nanoFIB for advanced focused ion beam (FIB) nanofabrication

In many ways, the nanoFIB column truly defines a new state of the art in focused ion beam (FIB) technology. Focused ion beam nanofabrication is being employed more and more to answer today's most pressing questions in nanoscale research, science, and prototyping. A focused ion beam brings various direct fabrication techniques such as milling, gas-enhanced etching, gas-assisted deposition, implantation, and functionalization within reach. Raith's proprietary focused ion beam technology has evolved to meet all critical requirements of advanced nanofabrication and lithography, resulting in a significantly advanced ion source and column technology combined with a dedicated system architecture for nanofabrication. The entire platform, with its optimized components, has matured over almost two decades and culminated in the VELION FIB-SEM covering the full range of FIB techniques and nanolithography.

This paper describes state-of-the-art focused ion beam column technology and its key strengths for nanofabrication applications by taking advantage of outstanding features like source stability and beam placement accuracy. Moreover, the pioneering extension for stable delivery of non-gallium nanometer focused ion beams enlarges the range of nanofabrication processes even further[1,2]. This proves to be a powerful technique for sub-10-nm advanced ion beam nanofabrication on various materials and real-world samples, with huge potential for advancing nanoscale science and engineering.

Raith Ga ion beam technology

The motivation for Raith's nanoFIB™ technology was to advance FIB techniques to the performance level of a lithography system. At this level, advanced FIB nanofabrication requires a long-term stable ion beam current and lowest beam position drift.

The key component is the ion source itself, which is typically a Liquid Metal Ion Source (LMIS). A LMIS consists of a tungsten metal tip covered with gallium metal to form a stable emission cone from which ions are extracted. The stability of the emission cone depends on the characteristics of the LMIS as well as its control and stabilization mechanisms. The stability of the LMIS is mainly determined by the flow of the liquid metal towards the tip, which in turn is affected by both shape and topography of the metal base wire and tip. Therefore, the LMIS of the nanoFIB comprises a liquid-flow optimized ion source due to its specific geometry and the sophisticated manufacturing process of the metal base tip. It gives an inherently more stable ion source without the need for frequent heating.

Raith's nanoFIB LMIS meets long-term stability requirements with guaranteed lithography specifications in a way that continuous operation over several days up to weeks are routinely possible.

Robust beam current stability data such as those in Figure 1 are unique to Raith's nanoFIB source technology and significantly advance the state of the art in gallium LMIS source stability.

The nanoFIB ion source is an essential part of the nanoFIB ion column, which itself already pushes the envelope in ion optics technology. Raith has designed

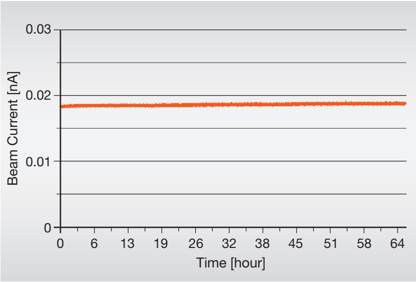

Figure 1: Probe current of Raith's nanoFIB™ Ga focused ion beam showing excellent long-term stability

this column as the leading technique on the VELION. The nanoFIB ion column is designed for highest resolution and excellent beam characteristics with a short optical length and optimized working distance. Focusing performance is optimized to the relevant beam current range for nanofabrication. The ultra-low distortion deflection enables accurate patterning, feature placement, and stitching of multiple writing fields.

Write fields are dynamically corrected for both stigmation and distortion to enable highest-level lithography specifications to be achieved.

For this purpose, nanoFIB ion column comprises dedicated two-stage octupole deflectors, which are optimized for low aberrations and minimum distortions independently from the separate stigmation octupoles.

Low-distortion beam deflection and high-precision laser stage movement achieve state-of-the-art stitching accuracy.

