# Nanofabrication using focused ion beams

**SVEN BAUERDICK**
Raith GmbH, Konrad-Adenauer-Allee 8, Dortmund, Germany

## INTRODUCTION

Nanofabrication techniques have been applied to the creation of nanoscale structures for decades and do mainly employ resist based lithography plus pattern transfer.

The use of ion techniques has further expanded those from the electron beam technology and allows direct (mask and resist less) patterning into substrates with nanometer precision. This article will look at the fundamentals of this technology and its modern-day applications in nanoscience and beyond.

## FUNDAMENTAL TECHNOLOGY

The first attempts to develop ion based systems were in excess of 70 years ago with the invention of the field ion microscope developed by Mueller in 1951[1]. By 1955 progress in the area lead to the scanning ion microscope in the form of an instrument using 20 kV accelerated $Ar^+$ ions focused to a 1 μm probe. Since then there have been further reports on the application of ion-based systems being used to make small structures or holes in materials.

In the 1960s Liquid Metal Ion Sources (LMIS) started to be used and became applied in FIB technologies from the 1970s largely using Gallium as the source material.

Since ion beams were proven capable of removing selected areas of material to a specific patterned resulting surface there has been a steady development of technologies and sources for the generation of the ions.

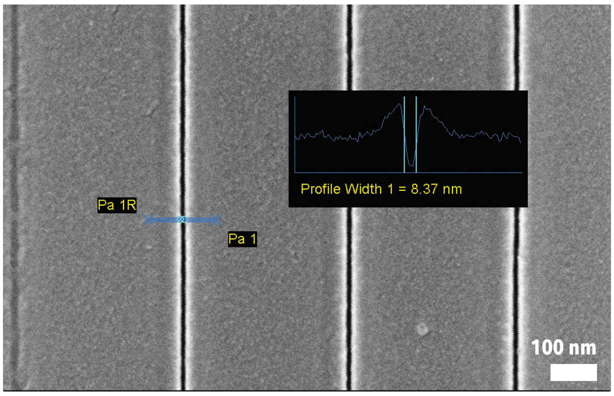



FIGURE 1 *FIB line cuts in a 20 nm thick chrome layer (SEM image) showing the patterning fidelity of Ga focused ion beam*

Now in 2018 there exist a range of distinct ion beam types, each with advantages dependant on the desired outcome and application.

Current column technologies can be summarised as follows:

**LMIS** – Liquid Metal Ion Source – Such sources employ a low temperature metal system and include Ga

**GFIS** – Gas field Ion source, like the ones first employed in the Field Ion Microscope, which use He or Ne and exhibit higher brightness for a smaller probe size

**PLASMA ION SOURCES** – Inductively coupled or electron cyclotron resonance plasma, this type of source including Xe giving access to higher currents than Ga LMIS sources, meaning more material can be removed in the same time period.

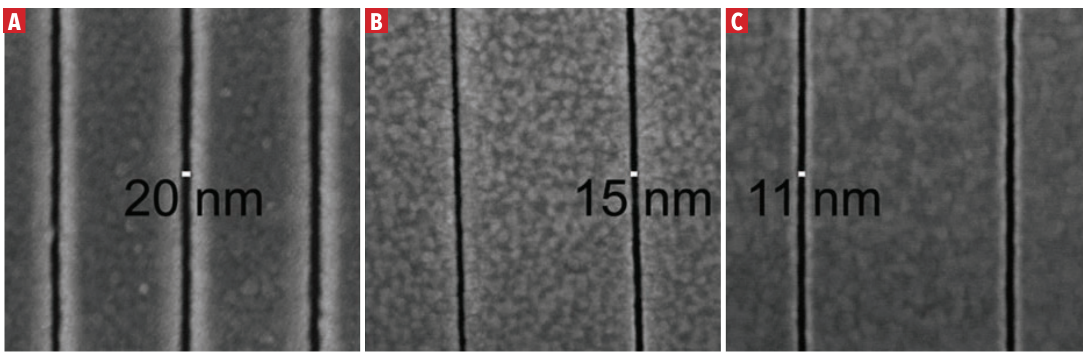
The details and design differences of the different types are beyond the scope of this text, however, in depth technical details can be found in[2].

