Introduction of a new technology platform to enable scalable fabrication of single silicon vacancy defect arrays

NCCAVS 2020 Technical Symposium

Fremont Marriott, 20 February 2020

Andre Linden, Raith America, Inc.

SOLUTIONS FOR NANOFABRICATION

RAITH NANOFABRICATION

Agenda

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Motivation

Developing the required technological environment

Results

Other applications benefiting from this new technology platform

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- Motivation
- Developing the required technological environment
- Results
- Other applications benefiting from this new technology platform

Motivation

ACS Photonics
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Scalable Fabrication of Single Silicon Vacancy Defect Arrays in Silicon Carbide Using Focused Ion Beam

Junfeng Wang,[†] Xiaoming Zhang,[†] Yu Zhou,[†] Ke Li,[†] Ziyu Wang,[†] Phani Peddibhotla,[†] Fucai Liu,[‡] Sven Bauerdick,[§] Axel Rudzinski,[§] Zheng Liu,[*,‡] and Weibo Gao[*,†,∥,⊥]

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- In recent years, defects in SiC have been successfully implemented as solid-state quantum bit
- Silicon vacancy defects in 4HSiC attracts increasing attention due to their excellent features, such as nonblinking single-photon emission and long spin coherence times
- In order to extend its applications in quantum information science, it is essential to develop a technique of scalable efficient generation of single V_{Si} defect arrays in 4H-SiC
- There are three current methods to generate a V_{Si} defect:

  Electron irradiation, neutron irradiation, and carbon implantation
- However, these methods either cannot control the position of the V_{Si} defect or need an electron beam lithography (EBL) prefabricated photoresist patterned mask

Motivation

One solution could be the approach to fabricate a maskless and targeted single V_{Si} defect array in 4HSiC using Silicon focused ion beam (FIB) implantation.

Technological requirements

- Focused Silicon ion beam with extremely sharp beam profile
- Stable and precisely controllable focused Silicon ion beam
- The ability to accurately control the ion dose per defect
- The ability to accurately position the ion on a full wafer substrate

Agenda

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Evolution of Raith FIB technology

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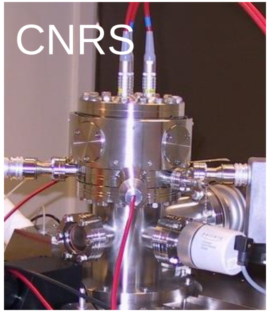
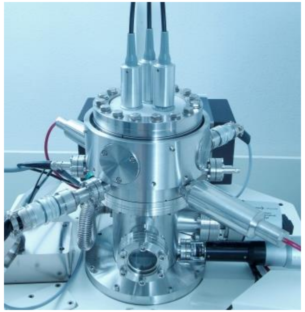
Start *"NanoFIB" EC project to develop a new class of FIB technology specially designed for precise and repeatable sub-10 nm nanofabrication*

2001 multiple iterations of performance improvements **2019**





alpha column › beta column › nanoFIB › nanoFIB Two › nanoFIB Three

nanoFIB Three column for nanofabrication

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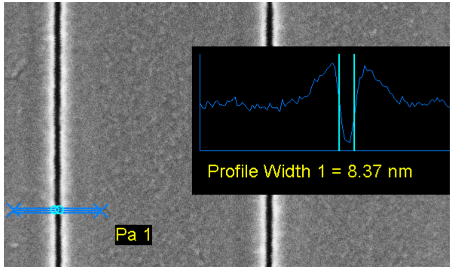
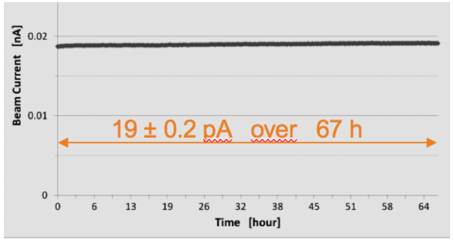
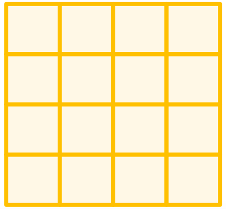
Sub-10 nm patterning capabilities



