Si substrate has already been demonstrated. In this contribution, cross-sectional scanning tunneling microscopy (XSTM) was used to structurally analyze differently grown InGaAs/GaP QDs on the atomic scale, investigating both, samples grown by metalorganic vapor-phase epitaxy (MOVPE) and molecular beam epitaxy (MBE). High-resolution images and a quantitative analysis of the local stoichiometry demonstrate that for a nominal MOVPE material amount of e.g. 3.0 monolayers (ML) GaAs and 2.0 ML $In_{0.25}Ga_{0.75}As$, indium-rich QDs with a truncated pyramidal shape, a reversed cone stoichiometry and a QD density of 2.4×10^{11} cm^{-2} form. In comparison, MBE samples with the same deposited material amount show QDs with similar size, shape and density.

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Stoichiometry determination of InGaAs/GaP quantum dots — Daehwan Jung[1], Christopher Prohl[2], Yuncheng Song[1], Minjoo Larry Lee[1], and •Andrea Lenz[1,2] — [1]Department of Electrical Engineering, Yale University, New Haven, CT, 06511, USA — [2]Technische Universität Berlin, Institut für Festkörperphysik, 10623 Berlin, Germany

InGaAs/GaP quantum dots are promising for the integration of III-V nanostructures in the well-established silicon-device technology. In order to understand and improve optoelectronic device characteristics of InGaAs quantum dots grown under various growth conditions, detailed investigations on their size, shape and stoichiometry are performed. In this presentation the stoichiometry of InGaAs quantum dots is revealed by energy dispersive X-ray spectra (EDX) in a scanning transmission electron microscope and also by cross-sectional scanning tunneling microscopy (XSTM). From XSTM images the local stoichiomety across a quantum-dot layer is determined by an evaluation of the local lattice parameter and a comparison with reference values

from strain relaxation calculations. EDX and XSTM were applied on the same sample and benefit strongly from each other: It is revealed that P atoms are absent in the quantum dots and InAs is incorporated within the quantum-dot center, especially for the case of a thin GaAs layer deposited on the GaP matrix material prior to the InGaAs growth.
This work was supported by the DFG, project LE 3317/1-1.

HL 44.7 Wed 11:00 EW 203

Deep-Level Transient Spectroscopy on In0.5Ga0.5As/GaP quantum dots with AlP barrier — •Leo Bonato[1], Elisa Sala[1], Gernot Stracke[1], Tobias Nowozin[1], André Strittmatter[1], and Dieter Bimberg[1,2] — [1]Institut für Festkörperphysik, TU Berlin, Hardenbergstr. 36, 10623 Berlin — [2]King Abdulaziz University, Jeddah, Saudi Arabia

Aiming to use self-assembled quantum dots (QDs) as storage units for novel memory devices [1], we studied the charge-carrier dynamics during the processes of charging and discharging QDs by using Deep-Level Transient Spectroscopy (DLTS). We investigated In0.5Ga0.5As QDs grown on a GaAs interlayer in GaP, with an additional AlP barrier, which yielded a localization energy of 1.14 eV and a storage time at room temperature of 230 s. This marks a definite improvement over the previous record values of 0.8 eV [2] and 1.6 s [1].

[1] A. Marent et al., The QD-Flash: a quantum dot-based memory device, Semicond. Sci. Technol. 26 (2011) 014026

[2] T. Nowozin et al., 800 meV localization energy in GaSb/GaAs/Al0.3Ga0.7As quantum dots, Appl. Phys. Lett. 102 (2013) 052115

Coffee break

HL 44.8 Wed 11:30 EW 203

Growth of GaN quantum dots on AlN by MOVPE — •Konrad Bellmann[1], Torsten Ernst[1], Tim Wernicke[1], Andre Strittmatter[1,2], and Michael Kneissl[1] — [1]Technische Universität Berlin, Institute of Solid State Physics, Secretariat EW6-1, Hardenbergstrasse 36, 10623 Berlin, Germany — [2]Otto-von-Guericke Universität Magdeburg, FNW/IEP/AHE, Universitätsplatz 2, 39106 Magdeburg