## ALTERNATIVE LIQUID METAL ION SOURCES

The principle requirements for an LMIS or Liquid Metal Alloy Ion Sources (LMAIS) are a low melting point, low vapour pressure (VP), low reactivity with the (Tungsten) solid needle which it is based on, high beam current and vacuum stable (long-life) source. With a melting point of 29 degrees, and low VP, Gallium has the added advantage that the emitted ions are 99% $Ga^+$. This means that the ions that can be columnated into a beam with low aberration, making the column design fairly straightforward without the need for[3] a mass separation filter.

The Gallium LMIS source is understandably the most widespread ion source applied to FIB instruments, however, there are many other

FIGURE 2 *SEM images of FIB direct written lines in a gold layer using (a) Au++, (b) Si++, and (c) Be++ ions[3]. Reproduced with permission from J. Vac. Sci. Technol., B 31(6), (2013)*

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RAITH NANOFABRICATION

## BIOGRAPHY

Sven Bauerdick studied physics at the Universities of Muenster and Tuebingen, Germany. He received his diploma in 2001 as well as a certificate in medical physics and technology at the University of Kaiserslautern. In 2004 he finished his PhD in micro and nano technology at the University of Tuebingen. In 2004 Bauerdick joined Raith and contributed to and managed various R&D projects on focused electron and ion beam nanofabrication systems. He's been product manager of focused ion beam nanofabrication systems since 2009 and is co-author of more than 20 papers in the area of nanotechnology applications and instrument development.

## ABSTRACT

Besides the well-established microscopy and sample preparation techniques, Focused Ion Beam (and FIB-SEM) instruments are increasingly employed for micro and nanofabrication applications. FIB nanofabrication provides complementary strengths like direct, resistless, and three-dimensional patterning to conventional "resist-accelerated" lithography. With the relative simplification of the overall process it still helps to achieve scientific results faster, in particular for patterning novel materials or ever changing devices and systems. The liquid metal ion source technology meets corresponding requirements offering excellent handling, stability, resolution and beam current range. Current and future applications for r&d nanofabrication and device prototyping will be discussed, both with high resolution Gallium as well as various new ion species.

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## CORRESPONDING AUTHOR

Dr. Sven Bauerdick, Senior Product Manager, Raith GmbH, Konrad-Adenauer-Allee 8, 44263 Dortmund, Germany
Tel: +49-231-95004-116
E-mail: sven.bauerdick@raith.de

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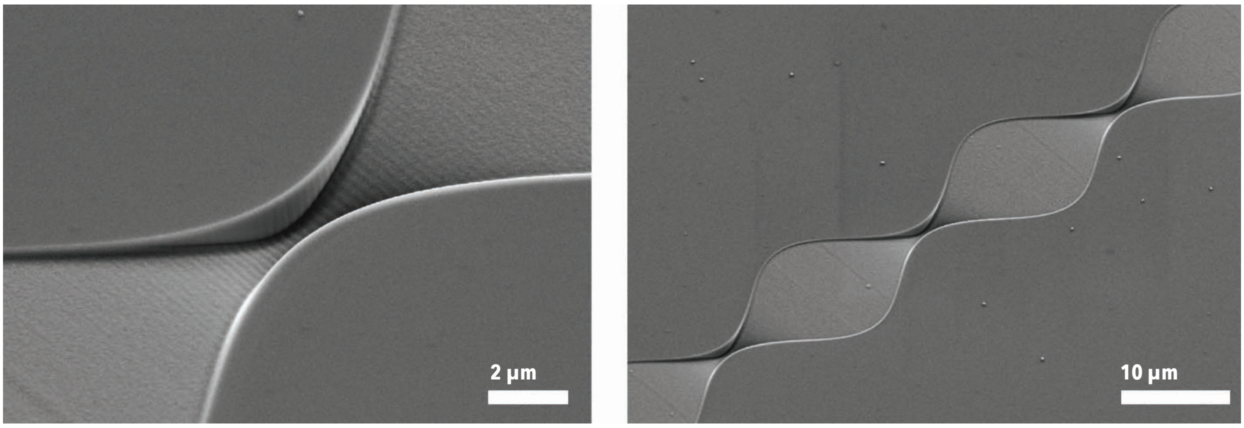


