GMe Forum 2011

Abstracts of the Poster Presentations

Vienna University of Technology
April 14 and 15, 2011

Society for Micro- and Nanoelectronics
Vienna, 2011

Society for Micro- and Nanoelectronics
c/o Institute of Sensor and Actuator Systems
Vienna University of Technology
Gusshausstrasse 27–29/366
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Narrow Photoluminescence Emission of Ge Islands Grown on Pit-Patterned Si(001) Substrates at Various Temperatures

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The advantages of Ge islands grown on pre-patterned Si(001) substrates as compared to randomly nucleated ones are the control over the nucleation sites as well as the island's homogeneous composition distribution. In this work we investigate the dependence of the island morphology and homogeneity on the substrate pattern period. By photoluminescence experiments the influence of the statistical size distribution on the optoelectronic properties of an island ensemble is monitored.

Ge islands were grown by molecular beam epitaxy at different temperatures (650 °C, 690 °C, 725 °C and 760 °C) on substrates pit-patterned by e-beam lithography with various pit periods p from 300 nm to 900 nm. Low Si capping temperature (300 °C) was used to preserve the island shape, size and Ge composition. Uncapped samples were grown for atomic force microscopy investigation.

We determine from the uncapped samples a clear correlation between the deposited amount of Ge per pattern unit cell with the size distribution and the morphological shapes of the islands. For the optimal amount, we observe significantly narrowed island photoluminescence emission peaks that are ascribed to the improvement of the Ge distribution homogeneity in the islands rather than to their shape homogeneity [1].

Beyond this optimal amount, dislocated superdomes are formed. As a consequence, the island PL becomes almost completely quenched for these samples.

These findings emphasize the importance of accurate control over a parameter space including the deposition rate, the amount of deposited material, the pit period and the growth temperature of heteroepitaxial island growth on pre-defined positions.

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Mid-Infrared Quantum Dot LEDs and Microdisk Laser Grown by MBE

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In spite of extensive research, mid-infrared (MIR) emission from self-assembled Stranski-Krastanow quantum dots (QDs) has remained difficult due to the unfavorable band alignments of the most narrow band gap semiconductor material systems. For the realization of quantum dots with strong infrared emission, we have therefore developed an alternative strain-free synthesis method in which dot formation is induced by phase separation rather than by heteroepitaxial strain. The resulting QDs exhibit almost spherical shapes with abrupt interfaces, are essentially defect- and strain-free and show intense mid-infrared photoluminescence (PL) even at room temperature [1].

In this work, we show for the first time mid-infrared light emitting diodes (LEDs) operating in cw up to room temperature and we demonstrate cw optically pumped lasing up to 200 K in microdisk structures based on these unique PbTe QDs.

The samples were grown by molecular beam epitaxy on high quality CdTe buffer layers predeposited on GaAs (001) substrates and the PbTe dots are formed by nanoprecipitation from thin 2D layers embedded in CdTe. The emission wavelength of the dots can be tuned either by changing the PbTe layer thickness [1] or by varying the growth temperature of the PbTe layer. The dot emission wavelength for an initially 1 nm thick PbTe layer grown at different temperatures ranges from 2.1 µm to 2.7 µm. This corresponds to a change of the diameter of the nearly spherical dots from 8 nm to 14 nm. An even more pronounced change of the emission wavelength can be achieved by changing the PbTe layer thickness. A variation of the layer thickness from 0.3 nm to 80 nm results in the tuning of the dot emission from 1.4 µm to 4 µm with dot diameters ranging from 5 nm to 30 nm.

For LED emission, p-i-n structures were fabricated, where the active PbTe dot layer is embedded in the center of a 0.5 µm thick CdTe intrinsic region. Cw electroluminesensce (EL) spectra were measured at various temperatures up to 300 K for dots with average diameters of 10 and 12 nm, respectively. The LED emission was compared to PL spectra from the same sample region using a 1064 nm laser with photon energy well below the CdTe band gap. At all temperatures from 30 K to 300 K the EL exactly matches the PL for both samples proving that the EL indeed arises from the embedded PbTe QDs. At 300 K the total output power was found to be 0.7 µW at 8 mA diode current [2].

To obtain lasing from the PbTe QDs, microdisks with a diameter of 40 µm were fabricated by photolithography and wet chemical etching. The single active PbTe dot layer is positioned in the center of the 2 µm thick CdTe waveguide. The QD microdisks were optically excited in cw below the CdTe band gap at a wavelength of 1030 nm, resulting in laser emission up to temperatures as high as 200 K with a maximum output power at 50 K of 0.15 mW considering homogenous emission. Thus, our unique PbTe QDs proof their suitability for novel mid-infrared optoelectronic devices.

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Coupling Strategies for Coherent Operation of Ring Cavity Surface Emitting Intersubband Lasers

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Since quantum cascade lasers (QCLs) [1] represent compact reliable coherently emitting devices in the mid infrared (MIR) and terahertz (THz) spectral region, investigations with respect to their material system and especially their resonator design are highly appreciated. The fact that their emission spectrum is rich in molecular absorption lines opens a wide field of real world applications including gas analysis for environmental and medical uses as well as chemical sensing. Since several tasks call for high optical output power, considerations in this direction become essential. Here, we report fundamental investigations on the capability of coherent operation of an arbitrary number of QCL devices. The gained results open up numerous future prospects for coupled QCLs, up to two dimensional QCL arrays for powerful, monochromatic emission at room temperature. Recently, our group presented an ideal elementary building block for two-dimensional laser arrays, the ring cavity surface emitting lasers (RING-CSELs) [2]. This resonator type provides the feasibility of producing symmetric low divergence optical beams combined with single-mode operation, reduced thresholds and enhanced radiation efficiency. It incorporates a ring shaped resonator, holding a second order distributed feedback (DFB) grating on top that acts as a Bragg reflector for surface light extraction. Its comparable large emission area in combination with an absence of facets make RING-CSELs show considerably enhanced properties in comparison to conventional edge emitting Fabry-Perot lasers. The present investigations on coherent coupling are executed using high performance RING-CSELs based on a InGaAs/InAlAs/InP material system with 8.05 µm nominal emission wavelength, as recently published by our group [3 and references therein].

