MBE growth and properties of GaAs, AlGaAs and InAs nanowires on SiC/Si(111) hybrid substrate

R R Reznik², I V Shtrom¹, I P Soshnikov¹, S A Kukushkin⁵, D A Kirilenko⁴ and G E Cirlin¹

¹St-Petersburg Academic University – Nanotechnology Research and Education Centre RAS, Khlopina 8/3, 194021, St-Petersburg, Russia
²ITMO University, Kronverkskiy pr. 49, 197101 St-Petersburg, Russia
³Institute for Analytical Instrumentation RAS, Rizhsky 26, 190103, St-Petersburg, Russia
⁴Ioffe Physical Technical Institute RAS, Politekhnicheskaya 26, 194021, St-Petersburg, Russia
⁵Institute of Problems of Mechanical Engineering Russian Academy of Science, Bolshoj 6, 199178 St-Petersburg, Russia

E-mail: moment92@mail.ru

Abstract. The possibility of GaAs, AlGaAs and InAs nanowires MBE growth on a silicon substrate with a nanometer silicon carbide buffer layer has been demonstrated for the first time. Under the same experimental conditions (including the same composition) the diameter of the nanowires is smaller than diameter of nanowires grown on silicon substrate. Based on the photoluminescence and TEM analysis it was suggest that when AlGaAs/SiC/Si NWs are grown, a physical complex structure is formed.

1. Introduction
The relevance of nanowires (NWs) investigations is explained by the necessity to solve important problems, i.e. to create new non-planar semiconductor nanomaterials and nanosystems with controlled properties on silicon (Si). We have previously demonstrated the ability to grow by high-quality GaN and InN NWs on a silicon substrate covered with a thin silicon carbide (SiC) buffer layer [1-3]. These and A³B⁵ materials are particularly needed (and already used) for the development of novel devices for microelectronics, optoelectronics, analytical biomedicine, emission cathodes, probes for scanning tunnelling microscopy, high efficiency solar energy converters, etc. [4]. Because of their large diameter which usually exceeds or is comparable to the de Broglie wavelength of a bulk material, NWs are not really one-dimensional, but quasi-one-dimensional nanomaterials. Hence, it is essential to reduce their diameter to fully exploit them as quantum materials. As shown in the literature [5,6], the critical diameter of the catalyst droplet, under which the NWs formation can be initiated, depends on the ratio of lattice constants between the NWs and substrate materials and decreases with an increasing ratio. Thus, it is expected that further ratio increase will lead to a decrease of the NWs diameter.
In this work, in order to reduce the GaAs, AlGaAs and InAs NWs diameter, hybrid Si(111) substrates with a nanometer SiC buffer layer were used for growth by molecular beam epitaxy (MBE). The lattice constant mismatch between these hybrid substrates and A\textsubscript{3}B\textsubscript{5} compounds is significantly greater than that between A\textsubscript{3}B\textsubscript{5} compounds and silicon.

2. Experimental procedures
Nanowires were grown by MBE using Riber Compact 21 setup equipped with a separate vacuum chamber for gold deposition. After HF treatment in water solution (1:10), SiC/Si(111) hybrid substrates were loaded into the vacuum chamber and outgassed at 850°C before the gold deposition at 550°C. The substrates were kept at 550°C for 1 min after the gold deposition to improve the droplet size homogeneity and subsequently cooled down to room temperature. After that, the substrates were transferred into the main growth chamber with no vacuum brake. For AlGaAs NW growth runs, the substrate temperature was set at 510°C, the nominal AlGaAs growth rate was fixed at 0.3 nm/s and the total V/III flux ratio was 3. Nominal Al composition \( z = 0.3 \) was chosen, as calibrated using reflection high energy electron diffraction oscillation technique on standard GaAs(001) substrates. For the growth of GaAs and InAs NWs, growth temperatures were chosen at 530°C and 300°C, nominal growth rates were fixed at 0.3 and 0.1 nm/s respectively.

The surface morphology was studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The photoluminescence (PL) was excited by a continuous-wave neodymium laser (wavelength 532 nm) at an excitation power density of about 10 W/cm\(^2\). A Hamamatsu R928 photomultiplier served as a photodetector. The PL signal was excited and detected in the normal configuration. Measurements were made at a temperature of 10 K with nanowire-containing samples placed in a closed cycle helium cryostat.

