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Ordered GaAs NW growth on Si(111) substrates modified by two-step FIB treatment

N.A. Shandyba [1] ✉, M.M. Eremenko [1], D.D. Dukhan [1], N.E. Chernenko [1], D.V. Kirichenko [1], A.D. Kugaevsky [1], I.S. Makhov [2], N.V. Kryzhanovskaya [2], S.V. Balakirev [1], M.S. Solodovnik [1]

[1] Southern Federal University, Taganrog, Russia;
[2] National Research University Higher School of Economics, St. Petersburg branch, St. Petersburg, Russia
✉ shandyba.nikita@gmail.com

Abstract. This work demonstrates, for the first time, the selective formation of ordered arrays of vertical GaAs nanowires on Si(111) with a native oxide layer using a two-step pre-treatment of the substrate surface with a focused Ga-ion beam. Based on our previous studies, we show that modifying the substrate through a two-step protocol — first applying a continuous surface treatment with low doses (up to 1×10^{-13} C/μm^2), followed by spot treatment with medium doses (from 1×10^{-13} to 1×10^{-12} C/μm^2) — effectively suppresses parasitic growth and enables nanowire formation at defined surface locations. Furthermore, adjusting the spacing between ion implantation points (from 0.5 to 5 um) allows precise control over the pitch of the nanowire array. By optimizing dose values, we achieve the formation of single, free-standing, vertically oriented nanowires at each ion beam impact site. The study of optical properties of nanowire arrays reveals their high structural quality, as evidenced by intense photoluminescence of GaAs up to room temperatures

Keywords: silicon, focused ion beam, molecular beam epitaxy, nanowires, III-V, nanopatterning, site-controlled

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Материалы конференции
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Упорядоченный рост нанопроволок GaAs на Si(111) подложках, модифицированных при помощи двухэтапной обработки поверхности фокусированным ионным пучком

Н.А. Шандыба [1] ✉, М.М. Ерёменко [1], Д.Д. Духан [1], Н.Е. Черненко [1], Д.В. Кириченко [1], А.Д. Кугаевский [1], И.С. Махов [2], Н.В. Крыжановская [2], С.В. Балакирев [1], М.С. Солодовник [1]

[1] Южный федеральный университет, г. Таганрог, Россия;
[2] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербургский филиал, Санкт-Петербург, Россия
✉ shandyba.nikita@gmail.com

Аннотация. Впервые продемонстрировано селективное формирование упорядоченных массивов вертикальных нитевидных нанокристаллов GaAs на подложках Si(111) с собственным оксидом, модифицированных путем двухэтапной обработки поверхности ионным пучком Ga^{+}. В данном подходе сначала проводится сплошная обработка подложки малыми, а затем точечная большими дозами, что позволяет подавить паразитный рост в области модификации и стимулировать формирование нитевидных нанокристаллов в заданных точках. Оптимизация доз и расстояния между точками воздействия ионного пучка позволяет получать одиночные вертикальные нитевидные нанокристаллы GaAs, демонстрирующие интенсивную фотолюминесценцию при комнатной температуре

Ключевые слова: кремний, фокусированный ионный пучок, молекулярно-лучевая эпитаксия, нитевидные нанокристаллы, полупроводники III-V, нанолитография, позиционно-контролируемый рост

Финансирование: Исследование выполнено за счет средств проекта № FENW-2025-0004 в Южном федеральном университете и проекта «Зеркальные лаборатории» НИУ ВШЭ.

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Introduction

III-V nanowires (NWs) open wide possibilities for the fabrication of integrated microscale light sources and detectors on cost-effective Si substrates. NW-based devices require efficient self-organization techniques that ensure precise positioning and control over nanowire properties. A promising approach to this problem involves the pre-treatment of the growth surface by focused ion beam (FIB) and nanowire formation via molecular beam epitaxy (MBE) [1]. However, this method remains poorly understood, especially in the context of creating regular structures and investigating their properties. In this work, we proposed a new approach to obtain regular NWs using a two-step pre-growth FIB treatment of the Si(111) surface with native oxide layer.

Materials and Methods

In our previous research, we have shown that pre-treatment of Si(111) substrate with a low ion dose leads to local suppression of NW growth, a medium dose intensifies NW growth and a high dose results in the formation of polycrystalline GaAs [2]. Understanding the mechanisms and optimizing the modes allows precise control of nanowire characteristics and prediction of surface morphology when using multiple ion beam processing modes simultaneously. In this work, to form ordered NW arrays without parasitic growth, a two-stage treatment of the Si(111) surface by ion beam with growth suppression and intensification modes is proposed. This approach will allow the creation of selective NW arrays without the need for additional masking layers. First, the area of growth suppression was created through low-dose FIB treatment (up to 1×10^{-13} C/μm^2) using a uniformly spread pattern. After this modified area was additionally patterned by FIB using a dot-template with different distances between ion beam impact points and a dose optimized for NW growth enhancement, varying in the medium dose range from 1×10^{-13} to 1×10^{-12} C/μm^2.

The modified substrate was subsequently annealed at 600 °C, followed by MBE synthesis of GaAs NWs at 750 °C. The resulting arrays were analyzed using SEM and PL techniques.

Results and Discussion

Figure clearly illustrates the effect of the proposed FIB treatment on NW growth – an ordered array of vertical GaAs NWs is formed, with nearly complete suppression of parasitic growth between neighboring NWs and within the array itself. A distinct transition zone is observed between the modified region (highlighted in orange) and the unmodified area of the Si surface, where random NW growth occurs. Increasing the spacing between ion beam exposure points results in a corresponding change in the pitch of the NWs. Notably, parasitic growth suppression remains effective even with a tenfold increase in the FIB-treated area size (50×50 μm, pitch 5 μm).

