MBE growth of thin AlGaAs nanowires with a complex structure on strongly mismatched SiC/Si(111) substrate

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Abstract. The possibility of AlGaAs nanowires MBE growth on a silicon substrate with a nanometer silicon carbide buffer layer was demonstrated for the first time. Under the same experimental conditions (including the same composition), the diameter of the AlGaAs/SiC/Si nanowires are smaller than nanowires diameter grown on a silicon substrate. Based on the photoluminescence analysis suggests that when AlGaAs/SiC/Si NWs are grown, a physical complex structure appears due to the self-organized formation of regions with different molar fractions of aluminum in the solid solution.

1. Introduction
The relevance of investigations nanowires (NWs) is explained by the necessity to solve and important problem, 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 high-quality GaN and InN NWs on a silicon substrate covered with a thin silicon carbide (SiC) buffer layer [1-3]. These and A'B' materials are particularly needed (and are 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 true 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 mismatch increase of the lattice constant between the substrate and NWs materials will lead to a decrease of the NWs diameter.

In this work, in order to reduce the AlGaAs NWs diameter, hybrid Si(111) substrates with a nanometer SiC buffer layer were used for growth by molecular beam epitaxy (MBE). For these hybrid substrates, the lattice constant mismatch with these A'B\textsuperscript{5} compounds is significantly greater than that of a conventional silicon substrate, e.g. 44% for AlGaAs and 4% for Si and AlGaAs).

2. Experimental procedures

MBE growth was carried out using Riber Compact 21 MBE growth system equipped with an additional combined vacuum chamber for the deposition of Au (metallization chamber). SiC/Si(111) hybrid substrates were used for MBE growth. Growth was performed in two stages: after the cleaning of SiC/Si wafer surface at the temperature of 950°C, the sample temperature was lowered to 550°C before a ~0.1–0.2 nm thick gold (Au) film deposition onto the substrate surface in the metallization chamber. The temperature was maintained for a minute to allow Au droplets to be formed. The surface was subsequently cooled to room temperature and then transferred to the growth chamber without breaking of ultrahigh-vacuum conditions. The substrate temperature in the growth chamber was increased to growth temperature - 510°C before Al, Ga, and As shutters were opened for AlGaAs NWs growth under As-stabilized growth conditions. The AlGaAs growth rate was maintained constant at 1 monolayer per second (ML/s) while Ga and Al flux were chosen in accordance with the required molar fraction x=0.3 in the Al\textsubscript{1-x}Ga\textsubscript{x}As solid solution. Total growth time was 20 min.

The surface morphology was studied by scanning electron microscopy (SEM). The photoluminescence (PL) was excited by a continuous-wave neodymium laser (wavelength 532 nm) at an excitation power density of about 10 W/cm\textsuperscript{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

Figure 1 shows the SEM image of AlGaAs NWs array grown on hybrid SiC/Si(111) substrate. It seen that 20 minutes of growth is enough to synthesize 4 μm long AlGaAs NWs. The study of AlGaAs NWs array morphological properties has shown that the NWs formed in various directions, with average surface density - 6 × 10\textsuperscript{7} cm\textsuperscript{-2}. Furthermore, the AlGaAs NWs have a conical shape, with a diameter of 80 nm at the bottom and 15 nm at the top of NWs due to the difference between the migration coefficients of Ga and Al adatoms, which is leading to an uneven lateral growth [7]. Nevertheless, the average diameter of AlGaAs NWs grown on the SiC/Si(111) substrate is substantially smaller than the diameter of the NWs grown on Si (100–120 nm [8]).
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 are contrasted against that of AlGaAs NWs grown on Si(111) with the same growth conditions are shown in Figure 2. In line with previous reports [8], AlGaAs NWs with a sufficient Al content exhibit a core–shell structure when grown on a Si(111) substrate, where the content of Al being almost nominal in the shell and substantially lower in the core [7, 8]. It was found that for the AlGaAs grown of SiC/Si(111), 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 [9]. In turn, 1.81 eV, which, to our knowledge, has not been reported to date 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 is 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 [8]. 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 [10–12]. It was shown in these studies that, in the growth of AlGaAs, NW shells 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 are currently studying the nanostructural properties of our AlGaAs/SiC/Si NWs by transmission electron microscopy (TEM).
4. Conclusions

In summary, the possibility of AlGaAs NWs growth by MBE on a silicon substrate with nanometer silicon carbide buffer layer was 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, these optical studies allow us to suggest that, during AlGaAs NWs growth, a physical complex structure appears due to the self-organized formation of regions with different molar fractions of aluminum in the solid solution.

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