FIGURE 3 **Gallium FIB has been used to fabricate a micro-fluidic mixing channel by direct 3D structuring (lateral pattern definition plus dose variation) over a total length of 1 mm[22]**

materials which may be used dependant on application and the desired outcome. A full in depth review covering the details of materials, source and column schematics and many other considerations are available[2], however, we summarise some notable chemistries:

For multi element ion sources those based on AuSi and AuGe eutectic alloys show the best performance and can be expanded by adding various materials. They offer multiple ions in one column, without the need to break vacuum.

By the inclusion of a mass-filter different species of the same element or species of different elements can be selected and guided to the sample surface as required. Such a system was demonstrated to (Figure 2) provide milled line widths of 20–11 nm and beam resolutions from 15 nm–4 nm depending on the ions used[3].

The different beams allow different rates of milling, and specific applications depending on the substrate *i.e.* milling layers on Silicon using a Si beam or functionalisation of surfaces by ion beam exposure (see application section). Light elements can be used for high resolution imaging or thin layer patterning due to their small achievable beam size. On the other hand give heavy ion species like Au a lower penetration depth and thus make more surface sensitive interaction possible, this gives a better depth resolution enabling sample functionalization or layer removal without deep damage to the substrate.

Depending on the application challenges more elements can be added. A recent example is given by research and technology in the area of quantum computing, sensors and data storage. Here the implantation of various ions like Si (Figure 7), Ge, other group 4 elements, Cr and Bi is required and could be met by using LMAIS technology.

Another important source material system is based on Bi (and Ga) alloys. Bismuth clusters can be used and find principle application in Secondary Ion Mass Spectroscopy (SIMS) instruments. The large clusters are good for layer-by-layer removal of sample surfaces, which can be subsequently interrogated using the in chamber mass spectrometer. A detailed review is[4] Moreover Bi shows interesting capabilities for nanofabrication

TABLE 1 ***A list of source types, ion sources and applicability. Ion species listed as "available" are well-developed sources and are featured in commercial instruments.***

| SOURCE TYPE | GENERAL PROPERTIES | ION SPECIES |
|---|---|---|
| Liquid metal ion sources | Virtual source size 10–20nm<br>Typical pattern res 10–20 nm<br>Typical beam currents up to a few nA forGa and up to a few 100 pA for most other species<br>Very good long-term stability and lifetime for Ga, improving performance for well-known systems like AuSi and AuGe<br>Sputter yield mostly medium to large | Available:Ga, Au, Si, Ge<br>Also exist:Ag, Al,As, B, Be, Bi, C, Ce, Co, Cr, Cs, Cu, Dy, Er, Fe, Hg, In, K, Li, Mg, Mn,Na, Nb,Nd, Ni, P, Pb, Pd, Pr, Pt, Rb, Sb, Sm, Sn, U, Y, Zn |
| Gas field-ionization sources | Virtual source size below 2 nm (He, Ne)<br>Typical pattern res 5–10 nm<br>Typical beam currents up to 10 pA<br>Limited stability and lifetime<br>Sputter yield mostly small to medium | Available: He, Ne<br>Also exist: H, Ar, N |
| Plasma sources | Virtual source size ~10 µm<br>Typical pattern res 100 nm–1 µm<br>Typical beam currents up to a few µA<br>Good stability<br>Sputter yield mostly medium to large | Available: Ar, Xe<br>Also exist: H, He, N, O |

applications (including ion implantation). It can be combined into a GaBiLi source combining work-horse Ga with very heavy Bi ions/ clusters and very light Li ions.

Decades of development and continued investment in the designs has resulted in a plethora of options to be determined by the end goals.

Table 1 demonstrates the range of chemistries and source technologies presently available, which cover a good portion of the periodic table.[5, 6, 7 8].

