THE LITHOGRAPHER

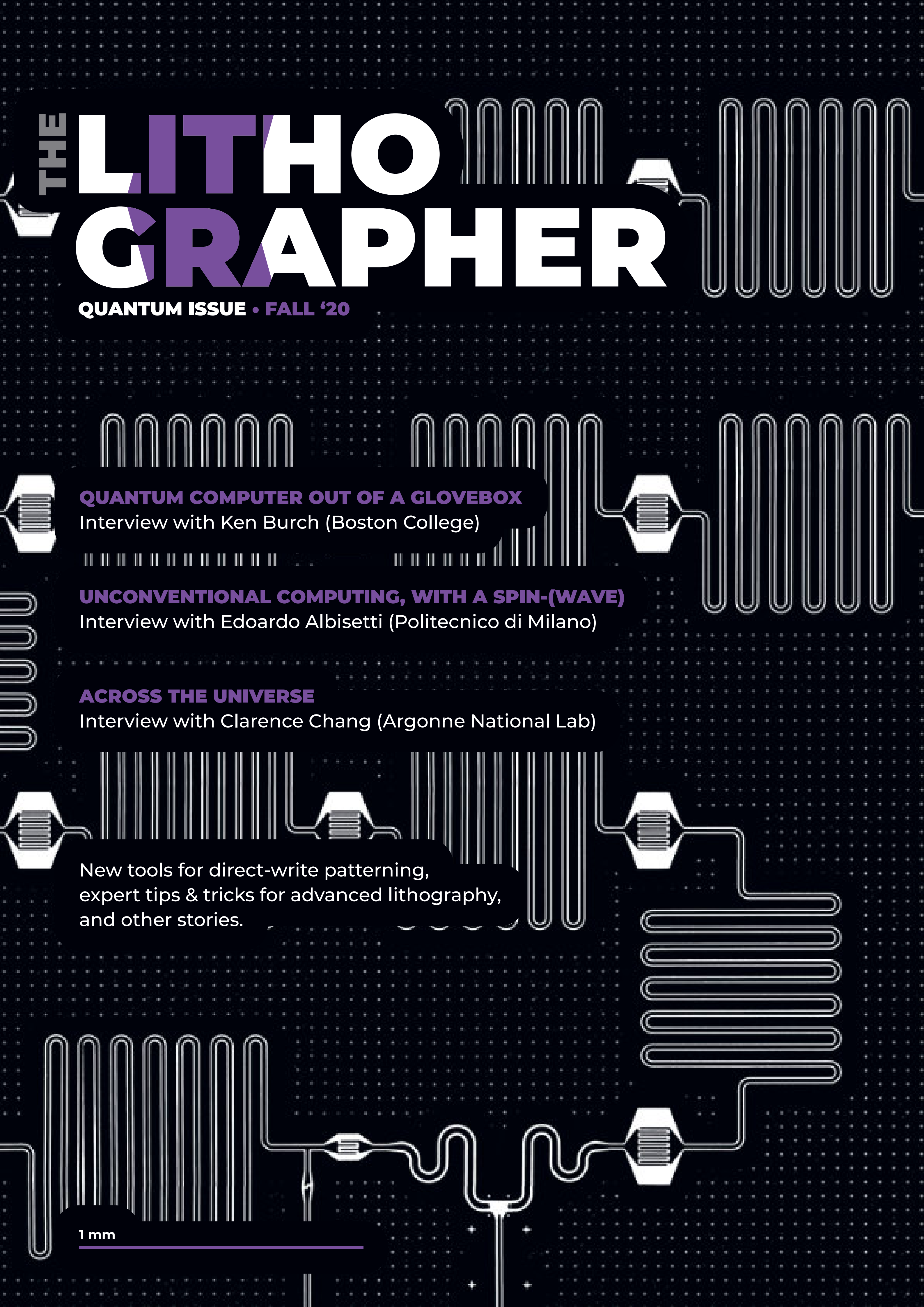
QUANTUM ISSUE • FALL ‘20

QUANTUM COMPUTER OUT OF A GLOVEBOX
Interview with Ken Burch (Boston College)

UNCONVENTIONAL COMPUTING, WITH A SPIN-(WAVE)
Interview with Edoardo Albisetti (Politecnico di Milano)

ACROSS THE UNIVERSE
Interview with Clarence Chang (Argonne National Lab)

New tools for direct-write patterning,
expert tips & tricks for advanced lithography,
and other stories.



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This year, we celebrate a few important anniversaries: Quantum Hall effect is 40 years, Atomic Force Microscopy is 35, Bose-Einstein condensate is 25, and Antarctica was discovered 200 years ago. Incidentally, this issue has something to do with all of these anniversaries.

This is the second issue of The Lithographer, and it is inspired by the recent progress in quantum computers. We focused on a few new ideas and techniques for fabrication of all things quantum: qubits, quantum sensors, etc.

The key fabrication challenges highlighted in this issue include:

- Critical dimensions (some platforms require atomic precision of placing the circuit elements).
- Sensitivity to defects: a stray atom or even a dangling bond can affect the device performance.
- New platforms used to host qubits: constituting materials are often very sensitive to the environment.
- Upscaling fabrication to large areas.

I hope you will enjoy The Lithographer. As always, your feedback is very welcome!

Stay safe,
Dr Anya Grushina, Editor-in-chief.

COVER: An optical image of the superconducting microwave circuit. The circuit was patterned using Heidelberg Instruments' MLA 150 and comprises an array of 11 identically designed, coplanar waveguide half-wave resonators, capacitively coupled to each other. The top end of the array is capacitively coupled to a tunable transmon qubit. The transmon is measured with a separate resonator, whose input line doubles as a charge bias for the transmon.

Courtesy: Yao Lu and David Schuster, Physics Department and James Franck Institute, University of Chicago.

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INTERVIEWS

EXPERTS' KNOW-HOW

THE LITHOGRAPHER

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New ideas for patterning of 2D materials

2D materials are very versatile in chemical composition, which leads to a wide variation in their properties. The range of application also varies greatly: 2D materials enable studies of complex quantum transport phenomena as well as promising applications such as sensors and enhanced optics or electronics. One of the things they all have in common, apart from dimensionality, is that making devices out of 2D materials can be very challenging.

Typically, 2D materials are contacted and patterned by e-beam or photolithography, which is followed by etching, metal evaporation and lift-off. However, there are other emerging patterning methods that are very promising.

One of such methods relies on thermal scanning probe lithography (t-SPL). A heated ultra-sharp tip can be used to locally evaporate the resist, which then serves as a mask for metal evaporation or etching. As a result, features under 10 nm can be produced[1]. It has been shown that t-SPL is very well-suited for contacting 2D materials. It produces less defects and leaves less residues as compared to e-beam, which leads to improved contact resistance (near 0 Schottky barrier).[2] Moreover, using the hot tip opens up other possibilities not available otherwise: thermomechanical nanocutting and thermochemical patterning.

[1] YK Ryu Cho et al., "Sub-10 Nanometer Feature Size in Silicon Using Thermal Scanning Probe Lithography", ACS Nano 11, 12, 11890–11897, 2017.

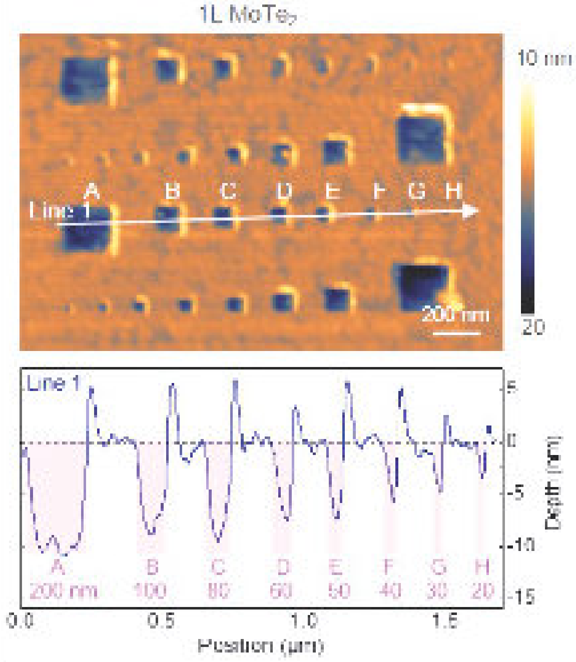
[2] X. Zheng et al., "Patterning metal contacts on monolayer MoS2 with vanishing Schottky barriers using thermal nanolithography", Nature Electronics volume 2, pages17–25, 2019.

Thermomecanical nanocutting of 2D materials

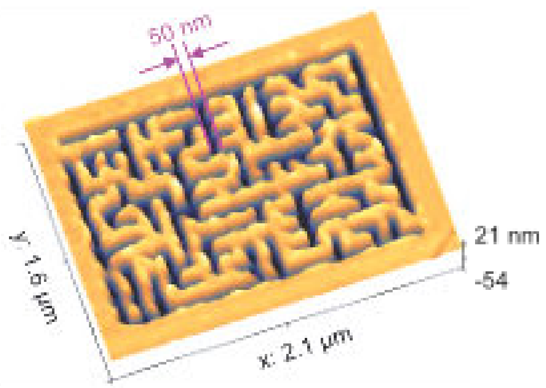
Dr. Xiu Liu et al. from Prof. Jürgen Brugger's lab at EPFL used thermal scanning probe lithography to cut 2D materials with accuracy down to 20 nm[1]. In this approach, the indentation force of the tip breaks the chemical bonds of the material. Simultaneously, the heat from the tip sublimates the PPA layer from under the flake. As a result, the flake can be patterned into any desired shape in a one-step process.

The authors show how thermomechanical nanocutting can be used to cut 1-, 2- and 3-layer flakes of different 2D materials (MoTe2, MoS2 and MoS2) into stripes, nanoribbons or any other arbitrary shapes. The smallest dimensions demonstrated in this work reach 20 nm for the smallest feature size and 50 nm for the narrowest line.

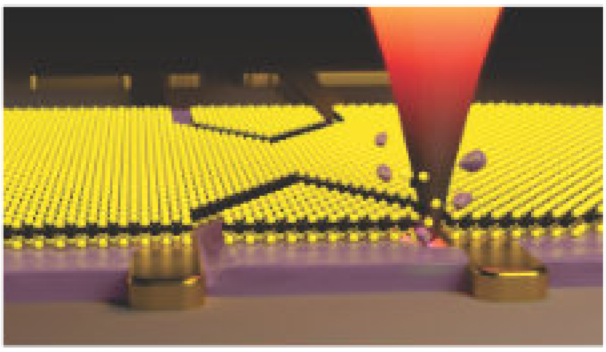
To confirm that the material is actually removed, the Raman spectra of intact areas, cut areas and boundaries between them are compared. The authors also measure sheet resistance of the 2D flakes transferred onto electrodes and cut into stripes or nanoribbons. As expected, when all the stripes are cut across, the resistance between the electrodes becomes infinite.



AFM scan and the line-scan (top) taken along the white line (bottom) in a showing square features fabricated by thermomechanical nanocutting in single-layer MoS2 flake. The lateral size of the squares ranges from 200 to 20 nm. Image courtesy Dr Xia Liu, EPFL.



AFM image of a "labyrinth" patterned by thermal nanocutting. Image courtesy Dr Xia Liu, EPFL.



Schematic of thermomechanical nanocutting process. Image by Dr Samuel T Howell, EPFL.

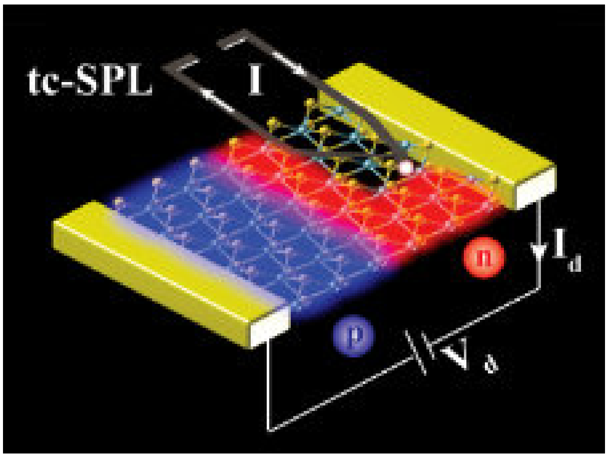
[1] X. Liu et al., "Thermomechanical Nanocutting of 2D Materials", Advanced Materials, 2001232, 2020.

Thermochemical patterning for local oxidation and doping control

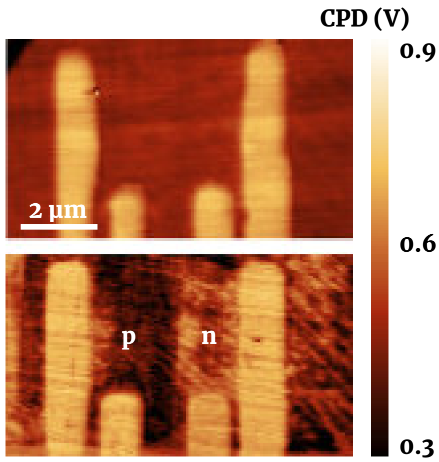
t-SPL, combined with a flow-through reactive gas cell, can be used to controllably introduce charged defects in 2D materials[4]. With this approach, doping of any polarity can be introduced at nanoscale resolution.

Dr. Xiaorui Zheng from Prof. Elisa Riedo's lab at NYU Tandon and his collaborators from CUNY Advanced Research Center, University of Pennsylvania, University of Illinois, University of Roma Tor Vergata and Politecnico di Milano have demonstrated this approach in their recent publication.

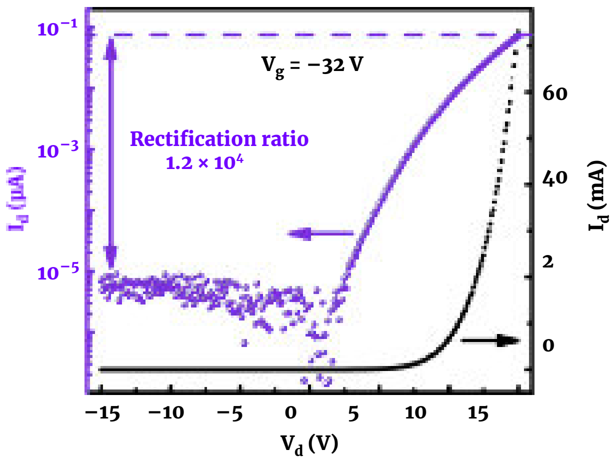
The authors used the NanoFrazor's heated tip in the controlled atmosphere of HCl/H2O or N2 to introduce p- or n-type defects in MoS2 flakes, which is otherwise more prone to only n-type defect forming. As a result, they could make p-n junctions with current rectifying ratio of over 104 in just 1 fabrication steps without any need for markers, development, etc. Defect nanoengineering combined with t-SPL's capability to image, cut and locally dope the flakes can be very useful for any application where devices with regions of different polarity are needed (e.g. optoelectronics, flexible electronics, energy harvesting devices, etc).



Schematic of the MoS2 p-n junction obtained by thermochemical scanning probe lithography. Image courtesy: Elisa Riedo, NYU.



c-AFM images comparing the MoS2 flake before (top) and after (bottom) tc-SPL. The areas of p- and n-doped regions between the electrodes have distinctly different contrast.



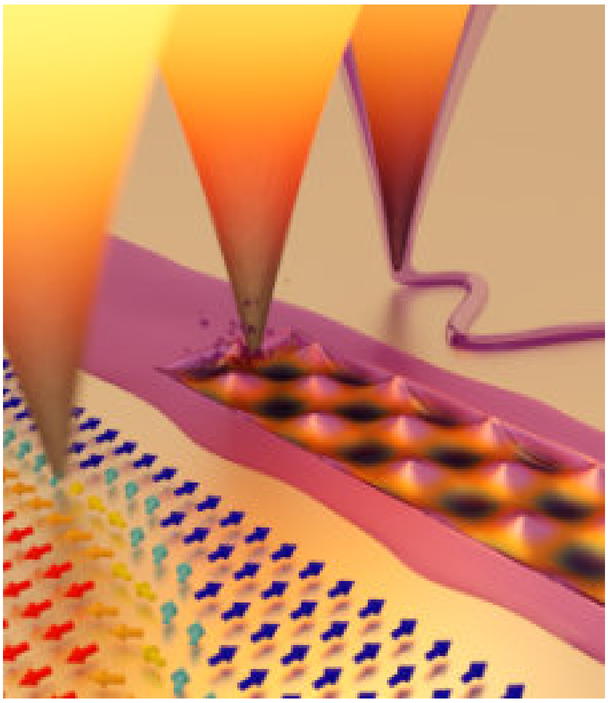
Schematic of thermochemical SPL to define p-n junction in MoS2 flake. Image courtesy: Elisa Riedo, Tandon School of Engineering, NYU.