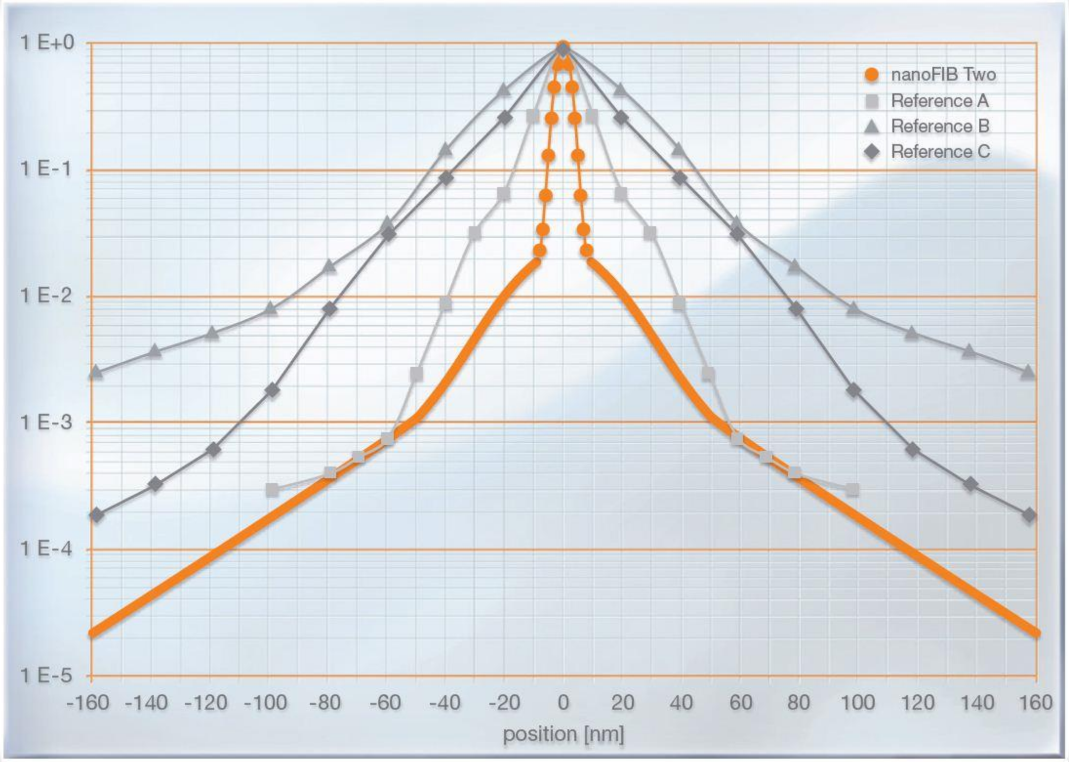
Superior beam current stability

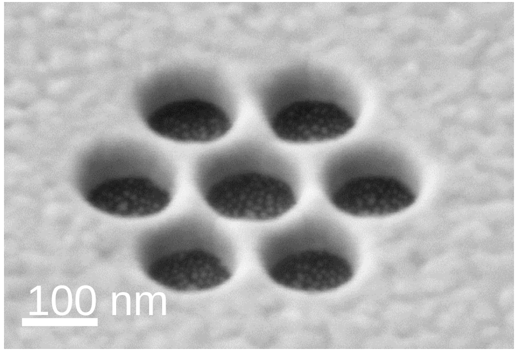


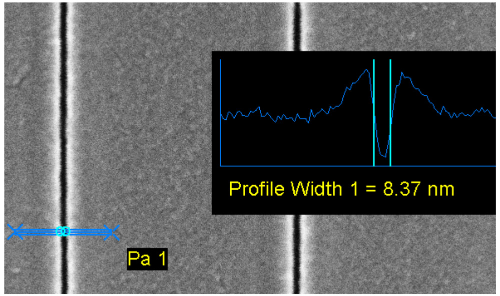
Excellent placement accuracy



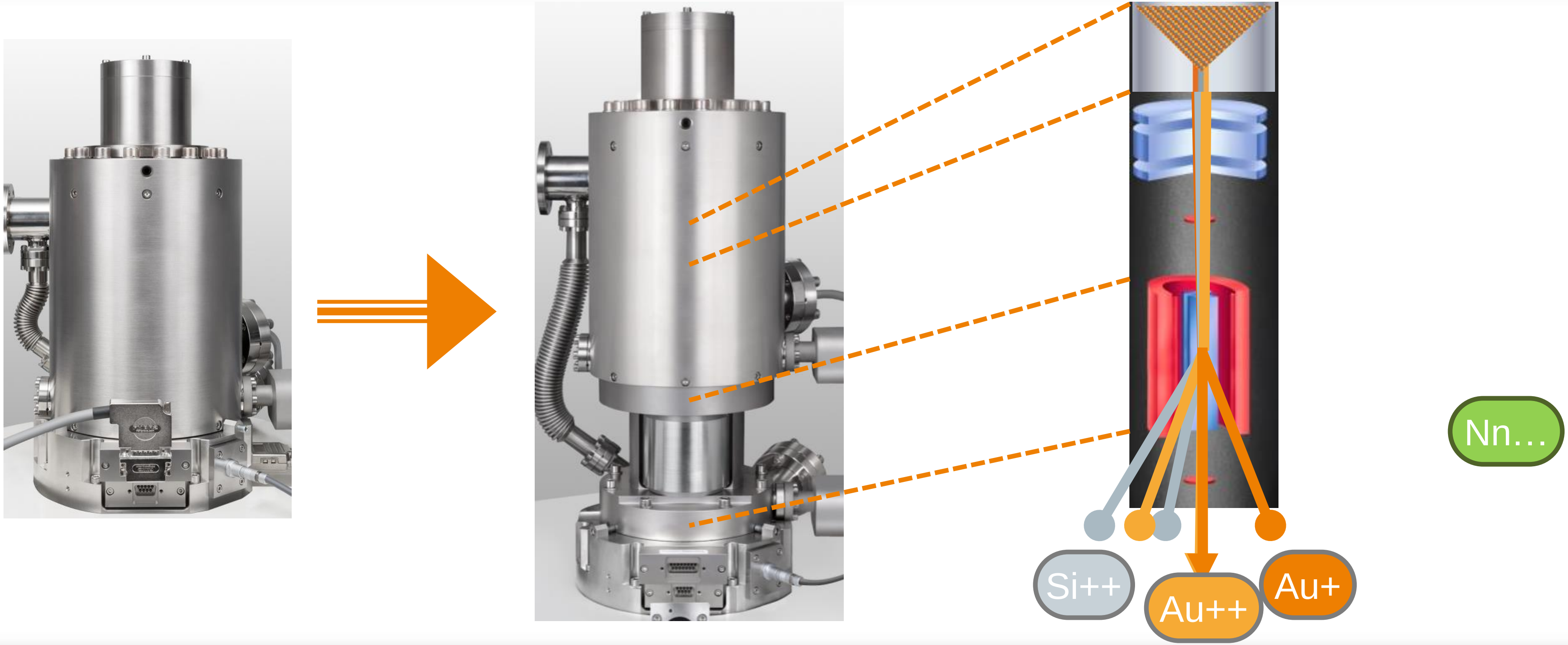
Unique superior Ga beam spot characteristics



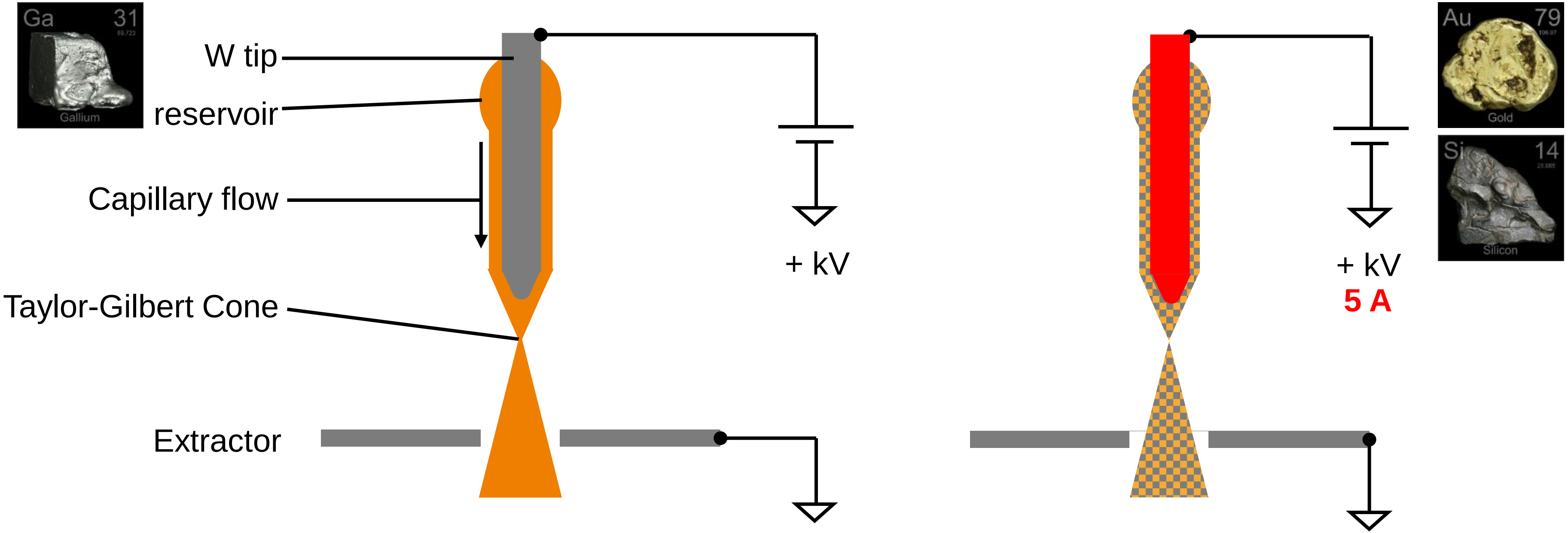




Raith's unique multi-species technology

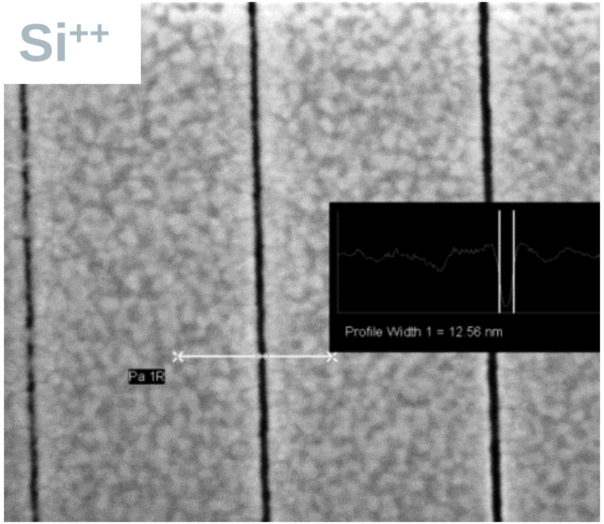


Raith's unique multi-species technology

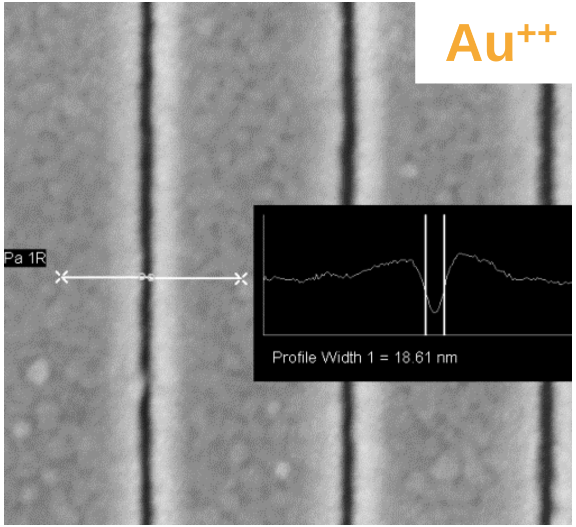


Patterning performance (gold on silicon)