## APPLICATION EXAMPLES

Many *Microscopy and Analysis* readers will be familiar with the combination of an ion beam with a scanning electron microscopy column commonly referred to as FIB-SEM. Typically instruments are located in research and development environments and are Ga LMIS source instruments, although Xe Plasma is increasing in popularity, due to the larger volumes that can be accessed. These instruments are commonly used for cross-sectioning and the preparation of TEM lamellae for transmission electron microscopy (TEM).

In contrast, the same ion beam technology can also be used to create something functional or a device on the small scale and under the right conditions over a large area. The removal of material to create tiny structures with very high precision has long been possible with the ion beam and can be referred to as nanofabrication or nanopatterning. These terms are related to patterning techniques like electron beam lithography (EBL) providing the same result but not in a direct way without resist or masking layers.

## NANOPATTERNING AND PROTOTYPING

Direct write ion beam nanopatterning which, uses a focused ion beam to create features directly into the surface reduces the number of steps compared to EBL[9], offers patterning in 3D as well as on 3D samples and provides the ability to etch and deposit in the same chamber[10, 11].

FIB nanopatterning is currently the only nanofabrication method capable of creating high-resolution 3-dimensional structures, which are of interest in templating applications. Other options are laser-ablation or laser based 3D two-photon polymerisation, although both typically lack the resolution that the FIB offers. What follows is an overview of the applications in which the FIB has been used. A number of good reviews are available and cover these areas in detail[12, 13, 14, 15].

## GAS ASSISTED ETCHING AND DEPOSITION

In addition to the many examples of ion beam milling, ion beam platforms are equipped with in chamber gas injection systems that use the ion beam to perform ion beam gas deposition[10, 11]. The options are numerous and include metals such as

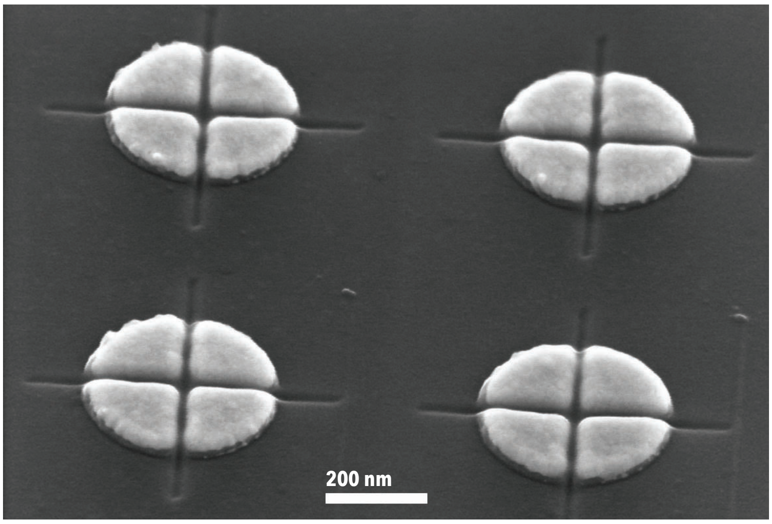


FIGURE 4 ***SEM micrographs of 40 nm thick segmented gold islands made by EBL plus precisely overlaid milling of crossing lines. Localized surface plasmons interact through the approximately 20 nm wide gaps that were intentionally overmilled deeper into the silicon, as this feature was predicted to favorably affect electromagnetic field enhancement[24]***