GaN quantum dots(QDs) embedded in an AlN matrix are very promising to achieve single photon sources at room temperature. This work will present a systematic study of GaN growth on an AlN layer by metal organic vapor phase epitaxy(MOVPE). Due to the 2.4 % lattice mismatch GaN growth on AlN is very sensitive to the surface energy during growth. A high V/III ratio >300 can shift the balance between surface energy and strain energy towards two dimensional growth. A low V/III ratio on the other hand shifts the balance towards Stranski Krastanow growth. We have investigated the GaN growth at 840 °C at different V/III ratios ranging between 70 and 1200 as well as different growth times from 0 s to 40 s. Independent of the V/III ratio GaN is first nucleating on the terrace until a uniform monolayer is formed. At high V/III ratio additional material gathers at the step edge leading to two dimensional growth with nonuniform edges. Growth at low V/III ratios results in three dimensional islands. The density increases during growth from $10^8\,\mathrm{cm}^{-2}$ to $10^{10}\,\mathrm{cm}^{-2}$. Typical QDs exhibit heights of 1 - 4 nm and diameter of 20 - 50 nm. The growth results are summarized in a phase diagram based on the model by Daruka and Barabasi.

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Growth of Site-Controlled InAs Quantum Dots by MOVPE — •Marc Sartison, Matthias Paul, Jan Kettler, Michael Jetter, and Peter Michler — Universität Stuttgart, Institut für Halbleiteroptik und Funktionelle Grenzflächen and Research Center SCoPE, Allmandring 3, 70569 Stuttgart

In the last decade, it has been demonstrated, that semiconductor quantum dots (QDs) have the potential to be excellent light sources for the application in single-photon devices. Normally, QDs with a high optical quality and structrual purity are grown self-assembled with a low spatial density. Hence, it is a challenging task to integrate QDs into optical circuits on chip, a precise control of the QD position is essential. It also has been shown, that the surface potential can be locally modified to create sites of higher nucleation probability by prepatterning the substrates. In this contribution, we present approaches of the site-controlled growth of InAs QDs on prepatterned GaAs substrates. To create nucleation sites, the substrate is structured with a hexagonal hole pattern, which is etched either by wet, or a combination of wet and dry chemical etching. Afterwards, the templates are overgrown with different GaAs buffer structures in our MOVPE system. The evolution of the holes and the nucleation behavior of the InAs QDs is monitored by AFM and SEM measurements. To reveal the optical characteristics, the QDs were capped with a GaAs layer. The microphotoluminescence measurements show single QD emission lines and two wetting layer peaks resulting from variations in the wetting layer thickness inside the holes and in the planar region in between.

HL 44.10 Wed 12:00 EW 203

Towards site-controlled In(Ga)As quantum dots at telecom wavelengths — •Caterina Clausen, Matthias Paul, Marc Sartison, Jan Kettler, Michael Jetter, and Peter Michler — Institut für Halbleiteroptik und Funktionelle Grenzflächen and Research Center SCoPE, Universität Stuttgart, Allmandring 3, 70569 Stuttgart, Germany

Single photon sources and sources of entangled photon pairs play one main part in quantum cryptography and quantum information technologies. The emission wavelength of 1310 nm correspond to the telecom O-band. In this range the dispersion and absorption of optical fibers is minimal. This characteristic is needed for loss free transmission in present communications networks. Semiconductor quantum dots (QDs) are excellent candidates for such applications due to very good optical properties and low area densities. The advantage of site-controlled grown QDs is simple integration into devices . The studied structures are produced by metal-organic vapor-phase epitaxy on exactly oriented GaAs substrates. The strain surrounding the QDs is reduced by a $In_{10}Ga_{90}As$ layer directly over the InGaAs-QDs. This leads to actual larger QDs, reduces the effective band gap, and shifts the emission to higher wavelengths. For the growth of positioned QDs, GaAs substrates are pre-structured with a hexagonal hole pattern. A GaAs buffer layer ensures a (100) growth surface in the etched holes. Then the QD material is deposited. It is possible to influence the nucleation in the holes by choosing the right growth parameter.