Si++



Au++



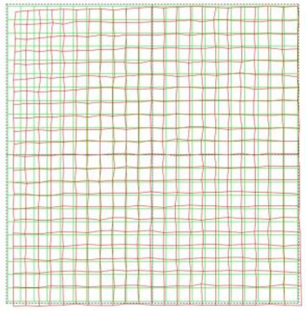
10 – 15 nm

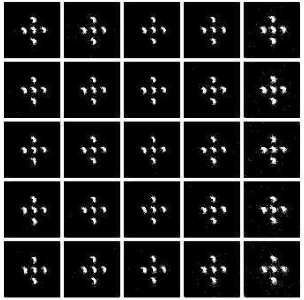
15 – 20 nm

“Single” ion implantation

- Applications in quantum computing or new sensors
- Current request for species: Si, Ge, Cr, B, P, N, Sb, Bi
- Single ion dose control possible (theoretically)
  - » 1 pA = 1 ion/ 140 ns
  - » Minimum dwell time of 20 ns
- Challenges
  - » Not deterministic

LIS Laser Interferometer Stage





Accuracy, repeatability, and stability

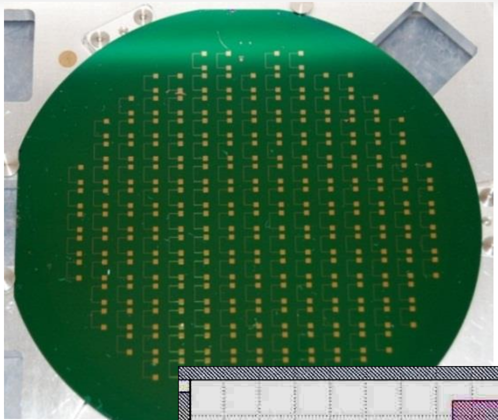
Unique for a FIB system

- Large area blind navigation
- Write field stitching

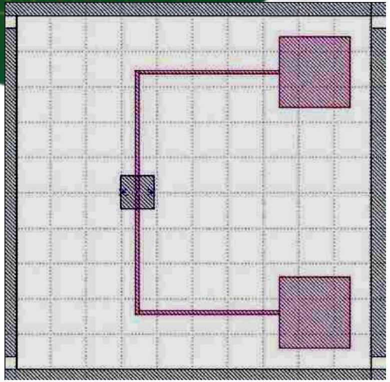
Sophisticated Pattern Generator

- 20-bit resolution
- 50 MHz
- In-field distortion correction
- Dynamic stigmator

Accurate positioning on wafer scale (here for nanopores)



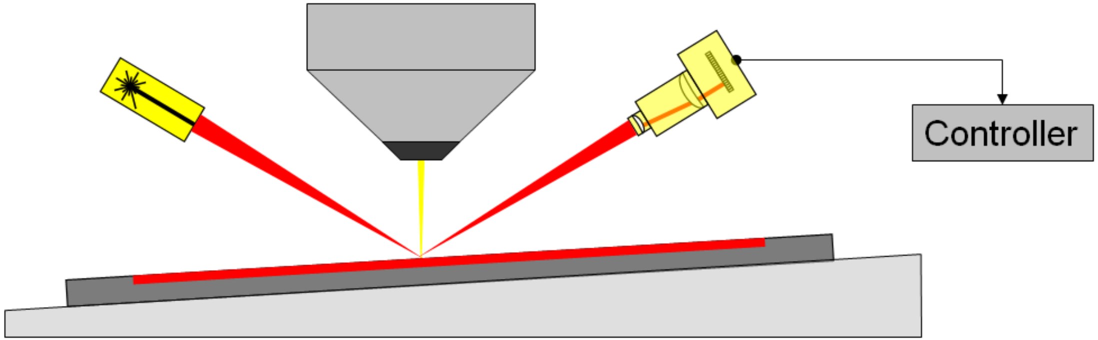
4 inch



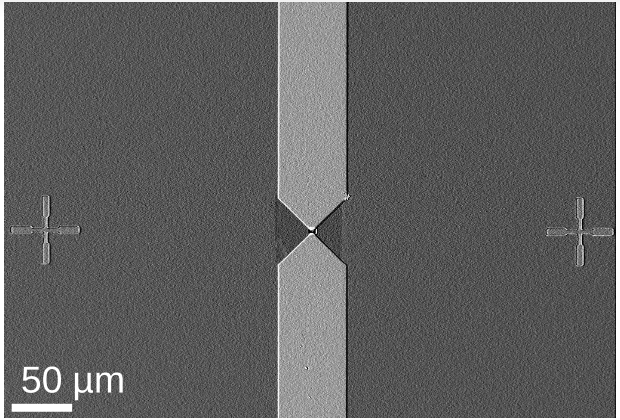
Imperial College,

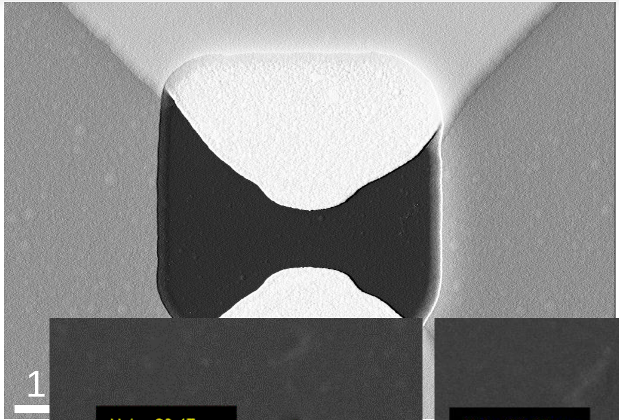
London

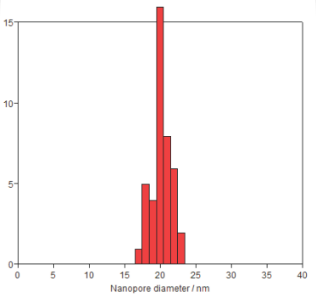
- small batch production of 175 membrane devices
- membrane and Au leads by optical litho & EBL
- Automated FIB drilling of nanopores
  - » auto height compensation