[4] X. Zheng et al., "Spatial defects nanoengineering for bipolar conductivity in MoS2", Nature Communications vol. 11, Art. n. 3463, 2020.

“Heat is a universal stimulus”

Thermal scanning probe lithography is increasingly popular for nanofabrication and nanoscale modification of materials by heat. A recent review on thermal scanning probe lithography, or t-SPL, covers most of the existing experiments on nanoscale patterning by means of a heated probe in a very wide range of fields[5].

First, the authors tell a story of how the t-SPL emerged from IBM Research’s Millipede project and the technique’s main features and open challenges. Then they discuss the factors affecting the tip-sample contact temperature and extensively review all known applications of the t-SPL that fall in 3 categories: material removal, conversion (chemical and physical) and addition. Authors also include a comprehensive table of all the materials and resists used in these experiments. This review is a good starting point for getting acquainted with this versatile nanopatterning method and can serve as a source of new ideas for future experiments.



A schematic showing three main types of patterning by t-SPL: modification, removal and addition of material. Image courtesy: Samuel T Howell, EPFL.

[5] S.T. Howell et al., “Thermal Scanning Probe Lithography — A Review”, Microsystems & Nanoengineering 6, Art.n. 21, 2020.

Across the Universe

Building detectors to see the first light

Research interests of Professor Clarence Chang from the U. S. Department of Energy's Argonne National Laboratory span the largest and the smallest scale physics there is: from studying the early universe by looking at the Cosmic Microwave Background (CMB), to micro- and nanofabrication. His team builds detectors for the South Pole Telescope: micron-scale devices featuring superconducting transition-edge sensors and MEMS. Professor Chang has kindly agreed to tell The Lithographer more about the exciting projects he is involved in.

Thanks a lot for finding time to talk! First of all: are you mainly focused on the detectors, or are you more involved in making sense of the data?

A little bit of all. The third-generation instrument of the South Pole Telescope (SPT) is doing extremely well, and it is collecting a lot of fantastic data that will tell us something new about the universe over the next few years. In the meantime, in the lab, we are developing the detectors for CMB-S4, an upcoming project with an estimated budget of $600 million.

CMB-S4 will need substantially more detectors than what we made previously. Building new telescopes, building new detectors for those telescopes, that's the kind of work we do.

Can you tell us a bit more about the CMB-S4 project?

It will be a multiple-site observatory at the South Pole, and in the mountains of Chile. Each site will have many telescopes. This project takes the next step towards mass-producing the kind of sensors we use for the detectors. I think it has not been attempted before. These telescopes will have a very large field of view and will be optimized for studying the early universe. We now know how to do that. The construction should start in a few years, so it's not too far away.

How do you draw the line, qualitatively speaking, between the early and the late universe?

For scientists like us, who study the Cosmic Microwave Background or CMB, the first thing we see is the earliest light in the universe. As we refine our measurements, we start seeing things like the galaxy clusters and gravitational lensing. More effects become visible as we improve our measurements, and they arise from events that are closer to us, things that happened more recently, or late from our perspective.

One of the goals of SPT is to investigate how dark energy participated in the galaxy clusters evolution. Could you please elaborate on that?

One of the big scientific goals for the SPT was to survey galaxy clusters, via how they interact with the CMB. The galaxy clusters take a long time to grow and to form. The oldest clusters formed and evolved in the period when dark energy was not that prominent. Younger clusters, however, were born in the time with more dark energy. Looking at the difference between the older clusters that are further away, and younger clusters, that are close by, we get a sense of what dark energy must have been doing.

How do you differentiate between farther and nearer clusters?

That's a good question. Because of how we detect the clusters, they all look similar. It is both a blessing and a curse. The advantage of our technique is that because we detect distortions in the CMB, we can see all massive clusters out to really far away. But the issue then is that because they all look the same, we don't know from our data how far away they are. So, after we find these clusters, we use another telescope — in this case, an optical telescope, sometimes on a satellite — and we study the spots we identify. This way, we can identify which clusters are nearby, and which ones are far away.

What kind of properties do you investigate?

We mostly study the distribution of galaxy clusters. The way to understand how clusters grow or evolve is to look at lots of them, and to measure how their distribution changes depending on how far away, or how old, these galaxy clusters are. Changes in this distribution hint at what space-time and dark energy must be doing.

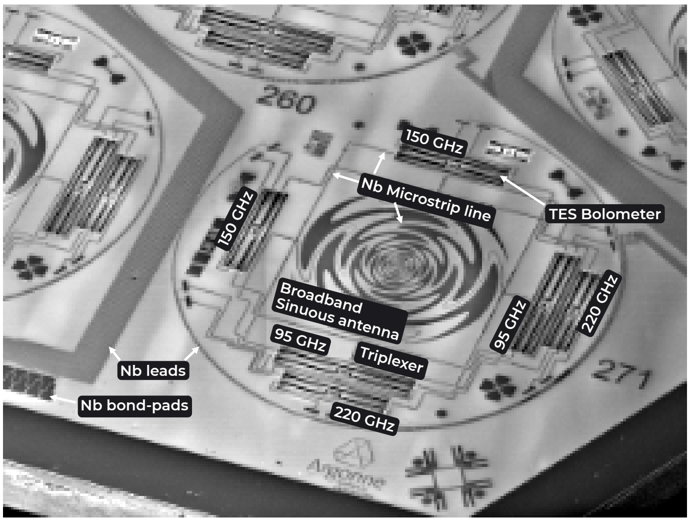
What exactly are you trying to learn about dark energy?

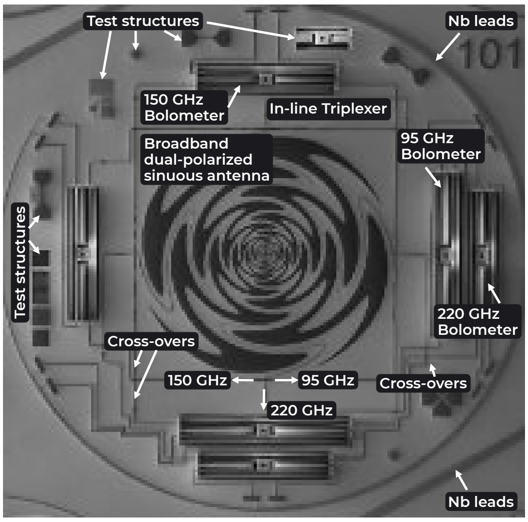
Our current picture basically shows that the universe is rather uniform, and it has two big components, dark matter and dark energy. The questions that drive us are "What is the nature of these things?", "How do they work?", "What exactly do they do?". So our measurements are more those of precision versus those of asking what is the best model to use.

We also try to better understand the early universe and how it informs particle physics. In particular, if we can find certain signals, then we can have a glimpse of the very early instances of the universe, the era of inflation, which is the story of how everything has gotten started.

What kind of features can you distinguish in CMB?

Many things imprint a pattern on the CMB. The galaxy clusters look like little dots, things that happened in the first 400 000 years look like blobs, and the gravit-





The detector arrays are fabricated from 150 mm wafers. Each array is built up from approximately 260 pixels. Each pixel includes a broadband sinuous antenna for coupling to free-space radiation, superconducting microstrip for transmitting the signal, an in-line triplexer circuit for channelizing the signal, and bolometers which measure the signal.

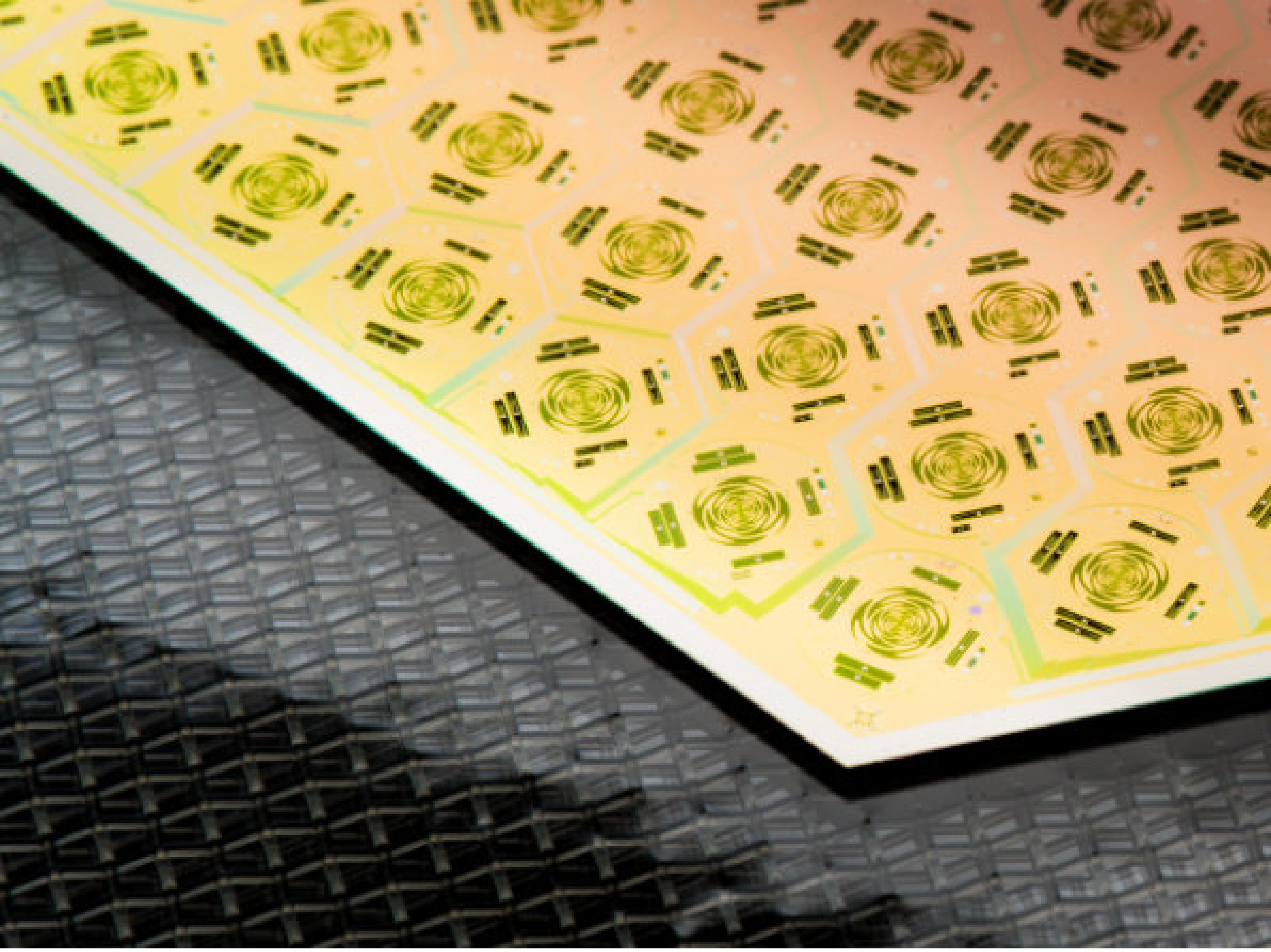
ational waves from inflation, imprint large patterns in the polarization that swirl around.

Is the polarization of the CMB photons preserved throughout this whole time?
Yes. The actual underlying physics is similar to why our sunglasses are polarized. The sunlight scatters off the air, it imparts off the polarization. The microwave background can be seen as scattering in the early universe, and so it has a polarization. And that pattern is preserved for the most part as the photons traverse 14 billion years to get to us. Analysing this pattern gives us another key to understand these scattering processes, and what was going on in the space-time of the early universe.

How do gravitational waves couple to all this?
In those first fractions of a second after the Big Bang, there was a new form of energy that drove everything. That physics also generated gravitational waves, which are different from what is measured by our current gravitational wave telescopes. These gravitational waves are made by the universe itself, for lack of a better word. They are very big, there is a lot of energy. They stretch the space-time differently, and they leave a signature in the CMB polarization since one of the ways the scattering can be influenced is through this stretching of space-time.

Can you tell us more about the detectors that you use to detect these features in CMB?
Most of the CMB photons are at a wavelength or frequency that we do not have good detectors for. They are somewhere between 100-200 GHz, which is a little too high for very good radio-type detectors, and a little too low in frequency for "normal" cameras which do not work well for the photons with so little energy. So, we detect these photons using a different technology, a superconducting transition-edge sensor. This sensor can measure the photons with a very high sensitivity. When we combine these transition-edge sensors with a sophisticated multiplexed read-out, we can make big focal planes. Just like the camera in a phone has about 10 million detectors, we need lots of detectors in the focal plane of our telescope.

The rest of the detector deals with the details of what goes into the measurement. We need to know the polarization of the CMB, so our detectors should



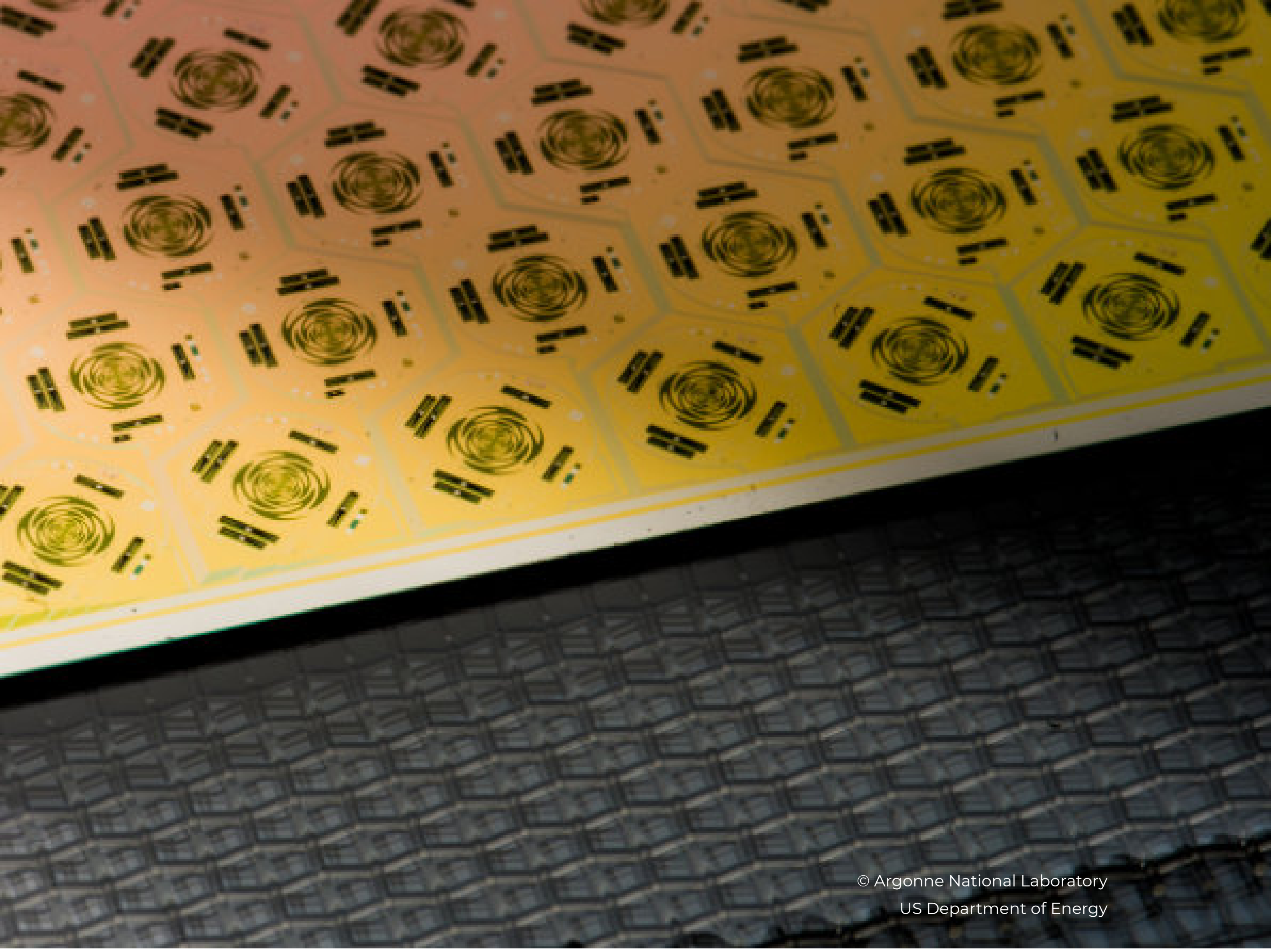
measure the polarization of incoming photons. We detect 3 specific frequencies, or 3 "colors," for two reasons. One is that is that on the ground, at the South Pole, there are certain "frequency windows" in which the atmosphere is very transparent. The other reason is related to distinguishing between early and late universe events. The microwave background has a very particular distribution between these colors. By measuring deviations from specific colors, we can distinguish between the microwave background from other sources.

