Final Report

Title of the project

“Direct growth of single-crystalline semiconductors on poly-crystalline metallic films and foils”

Leibniz-Institute: Paul-Drude-Institut für Festkörperelektronik

Reference number: SAW-2013-PDI-2

Project period: 01. May 2013 – 30. April 2017

Contact partner: Dr. Lutz Geelhaar and Dr. Oliver Brandt

Stand: 30. October 2017

Contents

Executive Summary Project: “Direct growth of single-crystalline semiconductors on poly-crystalline metallic films and foils”

The growth of single-crystalline materials in high structural quality has set the basis for advances in condensed matter physics and information technology, and nowadays both fields are unthinkable without single crystals. More specifically, many devices and fundamental studies rely on heterostructures composed of different materials that must be fabricated without introducing structural defects. Up to now, the only known way to fabricate such heterostructures of single crystals is their epitaxial growth where excellent structural quality is only achieved if the atomic structures of adsorbate and substrate are as similar as possible. Epitaxial growth is thus a powerful tool, but its requirements have drastically limited the choice of materials that can be monolithically combined in high structural quality. The goal of this project was to lift these constraints without sacrificing the crystal quality in the functional material, and thus to introduce a new paradigm for the synthesis of hybrid structures comprising highly dissimilar materials. For a proof of principle, we aimed at the direct growth of single-crystalline GaN (the nowadays most commercially important compound semiconductor) in the form of nanowires on single- and poly-crystalline metallic substrates, i. e. at the monolithic combination of two materials that differ in the type of chemical bonding, crystal symmetry, lattice constant, and even degree of crystallinity.

In this project we have demonstrated the growth of single-crystalline GaN nanowires on four different types of non-conventional and technologically relevant substrates: (i) single-crystalline metallic films, (ii) poly-crystalline metallic foils, (iii) single-crystalline graphene, and (iv) metallic foils covered with poly-crystalline graphene. The synthesis, morphological, optical, and structural characterization of the GaN nanowires was performed at PDI with only sporadic support from external collaborators. A large number of scientists from PDI have contributed to this project including Master and PhD students that were trained within the framework of the project. The results derived from our studies, which validate our initial hypothesis, have been published in peer-reviewed scientific journals with high impact factors and presented at numerous international conferences. Whenever it was actually possible, we have advertised and provided open access to our research through the PDI website.

The successful demonstration of the heteroepitaxial growth of single-crystalline GaN in the form of nanowires on highly unconventional and technologically relevant substrates is expected to enable the implementation of novel device concepts. At PDI we plan to further pursue the synthesis of complex nanowire heterostructures for two different applications: ultraviolet light emission and energy harvesting based on the piezoelectric effect.

1. Motivation and Objectives

Conventional epitaxy is essentially based on the concept of inducing the growth of a single-crystalline film by using the atomic lattice of the substrate as a template. Substrate and adsorbate can be considered as laterally infinite with respect to the unit cells of the two crystals. Consequently, crystal defects form very rapidly if the equilibrium configurations of the two atomic lattices are not almost identical. Typically, these defects are not confined to the interface region but extend throughout the entire sample and compromise its use for applications. Moreover, in the epitaxy of dissimilar materials, growth conditions generally strongly differ for the two materials, such that material A can be easily grown on material B but not vice versa. This effect is particularly pronounced for the combination of semiconductors and metals, for which the growth of semiconductors on metals has remained an unsolved challenge.

In this project we investigated a novel approach that exploits the fact that many materials can be induced not to grow as planar films but uniaxially as single-crystalline filaments, whiskers, or nanowires (NWs) that extend perpendicularly to the substrate. In this case, the formation of single crystals is the result of materials properties and growth conditions, instead of being enforced by epitaxy on a suitable substrate. As a matter of fact, it is often rather difficult to induce planar epitaxy for such materials, and the tendency for filamentary growth is most pronounced on dissimilar substrates. Furthermore, due to the limited interface area and the NW geometry, defects generated at the interface will exit the crystal at or close to the interface and will not propagate along the NW. Hence, a match in lattice constant and thermal expansion coefficient is no longer required. Most crucially, self-assembled NWs grow vertically in an ordered fashion even without epitaxial guidance, thus enabling the device processing of as-grown NW ensembles. Therefore, materials scientists, physicists, and device engineers alike are liberated in the choice of substrates. Filamentary growth is very well known for many metals, but also for semiconductors such as ZnO and GaN. The latter is commercially the most important compound semiconductor because of its use for display and optical storage technology as well as various lighting applications. Our project therefore was focused on this semiconductor. In particular, it is well established that GaN can be grown in the form of NWs without the help of any external catalyst or pre-patterning by plasma-assisted molecular beam epitaxy (PAMBE). The resulting NWs are free of extended defects and exhibit very intense and narrow photoluminescence. Moreover, this growth mode has been found for various types of substrates including single-crystalline AlN buffers, Si covered with thin amorphous Si_xN_y layers but also thick amorphous Si_xO_y buffers. Particularly remarkable is the last example where a single-crystalline semiconductor is grown on an amorphous substrate. This finding justifies our basic assumption that growth of single-crystalline semiconductor NWs is possible without interaction with a crystalline substrate.