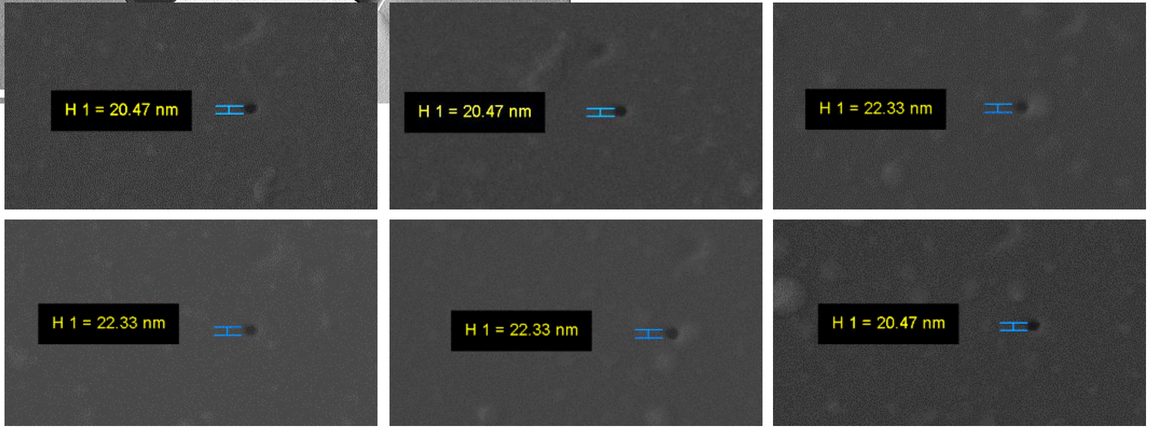


Nanopore devices on wafer scale









- FIB alignment for pore placement within electrodes
- EBL inspection on wafer-scale
- Fully automated process: 175 chips with 20 nm nanopores over 4”

Agenda

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Experimental setup

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Scalable Fabrication of Single Silicon Vacancy Defect Arrays in Silicon Carbide Using Focused Ion Beam

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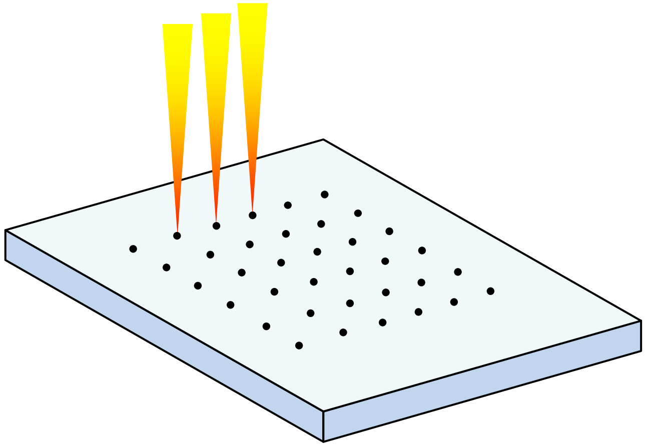
35 kV double-charged silicon ions (Si2+)



commercial high-purity 4H-SiC sample with a low background fluorescence

According to SRIM simulations (“Stopping and Range of Ions in Matter”) the average depth of the silicon ions is 18.5 nm

The implantation spots were targeted with between 40 and 700 Si ions with a 5−10 nm focused ion beam spot

Annealing the implanted defect array sample at 650 °C in air for 6 h

Sample in HNO3 for 24 h in order to decrease the fluorescence background

Results – 700 Si ions per defect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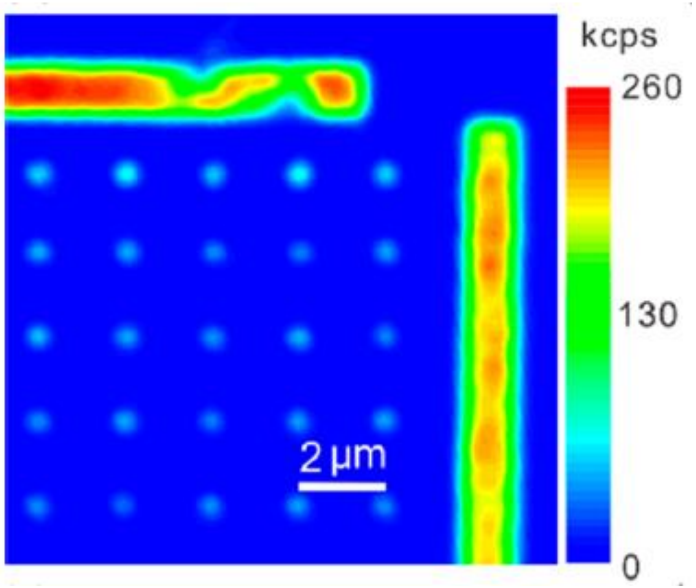
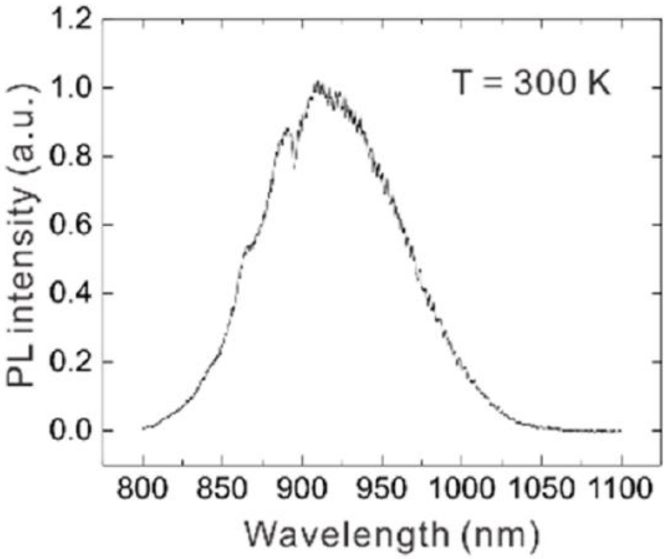
NANOFABRICATION



Confocal fluorescence image of the 700 Si ions implanted V_{Si} defect array on the SiC surface.



Room-temperature PL spectrum measurement of the V_{Si} defects shows spectrum is in the near-infrared range

Results – 40 Si ions per defect

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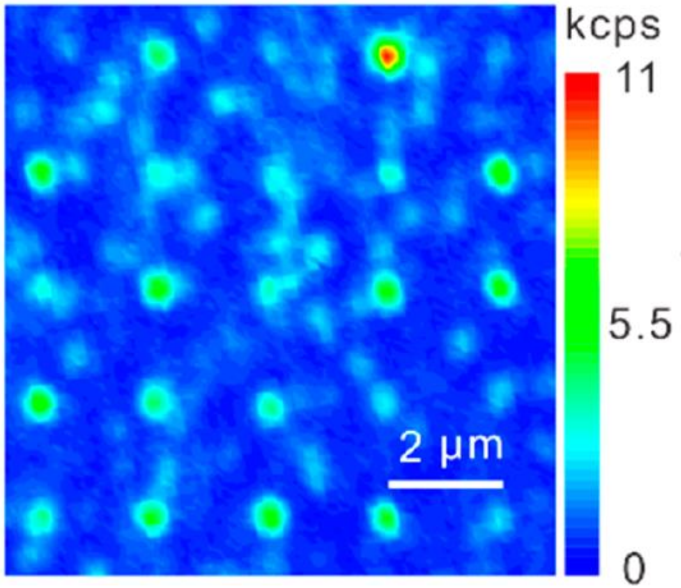
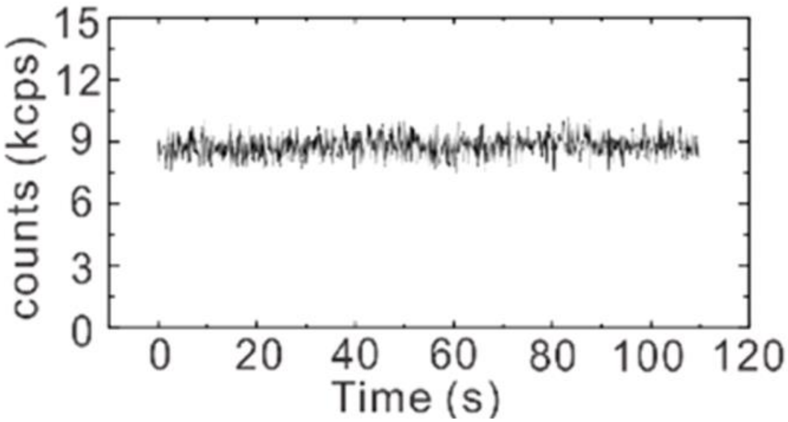


Confocal fluorescence image of the 40 Si ions implanted V_{Si} defect array on the SiC surface.



