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SANDiE

Self-Assembled semiconductor Nanostructures
for new Devices in photonics and Electronics

Instrument: Network of Excellence

Thematic Priority: Nanotechnologies, Materials, New Processes

Publishable Executive Summary for the third reporting period (July 2006 – June 2007)

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Project coordinator: Prof. Dr. Marius Grundmann
Project coordinator organisation: Universität Leipzig

Revision 1

Publishable executive summary

The Network

The Network of Excellence SANDiE within the 6th framework programme started on July 1st 2004. The acronym SANDiE stands for "Self-Assembled semiconductor Nanostructures for new Devices in photonics and Electronics". Thirty-two institutions from Portugal to Russia, among them five industrial companies, have established a close partnership to integrate their human resources, their facilities and their research agenda in the field of self-assembled semiconductor nanostructures on a European scale. The Network of Excellence is dedicated to the formation of an integrated and cohesive approach to research and knowledge in the field of self-assembled semiconductor nanostructures. The Network supports spreading of research results and excellence into the scientific community. In the third year of its existence the Network has again successfully reached all of its integration goals. Publicly available information can be found on the SANDiE website www.sandie.org.

The scientific scope

Most prominent on the research agenda are self-assembled semiconductor quantum dots. The self-assembly process allows fabrication of structures in the 10 nm size range during epitaxy without artificial patterning. These nanostructures can then be cemented in position by the deposition of further layers of the substrate material. By varying the semiconductor materials involved, the growth conditions, and by vertically stacking layers of nanostructures, a rich variety of novel materials can be produced for the study of the fundamental properties of strongly confined systems, and for the development of advanced electronic and photonic devices.

The scientific network activities are focussed into five topical areas. The involved Network partners are leaders in their respective fields, as detailed in the following. These research areas have been constantly discussed and updated. In year 2 road maps have been developed for the respective work packages and updated in year 3. By assembly decision, area 4 has been split into two work packages effective for the third year of the Network

<u>Area 1: Long-wavelength (1.3 µm and 1.55 µm emission wavelength) quantum dots</u>
Such quantum dots are attractive for fiber-based (data) communication devices such as lasers, amplifiers and detectors. For the most advanced long-wavelength structures application relevant properties such as their low chirp, bit error rates of transmission experiments and industrial feasibility of fabrication of large area homogeneous arrays are determined in close cooperation with industry. The area interacts with area 2 to merge long wavelength properties with single photon devices.

<u>Area 2: Single photon devices</u>
Single photons with designed physical properties such as controlled quantum statistics and entanglement of emitted pairs of photons offer novel quantum mechanically motivated communication schemes such as quantum cryptography and secure communication. Single quantum dots are the prime candidate for electrically driven solid-state light sources and are investigated also as detectors for such photons. Several SANDiE Partners, including an industrial company, are leading in this field and have established a close cooperation.

Area 3: Inter-sublevel optical transitions
Such transitions occur between various confined states and confined states and the continuum. Spectrally they have ultra-long wavelength (~20 µm), important e.g. for spectroscopy. Various approaches to novel mid infrared lasers are explored by the leading groups in Europe.

Area 4: Novel self-assembled nanostructures
The Network and the respective partners have a leading role within Europe with regard to novel self-assembled semiconductor nanostructures based on whisker-like growth in various material systems such as SiGe, III-V compounds (GaInAs, GaInP) and II-VI compounds (MgZnO). Such structures are promising for novel light emitters and one-dimensional electronics. Whisker growth allows defect-free epitaxy on dissimilar substrates such as GaAs/Si and ZnO/Al_2O_3. Also several other material systems and approaches to the fabrication of self-assembled semiconductor nanostructures are investigated on an exploratory basis. Two workpackages are devoted now to this area, focussing on 1D structures and novel materials, respectively.

Area 5: Theoretical simulation
The theoretical simulation of growth, electronic and optical properties, electron-phonon coupling and many-body effects and the comparison with experimental data, down to the level of imaging of individual wave-functions, are essential for a broad-based understanding, design and control of self-assembled semiconductor nanostructures. The Network unites the most comprehensive approach to this topic in Europe.

The resources and the approach of the Network reach from the study of fundamental phenomena to their exploitation for the design of novel materials, invention and analysis of novel growth processes, and for the use of the self-assembled nanostructures in advanced electronic, photonic and optoelectronic devices. Significant scientific progress was made by the partners in the last year in all topical areas. The Network helped to spread the knowledge among the partners, into the scientific community and into the public. A very large increase in joint publications indicates the harvesting of the integration efforts of the previous years.

The management

The Network is coordinated by Universität Leipzig (Prof. Grundmann) where the Network office has been established. The office is staffed with the scientific Network officer (Dr. Weber) and a secretary (Mrs. Wendisch), who oversee and run the day-to-day operations, organize events and prepare necessary documentation. The office has set up and maintains the website www.sandie.org that provides information to the public about the Network itself and events organized by the Network, e.g. workshops, training courses or Girl's days. The website also contains the intranet. The intranet is the backbone of internal communication and the electronic dissemination of information within the network. The Network is governed by the Executive Committee that has six distinguished members. Important decisions are voted on in the Assembly where each partner is represented with one vote. The Assembly convenes twice a year. The cooperation within the Network has been formally agreed by the partners in a Consortium Agreement that also regulates intellectual property issues. After establishing according procedures, the Network welcomes the accession of two new Partners from the New Member States and another major industrial company in the second year.

