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Scanning probe lithography implementation for $InGaS_3$ optical waveguides fabrication

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Abstract. Integrated nanophotonics faces challenges in matching the component density of electronics, largely due to the size limitations of silicon-based photonics. High-refractive-index materials like $InGaS_3$ offer a promising solution for miniaturized visible/UV photonic circuits. This study demonstrates the fabrication of $InGaS_3$ waveguides using mechanical scanning probe lithography (m-SPL), overcoming limitations of conventional lithography techniques. Test cutting in various directions shows that m-SPL trench quality in $InGaS_3$ depends on crystallographic orientation, with zigzag-aligned force producing clean edges while jagged armchair-direction leads to fractures. The method allows to simultaneously determine crystallographic axes and optimize waveguides side walls quality. This approach establishes m-SPL as a viable route for nanostructuring unconventional materials where standard etching protocols fail, advancing high density integrated photonics.

Keywords: $InGaS_3$, scanning probe lithography, waveguides

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Применение сканирующей зондовой литографии для создания оптических волноводов на основе $InGaS_3$

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Аннотация. Интегральная нанофотоника сталкивается с трудностями в достижении высокой поверхностной плотности упаковки функциональных компонентов, сравнимой с электроникой, по причине прозрачности кремния в ИК диапазоне, а также низкого показателя преломления SiO_2, SiO_x, Si_3N_4, SiN и т.д. Материалы с высоким показателем преломления, такие как $InGaS_3$, предлагают перспективное решение для миниатюризированных фотонных схем в видимом/УФ-диапазоне. В данном исследовании продемонстрирована реализация $InGaS_3$-волноводов с помощью механической сканирующей зондовой литографии (m-SPL), что позволяет преодолеть ограничения традиционных литографических методов. Тестовые разрезы в различных направлениях показали, что качество канавок, созданных методом m-SPL в $InGaS_3$, зависит от кристаллографической ориентации: приложение силы вдоль направления «зигзаг» позволяет получить ровные чистые края, тогда как разрез по направлению «кресло» приводит к образованию трещин. Этот метод позволяет одновременно определять направления кристаллографических осей и оптимизировать качество боковых стенок волноводов. Такой подход подтверждает, что m-SPL является эффективным способом наноструктурирования новых материалов, где стандартные методы травления неприменимы, что способствует развитию оптических интегральных схем с высокой плотностью функциональных элементов.

Ключевые слова: $InGaS_3$, сканирующая зондовая литография, волноводы

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Introduction

Integrated nanophotonics has become a key area of research for advancing the miniaturization of functional components. While all-dielectric photonics offers advantages such as high signal transfer speeds, negligible Joule heating, and non-interacting photon behavior, it still faces challenges in replacing electronic computing. Despite its limitations, such as quantum effects at nanoscale dimensions, charge carrier velocity constraints, thermal management issues, and leakage currents, modern electronics remains dominant due to its significantly higher functional element density (~6 orders of magnitude greater than integrated photonics). This disparity arises from the relatively large size of silicon-based photonic components. Although silicon fabrication technology is mature, cost-effective, and compatible with planar processing, Si indirect bandgap (1.12 eV at 300 K) restricts operation to the IR range. While silicon-derived materials (e.g., SiO_2, Si_3N_4) are transparent in visible and UV wavelengths, their low refractive indices (~1.4) limit the miniaturization of components below 300—400 nm and hinder dense integration. To enable higher packing densities, materials with a high refractive index and compatibility with planar fabrication techniques are essential, particularly for shorter-wavelength applications. For instance, structures based on GaP, including self-assembled nanowires grown on Si substrates, show great promise for nanophotonic integration [1, 2].

$InGaS_3$ is a wide-bandgap semiconductor (2.73 eV) with a high refractive index (~2.5). Unlike conventional van der Waals materials, it has a hexagonal layered structure with covalent interlayer bonding. However, the in-plane bond distribution is non-uniform, and the low areal bond density facilitates layer separation through various techniques [3].

This material holds significant promise for integrated photonics, particularly for passive optical components. Similar layered semiconductors (e.g., MoS_2, $MoSe_2$, WS_2, WSe_2) have already demonstrated the feasibility of precise layer exfoliation and transfer onto different substrates [4]. Thanks to its layered nature, $InGaS_3$ can be mechanically exfoliated with monolayer precision, enabling seamless integration into planar fabrication processes and high-precision control over device geometry. Due to these properties, thin $InGaS_3$ layers are a promising platform for developing passive light-guiding elements in integrated optical circuits.

Materials and Methods

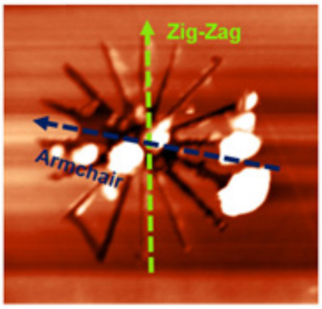
To fully explore $InGaS_3$'s light-guiding capabilities, nanoscale waveguides must be fabricated. However, conventional lithography techniques, such as electron-beam lithography, photolithography, focused ion beam (FIB) milling, nanoimprinting, and scanning probe lithography (SPL), are not yet optimized for novel materials like $InGaS_3$. While FIB can achieve nanoscale patterning, it often introduces a damaged surface layer (up to hundreds of nanometers thick) that requires post-processing annealing.