Coherent coupling plays an important role since it results in a significant enhancement of the spatial and spectral brightness. This application promises not only power enhancement under retention of coherence, coupled devices with different resonators can achieve remarkably increased overall mode selectivity by exploiting the Vernier effect. Different approaches showed optimal coupling for a coupling- gap of 1 µm. At this geometry, where two separated lasers couple via their evanescent field, a balanced relation between intercavity losses and sufficient coupling strength for robust coherence was achieved [4]. Furthermore, a geometry of directly coupled resonators is presented that features single mode emission at room temperature. These coherently coupled device pairs exhibit an interference far field pattern.

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Investigation of Double Metal THz Quantum Cascade Lasers by Terahertz Time-Domain Spectroscopy

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The study of terahertz quantum cascade lasers (THz QCL) employing a single plasmon waveguide by broadband Terahertz pulses has gained a lot of physical insight [1]. In comparison to the single plasmon waveguide the double plasmon or metal-metal waveguide QCL uses a metal/semiconductor/metal structure. The generation of broadband THz radiation at the facet of a gallium arsenide filled waveguide was reported [2] recently.

We fabricated THz-QCLs in a geometry that allows the generation of broadband THz pulses in the first section of the waveguide and lasing operation within the second section. The THz transient generation on the QCL facet was investigated first. Further the coupling of the broadband THz pulses to the active QCL ridge was studied in experiment and by finite element simulation. The cavity of the emitter section and QCL section were proved to be coupled by FTIR measurements.

The coupled cavity configuration enabled the bias dependent measurement of gain and loss of the THz QCL [3]. The gain and loss processes can be explained by comparison with the calculated bandstructure.

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THz Quantum Cascade Lasers with Superconducting Double-Metal Waveguides

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Quantum cascade lasers (QCLs) are promising sources for future applications in the terahertz (THz) regime like spectroscopy or imaging. The waveguide is crucial for the performance of the device. Double-metal waveguides are commonly used, where the active region is located in between two metal layers confining the optical mode. The waveguide loss is a limiting factor and needs to be minimized. The main contribution is the absorption of the THz radiation in the metal layers, Drude absorption. We replaced the commonly used gold layers by a superconducting material, namely niobium (Nb), to reduce the waveguide losses. We used a 4 well longitudinal optical (LO) phonon depletion design for the active region, with a designed frequency of 2 THz. We fabricated disk shaped resonators, where the optical mode is guided via total internal reflection at the facets of the disk. In this way high lateral confinement is provided. The next steps would be to employ an active region with lower frequency and a superconducting material with higher critical temperature.

THz Conductivity of Graphene

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Since its discovery [1] in 2004, graphene, a single layer of carbon atoms arranged in a honeycomb lattice, attracted enormous attention in many scientific fields. This is not only due to the fact that two-dimensional crystalline systems like graphene were supposed not to exist, but mainly due to the unique electronic properties and possible applications in nanoelectronics.

The crystal structure of graphene consists of two equivalent sublattices. Interaction of electrons between these sublattices leads to the formation of two energy bands that intersect at the points K and K' in k-space. In contrast to conventional metals and semiconductors, the electron dispersion relation is linear and gapless around these crossing points. Under certain conditions, this fact is expected to result into strong interaction between graphene and terahertz radiation and hence makes graphene a very interesting material for the terahertz spectral range.

We present an experimental approach to measure the optical conductivity of a graphene monolayer by means of THz time-domain-spectroscopy involving an on-chip coplanar waveguide structure for generation and detection of THz pulses. While the optical conductivity of graphene is constant in the visible spectral region, it is expected to show strong deviation from this behavior in the THz frequency region [2]. This is due to the fact that interband transitions dominate in the visible range, whereas below the mid-infrared range, intraband transitions are dominant.

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Development of Broadband, Polarization Insensitive Light Couplers for a SOI Based Integrated Optics

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The growing demand for quickly transporting big amounts of data within and between Si integrated circuit chips will hit the limits set by data transfer rates achievable with *electrical* inter-connects in the near future. Intra- and inter-chip *optical* data transmission is regarded as one of the most promising future strategies for providing sufficiently fast data channels. Thus, large efforts are spent world-wide to the development of a Silicon On Insulator (SOI) based optoelectronic platform [1]. Besides the challenges faced in the development of efficient Si based light sources, detectors and fast modulators for integration, also reliable interfaces between optical fibers and chips are required.

In our work, we develop interfaces for efficiently coupling light from optical fibers into SOI based integrated optical circuits that are both interesting for research as well as for commercial applications. The emphasis is devoted to couplers with high efficiency over a broad wavelength region (from 1400 nm to 1600 nm) and for all directions of polarization. From thorough simulations, "inverted taper" structures have been identified as most promising structures satisfying these demands while keeping the overall dimensions of the coupling device as small as possible. A detailed discussion of the working principle is presented that shows the matching the modes of the incident beam of light to the input of the coupler and then transforming the modes to fit the single SOI-waveguide mode at the end of the structure. We show that it is crucial to optimize the dimensions at the start and the end of the tapered waveguide according to "mode coupling" calculations for maximum coupling efficiency.