Fluorescence intensity trace of the single V_{Si} defect with a sampling time of 100 ms and 1 mW laser excitation power.
Count was very stable and had no blinking or bleaching, which verified that it is a stable single-photon source

Results – 40 Si ions per defect

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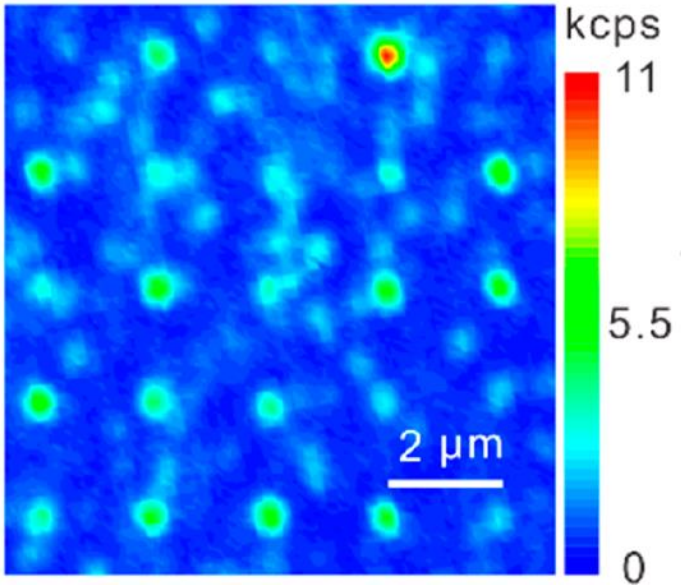
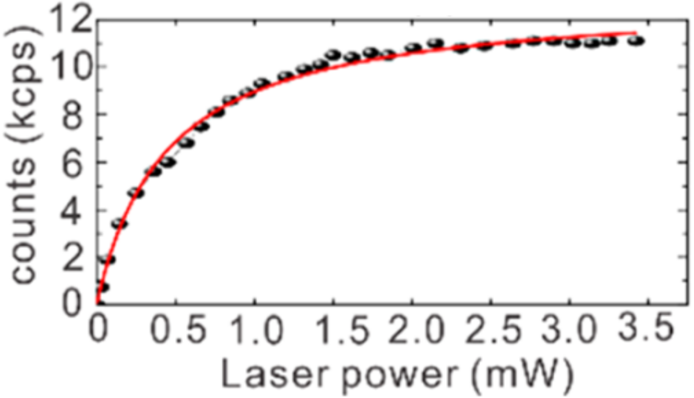


Confocal fluorescence image of the 40 Si ions implanted V_{Si} defect array on the SiC surface.



Fluorescence intensity measurements of a single V_{Si} defect emitter at different laser powers.

Conversion yield investigation

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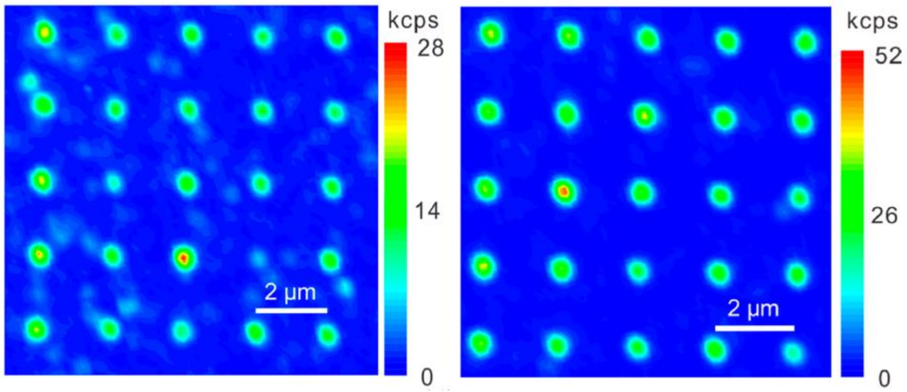
Systematically investigation of the conversion yield of implanted Si2+ ions to V_{Si} defects

Ion dose variation on the sample from 40 to 700 ions/spot. The ion dose determined the number of silicon vacancies created during the implantation process.

Fluorescence intensity measurement across a 10 × 10 µm2 region of constant implantation dose and normalized to the mean counts per spot



Typical confocal fluorescence images of an area of the 100 and 400 Si ions implanted V_{Si} defect array on the SiC surface

Conversion yield investigation

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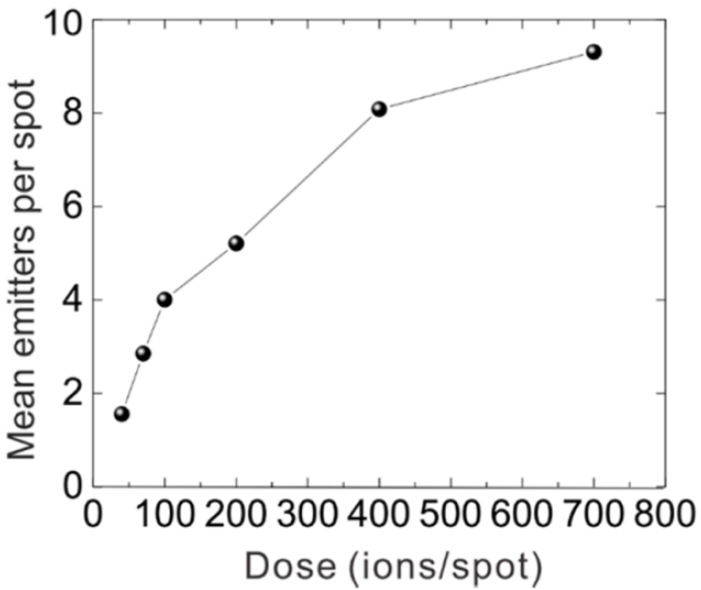

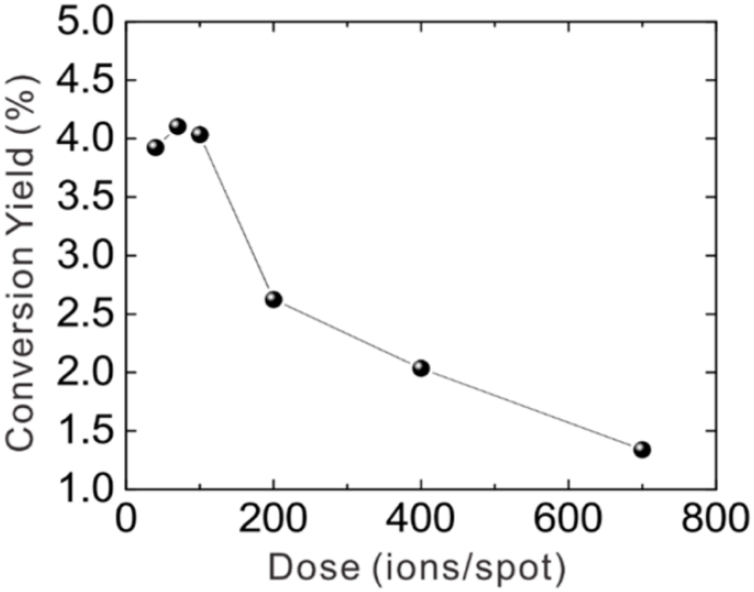

Mean emitters per spot = fluorescence counts per spot / single-emitter count

mean emitter numbers per spot has been normalized to the corresponding implanted ion number

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Results

- In conclusion, a method for scalable and maskless generation of arrays of silicon vacancy centers in SiC using focused Si2+ ion beam technology has been presented.

