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Role of the buffer layer on the mechanical strength of nanowire-substrate interface

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Abstract. Atomic force microscopy has been utilized to study the structure and mechanical strength of the epitaxial interfaces of InAs and GaP nanowires grown on Si substrates. Measuring the elastic forces during the controlled cleavage of individual crystals carried out by lateral mechanical action of atomic force microscope probe allowed us to establish a correlation between the strength of the epitaxial interface and the level of lattice mismatch. It was shown that InAs nanowires grown on InAs buffer layer demonstrate different mechanical strength compared with the ones grown directly on Si. Meanwhile, mechanical strength of GaP nanowires grown on GaP buffer is of the same order as that of GaP nanowires grown directly on Si. Analysis of the topography after nanowire removal confirmed differences in the failure mechanisms of the interface.

Keywords: nanowires, epitaxial interface, GaP, InAs, atomic force microscopy

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Влияние буферного слоя на механическую прочность интерфейса нанопровод-подложка

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Аннотация. Атомно-силовая микроскопия была использована для изучения структуры и механической прочности эпитаксиальных интерфейсов нанопроводов InAs и GaP, выращенных на кремниевых подложках. Измерение упругих сил во время контролируемого отщепления отдельных нанопроводов от подложки, осуществляемого латеральным механическим воздействием зонда атомно-силового микроскопа, позволило установить корреляцию между прочностью эпитаксиального интерфейса и уровнем решеточного рассогласования. Было показано, что нанопровода InAs, выращенные на буферном слое InAs, демонстрируют другую механическую прочность по сравнению с выращенными непосредственно на кремнии. В то же время, механическая прочность нанопроводов GaP, выращенных на буферном слое GaP, имеет тот же порядок, что и у выращенных непосредственно на кремнии. Кроме того, анализ топографии после удаления нанопроводов подтвердил различия в механизмах разрушения интерфейса.

Ключевые слова: нанопровода, эпитаксиальный интерфейс, GaP, InAs, атомно-силовая микроскопия

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Introduction

Semiconductor nanowires (NWs) are promising as active and passive elements for optoelectronics and nanophotonics. In particular, GaP NWs, due to their optical transparency, high refractive index, and high nonlinear coefficients, are promising for waveguides [1] and second harmonic generators [2], while InAs NWs, due to their high carrier mobility and direct bandgap, are promising for infrared light-emitting diodes and photodiodes [3]. One of the key advantages of the NW architecture over planar structures is considered to be the possibility of epitaxial growth of III-V compounds directly on silicon substrates without the use of buffer layers [4]. However, despite more than 20 years of active research, the efficiency of NW-based devices, in particular solar cells [5] and light-emitting diodes [6], still lags behind their planar counterparts. One of the reasons may be the high defect density at the NW-substrate growth interface induced by lattice mismatch, which degrades the electrophysical properties of devices despite the good crystalline quality of the NWs themselves. This work compares the mechanical properties of NWs depending on the level of lattice mismatch with the Si substrate $f_{NW} = (a_{NW} - a_{Si})$. In [7], we studied GaP NWs ($f_{GaP} = 0.37\%$) and InAs NWs ($f_{InAs} = 11.5\%$) grown directly on silicon, and experimentally demonstrated the influence of lattice mismatch on the interfacial misfit dislocations density and mechanical strength. In the present comparative study, arrays of GaP and InAs NWs grown on buffer layers are investigated in an analogous manner. The study was conducted using a previously developed methodology based on atomic force microscopy (AFM). The method involves removing individual NWs using a probe, with simultaneous recording of the elastic forces acting on the cantilever and subsequent scanning of the topography of the same area to check for the presence or absence of NW remnants (‘stumps’).

The results indicate a significant increase in the strength of the InAs/InAs interface compared to InAs/Si, while the strength of the GaP/GaP and GaP/Si interfaces differs only slightly. The results confirm the critical influence of the lattice mismatch at the NW-substrate interface on its mechanical properties, which should be taken into account when designing devices.

Materials and Methods

Arrays of NWs were grown by molecular beam epitaxy on silicon (111) substrates in the self-catalytic mode. Synthesis was carried out on Veeco Gen III system equipped with effusion cells for In and Ga, and cracker cells for P and As. A Zeiss Supra 25 system was used to obtain SEM images of the NW arrays. For the scanning probe measurements, we have utilized an NT-MDT NTegra Aura atomic force microscope (AFM) and a TipsNano HA_CNC probe.