Figure also shows that optimizing the dose allows to limit growth to a single NW at each FIB exposure point (e.g., with 1 μm pitch). However, increasing the dose disrupts array homogeneity, leading to the formation of multiple NWs at a single exposure point and the emergence of extended NW arrays ordered in a line. We attribute this effect to the lateral spread of ions, both during implantation and subsequent annealing. As a result, the growth intensification effect [2] extends over a greater distance at higher doses, promoting the formation of multiple NWs at a single point (e.g., pitch 5 μm). In turn, in arrays with closely spaced exposure points (pitch 0.5–1 μm), this leads to an overlap of the ion spreading areas between neighboring points and their mutual influence, resulting in the formation of NW rows with parasitic growth between exposure sites. The localized dose increases due to overlap likely shifts the process into the high-dose regime, where parasitic growth dominates, leading to the formation of GaAs polycrystals in these regions [2].

The optical characterization of these core-shell NW arrays reveals high structural quality, as evidenced by intense photoluminescence at room temperatures.

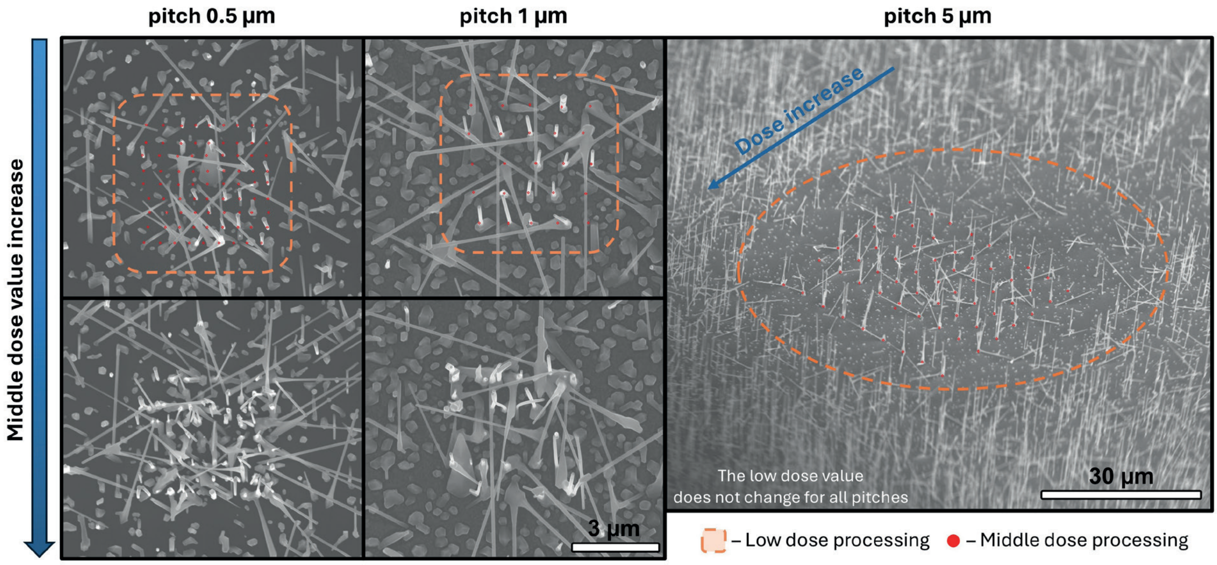

Fig. SEM images of the modified Si(111)/SiO_x surface after GaAs NW growth

Conclusion

Thus, we demonstrated that a two-stage FIB pre-treatment of the Si(111) surface with a native oxide layer enables the selective formation of ordered vertical GaAs NW arrays. The array parameters can be precisely controlled by modifying the FIB treatment template. Additionally, optical characterization revealed that the fabricated arrays exhibit intense photoluminescence, even at room temperatures.

REFERENCES

1. **Shandyba N., Kirichenko D., Sharov V., Chernenko N., Balakirev S., Solodovnik M.,** Modulation of GaAs nanowire growth by pre-treatment of Si substrate using a Ga focused ion beam, Nanotechnology. 34 (46) (2023) 465603.

2. **Shandyba N., Balakirev S., Sharov V., Chernenko N., Kirichenko D., Solodovnik M.,** Effect of Si(111) surface modification by Ga focused ion beam at 30 kV on GaAs nanowire growth, Int. J. Mol. Sci. 24 (1) (2023) 224.

THE AUTHORS

SHANDYBA Nikita A.
shandyba.nikita@gmail.com
ORCID: 0000-0001-8488-9932

EREMENKO Mikhail M.
eryomenko@sfedu.ru
ORCID: 0000-0002-7987-0695

DUKHAN Denis D.
duhan@sfedu.ru
ORCID: 0000-0002-6762-2053

CHERNENKO Natalia E.
nchernenko@sfedu.ru
ORCID: 0000-0001-8468-7425

KIRICHENKO Danil V.
dankir@sfedu.ru
ORCID: 0000-0001-7476-2778

KUGAEVSKY Alexander D.
kugaevskii@sfedu.ru
ORCID: 0009-0001-5183-5396

MAKHOV Ivan S.
imahov@hse.ru
ORCID: 0000-0003-4527-1958

KRYZHANOVSKAYA Natalia V.
nkryzhanovskaya@hse.ru
ORCID: 0000-0002-4945-9803

BALAKIREV Sergey V.
sbalakirev@sfedu.ru
ORCID: 0000-0003-2566-7840

SOLODOVNIK Maxim S.
solodovnikms@sfedu.ru
ORCID: 0000-0002-0557-5909

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