3. Results
Typical scanning electron microscopy images of GaAs, AlGaAs and InAs NWs grown on Si(111) substrate with SiC buffer layer are shown in Figure 1. It is seen that GaAs NWs are oriented in (111) and other orientations, their diameter is constant over the entire length of the NWs with average value - 35 nm, which is about three times less than for GaAs NWs grown on a silicon substrate (110 nm) [7]. The array of GaAs NWs on a hybrid substrate has a surface density - 2\( \times \)10\(^8\) cm\(^{-2}\), whereas they average height is 2 \( \mu \)m.

![Figure 1. SEM images of A3B5 NWs grown on SiC/Si(111) substrate: (a) – GaAs NWs; (b) – AlGaAs NWs; (c) – InAs NWs.](image)

The results of morphological properties studies of grown AlGaAs NWs arrays showed that, as in the case of GaAs NWs, AlGaAs NWs have grown in different directions, and their average height is - 2 \( \mu \)m. However, the arrays of such NWs have a smaller surface density - about 6\( \times \)10\(^7\) cm\(^{-2}\). In addition, AlGaAs NWs have a cone-like shape, their average diameter at the bottom is 80 nm and at the top - 15
nm. This shape is explained by the difference in Ga and Al adatoms migration coefficients over the sidewalls surface, thus, lateral growth occurs eventually [8]. Nevertheless, the diameter of AlGaAs NWs grown on the SiC/Si(111) substrate is much smaller than the diameter of such NWs grown on Si(111) (typically, 100-120 nm [8]).

Because of the considerable mismatch between InAs and SiC, the critical Au droplet diameter is very small [9], so InAs NWs surface density is extremely low. The diameter of such InAs NWs can’t be precisely determined by scanning electron microscope since NWs oscillate under the electron beam influence. With certainty their diameter as less as 10 nm can be evaluated, which is less than the de Broglie wavelength for InAs.

A PL study of AlGaAs NWs arrays on the hybrid SiC/Si(111) substrate showed interesting results. The low-temperature PL spectra of these NWs and AlGaAs NWs which were grown on Si(111) with the same growth conditions are shown in Figure 2.a. In line with previous reports [10], grown on a Si(111) substrate AlGaAs NWs with a sufficient Al content exhibit a core–shell structure, where the content of Al being almost nominal in the shell and substantially lower in the core [10, 11]. It was found that for the grown on SiC/Si(111) AlGaAs NWs, the spectrum displays two main peaks at 1.6 eV and 1.81 eV. The peak at 1.6 eV corresponds to an aluminum content of 0.1 consistent published data [12]. In turn, 1.81 eV, which, to our knowledge, has not been reported could correspond to AlGaAs with another fraction of aluminum. The PL band at 1.6 eV is attributed to the emission from the rod whereas the higher energy band at 1.81 eV can be associated to an emission from the shell. This band corresponds to an emission from AlGaAs with an Al content of about 0.22, which is in good correlation with our previous publication [10]. However, a fluctuation of the Al content can be observed in the shell of the AlGaAs NW. A possible reason why spatially inhomogeneous shells of the AlGaAs NW are formed, with its various parts having different compositions in the solid solution, was described in [13–15]. It was shown that the AlGaAs NW shell can be formed in a self-organized way as aluminum-enriched regions, alternating layers with different compositions and thicknesses of several angstroms, and AlGaAs quantum dots with an aluminum content lower than the average composition in the NWs. As a result of the quantum-confinement effect, the PL peak from these quantum dots is shifted to the region of 1.8–1.95 eV, which is in agreement with the energy of the additional PL peak observed in our AlGaAs NWs on SiC/Si substrate. In all of these cases, a broad (~120 meV) band is observed, probably constituted by a large number of discrete lines associated with an emission from single levels of quantum dot (0D) objects that are inhomogeneous in their composition and size. However, we could not explicitly discern separate discrete levels because of the insufficient resolution of the optical system used to support optical analysis. To investigate the hypothesis propose, i.e. the PL originates from 0D objects of the AlGaAs shell, we have studied the nanostructural properties of our AlGaAs/SiC/Si NWs by transmission electron microscopy. Typical TEM images of AlGaAs NWs grown on Si(111) substrate with SiC buffer layer are shown in Figure 2.b. The resolution of the measurements was not enough to confirm (or refute) these hypotheses. But it can be seen that the NW has an inhomogeneous phase along the length. Transitions between such phase changes can also contribute to the short-wave peak of PL. In the future, high-resolution measurements will be taken.
Figure 2. (a) – PL spectra measured at $T = 10$ K of AlGaAs NWs on hybrid SiC/Si(111) and Si(111) substrates; (b) – TEM image of AlGaAs NW on hybrid SiC/Si(111) substrate.