The AFM is equipped with a standard optical system for registering probe deflection, based on reflecting a laser beam from the cantilever onto a four-segment photodiode and recording differential photocurrents. The coordinates of the NWs are determined using the regular semi-contact scanning mode. Then, the amplitude of the cantilever oscillations and the feedback gain are significantly reduced, after which a lateral displacement of the probe along a straight-line trajectory passing through the NW is performed, as shown in Fig. 1. Mechanical contact of the probe tip with the side facet of the NW leads to elastic deformations of the cantilever and the appearance of the differential photocurrent signals I_{LF} ('lateral force-induced photocurrent'). When the elastic force acting on the NW exceeds its mechanical strength during further probe displacement, the NW breaks off from the substrate, after which the cantilever deformation also disappears, and the recorded photocurrent returns to its initial zero position. Thus, a photocurrent spike is observed on the oscillogram, the amplitude of which reflects the maximum load that the NW can withstand. The ratio of the spike amplitudes, recorded by the same probe on different samples under identical conditions, allows comparison of the mechanical strength of the NW-substrate contact. The more detailed description of the method can be found in [7].

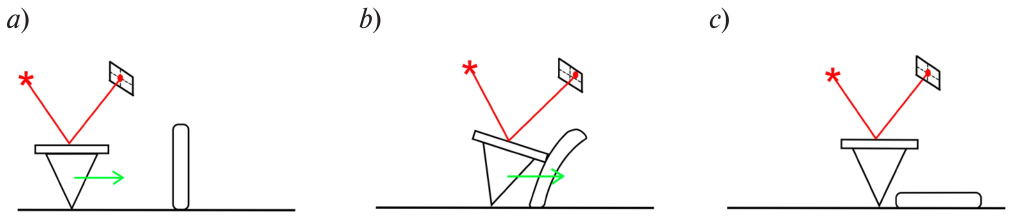

Fig.1. Schematic of the probe experiment for measuring the strength of the epitaxial NW-substrate contact

Results and Discussion

The obtained experimental data allow for a comprehensive assessment of the influence of crystallographic parameters, morphology, and epitaxial growth conditions on the mechanical strength of the NW-substrate contact. In the SEM images of all four arrays (Fig. 2), the features of the nanowire geometry are clearly distinguishable: both their lateral dimensions and the distribution in diameter and density vary. A NW with the mean geometric parameters from each array is schematically depicted above the corresponding SEM image. These differences directly affect the interaction between the probe and the NW during their removal, since the force acting on the cantilever upon contact with the side facet of the nanocrystal is determined by the lateral probe stiffness coefficient, which depends on the length from the tip base to the point of contact [7].