HL 44.11 Wed 12:15 EW 203

Direct growth of high-density InAs/GaAs core-shell quantum dots on silicon towards a new light emitting silicon based material platform — •Marc Sebastian Wolf and Johann Peter Reithmaier — Technische Physik, Institute of Nanostructure Technologies and Analytics (INA), CINSaT, University of Kassel

Beyond the successful integration of III-V light emitting material on silicon by wafer-bonding or direct planar growth by using thick relaxation layers, no approach yet is fully process compatible with silicon fabrication technologies. To avoid III-V processing, a new hybrid material based on III-V quantum dots (QDs) embedded in a silicon matrix is under investigation (Benyoucef et al., pss a 211, 817 (2014)). A key parameter is the development of core-shell QDs directly grown on silicon surfaces, which could be already successfully demonstrated at low-density structures (Benyoucef et al., APL 102, 132101 (2013)). In this work, InAs/GaAs core/shell quantum dots are grown in a solid source molecular beam epitaxy system directly on the silicon substrate. For efficient light emitting devices (e.g. LED, Laser) we aim for high-density QD layers with light emission in the range of 1.3 μm. The influence of growth parameters, like growth temperature, V/III ratio, deposited material thickness, on structural and optical properties are investigated and characterized by low-temperature photoluminescence (PL) spectroscopy and atomic force microscopy. Dot densities of $> 10^{10}\ cm^{-2}$ were obtained and first ensemble PL spectra will be discussed.

HL 44.12 Wed 12:30 EW 203

Strain in colloidal CdSe/CdS core/shell nanocrystals — •Narine Ghazarian[1], Amelie Biermann[1], Tangi Aubert[2], Marco Cirillo[2], Andrei Schliwa[1], Zeger Hens[2], Janina Maultzsch[1], Axel Hoffmann[1], and Christian Thomsen[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, Germany — [2]Physics and Chemistry of Nanostructures, Ghent University, Belgium

In the last decade colloidal quantum dots have attracted particular attention due to their unique size-tunable emission wavelength from UV to IR, their high photoluminescence quantum yield and long lifetime, thus they offer uses in the field of optoelectronics and biotechnology. Surface defects cause non-radiative recombination of charge carriers. One solution to this can be the coating with a shell material. However, overcoating the core with a shell leads to strain inside

the core/shell nanocrystals (NC) caused by the lattice mismatch between the different materials. Since strain has a significant bearing on optical properties, it is important to know what impact parameters such as temperature, reaction duration, crystal size and shell thickness have. In order to be able to assess the influences of these parameters on strain, we investigate different series in CdSe/CdS core/shell NCs with wurtzite and zinc blende structure by using Raman spectroscopy. We consistently find that core and shell show compressive and tensile strain, respectively. Increasing the shell thickness results an increased compressive strain in the core and relaxation of the tensile strain in the shell.

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In situ Raman monitoring of silica shell formation on colloidal CdSe/CdSe quantum dots — •Philipp Baumeister[1], Amelie Biermann[1], Tangi Aubert[2], Zeger Hens[2], Janina Maultzsch[1], and Axel Hoffmann[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, Germany — [2]Physics and Chemistry of Nanostructures, Ghent University, Ghent, Belgium

Colloidal CdSe/CdS quantum dots offer possibilities for a variety of applications, in particular for biological imaging. Due to their high luminescence yield, discrete spectrum and stability, quantum dots used as biological markers are in many cases superior to regular dyes. The toxicity of CdSe and CdS remains a problem for biological uses. Furthermore, for those applications the quantum dots need to be modified for water solubility and acid resistance. One approach to solve these problems is the coating the quantum dots with a silica shell.

In this talk we discuss the influence of the silica shell synthesis on the encapsulated CdSe/CdS quantum dots utilizing in situ Raman spectroscopy. This made it possible to monitor the formation of the silica shell in real time. We were able to measure an increasing strain in the CdS-shell during the first hours of the synthesis, despite the silica shell being an amorphous material.