4. Conclusions

In summary, the possibility of GaAs, AlGaAs and InAs NWs growth by MBE on a silicon substrate with nanometer silicon carbide buffer layer has been demonstrated for the first time. The morphology studies confirmed that an increase in the lattice mismatch between the substrate and the nanowires lead to decrease in the diameter of the NWs. Furthermore, optical studies results allow us to suggest that, during AlGaAs NWs growth, a physical complex structure is formed.

Acknowledgments

The authors thank the Ministry of Education and Science of the Russian Federation for financial support under grant 14.587.21.0040 (project ID RFMEFI58717X0040).

References

[1] Reznik R R, Kotlyar K P, Ilkiv I V, Soshnikov I P, Kukushkin S A, Osipov A V, Nikitina E V and Cirlin G E MBE growth and optical properties of GaN nanowires on SiC/Si(111) hybrid substrate  AIP Conference Proceedings 1748 040003 (2016)

[2] Reznik R R, Kotlyar K P, Ilkiv I V, Soshnikov I P, Kukushkin S A, Osipov A V, Nikitina E V and Cirlin G E The use of SiC/Si(111) hybrid substrate for MBE growth of GaN nanowires  Journal of Physics: Conference Series 741 012027 (2016)

[3] Reznik R R, Kotlyar K P, Ilkiv I V, Soshnikov I P, Kukushkin S A, Osipov A V, Nikitina E V and Cirlin G E Growth and Optical Properties of Filamentary GaN Nanocrystals Grown on a Hybrid SiC/Si(111) Substrate by Molecular Beam Epitaxy  Physics of the Solid State 58 no10 1952–1955 (2016)

[4] Dubrovskii V G, Cirlin G E and Ustinov V M Semiconductor nanowhiskers: Synthesis, properties and applications  Semiconductors 43 no 12 1539-1584 (2009)

[5] Chuang L C, Moewe M, Chase C, Kobayashi N P and Chang-Hasnain C Critical diameter for III-V nanowires grown on lattice-mismatched substrates  Appl. Phys. Lett. 90 no 043115 (2007)

[6] Cirlin G E, Dubrovskii V G, Soshnikov I P, Sibirev N V, Samsonenko Yu B, Bouravlevu A D, Harmand J C and Glas F Critical diameters and temperature domains for MBE growth of III–V nanowires on lattice mismatched substrates  Phys. Status Solidi RRL 3 no 4 112-114 (2009)
[7] Cirlin G E, Dubrovskii V G, Soshnikov I P, Sibirev N V, Samsonenko Yu B, Bouravleuv A. D, Harmand J C, Glas F 2009 Phys. Status Solidi RRL 3 112
[8] Dubrovskii V G, Shtrom I V, Reznik R R, Samsonenko Yu B, Kherbtov A I, Soshnikov I. P, Rouvimov S, Akopian N, Kasama T, Cirlin G. E 2016 Crystal Growth & Design 16 7251
[9] Cirlin G E, Shtrom I V, Reznik R R, Samsonenko Yu b, Kherbtov AI, Bouravleuv A D, Soshnikov I P 2016 Semiconductors 11 1421
[10] Duan X, Lieber C M 2000 J. Am. Chem. Soc. 122 188
[11] Bellotti E, Doshi B K, Brennan K F, Albrecht J D, Ruden P P 1999 J. Appl. Phys. 85 916
[12] Dimakis E, Konstantinidis G, Tsagaraki K, Adikimenakis A, Iliopoulos E, Georgakilas A Superlattices Microstruct. 36 497
[13] Grandal J, Sanchez-Garcia M A, Calle F, Calleja E 2005 Phys. Status Solidi C 2 2289
[14] Stoica T, Meijers R, Calarco R, Richter T, Luth J H 2006 J. Cryst. Growth 290 241
[15] Aksyanov I G, Bessolov V N, Zhilyaev Y V, Kompan M E, Konenkova E V, Kukushkin S A, Osipov A V, Rodin S N, Feoktistov N A, Sharofidinov S, Shcheglov M P 2008 Technical Physics Letters 34 479