We planned to exploit this phenomenon and extend it to the growth of GaN NWs on different types of single- and poly-crystalline metallic substrates. All of them provide high electrical conductivity and may serve as a bottom electrode in devices. In principle, the most ideal substrate is single-crystalline, and due to the high cost of metallic bulk crystals, we planned to fabricate single-crystalline metal films by sputtering. We also considered the use of single-crystalline epitaxial graphene sheets and films synthesized on SiC because they offer the benefit of mechanical flexibility after exfoliation and dry transfer. At the same time, the graphene surface is inert and smooth. Additionally, we also considered in our proposal the growth of GaN NWs on poly-crystalline metallic foils and films sputtered on amorphous substrates. The use of metallic foils is of particular interest because they are flexible and cheaper than graphene. However, their surfaces cannot be expected to be as clean and smooth and have to be prepared in situ.

The overall goal of this project was thus the direct growth of GaN NWs in high structural quality on single-crystalline and poly-crystalline metallic substrates. This goal was originally broken down into the following detailed objectives:

- Growth of single-crystalline GaN NWs on:
  - single-crystalline metallic films
  - poly-crystalline metallic films
  - poly-crystalline metallic foils
  - single-crystalline epitaxial graphene
- Elucidation of the filamentary growth mechanism
- Elucidation of the microstructure at the interface between GaN and the metallic substrate
- Achievement of GaN NWs with a crystal quality comparable to that of state of the art planar films
- Demonstration of a light-emitting diode (LED) directly grown on a metallic substrate

2. Project History

From 01.05.2013 to 31.12.2014, we accomplished the following tasks:

- Recruitment of a PAMBE tecnician and two PostDocs for the growth and ex situ characterization of GaN NWs.
- Installation of a sputtering chamber. The sputtering chamber was designed, constructed, and connected to our PAMBE system to enable the preparation of metallic films without exposing to the air the substrate before GaN epitaxy. This sputtering chamber can be used to sputter different metals by exchanging the target. The chamber has also been equipped with a N_2 line for reactive sputtering of nitride compounds as well as an Ar ion gun and an atomic H source for the preparation of the starting surfaces.
- Optimization of the sputtering of single-crystalline Ti films on Al_2O_3(0001) substrates.
- First growth experiments devoted to obtaining GaN NWs on single-crystalline sputtered Ti films.
- Optical and structural characterization of GaN NW ensembles prepared on sputtered Ti films payng special attention to the ocurrence of interfacial reactions.

Due to the extremely successful growth of GaN NWs on single-crystalline Ti films, we decided not to pursue the growth on other metals mentioned in the proposal such as Fe and Re. Instead, we focused our efforts on obtaining a comprehensive understanding on the growth mechanisms governing the self-assembled formation of GaN NWs on Ti as well as on exploring the synthesis of these nanostructures on flexible foils and graphene. During 2015 and 2016, we performed the following tasks:

- Installation of the acquired energy-dispersive X-ray spectroscopy system in our transmission electron microscope.
- Analysis of the growth mechanisms underlying the self-assembled formation of GaN NWs on sputtered Ti films.
- Investigation of the growth of GaN NW ensembles on flexible poly-crystalline Ti foils.
- Synthesis of epitaxial graphene structures on SiC using the surface graphitization method.

- Fundamental studies on the growth of GaN NWs on different types of single-crystalline epitaxial graphene layer structures synthesized on SiC. Specifically, we investigated the growth on three different types of graphene layer structures: singlelayer, bilayer and multilayer graphene.
- Optical and structural characterization of the GaN NWs prepared on epitaxial graphene.
- Publication of the results related to the growth of GaN NWs on Ti films and foils.