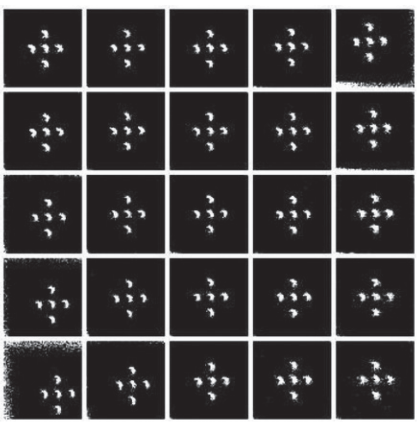

Figure 2: Write field before corrections; stigmation and distortions may harm stitching performance

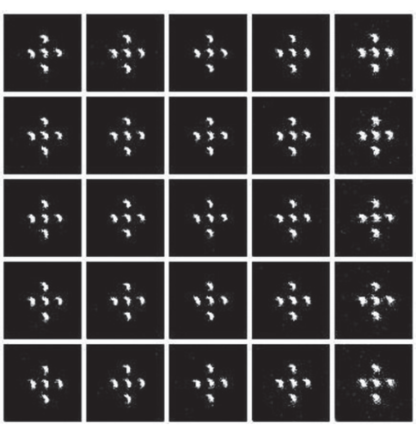

Figure 3: Features are placed free of stigmation and distortions, accurately, and all over a single write field after corrections to enable write-field stitching for nanofabrication

Ion beam spot characterization

Raith's nanoFIB column clearly presents the tightest beam spot of any gallium FIB by far. Beam spot characteristics can be defined by image resolution, beam diameter, or patterned feature sizes. The performance of nanofabrication instruments can be characterized by line scans over a sharp edge for measuring the beam diameter. Determination of beam diameter is a well-defined procedure that typically gives results in the range of 3–6 nm when applied to FIB. However, the actual value generated by this method is doubtful, given the destructive nature of the ions and the fact that ion beams from a LMIS do not exhibit a pure Gaussian current distribution.

Writing thinnest lines into a bulk sample is a meaningful alternative to determine ion beam milling performance when FIB nanofabrication is the focus of application.

Exemplary results obtained with the nanoFIB ion column are shown in Figure 4 and clearly demonstrate the sub-10 nm patterning capabilities of Raith's nanoFIB.

These important results and specifications still do not describe all aspects of the LMIS beam spot characteristics. The FIB spot is usually not a pure Gaussian distribution, it also exhibits significant beam tails outside the central spot. This can be seen in the beam current distribution (Figure 5).

Various FIB-related applications require consideration of different effective beam diameters. FIB imaging resolution is predominantly determined by the very center of the peak distribution, whereas milling performance is dominated by the narrow main peak (dotted line of

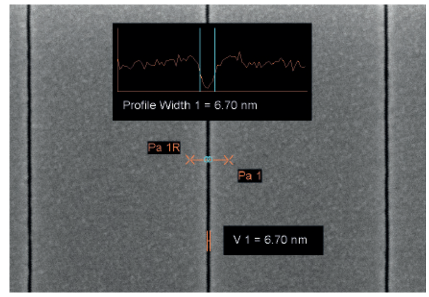

Figure 4: Minimum feature size obtained in a bulk sample. Gallium milling of a Chromium layer on silicon substrate, line width < 10 nm

the orange curve). Large beam tails can have a significant influence on patterning results, as the superposition of beam tails generates unwanted edge rounding or sample collateral damage. Low beam tails become important for gas assisted processes and patterning performance.

The exact measurement of the beam current distribution is quite sophisticated although the procedure is well understood [6,7,3]. This promising and precise method is based on the amorphization of single silicon crystals by gallium ion irradiation. For the purpose of determining the beam current distribution within the ion spot, a theoretical model is assumed which considers a central large-intensity Gaussian, a medium-intensity Gaussian, and a low-intensity exponential for beam tails. The result of the fitted beam current distribution for the nanoFIB column based on this method shows a significant improve-