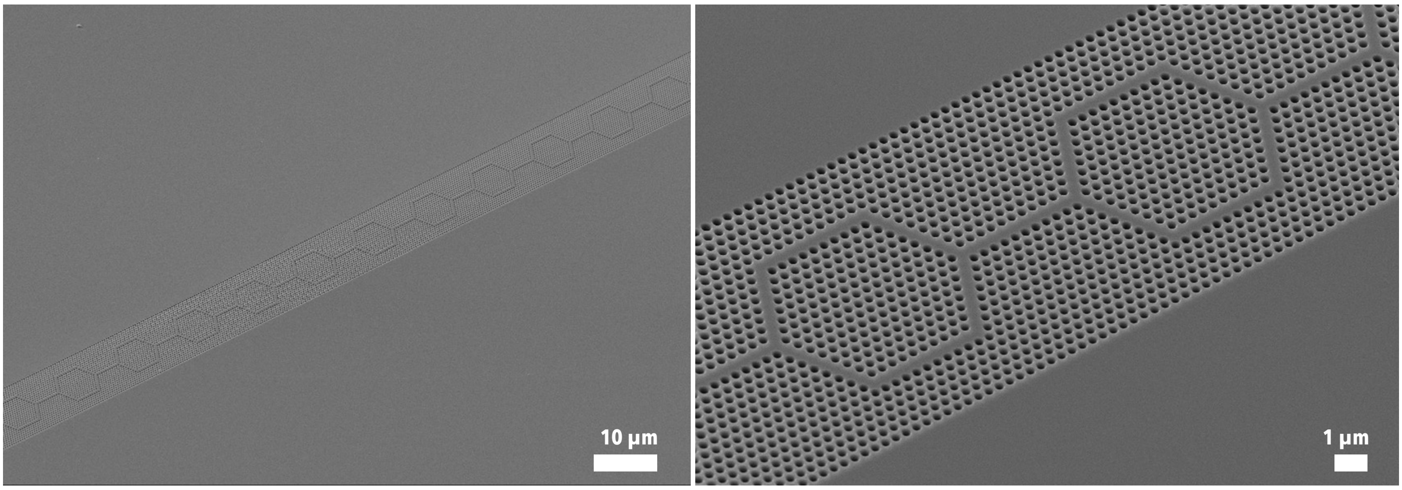


*FIGURE 5* ***Photonic waveguide structure prepared using a Ga FIB and precision stage technology for write field stitching***

platinum and tungsten or carbon or silicon oxide. On the other hand also etchant precursors like fluorine are commonly used in order to increase the removal rate or selectivity, reduce local contamination (implantation and re-deposition) and achieve higher aspect ratio structures.

## SURFACE MODIFICATION

Ion beams are capable of patterning a surface but also modifying the surface and thereby preparing it for subsequent processing steps. A good example of this is demonstrated in preparation or growth of graphene or nanowires[16, 17] where the Au and Si of a multi-source column was used to functionalise the surface. Exposure of a surface to the FIB has also been applied in the nucleation and growth of gold nanoparticles and CoPt nanoclusters[18, 19, 20]. Using the same technology GaAs epitaxially grown vertical nanowires were produced on GaAs surfaces[21].

## FLUIDICS

The area of microfluidics is an exciting one and offers new potential in multiple areas including healthcare and food sciences, however, the key to this is obviously the fabrication of the tiny and often complex structures that aim to ensure mixing. In this area the FIB is unparalleled in its ability to create three-dimensional (see Figure 3) structures of high complexity and low dimensions directly into the substrate[22] or into a mould that can allow straightforward replication and thereby lower production costs.

## PLASMONIC AND PHOTONICS STRUCTURES

Plasmons are electron plasma oscillations that are coupled to electromagnetic waves locally bound to an interface of a conductor and dielectric. The fact that they are confined to tens of nanometer distances means that surface films or structures (nanoparticles or islands) of gold and silver are commonly used. For a detailed review of nanofabrication of plasmonic structures see[23]. Milling can give rise to grooves, holes, gaps and the creation of nanostructures[24, 25] as in the case Figure 4, which depicts plasmonic structures that have been created using various nanoprocessing techniques including electron beam lithography and ion beam nanopatterning. All such structures help with the generation, propagation and manipulation of the plasmons. It is also important mention that the advantage of using Au and Si ion beams prevents Ga contamination effects that sometimes limit the prototype/device performance.

Often the desired structures cover larger than the field of view and so special techniques must be employed to reproduce the same pattern over and over with attention to any drift that the system may suffer and alignment of the multiple exposure areas. Repetitive stitching employing a high precision lithography stage (based on laser interferometer position detection) resulted in a 2 mm structure that took 4 hrs using at Ga LMIS at 35 kV (Figure 5).