At this time, we discovered, within the framework of a parallel project, that N-polar (In,Ga)N/GaN quantum wells are characterized by a complete absence of luminescence due to a massive incorporation of interfacial point defects [S. Fernández-Garrido et al., Phys. Rev. Applied, **6**, 034017 (2016)]. Since (In,Ga)N/GaN quantum wells are required for the fabrication of efficient LEDs in the visible spectral range and because of the fact that self-assembled GaN NWs are irrevocably N-polar, we decided not to pursue the fabrication of LEDs during the rest of the project.

During the last months of the project, from 01.01.2017 to 30.04.2017, we accomplished the following tasks:

- Analysis of the impact of substrate preparation on the growth of GaN NWs on Ti foils.
- Exploration of the growth of GaN NWs on poly-crystalline multilayer graphene films prepared on Cu foils.
- Publication of the results related to: (i) the growth mechanisms governing the self-assembled formation of GaN NWs on sputtered Ti films, (ii) the effect of substrate preparation on the synthesis of GaN NWs on Ti foils and (iii) the growth of GaN NWs on epitaxial graphene.

3. Project Results

3.1 PAMBE and Properties of GaN Nanowires on Single-Crystalline Ti Films

In a first step, we demonstrated the growth by PAMBE of vertically oriented self-assembled GaN NWs on a single-crystalline Ti film sputtered on Al_2O_3(0001). Both in situ electron diffraction as well as ex situ ellipsometry and energy-dispersive X-ray spectroscopy show that Ti is converted into TiN upon exposure of the surface to the N plasma. In addition, the ellipsometric data demonstrate this TiN film to be metallic. The diffraction data evidence that the GaN NWs have a strict epitaxial relationship to this film. Photoluminescence spectroscopy of the GaN NWs shows excitonic transitions virtually identical in spectral position, line width, and decay time to those of state-of-the-art GaN NWs grown on conventional substrates like Si. Therefore, the crystalline quality of the GaN NWs grown on metallic TiN and on Si is equivalent.

In a second step, we investigated in detail the underlying mechanisms behind the nucleation and growth of GaN NW ensembles on sputtered Ti films. Our results revealed that, under specific growth conditions, this type of substrate allows the synthesis of long and thin GaN NWs that do not suffer from coalescence [see Fig. 1(a)], a problem common to the growth on Si and other substrates. Only beyond a certain NW length that depends on the NW density and exceeds here 1.5 µm [Fig. 1(b)], coalescence takes place by bundling, a process triggered by the minimization of the total NW surface energy at the expense of the elastic energy of bending. The key factor leading to coalescence degrees as low as 7% in fully developed NW ensembles on TiN is their low NW number density of about 10^9 cm^{-2}. By analyzing the nearest neighbor distance distribution, we identified the diffusion-induced repulsion of neighboring NWs as the main mechanism limiting NW density during nucleation on TiN. Since on Si the final density is determined by shadowing of the impinging molecular beams by existing NWs, it is the difference in adatom surface diffusion that enables the formation of NW ensembles with reduced density on TiN.

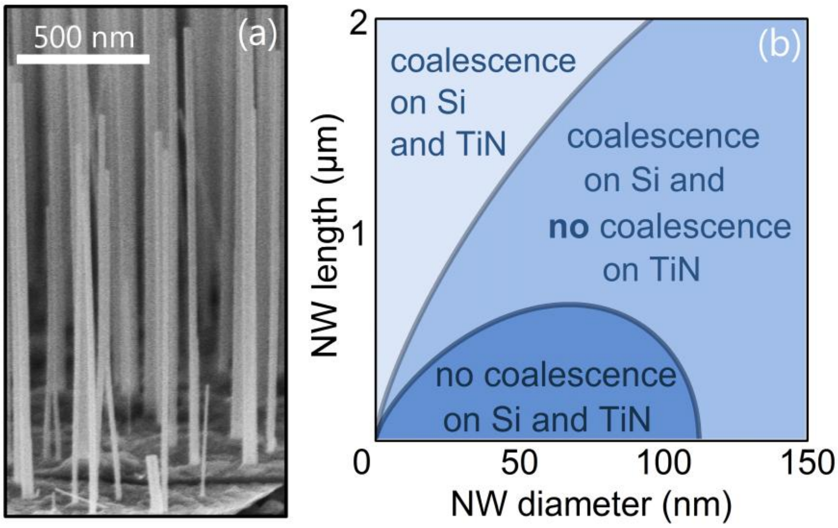

Figure 1. (a) Bird's eye view scanning electron micrograph of a GaN NW ensemble prepared on a single-crystalline Ti film sputtered on Al_2O_3(0001). (b) The graph indicates the values of the NW diameters and lengths for which it is possible to obtain uncoalesced GaN NW ensembles in TiN and Si. For a given diameter, significantly longer NWs can be grown on TiN without coalescence. Reprinted with permission from Nano Res. (2017). Copyright 2017 Nano Research.