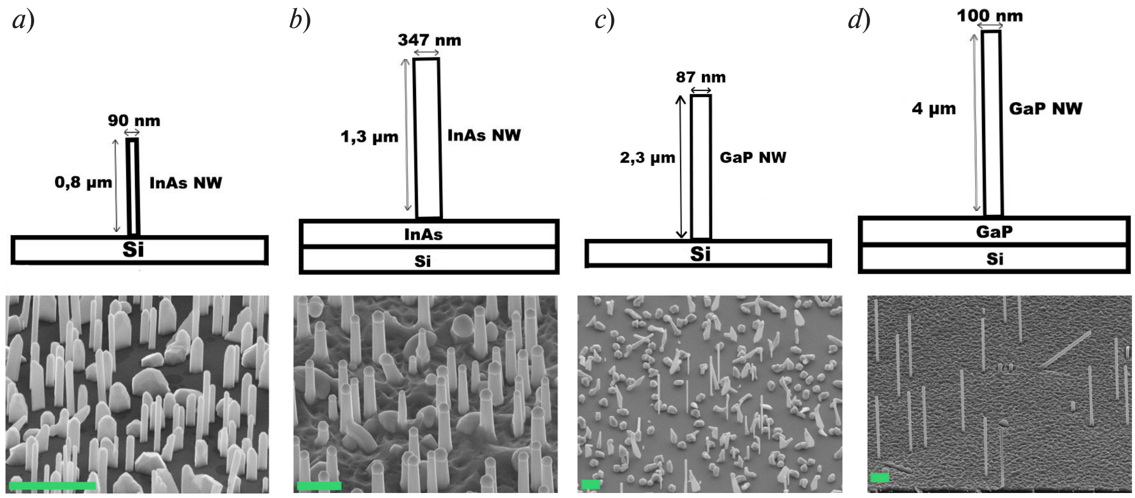

Fig. 2. SEM images of the studied samples. All scale bars are 1 µm long

Fig. 3 shows the ILF spikes amplitudes recorded on several NWs on each sample, recalculated from current units into force units using the previously developed methodology [7]. Comparison of the average amplitudes allows for a correlation between the materials of the epitaxial interface and its mechanical strength. The average values of the critical lateral elastic forces were: for InAs/Si: F_L = 813 nN, for InAs/InAs: F_L = 5195 nN, for GaP/GaP: F_L = 7109 nN, for GaP/Si: F_L = 7669 nN. Values for the GaP/Si and InAs/Si samples were taken from a previous work [7]. Significantly higher force values for both GaP NWs samples indicate greater mechanical strength of their epitaxial interface, which is explained by the low degree of lattice mismatch. It is important to note that the GaP/Si and GaP/GaP interfaces possess similar mechanical strength. In contrast, both samples with InAs NWs demonstrate lower critical forces. The high lattice mismatch between InAs and Si leads to the formation of initially highly-stressed growth interface which fully relaxes with the formation of high density of dislocations during the NW axial and radial growth. Such an interface is less robust, and therefore contact failure occurs at noticeably smaller cantilever deformations – hence the smaller I_{LF} amplitudes.

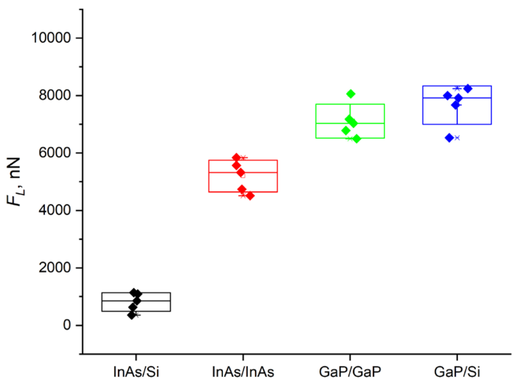

Fig. 3. Critical lateral force values corresponding to nanowire cleavage, obtained with AFM probe on several individual nanowires from each of four arrays. The boxes indicate average values, 10% and 90% percentiles

The InAs/InAs interface is approximately an order of magnitude stronger than InAs/Si, but still significantly inferior to GaP/Si and GaP/GaP. Taking into account the significantly larger lateral area of InAs/InAs interface, we normalize the measured forces to the interface area for all samples ($F^* = F/S$), obtaining for InAs/Si: F^* = 15.5 kN/cm^2, for InAs/InAs: F^* = 6.6 kN/cm^2, for GaP/GaP: F^* = 144.7 kN/cm^2, for GaP/Si: F^* = 118.2 kN/cm^2. It can be seen now that the normalized force for InAs/InAs is smaller than that for InAs/Si. Thus, the addition of a buffer layer weakens, rather than strengthens, the nanowire interface, which is counterintuitive.

To further study the nature of the NW removal, the topography of the vicinity of the growth interface of the removed crystals was investigated. The topographic features such as presence or absence of NW remains of any kind allow revealing the differences in the NW cleavage mechanism between the studied samaples.

From the previous work [7] it's known that cleaved GaP/Si NWs remain certain 'stumps' up to 200 nm height while cleaved InAs/Si leave atomically-smooth surface without any stumps. From Fig. 4 we can investigate the degree of NW preservation for GaP/GaP and InAs/InAs NWs. In both cases, approximately 200 nm high stumps remain after NW removal. It can be seen that the whole lateral areas of the NW bases are preserved. Thus, GaP NWs show similar behavior both with or without GaP buffer layer. This result reflects the specificity of GaP failure mechanism, i.e., the NW body is more fragile than GaP/Si or GaP/GaP interface. At the same time, InAs NWs leave stumps only with InAs buffer layer.