How do you implement the filters to pick up the color and polarization?

All of this stuff is done on-chip. The photons couple though antennae-like structures, which separate different polarizations, so the photons with one polarization go in one set of transmission lines, and the photons with the other – through another set of wires. And then on these wires, we build color filters.

How do you ensure reproducibility of the devices that go into detectors?

It is hard, it takes a lot of work. Making the detectors involves growing many thin films and then all the nanofabrication associated with that. All of those films are amorphous, and our simplistic understanding of the condensed-matter physics does not really explain their behavior. These are complicated structures with complicated material properties. We have to control, tune, and adjust many parameters. Adding to the complexity, we care about what these films do as superconductors. The physics we are interested in does not appear at room temperature, everything has to be cooled to 300 mK or lower in order for us to be able to measure the relevant transport.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You are switching to dilution fridges for the new-generation detectors. To set this up at the South Pole must be quite a challenge!

We benefit a lot from the overlap between the work that we do superconducting quantum information technology. There's a lot of interest these days in quantum information science, and that has boosted up all the work with dilution refrigerators. People who work with qubits make and test things that are very similar to ours.

Apart from the material challenges, what are the other things you need to take into account when building detectors?

We have about 15 layers of material, 20 or so process steps. From the research perspective, alignment and resolution tolerances are not particularly difficult. We don't need lines or alignment much better than a micron, but we need it over the entire 150 mm wafer. And we do need it to be consistent and repeatable. The ability to do it quickly is also important.

There is a big advantage in moving away from contact-based lithography: that process is dirty and therefore it compromises the yield. Any piece of junk or debris on the mask is transferred and then there is a blob on the wafer. Given these criteria, though Heidelberg Instruments did not realize they were making something perfect for us when developing the MLA150 and MLA300 technology, they were. We don't need exceptional resolution, but we do want contact-free printing, very quickly. We're basically trying to do for our detectors, what manufacturers do for cell phone cameras: we just want our stuff to go through the standardized processes and roll out from the other side.

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US National Science Foundation

At the moment, how long does it take to complete these 20 processes for one wafer?

The whole thing takes around 2 months. It is a mixture of different flavors of processing. On one side, it is a lot like superconducting qubits, with many interfaces, superconducting materials and a need to control the physics associated with that. On the other side, we actually have things that look like MEMS and have deep features. We have to use deep reactive ion and XeF2 etching. The processes required for each type of structures can interact with each other in a very complicated way. We need to control many things and to develop our processes in a very systematic way. It is a lot of work and it requires very detailed understanding of all the physics that is involved.

How is your work organized?

Our team has about 10 people. They have different areas of focus. About half of the team works in the cleanroom building the devices, looking at them, and trying out new things. The others are experts in taking these devices and building the instrumentation, measuring the devices and trying to understand them.

Ultimately, we need to get those detectors to work someplace else and to measure something related to physics that we do not understand.

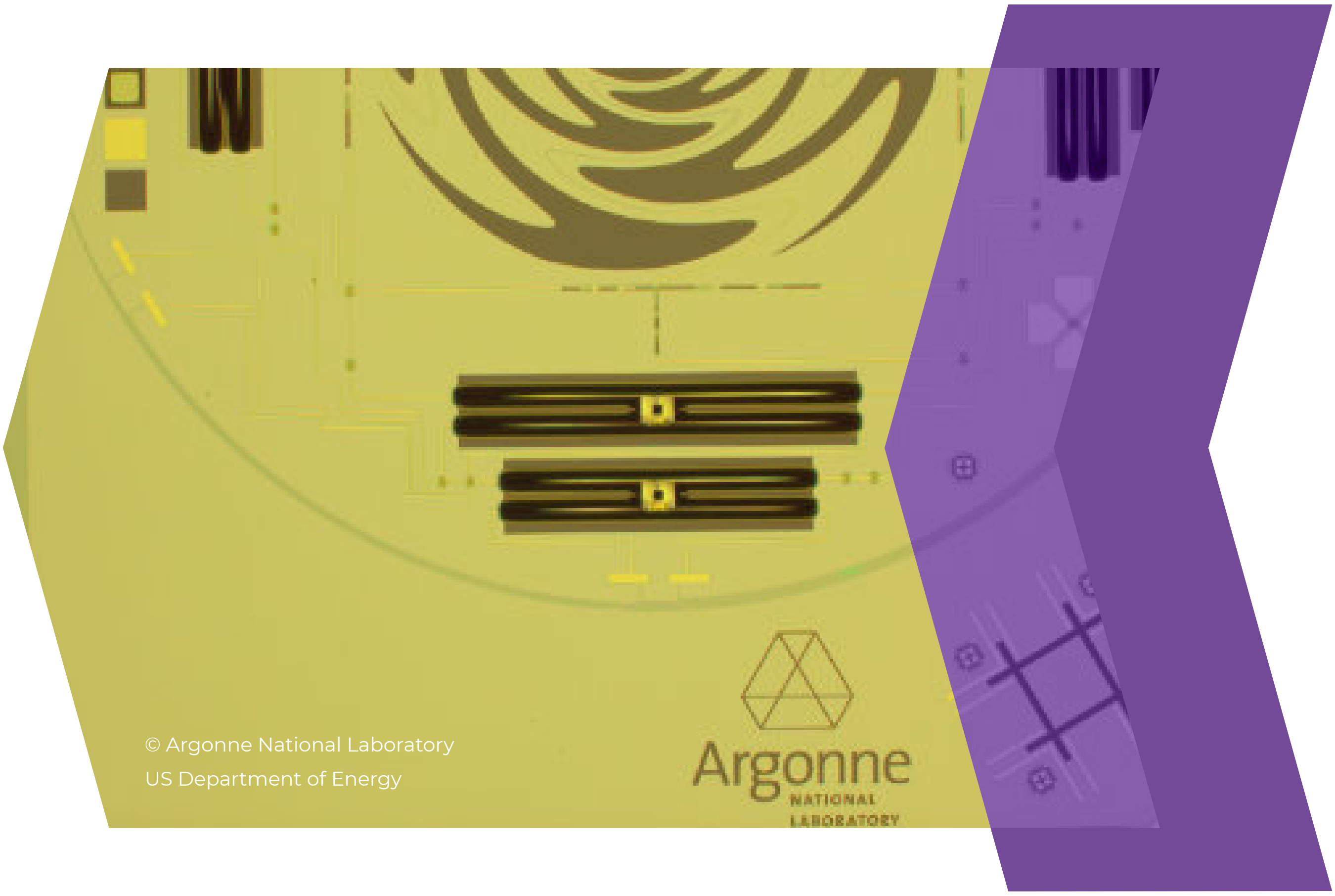
The development cycle is very fluid. We develop components in pieces. Once we have working components, we start putting them together. When some of the components no longer work, we have to fix that. We build things up from quite simple to much more complex.

In order to understand the processes at work, we vary device parameters and properties. Here, we take advantage of being able to write new patterns directly. This allows us to quickly make a new device where we have changed something, and measure it right away. We compare the results of these measurements, to see which changes improve our process. Because the development cycle is complex and takes quite a long time, it is very important to have the flexibility to make changes and to make them quickly.

What were the most unexpected things you had to fix in the process?

One of the things that needs to be controlled is the temperature: the material should not get very hot, above 200°C. But we don't always know what the temperature is everywhere. We have to infer it from measurements and inspections. And that is not particularly easy, especially for the MEMS-related deep reactive ion etchings, which are very energetic processes. We just do not know what the temperature profile is.

Another complexity arises from how we do the processing. As I said earlier, we make MEMS on one side, and superconducting sensors on the other. One of our big challenges is to understand and to control how all the different processes that we use to make our detectors interact with each other. For example, some of the processes produce byproducts which may remain on the detectors without our knowing and influence subsequent processing. Controlling these interactions in 20-25 process steps is very hard.



Now, what is your favorite part about it?

I think in its ideal sense, it is a little example of how science is done. Kind of like the early universe, with our devices, we only see what we can measure, right? We really want to know what is going on, but we do not always have the tools to observe it directly. So we study our devices with indirect means and we have to put together a story of what we think happens, and then we have to test it. For example, we think that "device A" doesn't work because of a chemical interaction between these two materials. How can we test this hypothesis? We make a new device and change the interface between these materials. And then we can check if there is that interaction, and if it scales the way it should scale. In some sense, this is exactly how science is done. Looking at what we do not understand, coming up with explanations, making some sorts of predictions, and testing them. In the heat of things, it does not leave much room to sleep. We try to balance things now.

Does your team actually get to go to the South Pole?

Yep, we do. It is a different experience. It is always in the state of semi-quarantine, as a way to look at it. There is no internet access most of the day. It is a very strange way to experience life these days. It is very beautiful there. There are two times when we go the South Pole: the winter up north and summer down there, from November to February, and a stretch that goes all the way from February to November, the night. Over the night, there are no flights. About 30 people who come there in February stay for the rest of the year.

It's almost like flying to space!

There are elements that are a lot like that, yes. It's really cold and really dry there, it is not terribly comfortable. It is hard for a human being, but that cold and that dryness make it a really good place for the kind of astronomy that we do.

The final question is a bit less scientific. Your span of expertise is really wide. Can you still enjoy science fiction?

Haha, definitely. The best sci-fi is not about science, or not only about science. It's about people. So we definitely enjoy sci-fi. In fact, at the South Pole, the team was watching the Battlestar Galactica!

Quantum computer out of a glovebox

Prof. Ken Burch from Boston College and his Laboratory of Assembly & Spectroscopy of Emergence study a wide range of topics: from fundamental studies of 2D topological magnets and superconductors to applied research on CVD-grown graphene for biosensing applications.

The lab of Prof. Burch is a unique place, as the entire fabrication process and much of the sample analysis is done inside a series of interconnected gloveboxes. Prof. Burch has kindly agreed to tell The Lithographer about his work and to share his experience in setting up a cleanroom-in-a-glovebox.

Thank you so much for finding the time for this interview. The scope of your scientific interest is very wide! How did you arrive at this specific range of topics and projects, what is your overarching scientific goal?

Thank you. I wish I could tell you it all happened entirely by design, as opposed to some luck and randomness. When I recruit students to work in our lab, I tell them that I want to understand how the different physical

properties compete or collaborate with one another, and how that leads to new behaviour, how new phases of matter emerge. Overtime, the focus has drifted towards using this knowledge and the techniques that we developed for something that is not only intellectually stimulating but also potentially useful.

Actually, this is how we ended up in biosensing. It was a bit of a coincidence. A student heard of our capabilities and asked if he could use our system. I agreed and asked him to tell me a bit more about his project. I got curious about it and wrote to his professor. I described what kind of materials we were working with, and what kind of biosensors one could make with them. So we started talking, and then, three years later, the paper came out. We have made a CVD-grown (chemical vapor deposition) graphene-based sensor capable of detecting different species of bacteria, including antibiotic-resistant strains, at relatively low sample concentration and very rapidly: in only 5 minutes. And the more I worked on this project, the more interesting physics questions appeared. The data, if you allow it, often will tell you something more interesting, than what you initially thought.

As for the other directions of my work — well, we cannot do everything, but we do have a variety of different techniques as well as different materials. My hope has always been that there will be a synergy, that new ideas will come out from bringing together people who are working on seemingly distinct things. Nowadays, the problems we face, even just scientifically, are so complex that not one tool is going to be good enough. In fact, the concept of the glovebox appeared as I looked for an easier way to bring together materials, to create devices and to probe them with multiple methods . This enables us to get novel insights, in a way that other groups cannot.

THE FUTURE OF CLEANROOMS IS NOT A CLEANROOM, IT IS THIS

Could you also tell more about the other branches of your research? You already mentioned graphene-based biosensors. What other 2D materials do you work with?

Right now, we are working on 2D magnets and superconductors with topological phases. The magnets, in our case, are heterostructures between relativistic Mott insulators and various non-magnetic 2D materials. They are bond-frustrated, which means that the direction of the magnetic interactions, roughly speaking, depends on the bond. And the reason why we are interested in this material is that we expect to get the so-called spin liquid phase. In this phase, there is no magnetic order even down to 0 K, but there is a topological order. One of the challenges is how to detect that order and particles that are meant to emerge in that state. This state itself can be a platform for a topological quantum computing.

Are you exploring this as a platform to realize quantum computers?

Yes, we use two very distinct approaches which are reflected in our choice of materials. We try to diversify our research portfolio, so to speak. We study 2D magnets to see if they can work as topological quantum computing systems, and we are interested in understanding how they would behave in heterostructures. If you make a real device, you need to know how the magnetism gets modified.

Alexey Kitaev came up with the idea of topological quantum computing with his first paper from 2001, on wires. Then in 2006 he predicted the spin liquid, which we now call the Kitaev spin liquid. In this model it is very clear how to perform braiding,. And then there are quite accurate predictions of the material for this model. One thing we are interested in is the realization of that model. But of course, the materials are never kind, they are never exactly like the mode.

What are the requirements to the material to form a spin liquid?
The original model is based on a honeycomb lattice, just like graphene, where you have a magnetic spin ½ in each of the atoms. And then there is a very special kind of exchange between them. One component of the spin interacts along one bond, another component along the other bond, and the other component — along the third bond. So you need a material that realizes this bond-dependent machinery in a very particular way. And of course the real materials may have the right strong spin-orbit coupling term, but usually they also have other terms, like standard magnetic interactions, and so the question is: How do you get rid of those other terms?

A separate question is, assuming there was a real spin liquid like Kitaev envisioned, how do you trap the Majorana fermions and move them around in a real system. When you have a 3D material, you can imagine straining it to create a local potential that traps the Majorana fermions, or you can move them around through spin injection with optical or electrical probes, things like that. I would say it is really early days, and we are far from a demonstration, but that's the direction in which we are interested.

For these Majorana to act like quantum bits (qubits), they need to be isolated, and only interact with one another in a controlled way (e.g. when you want to perform a calculation). A possible option for this is induce local strain that will trap them. For the 2D magnets, we envision applying similar approach as was done make quantum emitters, namely pre-fabricate a substrate with nanoscale spikes to induce local strain in MoS2,. Basically, what happens is that you manipulate the local exchange interactions in a way that would trap things. Of course this requires great care in minimizing unwanted disorder, which is where the glovebox will come in.

Why do you rely so heavily on Raman spectroscopy as the characterization method?
Raman spectroscopy is a powerful tool to measure important properties of 2D materials and their heterostructures including lattice orientation, defects, electron-phonon coupling, doping, strain and even the magnetic interactions. In last 10-15 years, one of the main ways to identify the new topological phases in many of the topological systems was ARPES (Angle-resolved photoemission spectroscopy). The one thing that always bothered me about that is that you do not measure the predicted parameter, which is Berry's curvature. And it turns out the Raman scattering can be connected to this curvature. You can directly show that many of the non-linear responses are roughly speaking proportional to the Berry's curvature. Our interest initially was to directly probe the topology and the Berry's curvature. Then it also turned out that the materials with very strong topological features also show very strong enhancement of the non-linear photocurrent. Now we are trying to understand how to optimize such non-linear response to use it in lasers or detectors, things like that.