- The investigated fluorescence properties of a V_{Si} defects show a photostable single-photon source with a saturation count rate of up to 13 kcps.

- The conversion yield of Si2+ ions to V_{Si} defects decreases for higher implantation doses.

Agenda

Motivation

Developing the required technological environment

Results

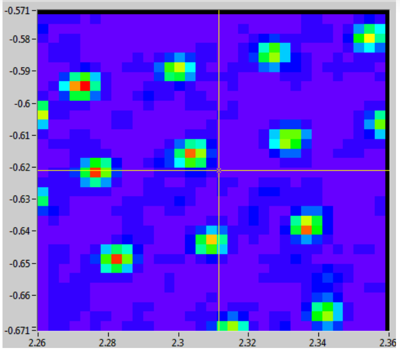
Other applications benefiting from this new technology platform

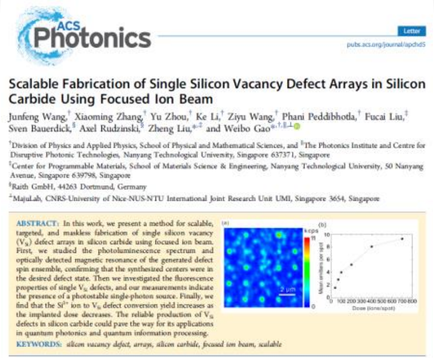
Low dose non-Ga ion implantation

- Applications in quantum computing or new sensors
- Current request for ion species: Si, Ge

  (Cr, B, P, N, Sb, Bi…)

NTU Singapore





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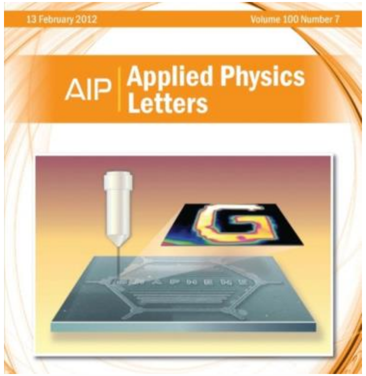
⊥MajuLab, CNRS-University of Nice-NUS-NTU International Joint Research Unit UMI, Singapore 3654, Singapore

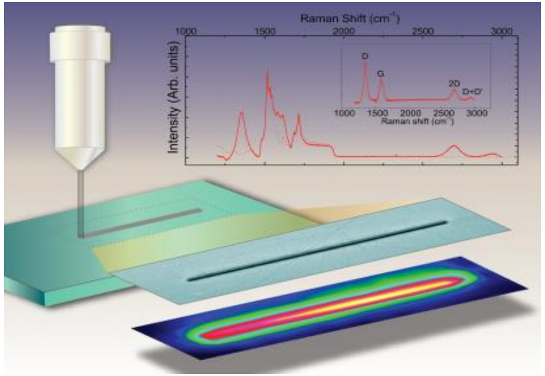
ABSTRACT: In this work, we present a method for scalable, targeted, and maskless fabrication of single silicon vacancy (V_{Si}) defect arrays in silicon carbide using focused ion beam. First, we studied the photoluminescence spectrum and optically detected magnetic resonance of the generated defect spin ensemble, confirming that the synthesized centers were in the desired defect state. Then we investigated the fluorescence properties of single V_{Si} defects, and our measurements indicate the presence of a photostable single-photon source. Finally, we find that the Si^{2+} ion to V_{Si} defect conversion yield increases as the implanted dose decreases. The reliable production of V_{Si} defects in silicon carbide could pave the way for its applications in quantum photonics and quantum information processing.

KEYWORDS: *silicon vacancy defect, arrays, silicon carbide, focused ion beam, scalable*