The properties of the NW ensembles obtained on Ti films are an excellent basis for the fabrication of more complex structures. Due to the low coalescence degree, the GaN NWs on Ti exhibit a much more regular plain-view cross-section than the irregular aggregates typically formed on other substrates. This feature may significantly improve the structural quality of axial heterostructures. As a matter of fact, on the basis of the results obtained in this project, we have recently demonstrated the fabrication of (In,Ga)N/GaN quantum discs embedded into GaN NWs with unprecedented structural properties [J. Bartolomé et al., Nano Lett., **17**, 4654 (2017)]. The GaN NWs obtained on Ti are also suitable for the fabrication of devices based on radial heterostructures (known as core–shell heterostructures) because their low number density enables the growth on the NW sidewalls, something hardly possible to achieve on conventional substrates without using pre-patterning techniques. Hence, our NW ensembles are promising templates for the realization of well-defined and homogeneous multi-shell heterostructures whose properties may prove useful for various applications.

The results reported in this section has been published in Nano Letters and Nano Research (see section 7.1).

3.2 PAMBE and Properties of GaN Nanowires on Poly-Crystalline Metallic Foils

We have demonstrated the growth of ensembles of single-crystalline, uncoalesced, and vertically aligned GaN NWs on a flexible poly-crystalline Ti foil using PAMBE (Fig. 2). The structural and optical properties of the sample, investigated by transmission electron microscopy and photoluminescence spectroscopy, were compared with those of standard GaN NW ensembles prepared on Si substrates. We found that both the structural perfection and the low temperature photoluminescence spectra of the NW ensembles prepared on Ti foils and Si substrates are fairly comparable. Furthermore, we do not observe any degradation of the luminescence upon bending the NW ensemble prepared on the foil down to a small curvature radius of 4 mm. Therefore, a GaN NW ensemble on a Ti foil is found to be indeed a highly flexible system suitable for the realization of bendable GaN-based devices. Nevertheless, we have also found that the orientation of self-assembled GaN NWs grown by PAMBE on Ti foils depends critically on both the chemical composition and the crystallinity of the native surface oxide layer as further explained below.

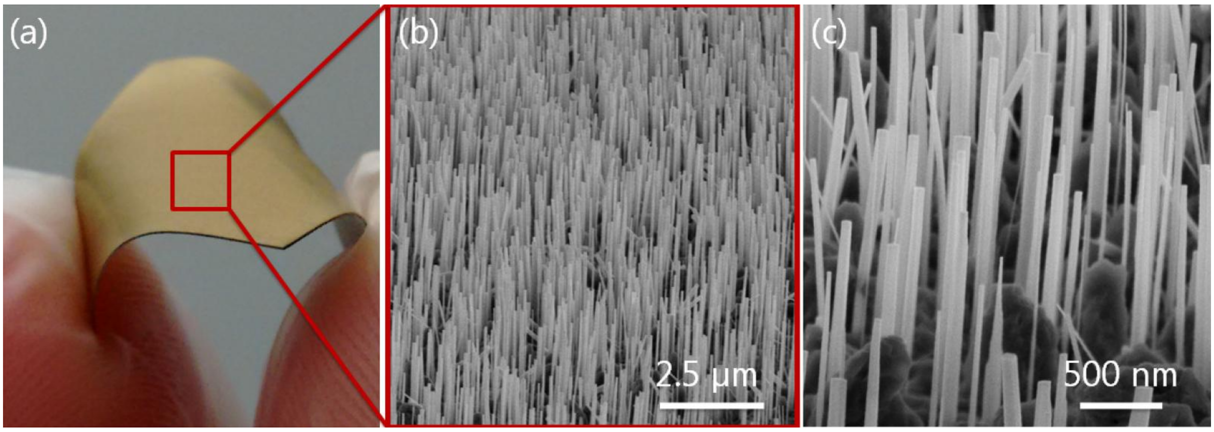

Figure 2. (a) Photograph of the Ti foil after NW growth demonstrating a high degree of flexibility. [(b) and (c)] Scanning electron micrographs of the GaN NW ensemble grown on the Ti foil taken in bird's eye view with (b) low and (c) high magnification. The red square in (a) is not to scale. Reprinted with permission from Appl. Phys. Lett. **108,** 202101 (2016). Copyright 2016 AIP Publishing LLC.