Can you also tell a bit about the topological superconductors? Why do they attract your attention as a qubit system?
Topological superconducting qubits are not to be confused with superconducting qubits featuring Josephson junctions. An example is the Fe-based superconductor, FeTe0.55Se0.45, as it turns out, is both topological and superconducting at the same time, which is quite amazing. We were the first to find some evidence that it is topological by observing the so-called hinge modes. And now we continue to figure out the properties of these modes, and to prove that they are what theorists claim they are, or to show that it is wrong.

According to theoretical predictions, in a topological superconducting material, you can have a vortex with a Majorana fermion “sitting“ inside. We use a different approach. If you look at the superconducting order in this material, then at its edge, a boundary between two edges or two surfaces — the so-called hinge, there is a 1D mode. And this is what is called a higher-order topological superconductor. A higher order here means that unlike in the conventional topological insulator where you get conducting surface states, here you get this mode at the contact of 2 surfaces. Our original paper was trying to show evidence that the mode was there, and now we are working on proving that this is indeed the case. There is a way you can localize this mode only at the corners. And if that works, that would be amazing because then you would have a scalable way to make many of these boundary modes. So rather than needing wires, etc, here you just need to take the material and cut corners. Literally, every time you get a corner, you get a mode.

If you could fabricate anything, disregarding time, costs, some minor technical issues — what would you do?

I am not so interested in a particular device. I want to create a new platform that would enable us to do something really new. Whether it is investigate new area of physics, or create next quantum computer platform, or take biosensing to the next level. For me, the devices themselves are not the end goal, it is what they enable us to do. Whether it is a device that allows us to manipulate the topology, or to make qubits, or tells you exactly whether it is a virus or a bacteria. Those are various “dream” devices that we are hoping to work, and that is what our setup is geared for.

Speaking of your cleanroom in the glovebox: did you conceptualize it from the beginning, or did it emerge over time?

Strangely, the answer is both. More than a decade ago now, when I was just starting out as a professor in Toronto, we started working on a material that needed to be exfoliated. We thought that this material was very sensitive to air (which turned out not to be quite right later). So we decided to try exfoliating it in a glovebox in order to protect it. We installed a cheap old used glovebox, a tiny little two-ports thing. Then we realized we had to keep it in there, so we put a microscope inside to find the flakes, and so on. But we still would need to take it to air to make a device. And of course that process would “kill” the material. At that time, I was also collaborating with people who worked in OLEDs (Organic Light Emitting Diodes), and I noticed that they did quite a lot of microfabrication inside a glovebox. It was nothing overly complex, but that was when I realized: “Ha! what we need is to do all the fabrication inside the glovebox, and that would be good enough to protect the sample.”

Moving to Boston College gave me an opportunity to try this. If I knew then how much we would have gone into it, I would have thought more carefully about it, but at that time, it was just a vision of going from exfoliation and characterization all the way to the entire microfabrication. I was not necessarily thinking of any cutting edge devices, just being able to do the things inside a glovebox. So the original idea was really to enable microfabrication of air-sensitive materials.

Plasma cleaner

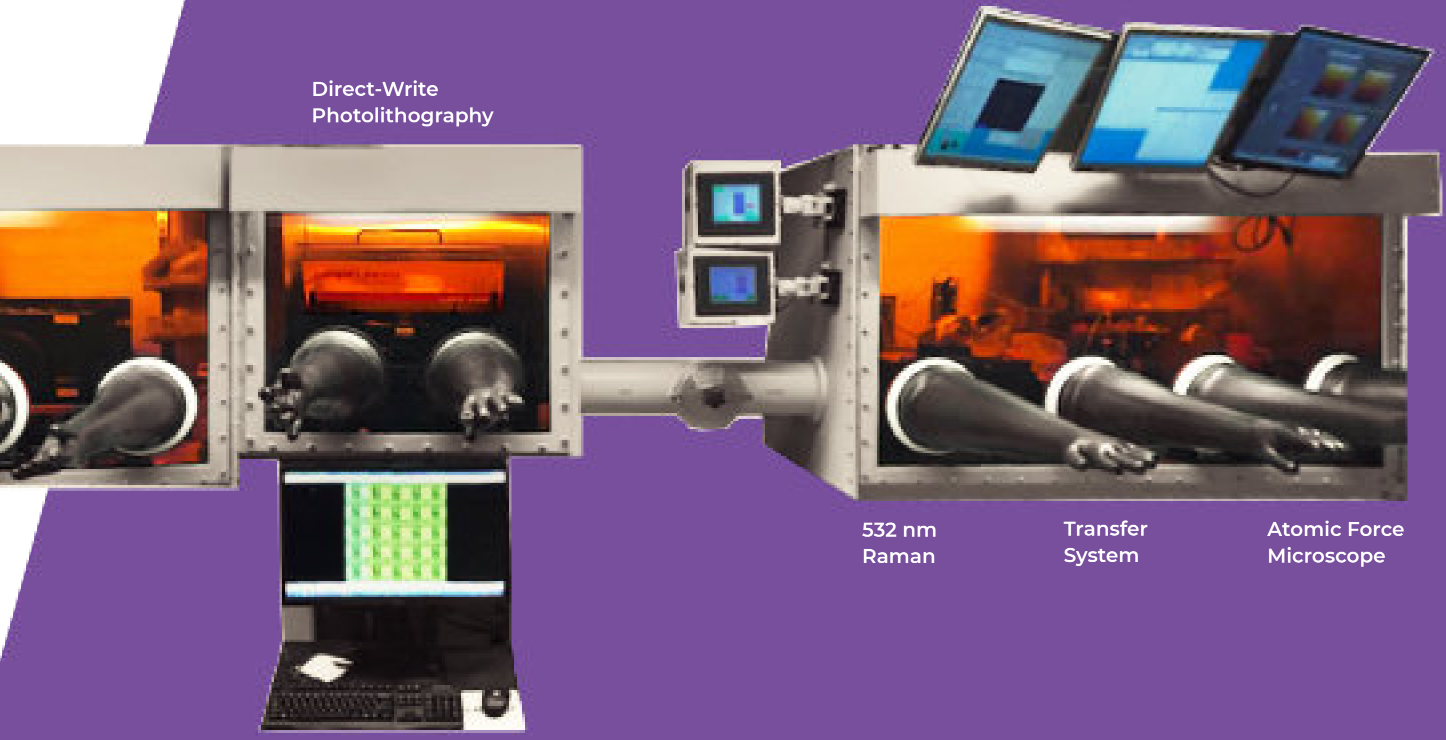
Thermal Deposition System

Spin-Coating System

What were the main difficulties and limitations that you had to face, as you built your system?

Luckily, we did not have to reinvent the wheel as much as I thought we would. The lift-off process with photoresist worked in the glovebox after some optimization.

The hardest part was in the beginning, when we needed to get the equipment inside, and we did not



A CLEANROOM IN A GLOVEBOX

A Cleanroom in a glovebox[1] brings together the controlled inert atmosphere of a glovebox and the fabrication and characterisation capabilities of a cleanroom.

The cleanroom in a glovebox shown on the image consists of a lithography and characterization chambers. They are connected via a small antechamber for taking samples in, out and between the chambers. The back of the glovebox is connected to an intermediate chamber for attaching a vacuum suitcase.

The vacuum suitcase is designed to couple to various ultra-high vacuum chambers. This way, air-sensitive materials can be moved to other UHV systems, e.g. electron-beam systems, scanning tunnelling microscopes, molecular beam epitaxy or angle-resolved photoemission spectroscopy tools.

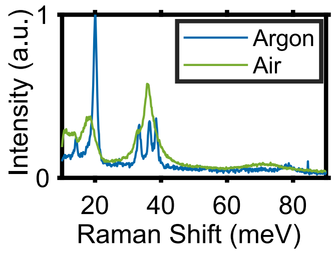
THE LITHOGRAPHY CHAMBER FEATURES:

- Heidelberg Instruments µPG101 Direct-Write tool with an optical auto-focuse system[2,3];
- Angstrom Engineering NexDep Physical Vapor Deposition and Plasma Etching system;
- Spin-Coating Systems G3 Spin Coater;
- A solvent scrubber the glovebox column
- Qorpak bottles to limit the exposure of solvents to the glovebox atmosphere;
- UHV suitcase transfer system.

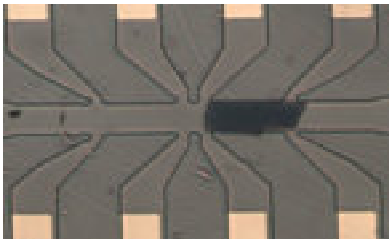
THE CHARACTERIZATION CHAMBER FEATURES:

- WITec Alpha300R confocal Raman system;
- A simple casing around the Raman system, made of black plastic sheets and 80-20 aluminium bars;
- Careful isolation of the fibers and wires via foam-sealing to the glovebox.
- Nanomagnetics ezAFM[4];
- A home-built 2D material dry-transfer system[3];
- Electronic BNC and banana cable feedthroughs.

1. A detailed description of the system and all the components can be found in a recently published article in Reviews of Scientific Instruments (Mason J. Gray et al., “A Cleanroom in a Glovebox”).
2. Standard air-pressure focusing cannot be used due to the changing dynamics of the glovebox air.
3. The air-bearing of the tool’s platform use argon supplied through a T-junction in the argon path. This solution also helps to vent the excess solvents and water from the clean atmosphere.
4. Placed on a large granite slab to prevent the vibrations caused by the gas-circulation system and sudden pressure changes from the users inserting there hands into the glovebox.



Air-Sensitive Materials: Raman spectra measured on αRuCl3 showing the difference exfoliation in the inert atmosphere makes. Raman measurements were taken using the WITec Raman System installed in the glovebox.



2D Materials: optical micrograph of a Bi2Sr2CaCu2O8+δ exfoliated onto a thin film of Ga1−xMnxAs. The film was then etched into a double hall-bar structure around the flake.

UHV Suitcase Transfers: Photo of the UHV suitcase during a device transfer from the glovebox to the low-temperature Raman system. The UHV suitcase is attached to the back of the glovebox.

know, for example, how much do we have to worry about how hot it gets inside the box, or about the solvents and how to get rid of them.

For the glovebox atmosphere, we went for Argon because Argon is heavier than Nitrogen, so it would require less Argon to reach low oxygen and water levels, and it is not much more expensive. I also thought that someday we might work with Lithium and intercalations.

We faced another difficulty related to argon that was actually funny. Nanodevices demand a very cautious approach to the electrostatic discharge. So we installed an autobalancing ionizer to significantly reduce ESD (electrostatic discharge) inside the glovebox. They started sparking right away, and at the same time, all the computer screens that were inside instantly blew! As it turned out, argon ionization energy is so low that something with reasonable voltage sparks in it right away. We had to pull out all the ionizers and to remove the screens. Then we found out that iPads work beautifully, since they are low-voltage to begin with. So we just bought a few and installed them inside, and ever since we had no trouble, we have never blown up a device inside the box. It is one of these funny things we did not appreciate initially.

Are there any other tricks that you have discovered?

Yes, a few. The students do a dose test in the corner of almost every chip just to double-check. One thing that is more variable than in a cleanroom is resist, because it dries up a little faster. We keep it self-contained and we developed a lot of little tricks, like special bottle caps. Actually, we do not leave a lot of solvents or resists inside, we just use tiny bottles. With this dose tests, everything seems to work most of the time. Of course, we sometimes have the usual lift-off issues, something did not go off well, or LOR (lift-off resist) did not work quite right. For example, the CVD-grown graphene devices, like the ones in our biosensing paper. Those actually were a real struggle. But once we have gotten the process down, it works pretty well, the yield is really high.

I think once we overcame the issues of the Argon, in some sense, our glovebox is cleaner than a real cleanroom. We know there are hydrocarbons from the pumps, you can see that in various things, but other than that it is really just argon.

Do you miss any capability that you would have in a cleanroom?

We would certainly like the ability to deposit more things. Right now, we can only do thermal deposition. Soon, we expect an e-beam deposition tool to arrive. At some point in the long run we would also like an ALD (atomic layer deposition) system. We would also like a capability to make 3-dimensional structures and nanoscale feature sizes. We applied for funding for a NanoFrazor that can go into a glovebox, that would solve this problem. Another thing that we have recently done is a UHV (ultra-high vacuum) suitcase. The purpose of that originally was two-fold: One was to get the MBE (molecular beam epitaxy) films in, and the other was to be able to get the samples out for an e-beam, SEM or TEM. Honestly, I have not seen a tool that we could not get, it is all a matter of time and money.

And what are the biggest advantages of the cleanroom-in-a-glovebox?

Initially we just wanted to make devices in the glovebox. What we realized was that this overall approach was far more productive. For one thing, the students do not wear the bunny suits. I know this sounds silly, but actually it is a real pain and has its own limitations. And everything is really self-contained and it is much safer. I do not worry that the students will spill a photoresist on themselves or something like that. I have first-year undergraduate students who fabricate their own devices! We really rely on easy-maintenance direct-write tools for our processes. Without µPG, for example, it all would have been hopeless. We do not need custom masks, and we can streamline the fabrication.

It is a very powerful yet easy to learn set of instruments. It democratizes the fabrication, and overall it is much cheaper. You do not need a separate building or a large area as for a cleanroom. Since it's cheaper, easier and faster to build, people who would otherwise not have access to a cleanroom can do fabrication. It also gives our group more independence, though of course it also means that my students and I have to maintain it. But honestly, I think that the future of cleanrooms is not a cleanroom, it is this. Though obviously, I am biased. But if you look at modern fab like the Albany NanoTech Complex in the New York state's SUNY Polytechnic. It is a 300 mi2 lab with almost no humans in there, mostly robots, taking wafers from one huge machine to another. To me, this is the future, not the giant cleanrooms where people have to wear bunny suits.

All images: courtesy of Kenneth Burch, Boston College.

Everything is under control

Professor Michelle Simmons is the Director of the Centre of Excellence for Quantum Computation and Communication Technology at the University of New South Wales in Sydney since 2010 and also a founding Director of Silicon Quantum Computing, Australia's first quantum computing company. In 2018, Prof. Simmons was named Australian of the Year and became a fellow of the Royal Society of London, just to name the most recent awards. She is also Editor-in-Chief of npj Quantum Information, Nature's premier journal in the emerging field of quantum information science.

Michelle Simmons has pioneered a novel approach to making atomic-scale devices using Scanning Tunnelling Microscopy (STM) and Molecular Beam Epitaxy (MBE). Her team now routinely creates atomically precise devices in silicon. Recently, they demonstrated the first 2-qubit gate using phosphorus atoms in silicon, and now the team is working to scale such qubit systems up. Prof. Simmons has kindly agreed to tell The Lithographer more about her work.

STM HYDROGEN RESIST LITHOGRAPHY

"In the beginning, the scanning tunnelling microscope was designed to be a visualization tool, that allowed one to see atoms. Using STM to pattern devices with atomic precision and integrating it with crystal growth technique to make complete atomically-precise devices, that's still quite new" – says Michelle Simmons. STM hydrogen resist lithography uses the STM probe to locally desorb hydrogen atoms covering an atomically flat silicon substrate. The remaining hydrogen then acts as an atomic-scale lithographic mask. The sample is then exposed to phosphine molecules that bind to the exposed silicon surface. After the mask is removed, epitaxial silicon is grown over the phosphorus atoms by MBE, encapsulating them into a crystalline environment free of dangling bonds, interfaces or defects. With this approach, the position of the phosphorus atoms is precisely controlled in all three dimensions.

Thank you so much for finding the time for this interview. Before diving into the technical details, please tell us a bit about how did this project begin in the first place?

Over 20 years ago, in the late 90's, Bruce Kane, a researcher from Bell Laboratories in the US, came over to Australia for a 3-year Australian Research Council Research Fellowship. During his time in Sydney, he came up with the idea of using phosphorus atoms-in-silicon as qubits for a quantum computer. In his paper, he suggested different fabrication methods of how to achieve this: either using the standard industry process of ion implantation or by trying to adapt a scanning tunnelling microscope to place the phosphorus atoms in silicon[1]. Back then the IBM group had just begun to manipulate metal atoms on metal surfaces and made the world's smallest IBM logo.