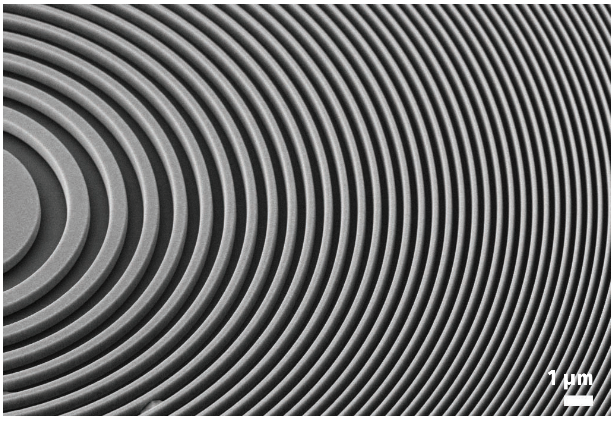


*FIGURE 6* ***A high aspect ratio and high resolution FIB fabricated Fresnel zone plate (100 µm and 100 nm outermost zones) prepared using gold deposition and a special long-term milling process. The zone plate showed a X-ray performance at least as predicted from theory***

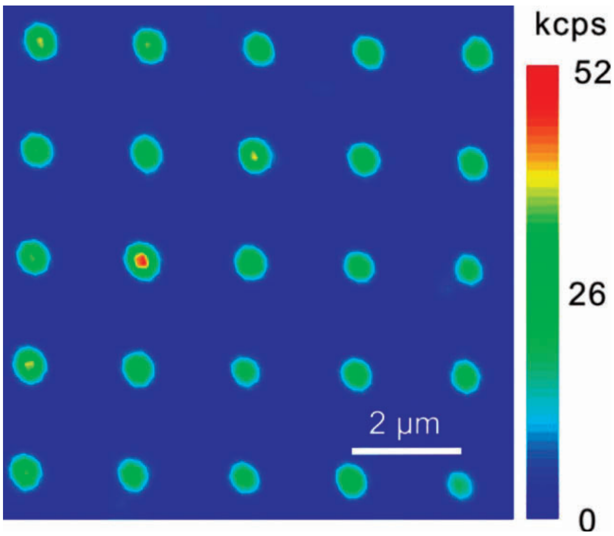


*FIGURE 7* ***Confocal fluorescence image of a silicon carbide surface directly implanted with focused beams of Si++ ions corresponding to an applied dose of 400 ions/spot. The scale bar is 2 µm[28]***

## ZONE PLATES

Zone plates allow x-rays to be focused and are concentric rings with a specific spacing between the rings. Understandably the fabrication of such structures require a precision technique such as nanofabrication. The deposition of gold and subsequent milling in the Figure 6 yielded a 100 µm zone plate[26, 27] with the outer rings having a width of only 100 nm.

## QUANTUM COMPUTING/ IMPLANTATION

Alongside the many uses of the FIB to mill or etch samples, little has been mentioned about its applications in implanting ions into materials. Silicon carbide (SiC) is a semi-conductor material that can be grown as inch-scale high quality single-crystal wafers that has been used in microelectronics and high-power systems. A promising area is in the application of the FIB in the creation of SiC with silicon vacancies for use in quantum computing or photonics. The Si ions based FIB system is ideal for the creation of such defects in specific areas (Figure 7) and has been shown capable of implantation $Si^{++}$ in tens of thousands of sites and allows scalable fabrication of the required defects that give rise to the desired spin and photon-emission properties[28]. Recently there is also a growing interest in various group 4 elements to be implanted into diamond as well as other ion-substrate material systems.

## SUMMARY AND CONCLUSIONS

Ion beam technology is now mature and has wide-ranging applicability in an ever growing range of fields. The choice of sources, beam technologies and deposition systems means that researchers and industrial users can do more with highly reproducible rates, boost productivity and create solutions to problems of nanofabrication more easily than ever before.

Whether using the GFIS (low beam current, currently highest resolution) for the creation of the smallest dimensions or Xe plasma FIB ICP (resolution optimized plasma ion sources, high probe currents) for large scale materials removal there are options on both ends of the scale. There can be no doubt that the versatile LMIS (Ga) has the widest reaching applications, however, not to be overlooked are specialist combination sources for nano patterning dedicated LM(A)IS instruments exhibiting good long-term stability, mid beam current, high resolution, maturity and a large selection of incident ions species.



*REFERENCES* ***To see the references for the article please visit: microscopy-analysis.com/editorial***