Regardless of the initial morphology of the as-received foil, we found a severe roughening of the substrate surface as a result of chemical reactions occurring between the impinging elements (Ga and N) and Ti. These chemical reactions and the concomitant roughness lead to the formation of randomly oriented GaN NWs. We have established an in situ surface nitridation treatment prior to GaN NW growth which reduces the surface roughening by transforming the topmost atomic layers into more stable compounds, i.e., TiN_x and TiO_xN_y. On nitridated foils, GaN NWs have been found to be well aligned, but their specific orientation depends critically on the crystalline properties of the surface oxide after nitridation. For the foils investigated in our studies, the native oxide layer was either crystalline or predominantly amorphous. When the native oxide is crystalline, GaN NWs grow homogeneously tilted at the surface of each individual grain composing the substrate. In contrast, the presence of an amorphous surface oxide prevents epitaxial growth. The NWs then grow vertically oriented all across the substrate. This result is consistent with other reports, where ensembles of vertically oriented GaN NWs were grown on amorphous Si_xO_y and Al_xO_y layers deposited on crystalline Si substrates. Our study allow us to conclude that a thermally stable amorphous layer of TiO_2 or TiO_xN_y serves as a suitable interlayer for the growth of vertically oriented GaN NWs on Ti foils. This finding may be exploited for the fabrication of GaN NW-based bendable devices without relying on lift-off or substrate transfer techniques. The successful direct fabrication of efficient bendable electronic and photonic devices from NWs grown on metal foils will of course depend strongly on the resistance introduced by the TiO_2/TiO_xN_y layer. Amorphous TiO_2 is an insulator with a high electrical resistivity. It follows that effective carrier injection from the Ti foil into the GaN NWs could only be achieved in the presence of extended defects (as in the case of GaN NW-based LEDs fabricated on AlN-buffered Si) or by electron tunneling, an effect that strongly depends on the thickness of the oxide layer. For the fabrication of devices, it is thus essential to control the formation of the surface oxide layer. Suitable control could possibly be achieved, for example, by an anodization processes. An alternative strategy to obtain vertically oriented NWs on a Ti foil, without sacrificing the benefit of a highly conductive substrate, would be the introduction of a conducting and amorphous interlayer, such as a TiO_xN_y layer fabricated under specific conditions. Finally, our findings could be extended to the formation of self-assembled and vertically oriented NWs of other semiconductors (e.g. ZnO) on different types of metal foils provided that the surface is passivated against detrimental chemical reactions and covered by a thermally stable amorphous layer.

The results reported in this section has been published in Applied Physics Letters and Nanotechnology (see section 7.1).

3.3 PAMBE and Properties of GaN Nanowires on Single-Crystalline Epitaxial Graphene

We have analyzed the self-assembled formation of GaN NWs by PAMBE on several types of single-crystalline epitaxial graphene layer structures prepared at PDI on SiC substrates employing the surface graphitization method in an inductively heated furnace. Our study demonstrates that graphene is etched during GaN growth by the impinging active N species. In view of the fact that the concentration of ionized active N species in the plasma is known to depend on the type of radio frequency plasma source as well as on the operation conditions (the power applied and the N_2 flow), it might be possible to minimize or even suppress the etching of graphene during the formation of GaN NWs in PAMBE. Further studies are required to elucidate this issue that might affect the conclusions of previous reports on the growth of GaN NWs on graphene. Moreover, these results are not only relevant for the GaN community but also of interest for the fabrication of graphene/BN heterostructures by PAMBE. Regardless of this possibility, graphene is etched very slowly (about 10 layers/h) for the conditions used in our study. Therefore, a certain number of graphene sheets survive the growth process when employing a film containing several tens of sheets [known as multilayer graphene (MLG)] for the synthesis of GaN NWs. We find that the resulting NWs (see Fig. 3), which preferentially nucleate at step edges and morphological

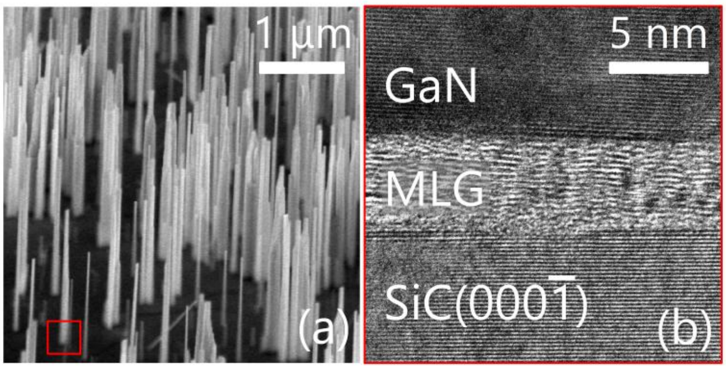

Figure 3. GaN (a) Bird's eye view scanning electron micrograph of a GaN nanowire ensemble prepared on an epitaxial multilayer graphene (MLG) film synthesized on SiC. (b) High-resolution cross-sectional transmission electron micrograph revealing the presence of a continuous multilayer graphene film between the GaN nanowires and the SiC substrate. Reprinted with permission from Nano Lett. **17**, 5213 (2017). Copyright 2017 American Chemical Society.