At that time, I was at the Cavendish Laboratories in Cambridge, UK, working on a project where we tried to see if we could make quantum devices reproducible, i.e. if we could make same device twice. Despite using very precise crystal growth techniques (MBE) that allowed us to engineer devices at the nanoscale, it was very difficult to replicate the exact same device behaviour. This was very frustrating. For me it became clear that if we wanted to replicate a quantum device, we would need atomic-level control. I then saw the paper from Bruce, with the idea of using individual atoms as quantum bits or qubits to build a quantum computer. And I remembered thinking that making a quantum computer would likely only be possible if we had the precision to fabricate each qubit with atomic precision. In fact, building the whole device with atomic precision seemed the best way to go. His theoretical paper proposed combining the only tools we had at the time that had atomic precision – a scanning probe microscope and molecular beam epitaxy. It was at this point when I realised that these skill sets were within my expertise as a researcher, and I thought: "I should give it a go!"

The complexity of your devices is truly amazing. Did the device architecture develop incrementally, or did you have a clear idea of how it should be from the start?

The original concept of using phosphorus atoms and how to operate them as qubits was in Bruce's paper, which was quite comprehensive. But the actual practicality of how to build the qubits and build the architecture around them wasn't there. From that point of view, it was like a puzzle to be solved. A lot of conceptual pieces were in different places, and bringing them together, I have to say, was a heck of a lot of fun. Over the years, we have had really fantastic people working in the team, each of them coming up with slightly different ways of thinking, for example, how to do fast read-out, how to add an ESR (Electron Spin Reson-

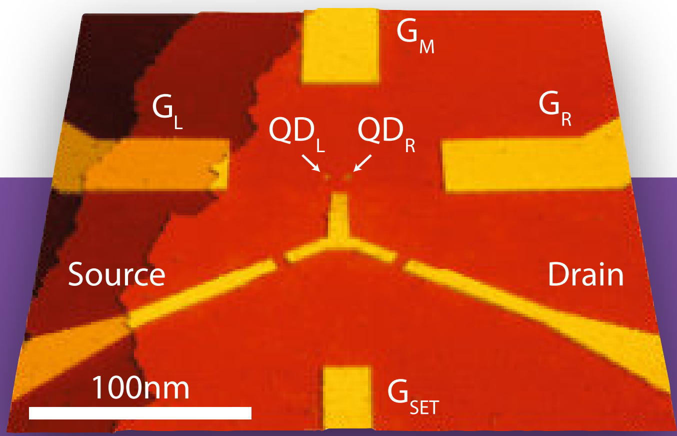
[1] B. E. Kane, "A silicon-based nuclear spin quantum computer", Nature v. 393, pp. 133–137, 1998.
[2] Martin Fuechsle et al., "A single-atom transistor", Nature Nanotechnology v. 7, pp. 242–246, 2012.
[3] Y. He et al., "A two-qubit gate between phosphorus donor electrons in silicon", Nature v. 571, pp. 371–375, 2019.

ance) antenna to the device, how to minimise noise, how to determine where the atoms are and how to connect to them. It has been an ongoing process with lots of ideas coming into the team every time we make a new hire. I have always had a clear vision of where we wanted to go and what do we wanted to get to. And then there was the whole series of technical challenges, both in engineering and in physics that required deep knowledge at nearly every level. It's been very satisfying to work on that.

The key aspect of the device architecture is to try to make a perfect qubit by making a crystalline environment around the qubit thereby moving it away from interfaces and surfaces. You can actually get phosphorus to be substitutional in the lattice and use MBE to provide a crystalline environment all around it so that the interface to the native oxide can be far away from the active area of the device. One of the key questions at the beginning was if the phosphorus atoms would stay put during the device fabrication process and if the crystalline quality of the silicon would be good enough. One of the great things about combining STM with MBE is that you can control numerous fabrication parameters. Together, you can actually put the dopants in place with atomic precision[2] and then grow epitaxial silicon around them, which results in very high quality qubits[3].

How do you control the exchange interaction between the quantum dots?

The long-term advantage of purely crystalline qubits is that the electrical noise is very low: our measurements show that the noise is orders of magnitude lower than in conventional CMOS devices with similar dimensions[4,5]. That's fantastic as noise is the key



A TWO-QUBIT GATE USING ATOM QUBITS IN SILICON

A scanning tunneling micrograph of a two-qubit gate device. The device is defined using scanning tunneling microscopy hydrogen-lithography on a hydrogen-terminated silicon-(2x1) reconstructed surface. The bright regions are where the hydrogen atoms have been removed from the surface and after subsequent phosphine doping create the electrical gates and qubits. The device consists of a single-electron transistor with source and drain leads used as a charge sensor, two quantum dots, QDL and QDR which confine the electron spin qubits, and four electrodes, GL, GM, GR, GSET used to control the electrochemical potentials of the quantum dots and single-electron transistor. The two-qubit SWAP gate is achieved by rapidly changing the voltages on GL and GR to push the electrons onto the same quantum dot thereby increasing the exchange energy between them. The exchange energy causes the anti-parallel spin states to oscillate in time and by judicious choice of interaction a two-qubit gate can be performed.

limiting factor in scaling semiconductor qubits. We consider our atom qubits equivalent to high-quality ion trap qubits but in a manufacturable solid state environment.

But atomic precision devices come with their challenges too. It is important to be able to turn interactions between qubits completely on and completely off. Their ability to interact is very much guided by where the phosphorus atoms are in the crystal. It was a big question from the very beginning: can we get the atoms close enough together to get them to interact and entangle but at the same time will they be too close physically, i.e. can we turn one qubit on and off completely without affecting the other qubit? It wasn't obvious, but it turned out that you can do that and achieve very fast gate operation times with independent qubit control.[3,6]

The control operations on our qubits use gates that are formed from heavily phosphorus-doped silicon. So we create a metallic gate inside the silicon crystal. With STM lithography, we can bring these electrostatic monolayer doped in-plane gates very close to the qubits to control the overlapping wave-functions.

So you write the entire circuitry of the device using the same method?

Yes. And that's amazing, I don't know how to describe it, it's an unusual concept. Essentially, you are writing the whole electronic structure of the device with the phosphorus atoms. Literally, the only two atoms in the device are phosphorus and silicon.

Where is the interface to the external pads to control the device?

The gates are the in-plane phosphorus doped gates in the same crystallographic plane as the qubits are. You can use the STM to pattern the leads from the active part of the device all the way out, so you just need to make Ohmic contacts to the buried leads. You can use different metals to contact the buried phosphorus underneath after the etching or annealing process. Everything is performed in our UHV chamber until the final metallization, which is always performed in the cleanroom.

To find the buried devices, we need registration markers etched in the silicon substrate that survive all the way through the various device fabrication processes. For example, when the substrate enters the UHV chamber, it is flashed at a very high temperature. We etch these markers into the silicon substrate before loading into the UHV microscope, and depending on their shape, they still survive after this high-temperature annealing. We can find them afterwards to align contacts to the buried device in the cleanroom.

How long does it take to make one of such devices?

Oh, that's the amazing part. With an STM device, you can design, pattern, process and test a device in a week, sometimes multiple devices at a time. This is very fast as compared to many-months cycle time if you want to run a new device architecture through a semiconductor manufacturing plant. Of course they can manufacture at much higher volumes but at this stage, rapid prototyping is actually very useful for us.

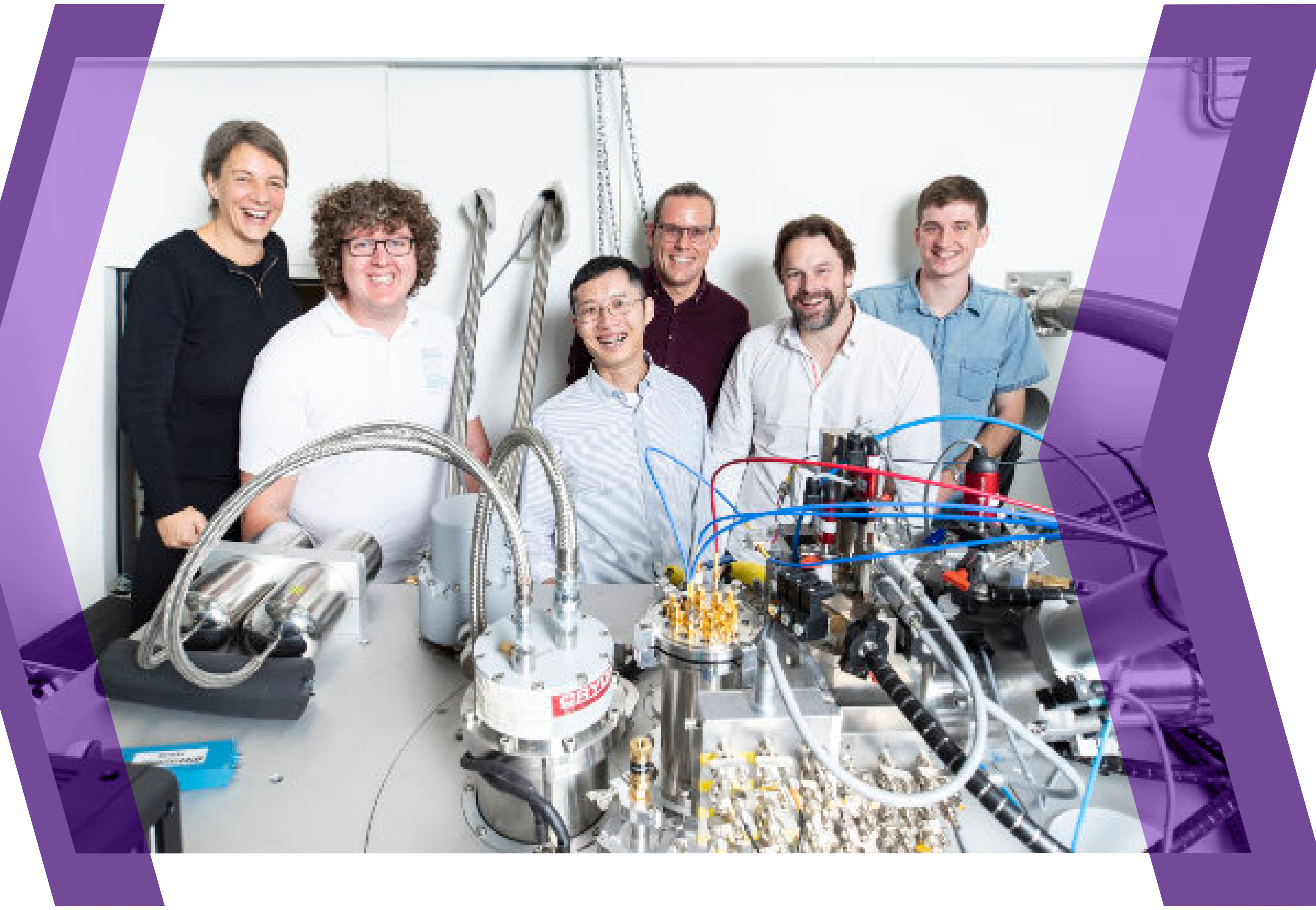
The yield is the other thing I like about the technology we have developed. When I was in Cambridge, we used to make gate-defined quantum dot devices. And the yield there was 30–70%. Of 12 contacts, we would

[4] L. Kranz et al., "Exploiting a Single-Crystal Environment to Minimize the Charge Noise on Qubits in Silicon", Advanced Materials v. 40, (2020), https://doi.org/10.1002/adma.202003361.

[5] S. Shamim et al., "Ultralow-Noise Atomic-Scale Structures for Quantum Circuitry in Silicon", Nano Letters 16, 5779, 2016.

[6] D. Keith et al., "Single-Shot Spin Readout in Semiconductors Near the Shot-Noise Sensitivity Limit", Physical Reviews X 9, 041003, 2019.

[7] Matthias Koch et al., "Spin read-out in atomic qubits in an all-epitaxial three-dimensional transistor", Nature Nanotechnology 14, pp. 137–140, 2019.



always find 4 or so broken. Whereas here, when the contacts are made using heavily doped phosphorus silicon the yield is much higher. We don't have to deal with electrostatically defined structures which can be very irreproducible.

In one of your papers, you propose a 3D architecture of an array of such devices[7]. Is this the direction you are heading to, to scale things up?
We are interested in several directions, and one of them is definitely 3D. We showed that we can pattern multiple layers with atomic precision on top of each other, all of them epitaxially. One of the layers is an active layer with qubits, and the gates are in separate layers above and below the qubits plane. These devices are incredibly stable and beautiful. We think that is because this extra highly doped layer is screening the surface from the active qubit layer beneath it. So we have a project going now, to see how many layers we can pattern on top of each other. It's an amazing system! A lot of things we didn't anticipate would work, have worked out.

By the way, do you still go to the lab yourself?
I do, it's my favourite place to be, but I don't do the actual, physical measurements anymore. The device fabrication, processing and running the measurements are undertaken by the team. It is a privilege to be able to build and test your own devices, something I have found incredibly rewarding over my career and I loved doing it. For now, I am happy to provide this opportunity to others and I use my expertise to make sure that they have a unique system with the best technology to play with and the most exciting and rewarding projects to do. And of course, I closely direct the experiments.

It's great that you are involved in the process on such a deep level.
Oh, I love it! Seriously, I wouldn't do this job if I couldn't be involved in every aspect of the research.

For me, the most exciting thing is when people send me the data on the new devices that we can discuss. And that happens every day!

And regarding the general outlook on the field: in the last couple of years, a lot of things happened around quantum computing, it became quite a buzzword. How do you see that? Is it a race? Do people collaborate?

It's a fascinating field to be in. There are so many different aspects of it. In general, building a whole new type of computer is such a complicated, complex problem, that it doesn't matter what material system you decide to build your qubits in – they are all challenging. There is a lot of different materials, and there is a lot of different platforms. And that is fantastic, because each platform discovers how to do things in different ways, and we all learn from each other. So I think there's a high level of camaraderie born from how incredibly difficult this problem is. And when somebody does a great experiment, we all celebrate it. But this is also a field that is moving at quite a pace. So you can't sit on your laurels, you have to keep going because so many things are happening. In some way it's like running a marathon, but at sprint pace. There are days when I feel like I've been running for weeks. And then I think "Oh, I'm just going to stop and take a day off" and – bang! – something new comes out and you are off running again. It's a full-on field.

And what are the important milestones remaining for the quantum computers to become really a practical tool, in your opinion?

I think error correction is critical. A lot of people are developing algorithms that require error correction. To realise this in the long term we need very stable qubit systems with fast control, which means a high level of materials control, and the ability to deal with fast electronics. These are two critical skills.

To understand how all the layers of the stack work and come together is another challenge. Everyone is becoming very specialized in different areas so you have to be able to step outside your expertise to bring everything together. For example, high-frequency control is something I had to pick up while working with others. And this happens constantly. It pushes you. Being able to interact across these boundaries is critical.

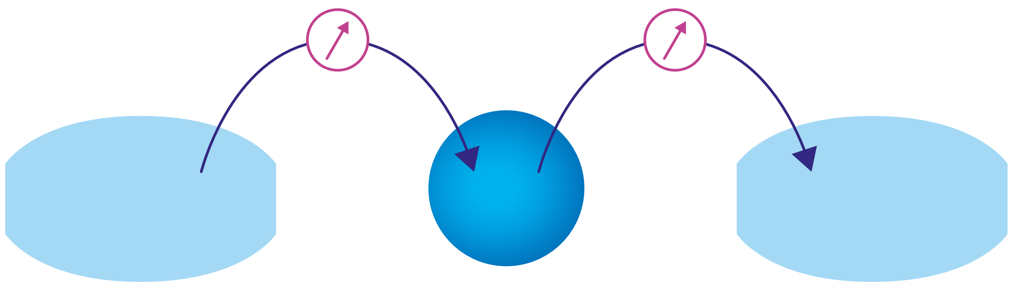
EVERY TIME HUMANS FIGURE OUT HOW TO CONTROL THE WORLD AT SMALLER LENGTH SCALES, GOOD THINGS HAPPEN

Do you think that quantum computers will remain a lab thing, or we can really scale it to make it robust, room-temperature, maybe even a desktop kind of thing?