The details for a framework of the sustained network structure after the EU funding period has been agreed on by the partners. It will be implemented within year 4.

The first three years

The Network has set itself, in negotiation with the European Commission, quantifiable goals with respect to the achievement of the integration of people, facilities, research and training events. The level of integration in each of these areas is measured numerically from a variety of indicators all of which are above target for the third year. The Network has established itself as a stable structure with well-defined decision making processes and a lively and amicable working atmosphere. Several joint projects and investigations have been performed and progress in existing efforts has been made that would not have emerged without the Network. It has expanded carefully by three Partners, well integrated now, in the second year.

The Network continues its joint programme of workshops and technical training courses that is to a large extent open to the public and can be found on our website. An increasing number of PhD theses within the Network are jointly supervised by two partners. The students perform their research in two or more facilities of the Network thus increasing their experience with complementary methods and using the infrastructure in the European Research Area efficiently.

The scientific success of the Partners can be seen in the coordination and the participation in numerous national and several European projects, such as IP's NODE, ZODIAC and the STReP's NATAL, TRIUMPH and NANDOS. These projects benefit from the integration of partners within SANDiE.

Progress in the five topical areas has been manyfold and is briefly summarized in the following:

Area 1: Long-wavelength (1.3 µm and 1.55 µm emission wavelength) quantum dots
SAN for long wavelength emission have been investigated mostly on GaAs and InP semiconducting substrates. Three approaches, a metamorphic buffer layer, capping with GaAsSb layers and a strain-egnieered InGaAs layer were all successful in achieving quantum dot emission around 1.55 µm. Record results have been demonstrated in the field of mode locked lasers with subpicosecond pulse generation at repetition rates of 130 GHz (InAs/InP lasers) and 80 GHz (InAs/GaAs lasers). Temperature independent Linewidth Enhancement Factor up to 85°C has been reported. Over 72 journal and invited papers have been published.

Area 2: Single photon devices
The control of the exciton fine structure splitting of single quantum dots for the generation of entangled photons, the preparation of potential quantum bit states by electron or nuclear spin polarisation of single quantum dots by optical pumping and the generation of single photons at telecom wavelengths from electrically driven sources has been achieved.
Fruitful tight collaborations and exchange of ideas within the workpackage partners resulted in the proof that the exciton fine structure splitting (FSS) can be permanently reduced to zero by post-growth thermal annealing of the quantum dots, or actively tuned to zero by the application of in-plane external electric or magnetic fields. The understanding of the FSS have made it possible to grow naturally zero split quantum dots, which have been used successfully in the development of an entangled photon pair source with the highest recorded fidelity of 76%. A bi-photon interferometer has been constructed, which has allowed the probing of a variety of properties of the entangled photon source. All this results have positioned the SANDiE network of excellence in a world leading position in the control and understanding of FSS.

Work on electrically excited single photon emission has been continued. An electrically driven single photon emitter at ~900 nm has been realized based on an oxide aperture that constricts the current flow in a way that only one single QD is pumped. Major improvements have been achieved on electrically excited single photon emission at ~1.3 µm. The measured degree of suppression of multiphoton emission from a planar cavity single photon LED has been improved from $g^{(2)}(0) \sim 0.4$ to ~ 0.28 before correction for dark counts, corresponding to $g^{(2)}(0) \sim 0.19$ for the source itself.

Area 3: Inter-sublevel optical transitions

During year 3, cooperation of various partners led to the following achievements: The enhanced electron-phonon coupling for quantum dots charged with two electrons has been evidenced. Also intervalence band spectroscopy was performed on quantum dot infrared photodetectors. The intersublevel absorption of a single quantum dot in the mid-infrared has been observed. Design and fabrication of two dimensional photonic crystals in order to enhance the interaction between intersublevel transitions and electromagnetic field has been achieved. The ultrafast dynamics and capture in doped quantum dots following an interband optical pumping has been investigated using time-resolved electro-optic sampling. The experimental studies were performed with the equipments available within the Sandie network or in collaboration with external partners (free-electron laser facility of Felix, CLIO, Rossendorf). Interaction with theory groups external to SANDiE network did provide additional support to interpret the dynamic experimental data.

Area 4: Novel self-assembled nanostructures

This area is focussed on one-dimensional nanostructures and novel materials. Growth and characterization of one-dimensional (linear) SAN and built-in nanostructures has emerged as a specific research area with many partners involved. Joint projects have been executed in the field of experimental research (growth and characterization of nanowires) as well as theoretical modeling of the growth process. In this area, also novel materials (other than the comparably well known GaAs/InGaAs), novel preparation methods and analysis methods for self-assembled nanostructures are investigated in an exploratory fashion.

Area 5: Theoretical simulation

The main objective is the calculation of the electronic structure of quantum dots on the basis of geometrical and structural data. The focus in the present period was on further refinement of the methods, in particular joint research efforts to integrate the effects of piezoelectricity and of an external magnetic field into the simulation tools. In the area of simulation of SAN growth, the attention has largely shifted to nanowires, as indicated by the establishment of WP15. Thus the theoretical analysis of the growth process was extended to nanowires. The efforts where focused on the question how the conditions of nanowire growth affect the morphology of the wires. This includes their internal atomic structure (zincblende or wurtzite), as well as the structure of their side facets.

Conclusion

The Network of Excellence SANDiE has continued its fruitful and successful course in the third year. The pace to the envisoned high level of integration has accelerated and the set goals have been overfulfilled. We are grateful to the EC for their support.