defects, are interconnected through the remaining graphene layers as desired for the fabrication of GaN NW-based devices on graphene. The NWs are vertical, elongate along the [000-1] direction, and exhibit a well-defined in-plane epitaxial relationship with the substrate, namely, the GaN⟨1-100⟩ directions are perpendicular to the zigzag edges of the graphene sheets. The structural perfection of these NWs is comparable to those of standard GaN NW ensembles prepared by PAMBE on conventional substrates like Si as demonstrated by photoluminescence spectroscopy. In comparison with previous reports on the synthesis of similar structures by PAMBE on transferred graphene, the NWs prepared on epitaxial graphene are better oriented and exhibit narrower excitonic transitions reflecting a reduced concentration of structural defects. Consequently, the synthesis of GaN NWs on epitaxial graphene does not only enable the direct fabrication of hybrid GaN/graphene devices on large area wafers without the technical inconveniences inherent to the graphene transfer process, but also improves the morphological and structural properties of the final NW ensembles. After demonstrating here the synthesis of GaN NWs on epitaxial MLG films, we will analyze the electrical properties of the resulting GaN/graphene interface. Such a study, which is underway at PDI, could then be used to conclusively evaluate the actual potential of using epitaxial graphene as a built-in bottom contact for the fabrication of NW-based devices by PAMBE.

The results reported in this section has been published in Nano Letters (see section 7.1).

3.4 PAMBE of GaN Nanowires on Ni Foils Covered with Poly-Crystalline Multilayer Graphene Films

We have explored the formation by PAMBE of self-assembled GaN NWs on a commercial poly-crystalline MLG film deposited on a Ni foil by chemical vapor deposition (CVD). As previously found for the growth of GaN NWs on epitaxial graphene, also CVD grown graphene is partially etched by the active N species during GaN epitaxy. Due to the large thickness of the starting MLG film (about 100 nm), some graphene sheets survive the formation of GaN NWs in PAMBE. The optical properties of the NW ensembles, studied by low temperature photoluminescence spectroscopy, are fairly comparable to those of GaN NWs grown on Si. MLG was found to efficiently interrupt the transfer of the epitaxial information from the underlying grains composing the Ni foil to the NWs, resulting in the formation of ensembles of nearly vertically oriented NWs over the entire substrate. However, the NWs exhibit distorted shapes and are highly coalesced. The large degree of coalescence is likely a consequence of the high density of defect-related nucleation sites present on CVD grown MLG. Further studies are required to elucidate whether on these substrates it is possible to obtain NW ensembles with morphological properties comparable to those of NW ensembles prepared on conventional substrates.

4. Exploitation

The successful demonstration in this project of the heteroepitaxial growth of single-crystalline GaN in the form of NWs on highly unconventional and technologically relevant substrates such as sputtered metal films, bendable metal foils, and graphene paves the way for the implementation of otherwise not possible device concepts of interest for different applications. Nevertheless, further fundamental studies are required prior to the fabrication of devices at a demonstrator level.

At PDI we plan to develop in the near future more complex NWs which will include axial or radial heterostructures and doped regions. Such more complex structures are a prerequisite for essentially any device, whose realization will be an additional step. Two different application fields are under consideration, ultraviolet light emission and energy harvesting based on the piezoelectric effect.

5. Cooperation with External Partners

The project was almost entirely developed at PDI. Beside the different research groups and departments involved in the project at PDI, we have also collaborated with several external partners:

- Laboratório de Filmes Semicondutores, Universidade Estadual Paulista Bauru (Brazil). We received the visit of a PhD student, Ziani de Souza Schiaber, from this university who worked part time on the growth of GaN NWs on epitaxial graphene during a 9 months stay.
- Technische Universiteit Eindhoven (Netherland). We received a Master student, Jelle Goertz, from this University who participated in the studies devoted to the growth of GaN NWs on sputtered Ti. Jelle Goertz carried out the major part of his graduation project at PDI during a 13 moths stay working on a topic closely related to the project.
- Department of Electronic Systems, NTNU Norwegian University of Science and Technology, Trondheim (Norway). We collaborated with the group of Professor J. K. Grepstad in Norway to analyze by X-ray photoelectron spectroscopy (an experimental technique not available at PDI) the surface of the Ti foils after different treatments.