A room-temperature quantum computer desktop! Gosh, I think that's going to be a long time away. However robust cryogenic quantum servers where you can send jobs that cannot be achieved on a reasonable time frame using conventional computers – absolutely! Every time humans figure out how to control the world at smaller and smaller length scales good things happen. I think having atomic level control of the world to create atom qubits is a great way to build a quantum computer. As we get better and better at this, the quantum processors we are building will grow and become ever more powerful!

All images courtesy of Michelle Simmons, The University of New South Wales.

Quantum Transport.
Measured.



Applications

- Quantum dot characterization
- Spin qubit readout
- RF-reflectometry
- Cross-correlation measurements
- Superconducting tunneling spectroscopy

Your Benefits

- Fast and easy setup
- Full device characterization
- Frequency range up to 600 MHz
- Low-temperature measurements compatibility
- Concurrent raw and demodulated signal acquisition

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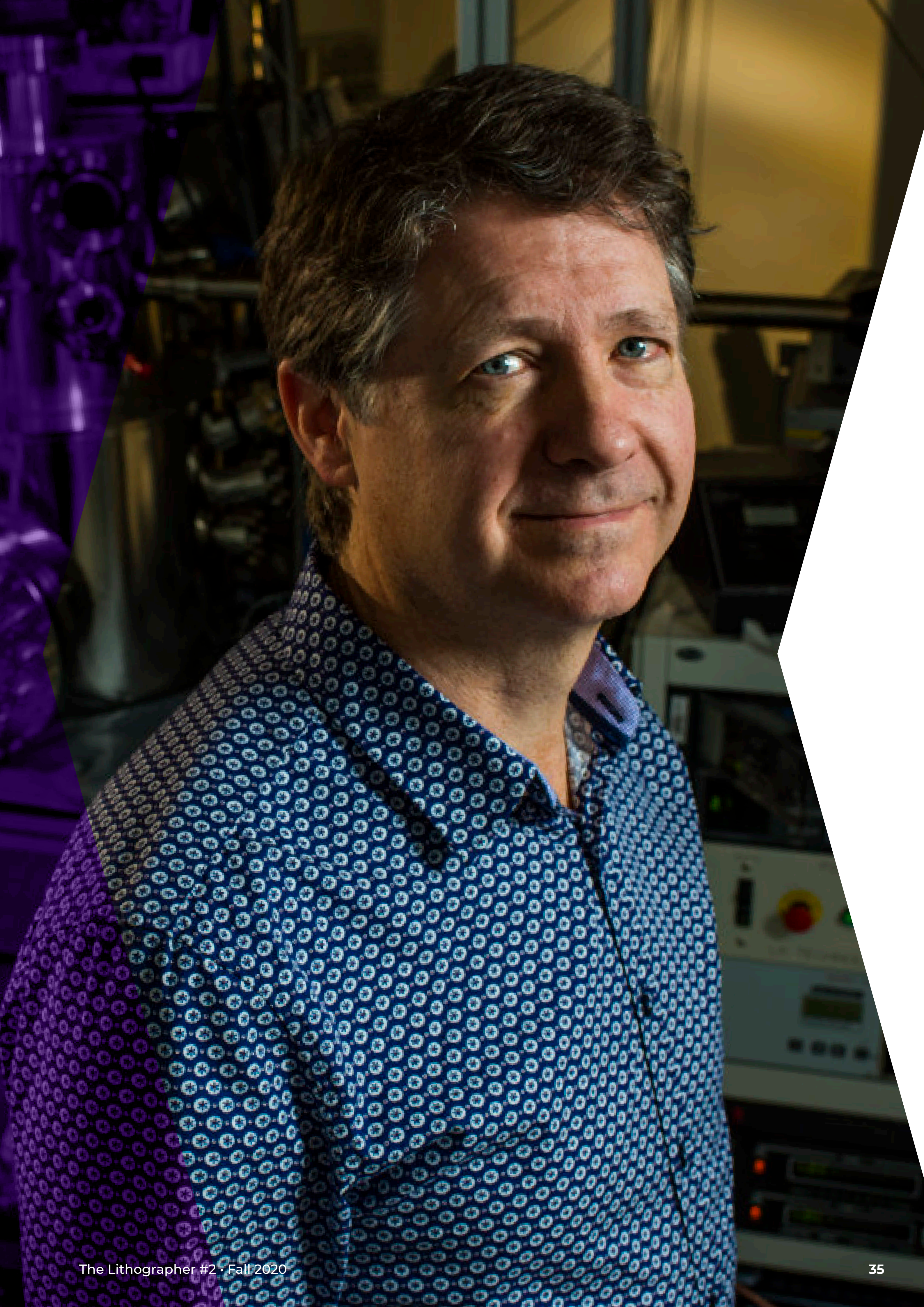
Atomic perfectionism

Robert Wolkow is a professor at the University of Alberta, a Fellow of the Royal Society of Canada and CTO of Quantum Silicon Inc. He and his team are working on altering and deploying atom-scale properties of silicon. They have placed Alberta at the forefront of new computing technologies while simultaneously capturing IP (intellectual property) in real, viable commercial activity.

Thanks a lot for finding time to talk about your work. You are in the field of STM from the very early days, isn't it?

Yes. I began with studying silicon. I wasn't the first person with STM to look at silicon, maybe the third or the fourth one. I was at IBM as a postdoc at that time. Some of the leaders in the world were right there just beside me, and I was learning from them, so I was able to move very quickly. I was looking at chemical reactions on the atomic scale. So I was actually the first person to see how an atom-scale picture changed as individual molecules reacted and dissociated from the surface. Several years later, Joe Lyding and John Tucker began studying hydrogen-terminated silicon surfaces, and they had the idea of removing individual hydrogen atoms with a tip. So they were really the innovators. And then many people looked at it, and we all found similar capabil-

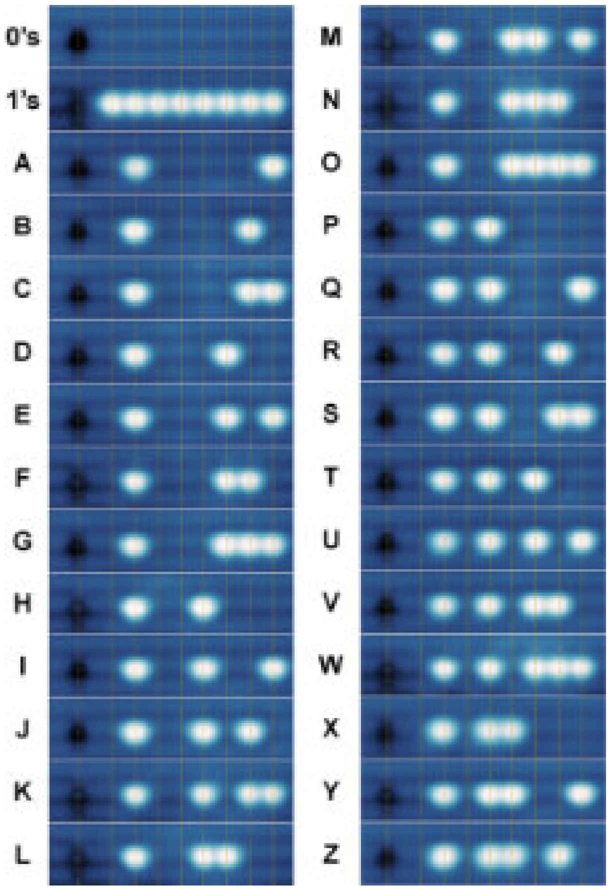


ities: it was very attractive, but it had many problems. I madly continued where most people gave up, I guess. I felt that somehow it must be possible to make it nearly perfect. It took about 20 years, but we have succeeded in that.

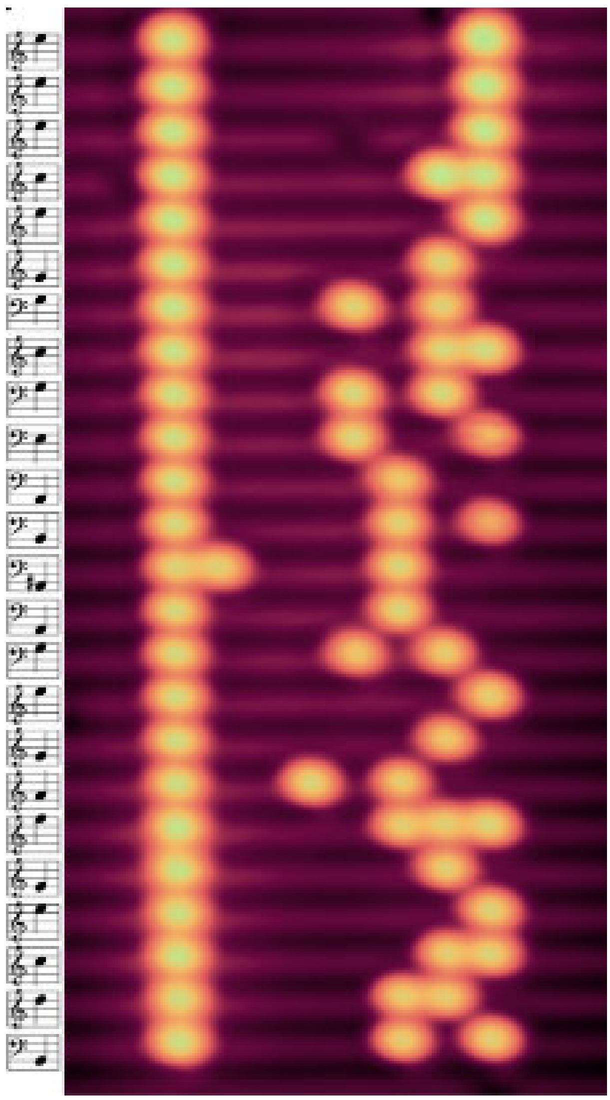
Can you tell a bit about your devices?

Our devices are quite simple, actually. They are made of pure silicon passivated with hydrogen, and the quantum dots are dangling bonds formed when hydrogen atoms are removed with an STM tip.

What we realized was that these dangling bond states are naturally in the bandgap of silicon. They are sitting there, rigidly bonded to the rest of the silicon crystal, but at the same time, they are electronically isolated. It's just a beautiful natural system where we can have all the electronic circuitry on the surface, and yet it is disconnected from the electrons moving around right there in the substrate. In this way, we avoid spreading of the electron wavefunction and preserve the "atomness" of our artificial atoms, or quantum dots.



Scanning tunneling microscope (STM) images of a rewritable 8-bit memory constructed from dangling bonds (DBs).



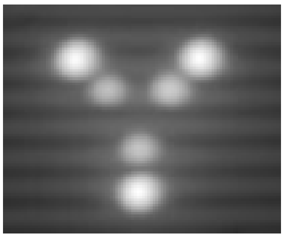
An STM image of an expanded 192-bit memory, storing 24 simplified notes (converted into binary) of the popular Mario video game theme song.

How exactly do you control the quantum dots?
We actually have a little spin-off company called Quantum Silicon incorporated, what we developed so far is the macro-to-atom interface. It uses fairly conventional lithography to make some special connections on silicon that are micron-sized at the edge and that taper down to atomic scale in the device region.

We have different strategies for input to and output from the atom scale. An input, for example, could be just a voltage difference on two wires. A very small electric field is sufficient to "imprint" binary or analogue information onto the atomic circuit between these wires. Output works in a very different way. Our binary information is represented as charge position. We must translate that to something a transistor can read. We use the fact that the position and movement of an electron cause a slightly different electric field distribution. A single-electron transistor (SET), which is the most exquisitely sensitive monitor of charge, transduces position to current: when electron position changes, the current changes. And that current is sufficient to drive a transistor circuit. What is special is that we can make the best single-electron transistors, and all out of the same quantum dots used elsewhere in the circuitry.

People love and hate SETs. It's a beautiful idea, very useful in single quantum dot or qubit studies. But SETs are always made with lithographic tools like e-beam that have uncertainties larger than the dimensions of the device — resulting in great uncertainties. Because our SETs are perfectly defined, with no variability of properties among SETs and with no stray charge issues we can at last put SETs to work.

We can make single-electron transistors with an exactly known number of atoms in the central quantum dot, one, two, three, or more, and we can have exactly reproducible tunnel gaps. Another wire serves as an electrostatic gate or a field controller, shifting the potential of the dot, causing a step change in current through the SET. It turns out that the smaller the quantum dot, the bigger the step in current.



A Dangling Bond OR Gate made of three pairs of atomic silicon dots.

Since we can make the smallest dots, just 1 atom, our SETs could readily work at room temperature. Actually, such SETs will be at the center of various new products.

We can use only one building block to make the whole circuit. The active devices, the passive devices, the controllers, the wiring, — everything. And it is just one printing process, no layers. This is of a large practical importance.

What were the problems you had to solve to be able to make such devices?
We could remove some atoms but we would also remove additional ones that we didn't want to touch, so we'd get poorly defined patterns. Over many years, we figured out how to make it truly perfect. First we reduced those errors, but not completely, and then we discovered an editing process where the few remanent errors could be erased then correctly rewritten. So reducing and correcting errors together, allows perfect structures. Now it is automated with the machine-learning methods. It doesn't work for everything yet, but in some cases we can just draw a picture by hand and the machine automatically reproduces it. And it can look at the surface before it starts and decide if there are pre-existing defects, and then it can avoid that area by shifting the placement of the circuit a little bit.

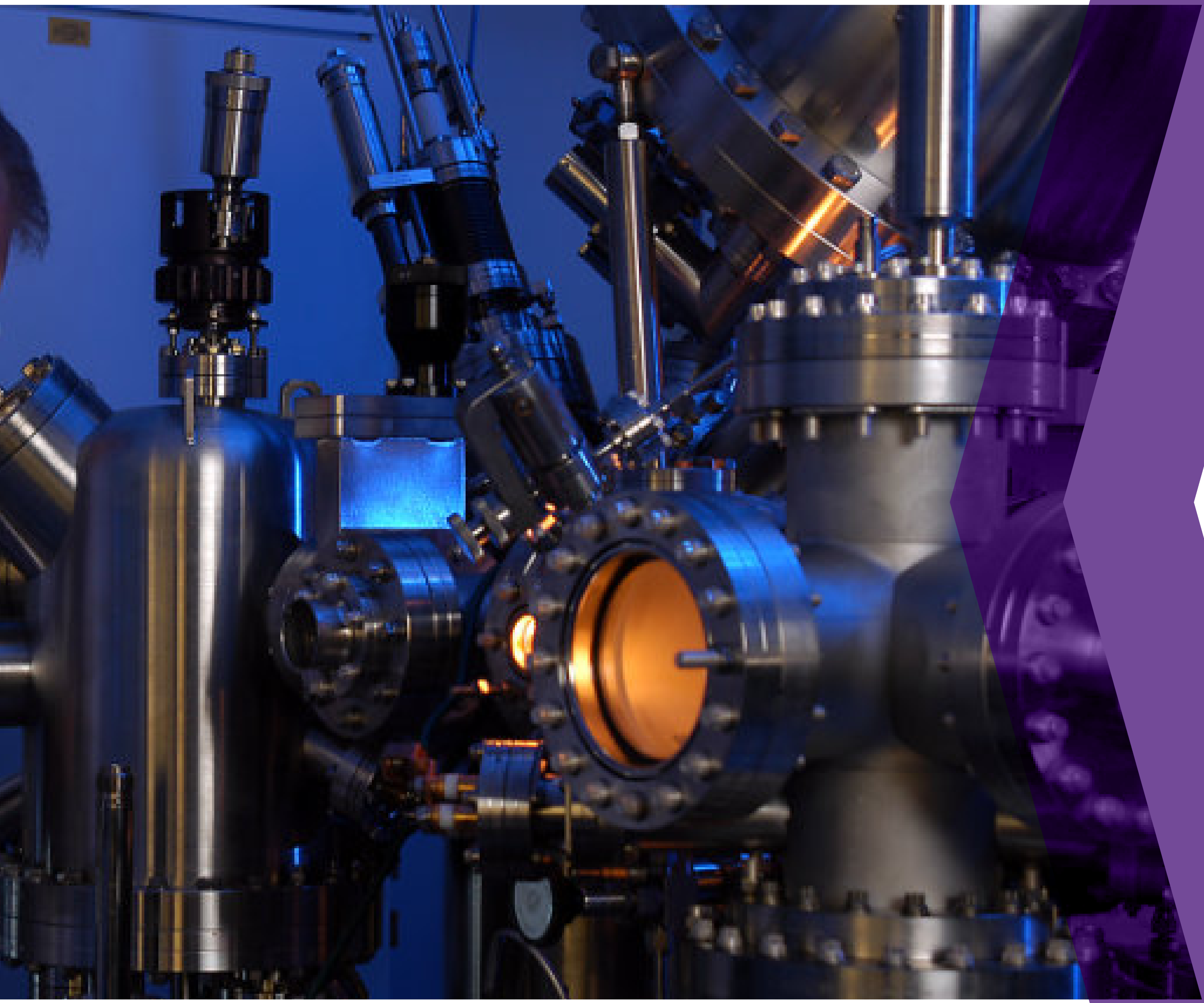
Was it hard to develop these machine-learning algorithms?
Part of the problem was that any learning of this kind requires a very rich data set labelled by humans. And this is both tedious and difficult. We have a wealth of data gathered over the years, so we started labelling it

all. Then we realized that we made many mistakes. We had several people labelling defects, but some of them were not so skilled and so they made mistakes and that lead to inaccuracy. When we realized this, we relabelled and got better and better results.