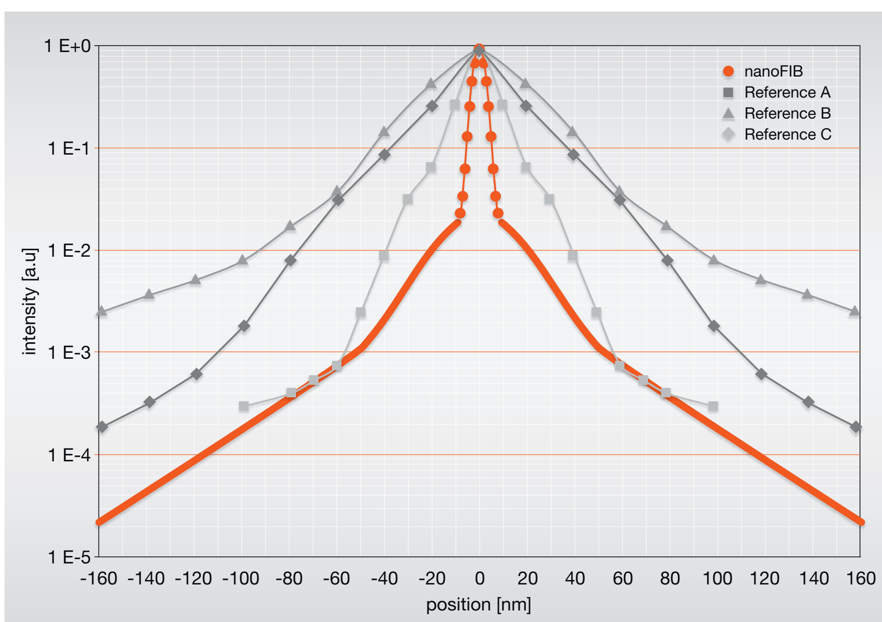

Figure 5: Beam current distribution for nanoFIB showing a narrow and large central spot and low tails compared to different data of conventional FIB technology. Reference results A to C can be found in 3, 4, 5, respectively

ment compared to data of conventional focused ion beam columns[3,4,5], mainly in terms of a very narrow and large central Gaussian part (carrying >85 % of the total current) and record low beam tails (Figure 5).

The most relevant part for milling is in the intensity range of 1 to 10^{-3}. With this extraordinary current distribution, nanoFIB technology provides superior performance with smallest spot size in gallium FIB.

Benefits for FIB nanofabrication applications

By taking advantage of low beam tails and precise pattern placement, unique nanofabrication applications become possible. In addition, long-term stability and a high degree of automation are the basis for reproducibility of well-controlled structures for a high number of single features over large areas. Examples can be found in the field of plasmonics, where many identical features must be patterned in a reproducible manner with high placement and pitch accuracy.

Figure 6 shows an array of 12,000 oligomers consisting of 7 holes each. The ribbons between adjacent holes are only 30 nm, all patterned into a 80-nm-thick gold layer. This structure is quite challenging because beam tails from several directions overlap in this area. The ability to maintain such a thin separation wall in gold is also great proof of excellent beam spot characteristics and record low beam tails. Due to dynamic beam correction, the feature looks the same all over the entire write field, with no visible distortions or stigmation effects.

nanoFIB stability, automation, and placement accuracy are vital for large-area patterning and stitching utilizing a laser stage. This applies for the relatively simple 4-mm-long waveguide structure (Figure 7) as well as for the more complex milling of the 2-mm-long photonic crystal waveguide (Figure 8). Excellent stitching is well known to be essential in nanophotonics, where even small placement errors in the order of 10 nm can dramatically degrade the performance of the photonic device. The VELION not only provides the necessary accuracy and stability through the nanoFIB column, but is also supplied with a laser interferometer stage and the option of including stitch-free writing modes,