6. PhD and Master Theses Connected to the Project

The following PhD and Master Theses were or are being developed in connection with this project:

- PhD thesis of David van Treeck. The thesis, which deals with the growth by molecular beam epitaxy of axial and radial group-III nitride nanowire heterostructures, is in progress since April 2015 and expected to be defended at Humboldt-Universität zu Berlin in 2018.
- Master thesis of Jelle Goertz. The thesis, entitled "(In,Ga)N heterostructures in self-assembled GaN nanowires grown on TiN by molecular beam epitaxy", was mostly developed at PDI and defended in 2016 at Technische Universiteit Eindhoven (Netherlands).

7. Publications and Conference Contributions[1]

7.1 Project-Related Publications

1. "Effect of substrate roughness, chemical composition, and native oxide crystallinity on the orientation of self-assembled GaN nanowires on Ti foils" by G. Calabrese, S. V. Pettersen, C. Pfüller, M. Ramsteiner, J. Grepstad, O. Brandt, L. Geelhaar and S. Fernández-Garrido. Nanotechnology, **28**, 425602 (2017).
2. "Molecular beam epitaxy of GaN nanowires on epitaxial graphene" by S. Fernández-Garrido, M. Ramsteiner, G. Gao, L. A. Galves, Bharat Sharma, P. Corfdir, G. Calabrese, Z. de Souza Schiaber, C. Pfüller, A. Trampert, J. M. J. Lopes, O. Brandt and L. Geelhaar. Nano Letters, **17**, 5213 (2017).
3. "Self-assembled formation of long, thin, and uncoalesced GaN nanowires on crystalline TiN films" by D. v. Treeck, G. Calabrese, J. Goertz, V. M. Kaganer, O. Brandt, S. Fernández-Garrido and L. Geelhaar. Nano Research (2017). DOI: https://doi.org/10.1007/s12274-017-1717-x
4. "Polarity-induced selective area epitaxy of GaN nanowires" by Z. de Souza Schiaber, G. Calabrese, X. Kong, A. Trampert, B. Jenichen, J. H. Dias da Silva, L. Geelhaar, O. Brandt and S. Fernández-Garrido. Nano Letters, **17**, 63 (2017).
5. "Molecular beam epitaxy of single crystalline GaN nanowires on a flexible Ti foil" by G. Calabrese, P. Corfdir, G. Gao, C. Pfüller, A. Trampert, O. Brandt, L. Geelhaar and S. Fernández-Garrido. Applied Physics Letters, **108**, 202101 (2016).
6. "Epitaxial growth of GaN nanowires with high structural perfection on a metallic TiN film" by M. Wölz, C. Hauswald, T. Flissikowski, T. Gotschke, S. Fernández-Garrido, O. Brandt, H. T. Grahn, L. Geelhaar and H. Riechert. Nano Letters, **15**, 3743 (2015).

Manuscripts to be submitted:

7. "Plasma-assisted molecular beam epitaxy of GaN nanowires on epitaxial single-layer graphene", by S. Fernández-Garrido, M. Ramsteiner, L. A. Galves, P. Corfdir, C. Sinito, G. Calabrese, Z. de Souza Schiaber, J. M. J. Lopes, O. Brandt and L. Geelhaar. Proceedings SPIE Photonics West 2018.

[1] The names of the persons directly funded by this project are underlined in the following subsections.

8. “Monitoring the formation of GaN nanowires in molecular beam epitaxy by polarization-resolved optical reflectometry” by P. Corfdir, G. Calabrese, A. Laha, T. Auzelle, L. Geelhaar, O. Brandt and S. Fernández-Garrido.

