Bouravleuv, Alexei D.; Ilkiv, I. V.; Reznik, Rodion; Shtrom, I. V.; Khrebtov, A.I.; Samsonenko, Yu B.; Soshnikov, I. P.; Cirlin, George E.; Lipsanen, H.

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MBE growth of nanowires using colloidal Ag nanoparticles

A D Bouravlev1,3, I V Ilkiv1,4, R R Reznik1, I V Shtrum1,4, A I Khrebtov1, Yu B Samsonenko1,3, I P Soshnikov1,3, G E Cirlin1,4, H Lipsanen5

1St. Petersburg Academic University RAS, St. Petersburg 194021, Russia
2Ioffe Institute RAS, St. Petersburg 194021, Russia
3Institute for Analytical Instrumentation RAS, St. Petersburg 190103, Russia
4St.Petersburg State University, St.Petersburg 199034, Russia
5Aalto university, Espoo FI-02150, Finland

e-mail: bour@mail.ioffe.ru

Abstract. Ag colloidal nanoparticles are used as a catalyst for growth of GaAs nanowires by the molecular beam epitaxy on the Si(111) and GaAs(111)B substrate surfaces. The scanning electron microscopy measurements revealed that the nanowire formation occurs in different ways on different substrates, but the parameters of the synthesized nanowires open great prospects for their further use.

1. Introduction

Semiconductor nanowires (NWs) are considered to be the one of the most promising materials for the realization of new nano- and optoelectronic devices. Nowadays, the majority of semiconductor compounds can be grown in a shape of these quasi one-dimensional nanostructures. Moreover, they can be formed on semiconductor substrates with large lattice mismatch, which opens up great technological advantages and opportunities. It is well known that the surface location of individual semiconductor NWs can be predefined by the location of catalytic droplets. Up to now, the NW synthesis via a well-established vapour–liquid–solid (VLS) mechanism has been carried out using different metals as a catalyst for their growth [1], since the most common catalytic metal, such as gold, could result in the incorporation of its atoms into NWs with solubility exceeding the solubility limit of the bulk materials [2-4]. The existence of uncontrolled doping can seriously limit the number of possible NW applications, because gold can introduce deep level traps the band gap and act as a recombination center for charge carriers. Therefore, the other technological approaches, for example self-catalyzed [5] or template-assisted growth of NWs [6], and the use of alternative metals, e.g. Ag, which creates relatively shallow energy levels, are of particular interest. The silver has been already used for the growth of different NWs, such as In$_2$O$_3$ [7], Si [8], InSb [9], Ge [10], InAs [11], InP [12], In$_{x}$Ga$_{1-x}$As [13] and GaAs [14]. The metal catalytic droplets can be formed on the semiconductor substrate surface by means of different methods. One of the most simple among them, which is the thermal annealing of preliminary deposited metal thin films, does not allow us to control the surface density and size distribution of metal droplets created by their decomposition. Furthermore it cannot provide ultra low surface density of the droplets, which is of importance for some NW applications and their investigations. Other techniques based on different kind of beam lithography are quite time consuming. Alternatively, metal nanoparticle colloids, which have gained widespread acceptance in
different areas due to their properties, are very attractive to be used for NW synthesis [15]. They, especially gold nanoparticle colloids, have been widely used as a catalyst for the growth mostly by different CVD methods [16].

Here we report on Ag and Au colloidal nanoparticle assisted MBE growth of GaAs NWs on Si and GaAs substrates.

2. Experiments

The solid-source Compact 21 TM Riber MBE system equipped with additional high vacuum connected chamber for gold deposition, which allows to perform the annealing of the samples at the temperatures up to 950°C, was used for the growth experiments. The growth of GaAs NWs was carried out on epi-ready Si(111) and GaAs(111)B substrates. We used commercially available gold and silver nanoparticle colloids with diameters of 40 and 20 nm, correspondingly, produced by BBI Company. The deposition of the colloidal nanoparticles was carried out after the substrate cleaning in deionized water and ethanol.

Prior to growth, the samples with deposited nanoparticles were loaded into additional chamber for the thermal annealing, which was carried out for 5 minutes at 850°C and 630°C for Si and GaAs substrates, correspondingly. Then, the temperature was decreased and the samples were transferred to the main chamber equipped with Ga effusion cell and As cracking cell in high vacuum conditions. After reaching the growth temperature of 580°C, Ga and As shutters were simultaneously opened. The growth rate was corresponded to 1 ML/s of 2D layers. The total NW growth time was equal to 15 minutes. The reflection high-energy electron diffraction (RHEED) method was used to control in situ the processes occurring on the substrate surface. RHEED patterns demonstrated the beginning NW nucleation appeared after 20 seconds of the growth. According to the RHEED patterns GaAs NWs had mixed wurzite/zincblende phases.

The morphological properties of the samples have been studied using scanning electron microscopy (SEM) Zeiss SUPRA 25.

3. Results

Figure 1. SEM images of GaAs NWs grown on the Si(111) substrates using Au (a) and Ag (b) colloidal nanoparticles. Scale bar corresponds to 2 μm (a) and 200 nm (b).

The GaAs NWs obtained by Au and Ag nanoparticle assisted MBE growth on the Si(111) substrates are shown in Figure 1. The results obtained demonstrate that arrays of vertical GaAs NWs can be grown using colloidal nanoparticles by MBE. The NWs grown on Si using Au nanoparticles have higher surface density may be due to the higher concentration of Au compare to Ag nanoparticles.
inside colloidal solution (see Fig. 1 a). Their average NW length is about 4.3 μm, whereas NW obtained using Ag nanoparticles were a bit smaller. They are of 3.2 μm in length. At the same time their diameters are quite close to each other, despite to different sizes of Au and Ag nanoparticles, which were 40 and 20 nm, correspondingly. The average diameter reasonably exceeds those values, since it is about 90 nm. This question requires an additional clarification. But it can be connected with different solubility of Ga atoms inside Au and Ag catalytic droplets. It should be noted that NWs were grown perpendicular to the substrate surface, i.e. they were grown along <111> crystallographic direction. As it was expected, they have quite small size distributions and they are do not change their shape along the growth axe. This opens up good perspectives for their implementations.

Figure 2. SEM image of GaAs NWs grown on the GaAs(111)B substrate using Ag colloidal nanoparticles as a catalyst for their growth. Scale bar corresponds to 200 nm.

The use of GaAs substrate for the Ag-assisted MBE synthesis of GaAs has also led to good results. The SEM investigation of the samples obtained shows that NWs obtained were also straight, as one can see in Figure 2. They were growth along <111> direction. But their average diameter (55 nm), as well as their length (about 0.6 μm) was smaller compare to the parameters demonstrated by NWs grown on Si substrates.

4. Conclusions

In summary, the GaAs NWs have been obtained for the first time by molecular beam epitaxy using Ag colloidal nanoparticles as a growth catalyst on the Si(111) and GaAs(111) substrate surface. The NWs obtained are straight and have small size distribution. It was found that despite similar growth condition, the formation of NWs on different semiconductor substrates could result in significant differences in the NW parameters.

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