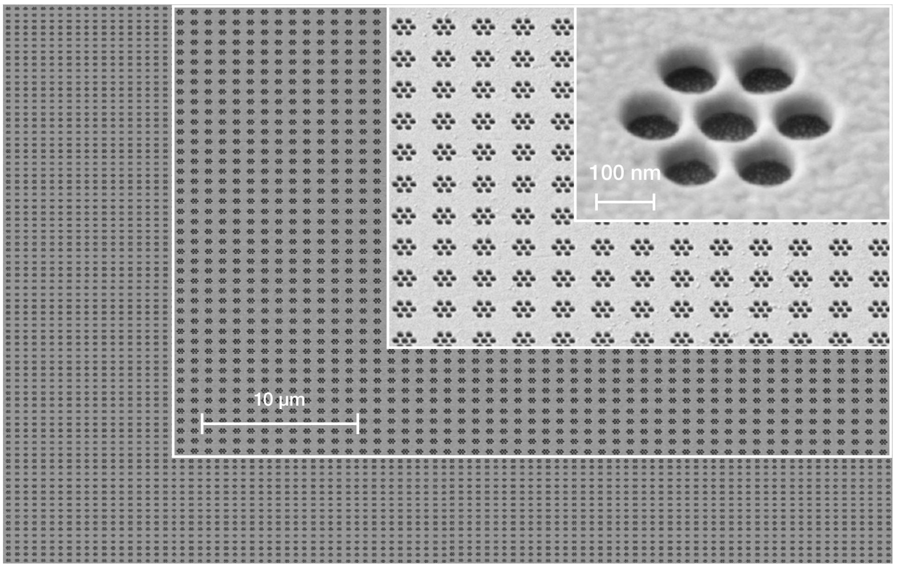

Figure 6: Oligomer Structures with Heptamer-arranged nanohole arrays[13]

ensuring highest performance regardless of its length.

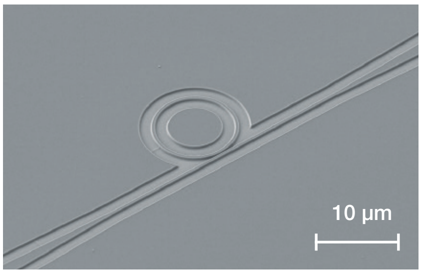

Figure 7: 4 mm waveguide and coupler directly milled with Ga ion beam into silicon substrate by nanoFIB

Fabrication of high-aspect-ratio nanogrooves is a challenging task for ion beam milling. The capabilities of the nanoFIB column, with its sharp beam shape and lowest beam tails, supports milling of high-aspect-ratio features. Results for exemplarily milled high-aspect-ratio slits are shown in Figure 9 and Figure 10. Both substrates were bisected to reveal the cross-section of the cut. Figure 9 shows the SEM image of a 20-nm-wide cut thus obtained, and reveals the high aspect ratio of 10 achieved for a soft material such as gold[17]. The groove in Figure 10 was directly milled into GaAs substrate without gas-assisted etching.

A stable ion beam is mandatory for setting up automated processes to perform unattended patterning over long periods of time. For high-resolution patterning, the spot size strongly depends on the selected beam current. Therefore, nanofabrication results can be further enhanced by reducing the beam current and applying an automated overnight process. However, this process can be conducted with a moderate beam current at high patterning resolution in an overnight process[10]. This has routinely been demonstrated for rapid prototyp-

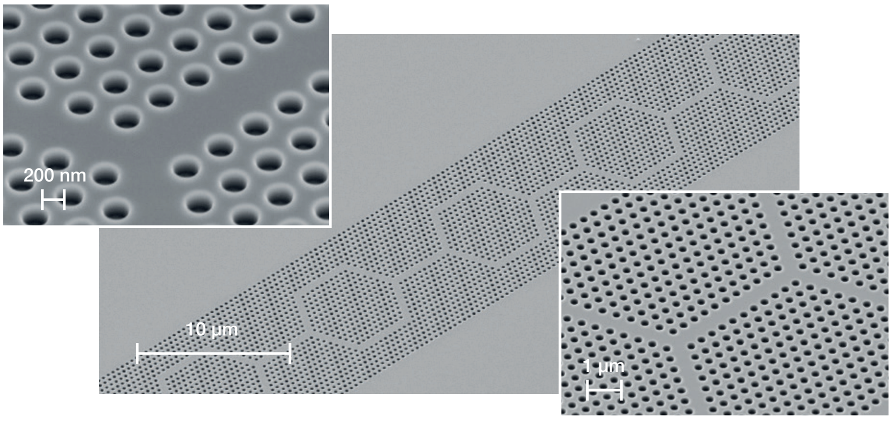

Figure 8: Structure of photonic elements directly milled into Si bulk material. Lowest beam tails result in straight cylinders with 200nm diameter and 200nm depth. In particular, edges are fabricated sharply and are not rounded or affected by beam tails