For the fabrication of our structure we use a combination of optical lithography and electron-beam lithography, exploiting the advantages of both techniques for optimal results. While optical lithography is used to quickly define waveguides over a wide working area, electron beam lithography allows to further alter and "fine-tune" the dimensions of the structures with a very high precision. Aside from this "mix and match" technique, which will also be used to define resonators, inter-chip couplers, feedback structures and devices for light amplification and detection with pinpoint accuracy, we also plan to further increase our range of possibilities for the fabrication of our samples by using nano-imprint technology.

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Photonic Crystal Slab Quantum Well Photodetectors

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Photonic crystals (PCs), structures with a periodic modulation of the refractive index, exhibit fascinating properties for the control of light. Most existing devices are realized as two-dimensional (2D) PC structures, as they are compatible to standard semiconductor processing. To confine the light in the out-of-plane direction the PC is often fabricated as a photonic crystal slab (PCS).

We present a PCS photodetector, designed for resonant absorption of infrared light in quantum wells. Quantum well infrared photodetectors (QWIPs) are reliable and sensitive detectors for the mid-infrared region. However, the performance of QWIPs at higher temperatures is limited by thermally generated noise. By using a PCS for resonant in-coupling of the external radiation it is possible to exceed this limitation [1]. Further, a QWIP is insensitive to surface normal incident light, caused by quantum mechanically forbidden electron transitions. With a PCS fabricated from QWIP material it is possible to achieve efficient coupling of surface normal incident light, increased photon lifetime in the detector active region and improved temperature performance.

The optical properties of PCs are represented by the photonic band structure, which we simulate using the 2D revised plane wave expansion method (RPWEM). Compared to an ideal 2D-PC, which extends to infinity in the out-of-plane direction, the photonic bands in a PCS exhibit a blue-shift, due to the modes leaking out of the slab into the surrounding air. Furthermore, additional resonance peaks appear in the measured photocurrent spectra, which cannot be explained by simple 2D band structure calculations. By processing various PCS-QWIP devices with different ratios between slab thickness and PC lattice constant we were able to identify these resonance peaks as higher order slab modes [2]. This additional knowledge will facilitate the further development of PCS-QWIPs to finally operate at room temperature for applications including thermal imaging or high speed data transmission.

The authors acknowledge the support by the Austrian FWF project IRON, the PLATON project within the Austrian NANO Initiative and the “Gesellschaft für Mikro- und Nanoelektronik” GMe.

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Nanowires at Fke

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During the last 10 years, important progress has been made in the growth of ideal 1D structures, such as carbon nanotubes and semiconductor nanowires. These 1D systems promise to be an exciting field for basic and applied research. At sufficiently small sizes solids exhibit significantly different mechanical, optical, electrical and magnetic properties, when compared to bulk material of macroscopic size. Their low dimensionality means that they exhibit quantum confinement effects. For example, narrowing the wire's diameter increases its band gap, compared to the bulk material. Controlled growth of non-carbon based 1D structures at well-defined locations has been demonstrated only in few examples. Therefore, an understanding of the growth kinetics, the physical and chemical processes on the nanoscale, and their dependence on the growth parameters and template properties is necessary. Researchers are making impressive progress in growing nanowires with precisely controlled properties with all sorts of different technologies including the realization of atomically abrupt heterostructure interfaces inside a nanowire. This better control could give nanowires an edge over carbon nanotubes in some of the same early applications ranging across sensors, batteries, solar cells, medical diagnostics, and high performance electronic devices.

With respect to sensors we demonstrated the formation of a complementary metal-oxide semiconductor (CMOS) compatible micro scale pH sensor with an antimony (Sb) nanowire (NW) network as the solid state pH electrode. The sensor is formed combining well known semiconductor processing techniques with a focused ion beam (FIB) based approach inducing the self assembled formation of Sb nanowires in room temperature ambient without using any additional material source.

As reliable contacts for nanoscale electronic devices we explored an approach for the formation, of copper-germanide/germanium nanowire heterostructures with atomically sharp interfaces. The copper-germanide (Cu_3Ge) formation process is enabled by a chemical reaction between metallic Cu pads and vapor-liquid-solid (VLS) grown Ge-NWs. The atomic scale aligned formation of the Cu_3Ge segments is controlled by in situ SEM monitoring thereby enabling length control of the intrinsic Ge-NW down to a few nm. The single crystal $Cu_3Ge/Ge/Cu_3Ge$ heterostructures were used to fabricate p-type Ge-NW field effect transistors with Schottky Cu_3Ge source/drain contacts.

Formation of Coherent PbTe Nanocrystals in MBE-Grown PbTe/CdTe Heterostructures

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We have demonstrated a novel approach for the synthesis of epitaxial quantum dots, which is based on phase separation between two lattice-type mismatched, immiscible materials in a coherent heterostructure fabricated by molecular beam epitaxy [1]. This principle is applied to the PbTe/CdTe semiconductor system, a combination of a rock salt and the zinc blende lattice of CdTe, which show almost identical lattice constants. Upon thermal annealing, 2D PbTe epilayers are transformed into quantum dots (QD) with highly symmetric shapes and atomically sharp heterointerfaces [2], [3]. Efficient photo- [1] and electroluminescence [4] from the QDs in the mid infrared spectral range has been demonstrated.