We have designed, and proven in principle, a new approach that does not rely on human labelling anymore. This could be called a Boltzmann Machine. automatically mimics or simulates something like a neural network. The electrons automatically spontaneously jump around in these arrays made of atoms. They find the natural energy minimum, the ground state. But, importantly, they also fluctuate, or occasionally deviate from this minimum. The distribution of states over time is a very precious kind of information. It allows us to train networks without using labelled data. That's called unsupervised learning. People don't do that very much yet because finding this distribution currently requires prohibitively expensive Monte Carlo Markov Chain estimates to be made with a conventional computer. All that information comes for free from our atom scale simulator. Instead of calculating, we just take readings. We only demonstrated this on a trivial sample with a few electrons but we've shown that the principle could work.

And once you have the device, how do you protect the surface?
We have a packaging process to protect the crystal surface with the circuit. It is a simple wafer bonding approach. The surface will have a little ridge around the device, and if we put another flat surface on top of it, this surface will not touch the device but form a miniature permanent vacuum chamber. It could protect the atoms on the surface forever. We are adapting commercial packaging devices to meet our requirements.

How long does it take to make one such device?
We want to build hybrid devices, where almost everything is CMOS, normal silicon technology. We will replace a component of a normal circuit that is too slow or is consuming too much energy. Or we can add some new capability that transistors are suited to such as the atomic-electronic neural network simulator that I mentioned previously. And so we embed the atomic circuitry in an otherwise normal circuit to enhance it. One of the things we have designed is an analogue-to-digital (ADC) converter, which is a very ubiquitous device nowadays. I was surprized to learn that none of these ADCs are as fast and as low-energy consuming as people would like. So we figured out how to make an ADC that would be extraordinarily fast, yet use very little energy and so now we're cooperating with Texas Instruments. At this point they are advising and supporting us to develop a prototype. If we can prove that the simplest part of an ADC is indeed superfast and super-low-energy, then it could be a viable commercial product.



To go back to your question, it takes only about a 1000 atomic patterning steps, which is something we could make really quickly, in about one hour. And we can either make it as a stand-alone device, or embed it in a CMOS transistor circuit. That natural compatability with existing CMOS silicon circuitry is an important part of our strategy. I think we can manufacture millions of such devices per year fairly economically, for tens of millions of dollars, not billions.

We are always building new machines, new instruments, improving scanning tunnelling microscopes. We have almost gotten rid of one of the most irritating persistent problems that all scanning microscopes have: the non-linear behaviour of the scanning machine. We figured out how to make it almost an ideal scanner with no creep, or unintentional movement of the probe, and we are expecting to get that technology into commercial machines.

I am talking quite a lot about commercialization instead of physics because I love both of them. I am really determined to make something commercially successful — to create jobs. What we make is an example of the greenest possible technology. We use the least amount of material, our fabrication process eliminates the need for many chemicals typically used in fabrication, we end up making a device that uses far less energy then current devices. We predict that we can make 100 times more energy-efficient devices. Everything we make can be easily recycled because there are no weird materials in it. I think the world desperately needs to embrace green technology. It is often true that doing a right thing is also the economically viable thing.

What other applications do you have in mind for your platform?

I believe we can make various kinds of quantum sensors. We're working right now on quantum metrology devices. Things that use our atomic system to make very exact measurements or standards. For example, an electrical current standard has proven to be very elusive. And there was an idea, many years ago, that you could make it from a variation of a single-electron transistor. Essentially, we would make the barrier that the electrons tunnel through lower and higher, and the probability of an electron to tunnel through the barrier depends exponentially on the height. You can almost deterministically make the barrier so low that you are sure an electron will pass. Or make it so high that you are sure an electron won't pass. With some statement of how sure you are, of course, which could translate to perhaps 9 significant digits. With this so-called electron turnstile you could count electrons. In this way, a frequency standard, which does exist today with 9 or more digits of certainty, can be turned into a current standard.

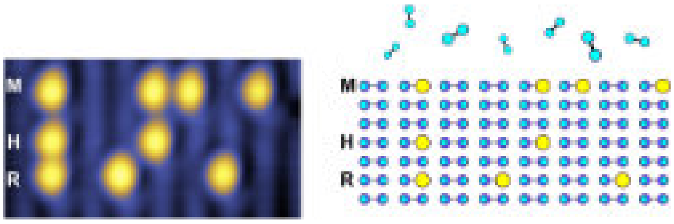
I also want to make exquisitely sensitive and discriminating molecular sensors. Actually, once a week or so, I ask myself: why don't we just drop all of this and make sensors, which are relatively easy and have very large commercial potential? I spent 10 years studying how molecules attach to the silicon surface. We learned so much about how exactly they bond, about their energies, configurations and vibrations. We have recently shown that we can electrically detect the arrival of a single molecule with a tremendous signal-to-noise ratio. It is not a universal thing yet, just a demonstration of principle, but I think we could make all kinds of really powerful sensors, and they don't need to be expensive. We could make a very simple electrical circuit — actually, one of the reasons why I want to get a NanoFrazor that has 10 thermal probes is that I think it could become an economically viable production facility, I could be printing these sensors many a day. You could use such sensors in any phone or in a medical office. And they could also help bring medical care to the areas of the world that cannot afford million-dollar machines.

Speaking of medical care, how is your experience with the pandemic?

I am losing the concept of weekends, I just work all the time. In fact, some of our labs stayed open because we could use our machines to study issues related to the COVID-19 virus. Our microscopes give far more detail than the very best cryo-EM microscopes, but we have trouble to look at biologically relevant molecules. So we have been trying to solve some of those problems. We made some progress but

QUANTUM SILICON AND HEIDELBERG INSTRUMENTS NANO SIGNED A COLLABORATION AGREEMENT. Quantum Silicon will use the NanoFrazor technology to cleanly contact their atomic devices. In this project, the new NanoFrazor Decapede — which features a recently developed write-head with an array of 10 thermal cantilevers — will be used for nanodevice fabrication for the first time.

Quantum Silicon and other collaborators in Edmonton will first test the new NanoFrazor and use it for prototyping of devices. After the beta-testing is complete, the tool will be used in fabrication process combining the NanoFrazor lithography and the Quantum Silicon's STM lithography. The goal of this project is to achieve industrial manufacturing of advanced atomic devices, which can be integrated on standard CMOS chips.



STM image (a) and a schematic (b) of the 24-bit memory array after the interdimer sites have reacted with hydrogen molecules, thereby rewriting the stored information. The remaining hydrogen gas in the chamber does not react with the isolated DBs in the array and can be used in further rewriting operations.

we have nothing really exciting to publish yet. And at our university, we now all have to wear masks and clean everything, — regular precautions.

Our tips — the sharpest in the world — in addition to being useful as STM tips, are also the best coherent source of electrons. We used them to make a holographic-projection electron microscope. That has become one of our COVID-19 projects. We are using this perfect tip as a source of electrons to illuminate a single molecule. Scattering from the molecule plus the electrons direct from the tip together produce a hologram, which can be reconstructed to obtain the real-space image of the molecule. If the coherence is good enough one can resolve individual atoms, and we get very close to that. I would like to solve some protein structure problems, that would be amazing. Now one producer of electron microscopes is adapting our technology to their machines.

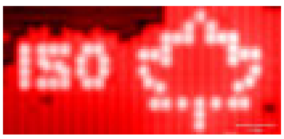
How do you make these tips?

We invented and patented a chemically assisted, spatially controlled, field evaporation method. We use an electrical field so strong that it rips atoms and their electrons apart (ionizes them). What remains is a positively charged ion that can be removed by the electric field. Where the tip is the most curved, the field is the most enhanced. But to rip-off the atoms from there actually leads to a dulling, not sharpening of the tip, which is not so good. What we did is to add some reacting gas, which is just air or nitrogen. It turns out that the electric field can cause the atoms that land on a tip to immediately field-evaporate. Away from the tip apex, where the field is weaker, gaseous molecules can hit the tip and chemically react, so they become a local spike on the surface. On a low-curvature area, there is suddenly a spot with a very high curvature, so a high-field point is formed. And that leads to ripping off that spike comprised of an incoming atom, and it also an atom of tungsten (or whichever metal we use to make the tip) with it. As a result, we take the tip which is already quite sharp, and instead of dulling it through the field evaporation process, we do not attack the apex but we scoop away the atoms from the sides, and we end up with this perfect atomically-sharp tip. We found this by accident some years ago and then we figured out what it was and how to make it work better. This is my funny claim to fame — it was a record in the Guinness Book of Records — the sharpest man-made object, so little school kids who read that book for fun know about it.

Do you know that the NanoFrazor is also in that book? For the smallest replica of the world map and the Matterhorn peak, I think.

Yes. We also made an atomically defined maple leaf, like that on the Canadian flag. And we made it so small that it was around 100 times smaller than the world-record lithographed maple leaf. And the Guinness people refused to register that as a record, even though we clearly beat the other guys, because they said we beat them too extremely and they couldn't see how anyone could ever beat us, and they are interested in the ultimate things that still invite more competition. Haha, so we do not have 2 Guinness entries yet, only the one.

All images courtesy of Bob Wolkow, University of Alberta.



The smallest maple leaf in the world.

Unconventional computing, with a spin-(wave)

Edoardo Albisetti is an assistant professor in the NaBis group, Politecnico di Milano, Italy. His research spans a wide range of topics: from fundamental solid-state physics to applied biophysics. His recent work is focused on engineering optically-inspired magnonic devices for wave-based computing. Prof. Albisetti has kindly agreed to tell us about his projects.

Edoardo, thank you very much for finding time for this interview! First of all: could you please explain what is magnonics?
Magnonics aims to use spin waves for information processing (like electronics that uses electrons). Spin waves are perturbations in the orientation of spins and propagate in magnetic materials such as iron. Compared to electromagnetic waves, magnons have ultra-short wavelength (down to a few nanometers) and unique properties that make them very promising for miniaturised wave-based computing systems.

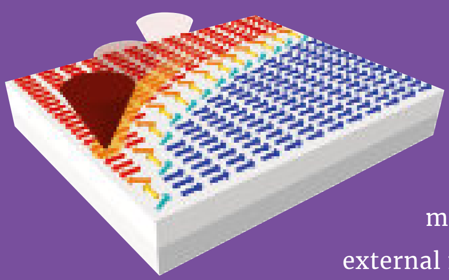

Hard Rock
Hard Rock
CAFE
Los

What are the unique properties of spin waves?
The first property that is very interesting for integrated devices is that the wavelength is much shorter than that of typical electromagnetic waves, and can go down to a few nanometers in the GHz frequency range. The dispersion relation between the frequency of the wave and its wavelength is not the same as for the electromagnetic waves and is determined by the magnetic properties of the material. In fact, different materials have different types of magnetic ordering (ferromagnetic, antiferromagnetic, ferrimagnetic), which influences the dispersion relation and can produce nanometric spin waves.

Non-reciprocity is another important property. Spin waves that propagate in one direction can be very different from those propagating in the opposite direction. Non-reciprocity is relevant for wave-based communication and computing: for example, in photonic systems this is a very sought-after property, and one has to carefully engineer the materials to have it. Here, non-reciprocity comes naturally, due to the intrinsic properties of spin-waves at least in some systems, where spin waves can propagate only in one direction. This helps to avoid backscattering from edges or defects, that would otherwise spoil the interference pattern.

And then there is non-linearity, too. Magnons, the quanta of spin-wave excitations, can interact with themselves, so that one can build devices which use magnons to control magnons. Non-linear effects in optics require non-linear materials and very high power, whereas for spin-waves it comes more easily.

Another important thing is that propagation of the spin waves strongly depends on the direction of the magnetization. So, if you control the direction of magnetization, as we do with tam-SPL, then you can spatially control how the spin waves are excited and propagate. You can also tune the system by applying external electric and magnetic fields, therefore building reconfigurable magnonic metamaterials. Importantly, the combination of tam-SPL with conventional micro- and nanofabrication techniques produces a rich set of tools for engineering the spin-waves properties.



TAM-SPL (THERMALLY-ASSISTED MAGNETIC SCANNING PROBE LITHOGRAPHY) enables reversible nanoscale control of the direction of magnetization in a magnetic film. A hot ultra-sharp probe locally heats the material above its blocking temperature, and as the material cools down in an external magnetic field, its magnetization is set accordingly. This process takes a few microseconds for each pixel. tam-SPL can write magnetic domain walls with precisely controlled direction of magnetization at nanometer scale. Resulting 0-, 1- and 2-dimensional spin textures can be used to store information or to emit, guide and manipulate spin-waves. Refer to the Experts' know-how material on p. 52 for experimental details and examples of different spin textures obtained via tam-SPL.

How do you optimize the systems in which you study the spin-wave propagation?

A lot of things have to come to the right place. First, the composition and thickness of the thin film materials should be optimized in order to be able to do tam-SPL and controlling the spin texture. Second, the material should be good for spin waves. For example, one of the open issues in the field is the fact that spin waves usually dampen out very quickly: in most materials, they exponentially decay in a few tens of microns. The thicker is the sputtered film, the further the spin waves can propagate, but at the same time, it gets more difficult to perform tam-SPL. So, two of the most critical factors involved in the optimization are the films composition and thickness.

In this sense, we use heterostructures composed of stacked nanometric films, and we can tune the relative composition of the elements in order to optimize their magnetic and magnonic properties. A striking example: in our first work, we used a single ferromagnetic layer, while in our last nanoantennae experiment, we stacked two ferromagnetic layers oriented in the antiferromagnetic way. In these two apparently very similar systems, the properties of the spin waves changed completely: the coupling between the layers gave rise to non-reciprocity, and to a remarkably different dispersion.

How does tam-SPL combine with other techniques?