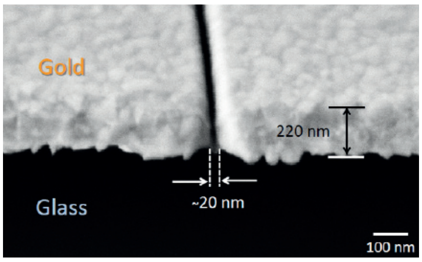

Figure 9: SEM image of a 45-degree-tilted 20 nm groove in 220 nm Au film on glass substrate[17]

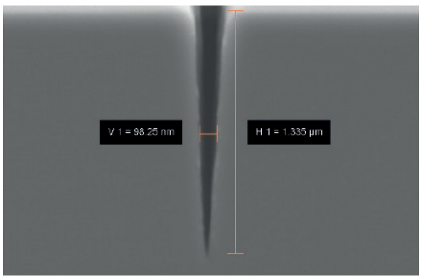

Figure 10: X-section of cleaved substrate perpendicular to a 1mm-long line, GaAs Aspect ratio: >13; Princeton University, 2019

ing of X-ray zone plates, where huge amounts of material must be removed at highest beam placement with highest aspect ratio [11, 12].

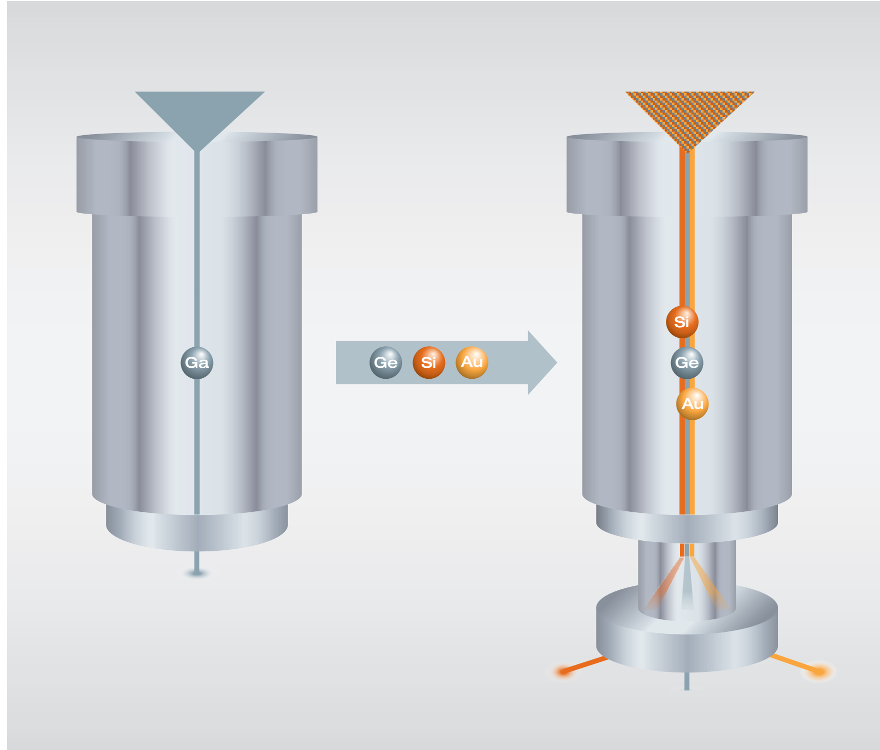

Figure 11: The extended nanoFIB with IONselect upgrade including alloy ion source and ion selector

Multi-species ion beam technology

Raith has implemented its proprietary IONselect technology in the nanoFIB column to extend FIB nanofabrication availability to other ion species than gallium. Applications in nanofabrication make high demands on this technology. Sophisticated nanofabrication depends on long-term stability as well as simple and reliable selection of ions.

LMAIS

The most advanced component of the IONselect package is the Liquid Metal Alloy Ion Source (LMAIS), which consists of a eutectic alloy instead of gallium. LMAIS eutectic alloys are not liquid at room temperature. Although the melting temperature of the eutectic alloy is lower than the melting temperature of the individual metals, continuous source heating is needed to liquefy the alloy.