To monitor the formation kinetics, we performed in situ annealing experiments with a heatable TEM sample holder. Time resolved measurements reveal the kinetics of the complete disintegration process, which is either governed by interface or bulk diffusion processes. The starting points of this evolution are small CdTe columns penetrating the PbTe epilayer. These columns start to grow laterally and merge, which leads to local trapping of PbTe regions in the form of elongated islands. These islands then develop constrictions and finally small islands are separated. Subsequently, the islands evolve into the highly symmetric equilibrium shape of a small rhombi-cubo-octahedron, which is defined by atomically sharp {011}, {011} and {111} interfaces.

We monitored the different stages from the breaking-up of the 2D layer over the ripple-like PbTe network towards the formation of PbTe QDs in their equilibrium shape. The formation processes are governed by interface diffusion until dots with their final material volume are separated from the PbTe network. The breaking-up of the 2D layer and the disintegration of the wire-like structure are induced by capillary instabilities and driven by interface energy minimization. Separated dots can also reconnect under special conditions and can use the fast interface diffusion to reach the equilibrium shape. Only ripening processes of separated islands, which need longer annealing times or higher temperatures in comparison to the dot formation parameters, are governed by bulk diffusion. These can be quantified by following the disappearing of small dots below a critical radius.

Discussions with W. Heiss and G. Springholz are gratefully acknowledged. This work financially supported by FWF, via project SFB 025.

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Self-Seeded Growth of InAs Nanowires: Fundamental Growth Study and Complex Structures

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Due to the possibility to epitaxially grow high quality heterostructures under a large lattice mismatch, semiconductor nanowires have received a lot of interest. Especially the combination of III-V compound semiconductors with Si is an attractive combination for applications. Most nanowire growth methods use Au particles to seed the one-dimensional growth. This poses a severe setback for electronic and optoelectronic applications, as Au is a deep-trap in Si, effectively making the Si useless for electrical applications. To overcome this problem, mechanisms for Au-free III-V nanowire growth have been developed, like self-seeded particle-assisted growth (SPAG) and selective area growth (SAG).

In this poster an overview over the outcome of our group over the last years of research on this topic are presented.

The results include extensive studies performed to deepen the understanding of InAs nanowire growth using a SiO_x mask layer. In the progress of this work it is shown that SPAG is the only possibility to describe the experimental findings [1].

Additionally, the temporal development of nanowire length and diameter are studied. Results obtained by growing 3 sample series, each evaluating the nanowire dimensions over growth time, are used as basis for a surface diffusion model describing nanowire growth. Interestingly, the only way to explain the obtained results is by assuming that only a single crystal layer at a time can grow at a wire mantle facet.

Using the knowledge of these fundamental studies, we tried to understand more complex and completely new systems:

First, we studied the position-controlled growth of InAs nanowires on Si substrates, which is achieved by a SiO_2 mask layer into which openings are etched. Using patterns with different opening dimensions, we can show that the nanowire dimensions for opening dimension ranging from 80 – 250 nm are independent of the opening size. In addition, much larger openings are tested as well, yielding the growth of crystallites instead of nanowires. This result is in agreement with the observations of the growth mechanism study and can be explained by a liquid In particle seeding nanowire growth.

In a second study the possibility to growth axial InAs/InAsP heterostructures is tested. As it is known that SPAG leads to nanowire growth, such heterostructures should be possible to achieve, if the particle can be preserved during the change of the group V precursor ratio. Here we will demonstrate the method used to obtain such a result, and how such a heterostructure typically looks like.

In a last project the principal possibility to grow another material with SPAG supported by a SiO_x layer is investigated. We can demonstrate that InSb wires can be grown in a self-seeded mechanism using the same type of sample preparation [2].

In conclusion, we demonstrated that self-seeded particle-assisted growth of nanowires is a versatile tool for nanowire growth. Still, many detailed aspects of this growth method remain to be investigated, offering exciting research opportunities.

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Intersubband Plasmons in InGaAs Quantum Wells

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The excitation of intersubband plasmons (ISP) is a promising new effect for the design of novel THz emission sources. The effect studied in this work is based on the interaction of two resonant plasmon modes. To study this phenomenon a special nanostructure was designed [1], [2]. The core of the structure consists of an RTD and an InGaAs well, providing three energy levels. The idea is to bring the energy difference between the higher energies ΔE_{32} in resonance with the energy difference of the two lower levels ΔE_{21} by tuning the energy levels with occupation differences. As the lowest level is highly populated, the inversion between the levels E_3 and E_2 is achieved by injection of electrons into the third level and the extraction from the second level by the RTD. This way the ISPs can be tuned into resonance by depolarization shifts which depend on the population differences. The coupling between these two ISPs can result in a plasma instability providing growing plasma modes at a resonance frequency $\hbar\omega_r = \Delta E_{31}/2 = (\Delta E_{21}+\Delta E_{32})/2$. This process can be described as a collective electron-electron scattering process [1]. The resonance leads to a very strong extraction of trapped electrons from the lowest level. The lowest level is refilled by an efficient scattering process 3 → 1. The strength of the effect is related to an interplay between the extracting resonant plasmon process and the refilling scattering process. We have grown three samples with varying InGaAs well widths ((a) 31 nm, (b) 28.2 nm, and (c) 26.8 nm) resulting in a variation of E_{31}. Thereby the calculated values for E_{31} ((a) 31 meV, (b) 37 meV, and (c) 40 meV) vary around the LO phonon frequency. Due to the filling of the lowest level, charging leads to a lowering of the energy difference E_{31} resulting in a blocking of the LO phonon process. The resonant plasmon effect is also evident directly in the IV-curves. When the two ISP resonances are tuned to equal values by the injected current a sharp increase of the current is observed.