- Au implantation in SiC
- selective growth of graphene

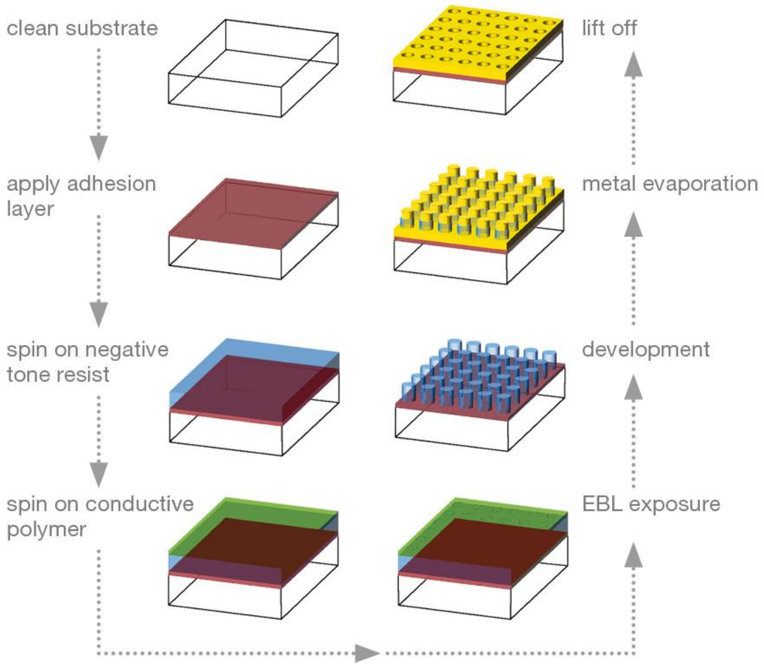
University of Florida



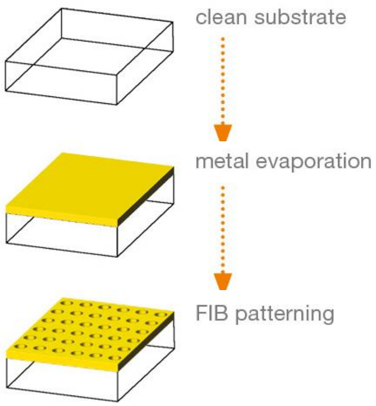


Simplified processes

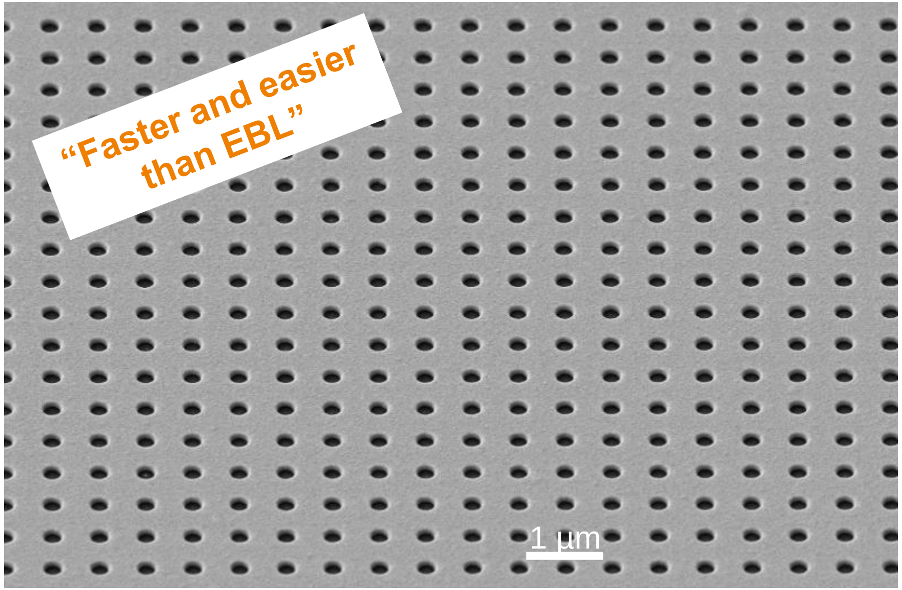
EBL



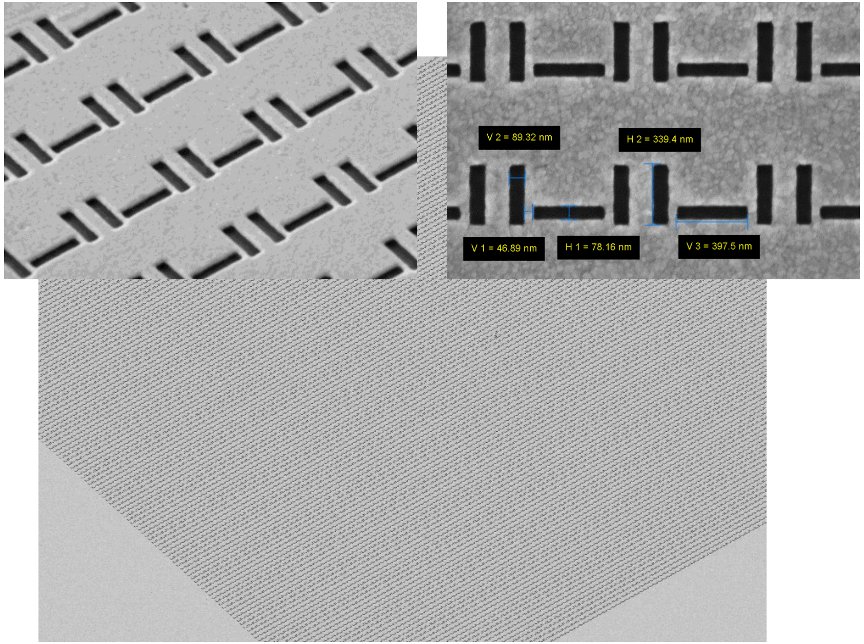
FIB



Plasmonic device for protein diagnostics



Boston University / Georgia Tech



Stuttgart University

Ga milling on 200nm SOI for photonic devices

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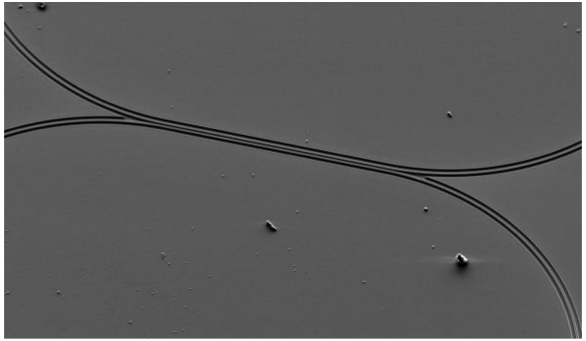
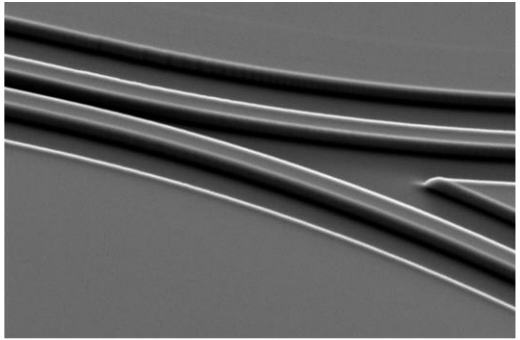
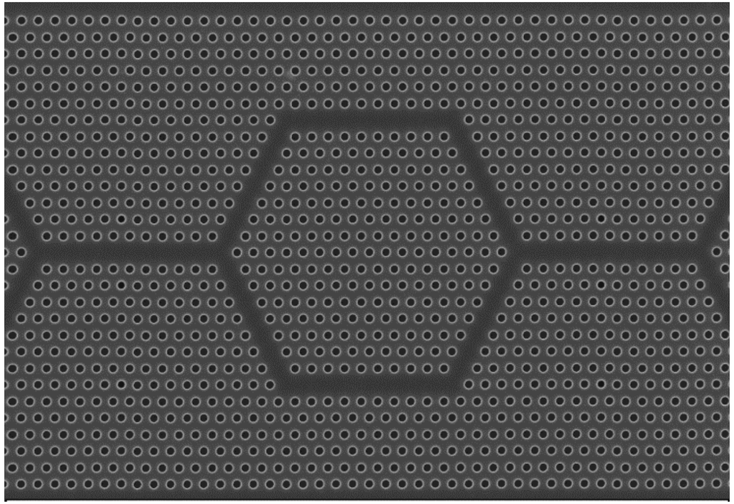
Waveguide coupler





Photonic crystal



Waveguide: 420pA, width: 520nm,

Sample courtesy of UCSB, USA

PhC: 36pA, diam.: 350nm

Waveguides and PhC: 2.5 mm x 0.7 mm (total working area)

<u>fully automated workflow</u>

stitch boarder shifts

Stitch-free Patterning periodixx

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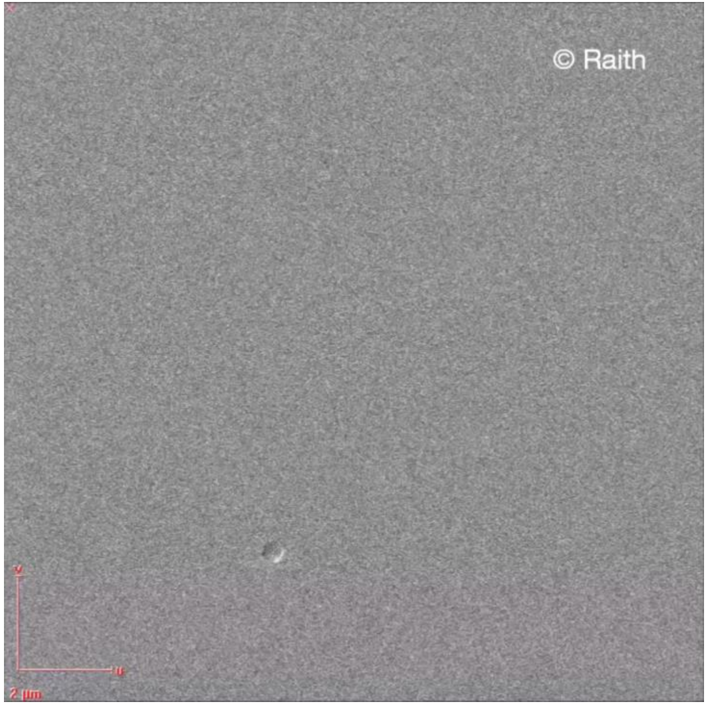