The required source heating is easily achieved by applying a low current of a few amps during normal operation. Moderate continuous heating and sophisticated source design provide an outstanding stable ion source supplying ion species other than Ga for FIB. As the data in Figure 12 demonstrate, it effects user-friendly long-term access to gallium-free ion sources for advanced FIB nanofabrication.

ExB Filter

Where numerous available ions are all emitted from a single source, a fast and reliable switching process is important. For this purpose, a mass separation filter operates as an ion selector, representing an essential part of the extended ion optics. The filter is designed to keep additional aberrations low, thus preserving small beam diameters. The actual ion selection is achieved by applying small electric and magnetic fields in an ExB filter arrangement. Electrical field settings are changed for ion selection, whereas the magnetic field is kept fixed by a permanent magnet. This setup ensures long term stability without current-induced drift from the magnetic field. As the switching is accomplished by the mass filter, neither changes at the ion source nor any mechanical column alignment are required. Switching between different ions is fast and easy and the switching process can be easily integrated into long term FIB nanofabrication workflows.

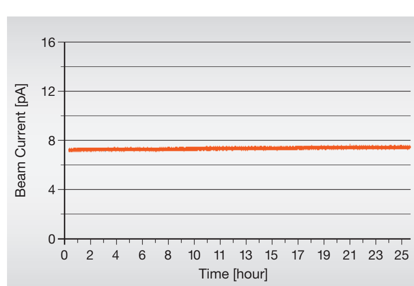

Figure 12: Probe current of Raith's LMAIS showing excellent long-term stability suitable for most nanofabrication tasks

As for gallium-based FIB nanofabrication, all long-term stability requirements are met by the nanoFIB with IONselect. Maintaining highest resolution capabilities was the main impetus for the mass filter design. Line scans over a sharp edge delivered beam diameters from less than 15 nm to a few nm. The ultimate beam diameter depends on the physics of selected ion species; light ions typically reveal smaller spot sizes than heavier ions.

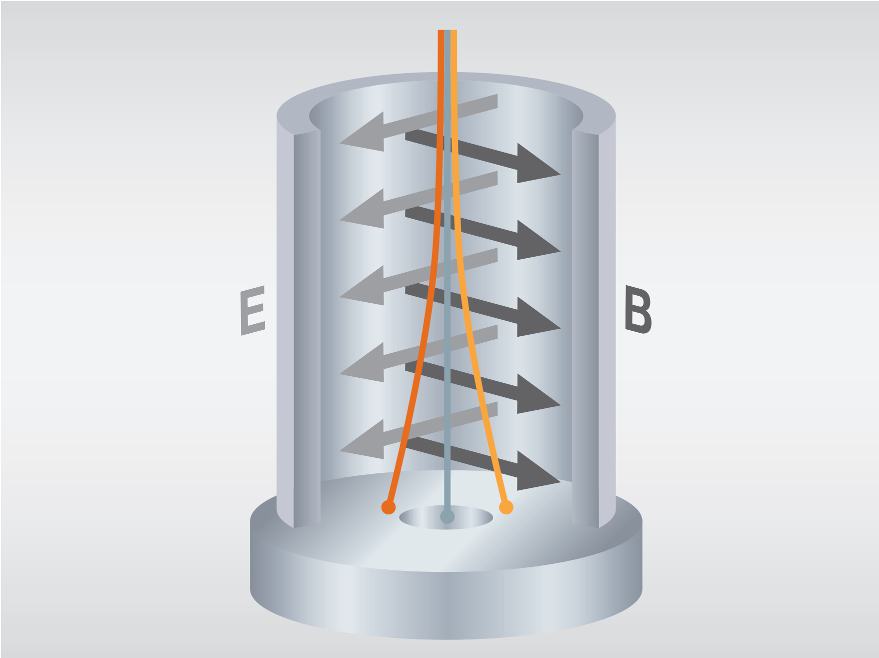

Figure 13: ExB Filter

LMAIS patterning performance utilizing nanoFIB

To determine nanofabrication capabilities of the nanoFIB with IONselect, the achievable minimum feature size of direct milling into a thin layer was investigated [1]. For this evaluation, a popular and sensitive substrate such as gold was selected.