In contrast, SPL methods, particularly mechanical SPL (m-SPL), offer nanometer-scale precision by locally modifying surfaces using a high hardness probe. The advent of diamond-tipped probes has further expanded m-SPL's applicability, making it suitable for patterning nearly any material with the resolution required for nanophotonic devices. For fabrication, we employed an Ntegra Aura (NT-MDT) scanning probe microscope with DRP_IN (Tipsnano) cantilevers featuring monocrystalline diamond tips (10 nm curvature radius, 250 N/m stiffness). $InGaS_3$ flakes were transferred onto a Si/SiO_2 substrate by mechanically pressing a bulk crystal onto the surface, resulting in flakes of varying thicknesses and areas. Optimal flakes were selected via atomic force microscopy (AFM) inspection.

Results and Discussion

The edge quality of trenches fabricated by m-SPL is influenced by multiple parameters including probe tip geometry, loading force, and probe stiffness. Initial investigations involving angled line patterning at 10 μN were performed to identify optimal conditions for smooth-edged waveguide production (Fig. 1).

a)



b)

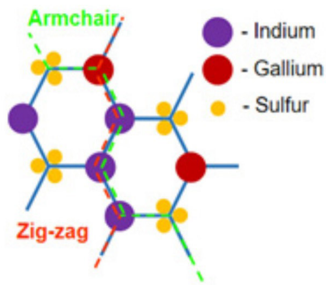


Fig. 1. AFM-scan of the cut trenches along different directions on $InGaS_3$ flake (*a*); schematic of the $InGaS_3$ crystal lattice structure with indicated 'zig-zag' and 'armchair' directions (*b*)

The patterning results demonstrate strong crystallographic orientation dependence: trenches exhibit sharply defined profiles in certain directions, while developing broader, irregular edges with flaking in others. This anisotropic behavior originates from the $InGaS_3$ crystal's intrinsic mechanical properties. Like other TMDs in the $P6_3/mmc$ space group, the material shows markedly different mechanical responses along different crystallographic axes - with armchair directions exhibiting 1.5-2.2× greater tensile strength than zigzag orientations [5]. This anisotropy leads to preferential fracture propagation along zigzag directions under mechanical stress.

Consequently, zigzag-aligned force application produces clean cleavages, while armchair-oriented loading tends to cause jagged fractures and localized delamination. The observed dependence of trench morphology on sample rotation validates this approach's dual functionality: 1) crystallographic orientation determination; 2) optimal sample alignment for side walls quality control.

To demonstrate the implementation of m-SPL technique strip waveguides were fabricated (Fig. 2). Experiment employed flakes oriented along 'zig-zag' direction, with trenches fabricated through cyclic scanning of a 32×1024-point matrix (0.95×30 μm) in contact mode. Using a horizontal fast-scan direction at 230 μm/s with 2 μN applied force achieved controlled material removal at 10 nm per scan pass. Characteristic edge asymmetry emerged - the left edge maintained atomic-scale smoothness while the right edge showed pronounced material accumulation due to probe tip geometry. Edges were processed via horizontal trenches formation and surface was cleaned in contact mode (400 nN).

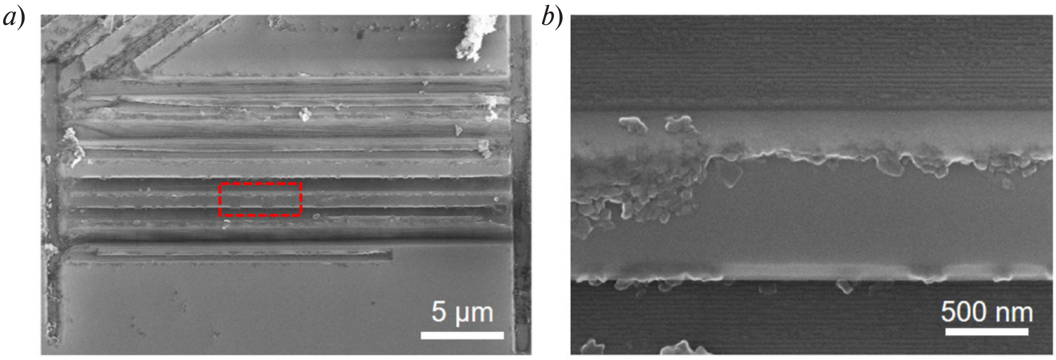


Fig. 2. SEM-images of strip waveguides fabricated via m-SPL technique on 70 nm thick $InGaS_3$ flake cutted along the 'zig-zag' direction (*a*); enlarged area (red dotted rectangle) demonstrating the high quality of the waveguide side-walls (*b*)

It is evident that m-SPL technique allows to fabricate multiple ~25 microns long waveguides separated from each other by the value of its width. The side walls demonstrate high verticality and evenness, as it's performed in the enlarged SEM image (Fig. 2, *b*).

Conclusion

To sum up the array of strip waveguides 70 nm thick and 700-900 nm wide were fabricated via m-SPL technique. $InGaS_3$ mechanical anisotropy dictates the evaluation of the optimal cutting direction. It was demonstrated that the following method allows to fabricate waveguides of various design based on non-conventional novel material $InGaS_3$ which etching protocols via standard methods are not applicable.

Acknowledgments

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