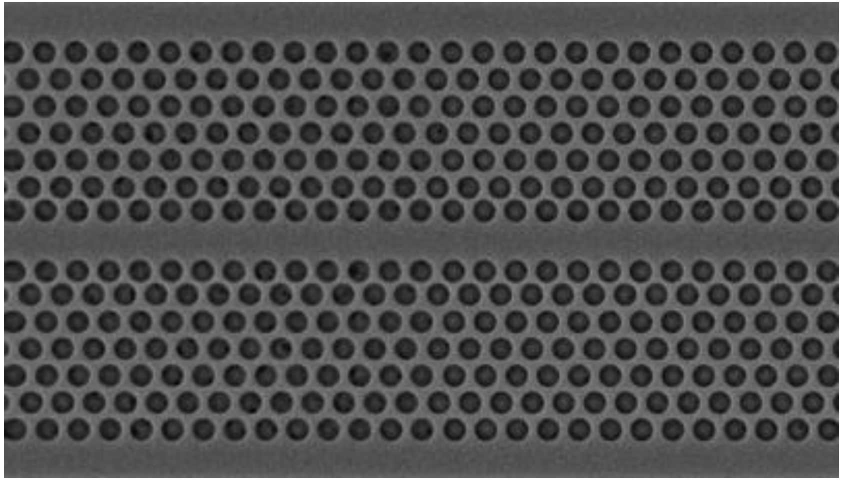

mm long periodic structures with zero stitching artefacts

True 3D in one go on mm scale

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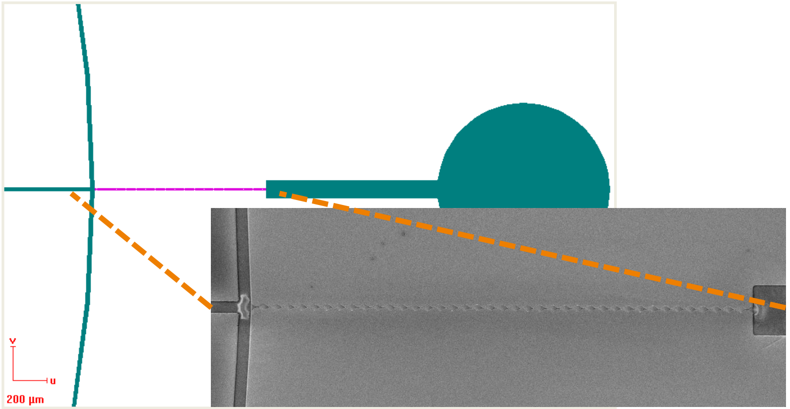
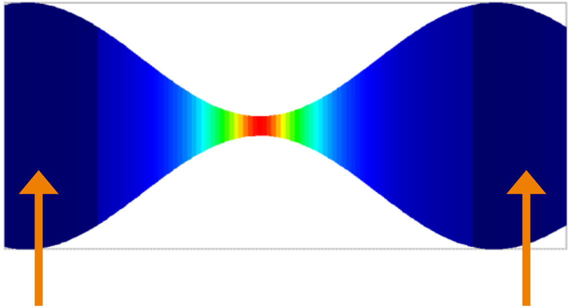
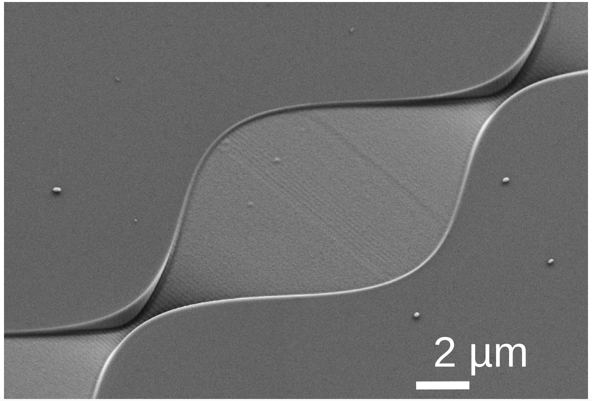


Argonne National Labs



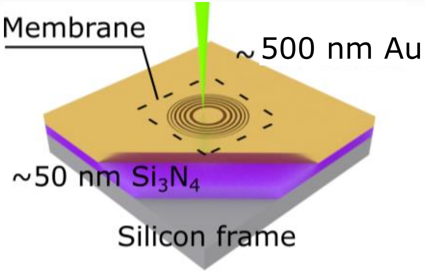


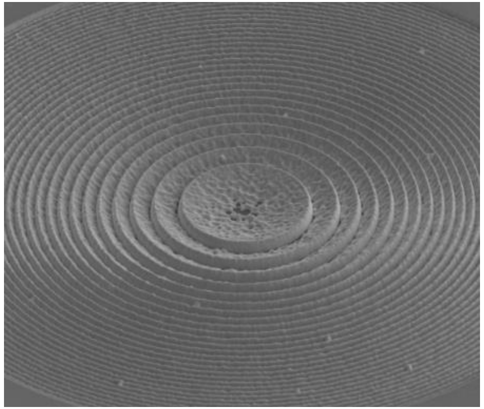
- reduced edge effects for stitch milling by overlapping parts
- true 3D: simultaneous control of lateral shape and depth

Beyond Gallium, for 3D X-ray zone plate

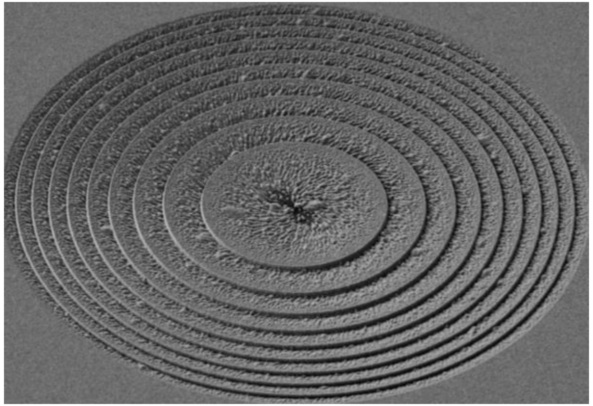
RAITH NANOFABRICATION

MAX-PLANCK-GESELLSCHAFT

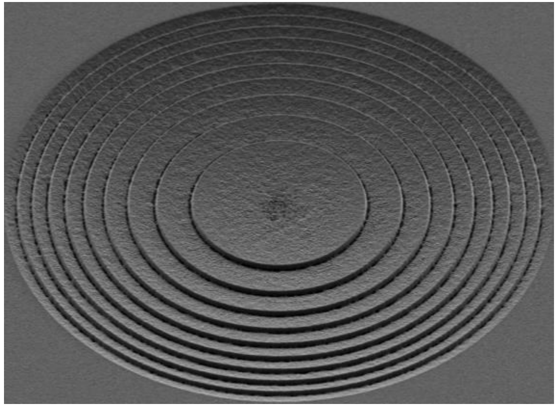




Ga^+-FIB



Au^{++}-FIB



Si^{++}-FIB

Beyond Gallium, for materials

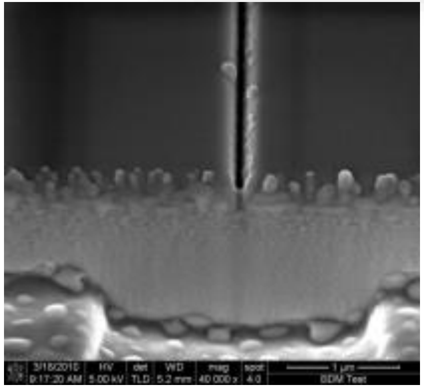
RAITH NANOFABRICATION

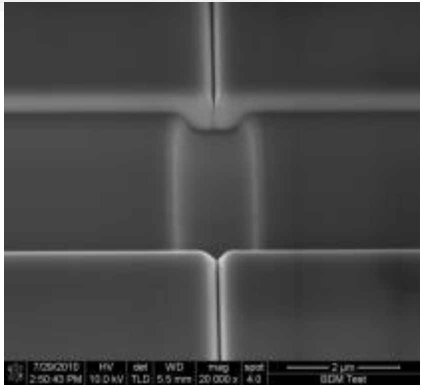
MICROSCOPY AND ANALYSIS

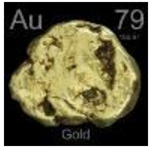
NEW FOCUSED ION BEAMS

Applications of new focused ion beams in nanofabrication and material studies

Brent P. Gila
Nanoscale Research Facility, Department of Materials Science and Engineering, University of Florida, Gainesville, FL, USA







VELION

Agenda

Motivation

Developing the required technological environment

Results

Other applications benefiting from this new technology platform

RAITH

NANOFABRICATION

Your challenge is our mission.