Figure 14 and Figure 15 show results for silicon and gold focused ion beams that were used for milling into a thin Au layer. The line width represents the minimum feature size and reveals the excellent patterning performance of LMAIS Au and Si ion beams.

Excellent long-term stability and superior milling performance are clear drivers for utilizing LMAIS beams for Ga-free direct pattering in key applications such as nanophotonics or plasmonics. Many of the applications that were discussed above exhibit improved results when Ga contamination is avoided.

Beside photonics and plasmonics, many additional examples can be found in the fields of ion implantation [18], Si membrane devices, III-V materials, and selective growth and processing of nanoscale materials.

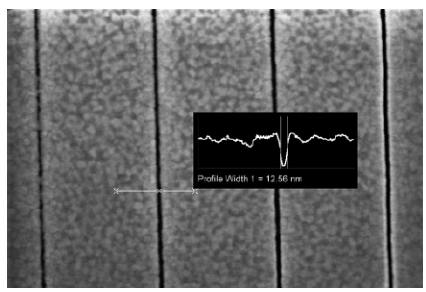

Figure 14: 13nm Si ion beam for Au layer

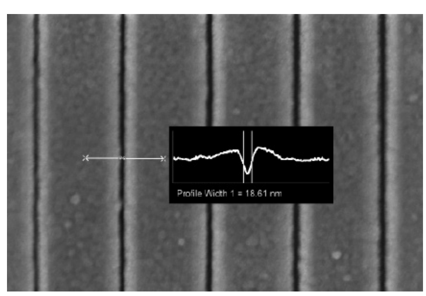

Figure 15: 19nm Au ion beam for Au layer

The first research results have been achieved for nanopore devices [8], direct milling of III-V semiconductors [14], catalytic MBE for nanowires, and selective growth of graphene [15, 16].

References

1 S. Bauerdick et al., JVST B 31, 06F404 (2013)
2 L. Bruchhaus et al., Appl. Phys. Rev 4 011302 (2017)
3 S. Tan et al., JVST B 30, 06F606 (2012)
4 M. Hillmann, PhD thesis, Bochum (2001)
5 J. W. Ward et al., JVST B 6, 2090 (1988)
6 G. Ben Assayag et al., JVST B 11, 2420 (1993)
7 C. Vieu et al., Nucl.Instr.Meth. B 93, 439 (1994)
8 Raith Whitepaper FIB-SEM"
9 N. Liu et al., Nano Lett. 10, 1103 (2010)
10 Raith application note "X-ray lens"
11 A. Nadzeyka et al., Micr. Eng. 98, 198 (2012)
12 K. Keskinbora et al., Opt. Expr. 21, 11747 (2013)
13 M. I. Stockman, Nature 467, 541 (2010)
14 B. Gila et al., Micr. & Anal. (2013)
15 S. Tongay et al., APL 100, 073501 (2012)
16 M. G. Lemaitre et al., APL 100, 193105 (2012)
17 G. Seniutinas et al., Nanofabrication 2015-0006; 2: 54–62 (2015)
18 Yu Zhou et al New J. Phys. 20 125004 (2018)

Final note

Raith's proprietary nanoFIB™ technology has been specifically developed for the requirements of advanced nanofabrication. The nanoFIB column employs either a Ga-focused ion beam alone or myriad ion species for sub-10-nm patterning on a variety of materials.

- nanoFIB is unmatched in beam spot characteristics and stability, and sets new standards in ion source and column technology
- IONselect provides a user-friendly, easy-to-use source of non-gallium ions
- nanoFIB column exhibits superior capabilities and delivers cutting-edge application results
- nanoFIB column is the central component of the VELION system. Combined with a laser interferometer stage and customized SEM, the VELION forms a versatile and outstanding nanofabrication system and sets a new benchmark for nanoengineering applications

Explore the huge potential of next-generation research instrumentation in nanoscale science, and experience the advantages of new ion species!
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