Together, both groups of data, the dynamics of the I_{LF} signal and the analysis of post-removal topography, form a comprehensive picture that allows for a quantitative and qualitative assessment of the mechanical strength of NW epitaxial contacts. However, the utilized approach seems promising for further investigation of mechanical properties of nanostructures. However, the obtained results for InAs are somewhat counterintuitive. On the one hand, after removing the InAs NWs from the buffer, stumps remain, indicating that the fracture occurs within the InAs bulk, not at the growth interface. On the other hand, the assumption that the buffer would increase the strength of the InAs nanowires was not confirmed. On the contrary, a 300% reduction in the normalized critical lateral force was observed. Thus, InAs/Si interface is stronger than InAs/InAs despite potentially higher defect density.

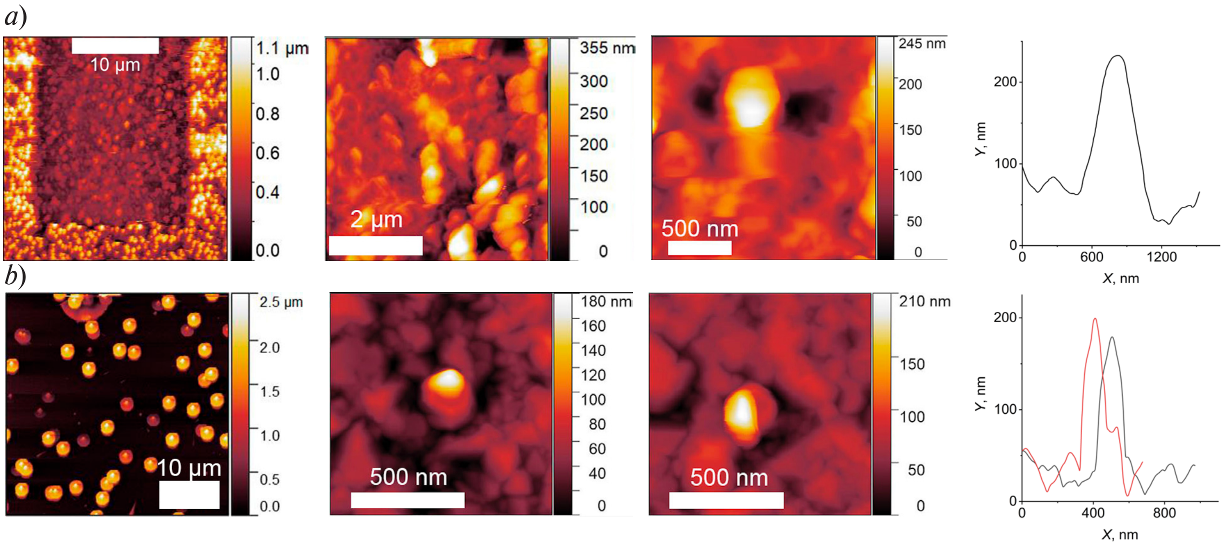

Fig. 4. Topography and topography profile of the InAs/InAs (*a*) and GaP/GaP (*b*) surface before (left pictures) and after (close-up right pictures) NW removal. The rightmost panels show 1D height profiles drawn horizontally through the stumps centers

Conclusion

Mechanical strength of individual GaP and InAs nanowires, grown on the homoepitaxial buffer layers, is investigated and compared with that of the nanowires grown directly on Si substrates.

In both cases GaP nanowires demonstrate similar strength and incomplete removal from the substrate, leaving 200 nm high stumps, indicating that both GaP/Si and GaP/GaP interfaces are stronger than the nanowire body itself. InAs nanowires demonstrate different mechanical properties with respect to the base material. The ones grown on Si are cleaving without any remains, indicating that the cleavage occurs at InAs/Si interface. The ones grown on InAs buffer are cleaving similarly to GaP nanowires, leaving stumps, but enduring 300% lower critical mechanical forces. The obtained results demonstrate the high sensitivity of the proposed methodology to structural differences between homo- and heteroepitaxial systems. Further understanding of underlying physical phenomena defining mechanical properties of nanowires requires the use of structural analysis techniques such as TEM. However, the presented approach can be used to optimize the growth conditions of nanowires and improve technologies for creating optoelectronic devices based on them.

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