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Reversible Nanofacetting and 1D Ripple Formation of Ge on High-Indexed Si (11 10) Substrate

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Silicon-germanium has been an intensely studied model system for the growth of self-assembled quantum dots by the Stranski-Krastanow mode. A prominent feature of these dots is their highly facetted pyramidal or dome-like shape [1] that is governed by the formation of energetically favored side facets. The formation of the different dot shapes not only depends on the Ge coverage and growth condition, but also on the substrate orientation [2]. The (11 10) Si substrate orientation is special because of its particular relationship to the low energy {105} facets of compressively strained Ge pyramids, in which case the intersections of these facets are parallel to the (1110) surface. In addition, local (1 1 10) Si substrate facets also play a major role in site-controlled growth of Ge islands on pit-patterned or stripe-patterned Si substrate templates [3], [4].

In the present work, Ge growth on high-indexed (11 10) substrates was studied systematically using *in situ* variable temperature scanning tunneling microscopy. The experiments were performed in a multi-chamber MBE/STM system, allowing sequential growth and imaging of the epitaxial surface structure formed after each growth step [4]. The results demonstrate that the (1110) growth properties radically differ from those on the usual (001) Si substrates. At certain critical coverage of ~4 monolayers (ML), a highly stable quasi-periodic 1D ripple structure is formed perpendicular to the dimer direction. Well defined {105} facetted ripples completely cover the whole (1110) substrate surface, in contrast to the usual isolated Ge islands formed by the Stranski-Krastanow growth mode on (001) surface.

A quantitative analysis shows that in the ripple formation process, the initial 2D Ge wetting layer is completely consumed, i.e., no wetting layer remains underneath the ripples. Thus, the ripples represent a novel pathway for lowering the free energy of the system. Moreover, the ripples show a well defined and unique width and height with a lateral periodicity of ~20 nm with a rather narrow size dispersion. Most strikingly, during thermal cycling of the Ge layers on Si (1110), a reversible transition from the rippled surface to a flat surface is found to occur when the annealing temperature is raised above a critical temperature of 600 °C. This process is reversed when the temperature is lowered again. This was demonstrated by variable temperature STM, when the rippled surface was heated from 500 °C to 590 °C and then cooled down again to 500 °C. Moreover thermal cycling was monitored using RHEED, that the intensity evolution of the ripple spot present hysteresis behavior during multiple heating and cooling cycles. Both factors clearly demonstrate that the ripples represent an equilibrium structure and their formation closely resembles a thermodynamic phase transition.

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Pre-Defined SiGe Island Growth on Large-Area, High-Density Pit-Patterned Si Substrates Fabricated by UV Nanoimprint Lithography

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We present the fabrication of pit-patterned substrates using ultra-violet nanoimprint lithography (UV-NIL) [1] for the ordered growth of silicon-germanium (SiGe) islands. For the realization of optoelectronic devices and circuits, it is mandatory to precisely address the position and control the size and chemical composition homogeneity of the islands by pits etched into the substrate [2].

We fabricate replica molds for imprinting by a replication process of a Si master. The molds (17.5 x 17.5 mm^2 in size) contain a pillar pattern [Figure 1 (a)] which is transferred to a hole pattern in the resist during the imprint process. Four fields, each extending over a continuous area of 3 x 3 mm^2 are defined in one imprint step. The hole pattern is transferred to the Si substrate by reactive-ion etching to a depth of 35 nm. We increase the pattern density by reducing the pit period of each field from 260 nm down to 170 nm in steps of 30 nm. The diameter of the pits is reduced as well, down to 120 nm for the smallest period of 170 nm.

After the molecular-beam epitaxy growth of a Si buffer layer, 8.3 monolayers of Ge are deposited at 625 °C. Then, the island surface is capped with a 10-nm-thick Si layer. Atomic force microscopy (AFM) images reveal the nucleation of one SiGe island per pit [Figure 1 (b)]. Photoluminescence (PL) measurements show two narrow peaks for the signal of the ordered islands at 0.79 and 0.85 eV [Figure 1 (c)]. Under these growth conditions, the island-signal shifts to lower energies compared to previous work [3] in which islands were grown at 690 °C with a Ge coverage of 6 ML. Furthermore, dislocations are already introduced in the islands on the planar substrate area, and therefore the PL signal is vanishing.

Our results suggest that UV-NIL opens a route to define high-density SiGe islands with sub-100 nm period over large areas and excellent optoelectronic properties.

This work was performed in the NILaustria project cluster (www.nilaustria.at) and supported by the Austrian NANO Initiative (bmvit and FFG), the IRON project (FWF) and GMe, Austria.

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X-Ray Diffraction and Strain Studies on a Single SiGe Quantum Dot Integrated in a Field Effect Transistor

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We report on the analysis of a single island in a 2D periodic array of SiGe dots. The sample was grown by MBE on e-beam pitpatterned Si (001) substrates and capped with Si for the realization of an n-channel DotFET device. These devices employ epitaxially grown SiGe dots for as stressor for a Si channel to achieve higher tensile strain values compared to conventional Si based MOS devices [1]. We successfully recorded reciprocal space maps of the (004) and (224) Bragg peak of a single SiGe dot with a diameter of 220 nm integrated in a fully processed device with a TiN + Al(1%Si) gate stack and source, gate and drain contacts in place, employing a 400 nm focused X-ray beam at the ID01 beamline of the ESRF in Grenoble [2]. Strain fields in the dot and the Si channel were determined using FEM and X-ray simulations, with the experimental data serving as reference. A maximum in-plane tensile strain of 1% in the Si channel was found, substantially higher than achievable for dislocation-free tensile strained Si on planar substrates.