7.2 Project-Related Conference Contributions and Seminars

7.2.1 Invited Talks and Seminars

1. “Flexible metallic foil and graphene as substrates for the self-assembled growth of GaN nanowires” by L. Geelhaar. Materials Research Society Fall Meeting, Boston, to be presented in November 2017.
2. “Self-assembled growth of GaN nanowires on metallic substrates” by L. Geelhaar. American Conference on Crystal Growth and Epitaxy, Santa Fe, NM, USA (2017).
3. “GaN nanowire growth on flexible metallic substrates” by L. Geelhaar. International Workshop on Epitaxial Growth and Fundamental Properties of Semiconductor Nanostructures, Como, Italy (2017).
4. “Spontaneous formation of GaN nanowires in molecular beam epitaxy: substrates and growth conditions” by S. Fernández-Garrido, J. K. Zettler, P. Corfdir, C. Hauswald, E. Luna, U. Jahn, A. Trampert, M. Wölz, D. van Treeck, L. Geelhaar, and O. Brandt. 5th International Workshop on Epitaxial Growth and Fundamental Properties of Semiconductor Nanostructures, Hsinchu, Taiwan (2015).
5. “Self-induced formation of GaN nanowires on Si and TiN: growth mechanisms and optical properties” by L. Geelhaar. Wilhelm and Else Heraeus Seminar on III-V Nanowire Photonics, Bad Honnef, Germany, (2015).

7.2.2 Oral Contributions

1. “Molecular beam epitaxy of GaN nanowires on flexible metal foils: challenges and prospects” by G. Calabrese, C. Pfüller, P. Corfdir, S. V. Pettersen, G. Gao, M. Ramsteiner, A. Trampert, J. K. Grepstad, O. Brandt, L. Geelhaar and S. Fernández-Garrido. The Austrian MBE Workshop, Vienna, Austria (2017).
2. “Molecular beam epitaxy of GaN nanowires on graphene layer structures synthesized on SiC” by S. Fernández-Garrido, M. Ramsteiner, L. A. Galves, B. Sharma, J. M. J. Lopes, P. Corfdir , Z. de Souza Schiaber, G. Gao, O. Brandt and L. Geelhaar. International Workshop on Nitride Semiconductors, Orlando, Florida, USA (2016).
3. “GaN nanowires free of inhomogeneous strain grown on a metallic TiN film” by G. Calabrese, D. van Treeck, P. Corfdir, B. Jenichen, V. Kaganer, L. Geelhaar, S. Fernández-Garrido and O. Brandt. International Workshop on Nitride Semiconductors, Orlando, USA (2016).
4. “Self-assembled growth of single crystalline GaN nanowires on a flexible Ti foil” by G. Calabrese, P. Corfdir, G. Gao, C. Pfüller, A. Trampert, O. Brandt, L. Geelhaar and S. Fernández-Garrido. 19th International Conference on Molecular-Beam Epitaxy, Montpellier, France (2016).
5. “Self-Assembled Formation of Dense Ensembles of Long, Thin, and Uncoalesced GaN Nanowires on Crystalline Ti films” by D. van Treeck, G. Calabrese, J. Goertz, J. Bartolomé Vilchez, A. Trampert, O. Brandt, S. Fernández-Garrido and L. Geelhaar. International Conference on Molecular Beam Epitaxy, Montpellier, France (2016).

6. “Growth of GaN nanowires on crystalline TiN films by molecular beam epitaxy” by D. van Treeck, G. Calabrese, C. Pfüller, O. Brandt, L. Geelhaar and S. Fernández-Garrido. DPG-Tagung, Regensburg, Germany (2016).

7.2.3 Poster Contributions

1. “Suppression of interfacial reactions during the growth of uncoalesced GaN nanowires on Ti layers sputtered on Al_2O_3(0001)” by G. Calabrese, D. van Treeck, P. Corfdir, C. Pfüller, G. Gao, A. Trampert, O. Brandt, L. Geelhaar and S. Fernández-Garrido. Nanowire Week, Lund, Sweden (2017).
2. “Analysis of the radial growth of GaN nanowires for the fabrication of homogeneous multi-shell nanowire heterostructures” by D. van Treeck, O. Brandt, L. Geelhaar and S. Fernández-Garrido. International Conference on Nitride Semiconductors, Strasbourg, France (2017).

8. Press Releases

The magazine *Compound Semiconductors* informed in June 2016 about our studies and results related to the growth of single-crystalline GaN NWs on poly-crystalline metallic foils. The article can be found here.

9. Dissemination of Project Results

The most relevant results obtained in this project have been published in peer-reviewed scientific journals (Applied Physics Letters, Nano Research, Nanotechnology and Nano Letters) with high impact factors (between 3.4 and 12.7). The articles are made accessible to the general public through the PDI repository. In those cases where the publication policy of the journal does not allow us to provide open access to the article, a link to the corresponding journal page can be found in our website. Furthermore, we have also regularly informed in our website about the most interesting results obtained in this project. They can be found in the section “Scientific Highlights”.

In addition, the results have been disseminated within the scientific community by presenting them at different international conferences in numerous occasions as described above.