The electrical evaluation of this transistor was performed by comparing to non-strained reference devices processed on the same wafers but without dots: the DotFET showed an increase of drain current between 20 and 60 % [3].

This work was supported by the EC d-DOTFET project (012150-2) and the FWF Vienna (SFB025 IR-On).

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Microstructural and Electrical Analyses of Oxygen Diffusion into Iridium Metal Gates

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Iridium is used as gate metal for GaN-based $In_{0,17}Al_{0,83}N$/AlN barrier High Electron Mobility Transistors (HEMTs) 0. Before annealing, a high oxygen concentration confined at the Ir/InAlN interface is detected, but neither an aluminum nor an indium oxide interfacial layer has been formed. In this work we investigate the annealing-induced diffusion of the oxygen-rich interlayer and its electrical effects on the device. No stable iridium oxide forms – instead oxygen is able to diffuse out of the interlayer into the iridium gate metal, thus the interlayer is reduced. Above 700°C a homogeneous oxygen concentration is observed in the iridium layer, whereas at 500°C oxygen is distributed inhomogeneously. This behavior is also verified electrically.

The diffusion length of oxygen in evaporated iridium is only in the order of 1 nm for 2 minutes annealing at 500 °C 0. Therefore, oxygen cannot diffuse efficiently in dense iridium at that temperature, so that oxygen diffusion, enhanced by crystal defects and grain boundaries, is assumed. Annealing at 700 °C increases the diffusion length to about 100 nm 0 and allows homogenous diffusion of oxygen into iridium, leading to the most complete removal of the oxygen interlayer, as seen from the C-V-measurements. Additionally, the analysis of the microstructure proves that the thickness of the InAlN/AlN barrier does not change after annealing and metal does not diffuse into the barrier. That confirms the already proven robustness of InAlN.

The rapid thermal annealing was performed for 2 minutes at 400 °C, 500 °C and 700 °C. Two samples with different gate metals (iridium and nickel) are analyzed in order to investigate the dependence on the metal. High-Resolution Transmission Electron Microscopy (HRTEM) gives detailed analysis of the microstructure at the different interfaces. Electron Energy Loss Spectroscopy (EELS) shows the two-dimensional element distribution in the samples. I-V- and C-V-measurements are used to determine the electrical properties.

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ALD Based La_2O_3 Ge Interface Passivation for High Performance MOS-Device Applications

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Ge is the most attractive channel material for next generation p-channel metal-oxide semiconductor (pMOS) devices due to its highest hole mobility and its low dopant activation temperatures. The disadvantage of Ge not to offer a stable, natural homogenous oxide requires the application of an “extrinsic” heterogeneous oxide in terms of electrical and chemical compatibility. For ultrathin dielectric layers envisaged for future CMOS-devices, Atomic Layer Deposition (ALD) is one of the favored deposition processes for high-*k* dielectric materials due to its high uniformity, high conformity, and excellent thickness controllability of the layers. Several very capable approaches for Ge surface passivation techniques have been reported, and superior electrical behavior of the dielectrics by using Atomic Layer Deposition (ALD) mainly on interfacial GeO_2 has been observed. The rare earth oxide La_2O_3 is one of the most promising high-k dielectrics in order to passivate the hardly controllable Ge interface. It seems that La_2O_3 passivations can uniquely meet required scaling abilities and low interface trap densities. In this discussion, both aspects will be addressed: On the one hand, it will be shown that ALD grown La_2O_3 is capable to reach 0.5 nm equivalent oxide thickness (EOT) and on the other hand, a strong reduction of interface trap densities down to mid-10^{11} $eV^{-1}cm^{-2}$ will be presented by a Pt-assisted annealing approach of La_2O_3/ZrO_2 oxide stacks. Conductance measurements also indicate the absence of compromising mid-gap traps by using La_2O_3 passivation layers.

This work is funded by the Austrian Science Fund (FWF), project No. P19787-N14. The Gesellschaft für Mikro- und Nanoelektronik (GMe), as well as the ZMNS, are gratefully acknowledged.

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Utilizing Pressure Waves for Sensing the Properties of Liquids

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As the detection of fluid properties is of importance for numerous technical processes, sensors for liquid condition monitoring are an important asset for process control. Industrial applications require reasonably priced sensors which are small in size, lightweight, robust, need little maintenance, and are preferably suitable for online monitoring. A lot of recent work has been focused on viscosity sensors. Laboratory equipment for determining the shear viscosity involves motors and rotating objects immersed in the liquid and is commonly bulky, maintenance intensive, and not suitable for online monitoring. Miniaturized sensors for fluid viscosity (e.g. small, vibrating structures immersed in the liquid) often utilize shear vibrations. With these devices, due to the small penetration depth (in the range of a few micrometers, depending on the frequency of the vibrations), only a thin film of the fluid is measured, which represents a crucial disadvantage for many applications. An alternative approach is to use pressure waves instead of shear waves so that a bulk of a sample is probed. With this approach not the pure shear viscosity but the so-called longitudinal viscosity is determined. The longitudinal viscosity can be equally useful for condition monitoring applications as the shear viscosity. At the moment material data for the longitudinal viscosity is rare because this parameter has not been widely experimentally investigated. We will introduce a concept utilizing standing acoustic pressure waves in a liquid sample chamber (consisting of two rigid boundaries) excited by a PZT transducer. We discuss the impact of fluid parameters (sound of speed, longitudinal viscosity) on these resonances. First the evaluation of a 1D-model for the sensor setup including simulation results is presented. Furthermore first measurement results obtained with a first prototype device are presented.

A Feasibility Study on Tuneable Resonators for Rheological Measurements

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In this contribution a feasibility study on resonating sensors for rheologic properties such as e.g., viscosity facilitating measurements at tunable frequencies is presented. For the concepts presented in this work, sample liquids are subjected to time harmonic shear stresses induced by a resonating wire and a suspended resonating platelet, respectively. From the resulting frequency response the liquid's rheological properties can be deduced by fitting the parameters of an appropriate closed-form model representing the physical behavior of the sensors. To allow large penetration depths of the shear waves being imposed by the resonating mechanism into the test liquid, it is desired to have oscillators with resonance frequencies in the low kilohertz range. Large penetration depths become important when examining complex liquids such as multi-phase systems as, e.g., emulsions. For the investigation of liquids showing shear thinning (or thickening) or viscoelastic behavior, it is necessary to record the liquid's characteristics not only at one single frequency but in a range of different frequencies, which in the best case should cover several decades of resonance frequencies. For this purpose, especially in the case of resonating microsensors, it is desired to have devices which can be operated at tunable frequencies without changing their geometries. For the two concepts presented in this work, the ability of tuning the sensor's resonance frequency is based on varying the normal stresses within tungsten wires. The use of appropriate materials and different micro-fabrication techniques are discussed and the applicability of the devices for rheological measurements is outlined. The models are compared to measurement results and the capability of the particular resonator for accurate and reliable sensing is discussed.

Impedance Spectroscopic Measurements on Fluids in a Digital Microfluidic Platform

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Digital microfluidics combines the advantages of low consumption of reagents with a high flexibility of processing fluid samples automatically. For applications in life sciences not only the processing but also the characterization of fluid analytes is crucial. In this contribution a microfluidic platform combining the actuation principle of electro wetting on dielectrics for droplet manipulations and the sensor principle of impedance spectroscopy for the characterization of fluid composition and condition is presented.

The fabrication process of the microfluidic platform comprises physical vapor deposition and structuring of the metal electrodes onto a substrate, the deposition of a dielectric isolator and a hydrophobic top coating.

The key advantage of this microfluidic chip is the common electric nature of the sensor and the actuation principle, so no additional sensor integration is necessary. Multiple measurements on fluids of different composition (including rigid particles and biologic cells) and of different conditions (temperature, sedimentation) were performed as well as online monitoring of in process parameters changing over time. These sample applications demonstrate the versatile applications of this combined technology.

A Microfluidic Chip for Infrared CH_2-Stretch Ratio Measurements of Suspended Mammalian Cells

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Since cancer has been one of the major causes of death in the recent years, the early detection and accurate staging of primary tumours are highly important for increasing the overall survival rate of cancer patients. Unfortunately, commonly used techniques that are based on morphological and molecular features in order to screen suspicious tissue or cell samples, e.g. visual inspection after staining cellular components, still produce a high number of false positives and negatives.

As alternative screening method a four-wavelength mid-IR sensor system for measuring the CH_2-symmetric/CH_2-antisymmetric stretch ratio of mammalian cell samples was realized and it was shown that this CH_2-stretch ratio is significantly increased for epithelial kidney carcinoma cells compared to the normal cell type [1], [2].

In this contribution we present a method for measurements of the CH_2-stretch ratio of suspended mammalian cells. Instead of the elaborate and time consuming step to obtain a confluent cell monolayer attached to an infrared transparent CaF_2 (calcium flouride) slide followed by drying, the cell sample is suspended in PBS (phosphate buffered saline) and directly introduced into a sample chip. The chip consists of two bonded CaF_2 wafers with SU-8 chamber structures in between. Each sample chip is composed of three equal microfluidic chambers with a height of only 20 µm in order to overcome the strong infrared absorbance of water while permitting an even distribution of the approximately 15 µm large epithelial kidney cells throughout the sample chamber.

The IR absorption of two epithelial kidney cell lines MDCK (Madin-Darby Canine Kidney) and Caki-1 was measured and we successfully distinguished normal MDCK from malignant Caki-1 by comparing their CH_2-stretch ratio.

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Cell Separation in a Continuous Flow by Traveling Wave Dielectrophoresis

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In this contribution we present a microfluidic chip for the continuous and label-free separation of cells. The microfluidic channel, fabricated by PDMS soft lithography is placed on top of a glass with strip electrodes along the channel. These electrodes produce a traveling electric field perpendicular to the pressure driven flow. Viable cells are deflected parallel to the field by traveling wave dielectrophoresis (twDEP) according to their volume and dielectric properties. With the present device we have successfully separated viable *Saccharomyces cerevisiae* and *Jurkat* T-cells from debris, non-viable cells and *Lactobacillus casei*.

Common separation techniques of suspension grown cells, such as Fluorescent Activated Cell Sorting (FACS), require elaborate protocols and equipment. Dielectrophoresis has been widely applied for the label-free separation of particles and biological cells [1]. In contrast to conventional dielectrophoresis, twDEP does not require a nonlinear electric field. Therefore, the twDEP force is constant across the channel and cells can be moved with a better efficiency [2].

In experiments we demonstrated the efficient separation of viable *S. cerevvisiae* and *Jurkat* T-cells from debris, non-viable cells and bacterial contamination (*L.casei*). Altogether, 87% of *S. cerevisiae* and 86.5% of *Jurkat* cells traveled across the entire channel and left the device as a purified sample stream close to the channel wall.

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In Incubator Live Cell Imaging Platform

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In this contribution we present an imaging platform for the simultaneous investigation of multiple cell cultures. It operates in standard incubators and is compatible with disposable multi-well plates. The system consists of four image sensors (Charge-Coupled Devices with a resolution of 640 × 480 pixels) located in a custom made holder, below a multi-well plate that can be positioned without any further alignment. Each sensor is provided with a mini lens with *f* 2.0 and 4.3 mm focal length. The distance between the sensor and its lens is adjusted in order to focus at the base of the wells of interest, where adherent cells grow. In these conditions, a field of view of 3.26 × 2.45 mm^2 on the focal plane is achieved. This corresponds to an optical resolution of 5.1 µm in both directions. Above the sensors and the biological samples, white emitting LEDs with an aperture are mounted to provide orthogonal illumination.

For the observation and understanding of tumour progression, the study of cell motility is of great importance. For this reason, a sensor system that monitors in real-time cell motility in four different wells has been designed and realized. This makes the imaging system advantageous for testing a cell line with different analyte species/concentrations and for extracting statistically relevant biological parameters by having more samples under the same conditions.

The system has been tested by monitoring the motility in two stimulated and two control cell populations. For this purpose, epithelial Madin-Darby Canine Kidney (MDCK) cells have been used. To promote cell movement, Hepatocyte Growth Factor (HGF) in a concentration of 20 ng/ml has been added to the cultivation media. Successful cell trajectory tracking has been obtained by the real-time monitoring. Furthermore, the mean cell velocity of HGF-stimulated and control cells has been calculated from the observation of 10 individuals per population.

Diagnostic Polymer Disc for Process Speed-Up of DNA Microarrays for Bacterial Classification

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Infectious diseases are a major health threat, in particular when they are not treated in an early stage. In addition the causative bacterial species are rarely identified prior to initiation of therapy, which decreases treatment efficiency and may induce novel antibiotic resistances. Therefore a rapid assay for species-specific identifications is of great importance for effective patient convalescence and confining drug resistances of pathogens. One of these assays is DNA microarray technology; however it is time and labor demanding and requires trained technicians. With our developed polymer disc we can reduce processing and hands-on time and increase process automation.

The developed polycarbonate chip is designed to transform low amounts of bacterial DNA into fluorescently labeled amplicons ready for microarray hybridization. This is performed in a spiral microfluidic channel with 40 turns and two meanders for pre-denaturation and post-annealing respectively. The whole chip is tempered with three symmetric external heating sectors for denaturation, annealing and extension. When the samples are pumped through the spiral, they undergo a polymerase chain reaction (PCR) protocol. The fabricated polycarbonate disc was compatible to biological samples and required reagents. The channels were molded correctly and the bonding of the polycarbonate film was withstanding the used flow rates of 111 $nl.s^{-1}$. This makes the disc ready for mass production. The thermal distribution across the disc showed deviations of maximal 1.5 °C in the outer regions, which was appropriate for fast transitions between the temperature stages. The chip was tested with Staphylococcus aureus and led to a sensitivity of 100 cells per reaction, which qualifies the system for clinical applications. Performing the reaction in the microfluidic disc showed a time saving from 6 h to 1.5 h, because of absent ramping times between temperature stages, which limit the speed in conventional thermocyclers. The combination of DNA amplification and fluorescence labeling in a one-step approach reduced hands-on time and increased process automation. We have overcome the limit of analysis time for microarrays by accelerating the overall process 4-fold, resulting in a processing time of 1.5 h. The fabricated disc is biocompatible and the production technique is capable for mass production. Therefore the diagnostic disc presents a rapid assay for species identification.

Analytical, Numerical and Experimental Analysis of Capacitive Transducers Damping Constant

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Designing a tailored transducer for specific applications needs the knowledge of mechanical system parameters like mass, spring constant and damping constant. Latter one can be determined analytically, numerically and by setting up an experimental design. Numerical and analytical solutions have the advantage that they don't afford expensive manufacturing of test samples and don't need test equipment. However, mathematical solutions have to be accurate in order to be of advantage for the design process.

To investigate the benefit of analytical and numerical damping calculations for the design process of micromachined transducers, capacitive MEMS prototypes with varying damper geometries were produced and an experimental setup was engineered. The setup contains a custom made vacuum chamber and a custom made shaker unit. Both allow the analysis of the damping behavior in the continuum flow and in the slip flow regime. Especially the latter regime is important for capacitive transducers as it is an often found condition in microstructures due to small geometry dimensions.

The analytical solution of the damping behavior shows differences compared to experimental data. This is in consequence of tight boundary conditions in order to solve analytical equations. Furthermore, not all conditions in the prototyped microstructure are regarded in state of the art solutions. Despite this, analytical equations are a sufficient method for the first designs iteration of micromachined transducers. In contrast to the analytical data, numerical data are corresponding with experimental data. This is due to the fact that the boundary conditions of the prototype devices are mainly included in the simulations model. However, configuration parameters of the numerical Navier-Stokes simulation are based on analytical calculations. Therefore, both approaches, analytical and numerical, are necessary for the design of tailored transducers, especially if complex geometries with a broad set of boundary conditions are used.