So far, we did not focus much on combining tam-SPL with other nanofabrication techniques, but it is definitely a promising way to go. In fact, tam-SPL and conventional nanofabrication allow to control complementary aspects of the material. For example, one can combine tam-SPL with e-beam, NanoFrazor or optical lithography to pattern geometrical structures out of the magnetic films. In such periodically nanopatterned systems, called "magnonic crystals" in analogy to the photonic crystals, the magnonic band structure can be designed precisely by controlling the periodicity on a smaller scale than the spin-wave wavelength. In this way,

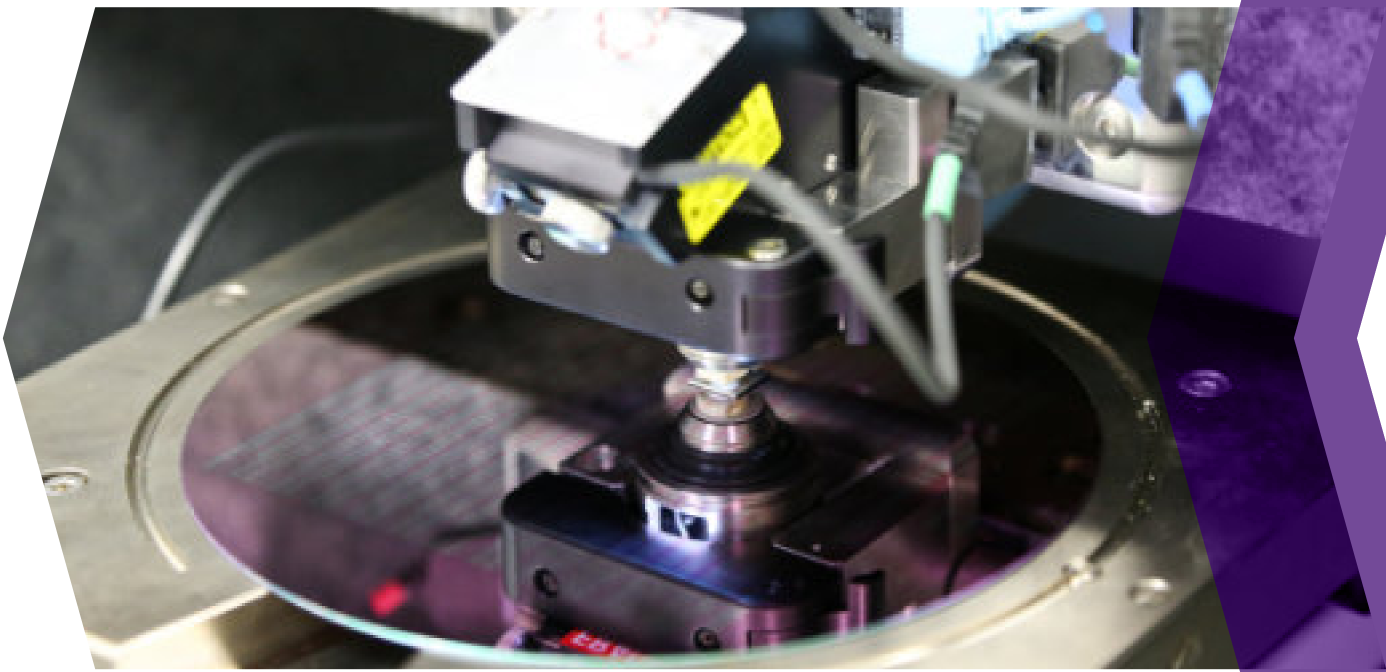
you can obtain new meta-, or artificial materials with unconventional magnonic properties which do not exist in nature.

What kind of devices are you making?

The main goal of our project is to develop new efficient ways to emit and steer spin waves and to build integrated magnonic devices for computing and signal processing. One of the first devices we demonstrated was a nanoscale spin-wave waveguide which confined and steered spin waves similar to an optical fiber. Then, we combined two such waveguides and created a "nanoscale printed circuit" where spin waves could propagate and interfere in a controlled fashion. In our recent work, we demonstrated a new type of "magnonic nanoantennae" that generate highly controlled spin waves with nanometric wavelength. For example, it is possible to obtain radial wavefronts (such as those generated by throwing a stone into a pool of water), or planar wavefronts (as ocean waves on the beach), as well as focussing directional spin-wave beams. The next steps will be to combine all these building blocks in a proof-of-principle computing device, such as a digital logic gate, or an analog optics-inspired system for signal processing.

What kind of applications do you envision for this type of devices?

The final goal is to build highly integrated wave-based computing devices, which use the interference of spin



waves for performing specific information processing tasks in a much more efficient way as compared to the conventional digital systems. Before the era of digital computers (i.e. our computers), it was not at all clear what was the best paradigm. "General purpose" digital computers won the race thanks to the miniaturization of transistors, which allowed a huge computational power. Nowadays, we are reaching the bottleneck with the miniaturization, so that alternative "non-conventional" computing paradigms are gaining more and more interest again. The idea of optical wave-based computing is not new, and we are trying to adapt it for spin waves. They combine a rich wave-like behaviour with potential for miniaturization. It is very promising for such devices as filters, isolators, and energy-efficient neuromorphic computers for pattern and speech recognition.

What are the main challenges that you face in this project?

One of the technical challenges we have to face everyday is that spin waves are quite hard to see, especially at the nanoscale. So, we need to use very specific techniques. One of them is the laser-based Brillouin Light Scattering that is done by our collaborators from Perugia. The light interacts with the magnons, and with the resolution of the laser spot, we can probe the properties of the spin waves. The other technique uses X-rays spectroscopy at SLS-PSI synchrotron in Switzerland, which allow us to record beautiful "videos" of the spin-waves propagating within the film. Both techniques require a very careful preparation of the system. We usually design the experiment via simulations beforehand in order to be reasonably sure of what to expect from the measurement. Now that we are still learning how the magnonic systems behave, we focus on observing the spin waves. Once we understand how things work, we will not need to visualize them anymore, and the transduction from magnonics to electronics will be crucial.

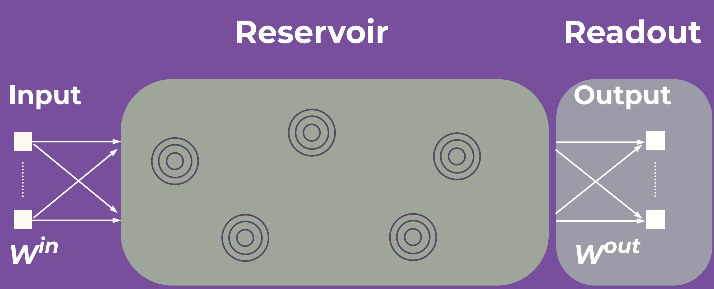
How can you integrate magnonic and conventional electronics or optical devices?

This is a crucial aspect for the whole field of magnonics. For building "conventional" logic devices with spin waves, there must be the possibility to cascade multiple devices so that the output of the first device is used as input for the next one. One way of doing this is to convert the magnon output into an electrical one, amplify it, and convert it back to magnons as input of the second device. For doing so, we need energy-efficient transducers, otherwise we would lose the energetic advantage of using spin waves instead of electrons. There are multiple physical mechanisms allowing transduction from spin waves to electrical signals (such as the Inverse Spin-Hall Effect), but their efficiency is still too limited. In fact, this is one of the biggest open questions in this heavily investigated field.

An interesting alternative solution is to have everything in the magnon regime, so that multiple steps of transduction are not needed. For doing so, one cannot simply "adapt" digital computing devices, such as logic gates, to magnonics. Instead, one has to develop new computing architectures which exploit the peculiarity and strengths of spin waves. One of such unconventional architectures is the wave-based computing that I mentioned before, where computing exploits the formation of interference patterns. This method can be used for example to perform Fourier transforms or filtering. Another recent theoretical work proposes to use spin waves for neuromorphic computing.

How would a magnonic neuromorphic computer work?

There was an interesting theoretical proposal to use spin-waves for doing reservoir computing[2]. The idea is the following: there is a continuous film (the so-called "reservoir"), where spin waves are excited by multiple sources (the data inputs) so that at a given time, a complex interference pattern is created within the film. This pattern is then detected in multiple locations (the outputs). The crucial function of the reservoir –the material where spin waves

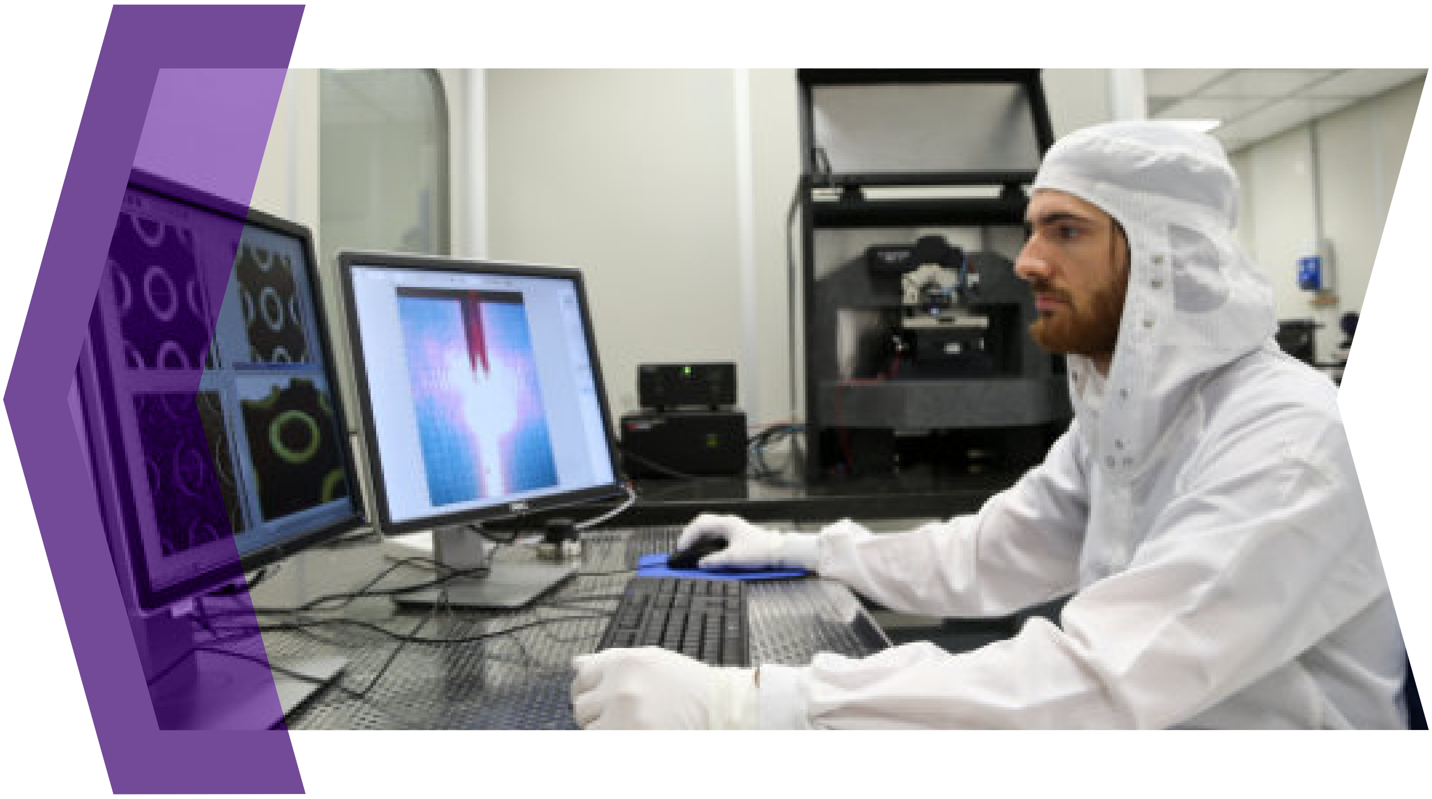


Reservoir computing (RC) is a computational framework suited for temporal/sequential data processing. A reservoir computing system consists of a reservoir for mapping inputs into a high-dimensional space and a readout for pattern analysis from the high-dimensional states in the reservoir. The reservoir is fixed and only the readout is trained with a simple method such as linear regression and classification. Thus, the major advantage of reservoir computing compared to other recurrent neural networks is fast learning, resulting in low training cost.

The role of the reservoir in RC is to nonlinearly transform sequential inputs into a high-dimensional space such that the features of the inputs can be efficiently read out by a simple learning algorithm.[1]

The schematic shows an RC framework where the reservoir is fixed and only the readout weights Wout are trained. In this physical RC system the reservoir is realized using a magnonic system (concentric circles refer to the spin-waves).[2]

[1] G. Tanaka, T. Yamane, J.B. Héroux et al., "Recent advances in physical reservoir computing: A review", Neural Networks 115, 100–123, 2019.
[2] R. Nakane et al., "Reservoir Computing With Spin Waves Excited in a Garnet Film", IEEE Access vol.6, 2018.



propagate– is to transform the "simple" input signals into complex, non-linear data, which are then extracted via a learning mechanism by analysing the spin-wave interference pattern. Reservoir computing requires a system with certain properties: It must be non-linear; And the response of the system should depend on the history of the inputs. This requires a non-linear system with a time-dependent response. Both these requirements are naturally fulfilled in spin waves. This means that spin waves can be used for neuromorphic computing. Engineered spin textures are very appealing for this application, and we would definitely like to try to build such a system in the future! Of course, there are also other more conventional architectures which are actively investigated, such as building spin-wave logic gates using Mach-Zehnder type interferometers.

Can spin waves also host qubits?

Oh, this is a cutting-edge topic. I'm not currently working on that, so I will give a general answer without going in-depth. The short answer is yes. Some people already proposed to do that. So far, one of the systems that worked well for quantum computation uses superconductors. It is based on superconducting islands that host qubits and form a quantum circuit when cooled down. But these qubits have a relatively short coherence time, since they interact with the environment via their electrical charge.

Magnons are not electrically charged, so they interact less with the environment. That can lead to a really long coherence time. The idea is that if we cool a spin-wave system down, we can create Bose-Einstein condensate of magnons which can be used for building qubits. In principle, magnonic qubits could have coherence time surpassing seconds, which would be great. But still, I think it is really at initial stage and I'm not aware of any experimental demonstrations.

One of the most actively developing approaches in quantum magnonics is to interface magnons with other qubits (instead of building qubits with magnons). For example the coherent coupling of magnons and superconducting qubits has been demonstrated experimentally using a microwave cavity. Such hybrid devices are very promising for building new quantum computing technologies. We will for sure see a lot of exciting new things in the next few years.

In the pictures: PoliFab, the micro- and nano-fabrication facility of Politecnico di Milano.

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NanoFrazor Explore

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Experts' Know-how: NanoFrazor for Patterning of Nanoscale Spin Textures

Edoardo Albisetti, Politecnico di Milano.

All images in this article are courtesy of Edoardo Albisetti and Politecnico di Milano.

Many NanoFrazor applications are based on the material removal by its heated tip. But this versatile tool can also be used for inducing local phase changes driven by heat.[1]

This application note is focused on using the NanoFrazor tip to create so-called "spin textures" by locally controlling the magnetic properties of thin films. With this approach, nanoscale areas with complex magnetization configurations can be created. Such structures can be used in the field of magnonics for generating, modulating and guiding spin waves (similarly to optical elements that do the same with light).

THERMALLY-ASSISTED MAGNETIC SCANNING PROBE LITHOGRAPHY

A general strategy for the direct writing of nanoscale magnetic domains with the desired shape and direction of magnetization in an exchange-biased ferromagnetic layer[2]:

1. Locally heat the sample surface above the blocking temperature by raster-scanning the sample surface with the NanoFrazor's tip.
2. Cool it in the external magnetic field, or writing field, to set a unidirectional magnetic anisotropy in the ferromagnet due to the exchange-coupling with the adjacent antiferromagnet. This process locally pins the magnetization of the ferromagnetic layer, which is observed as a shift in the hysteresis loop.
3. To reconfigure: heat above the blocking temperature and then cool in the presence of the re-writing magnetic field (direction different to the writing field).

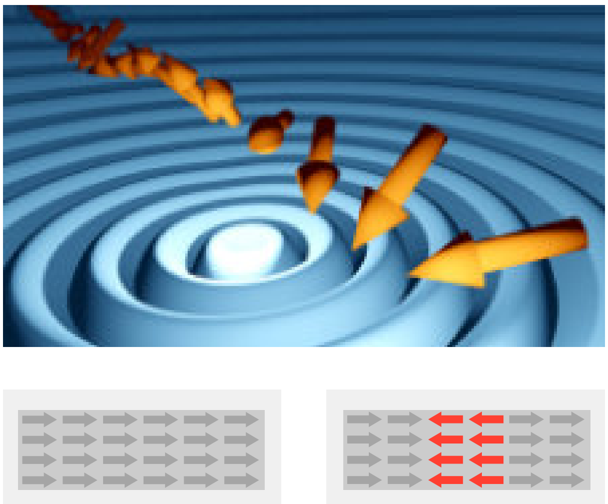
Same approach can create other types of spin textures, such as straight, angular or curved magnetic domain walls, which cannot be normally stabilized by means of conventional micro- or nanofabrication techniques. The resulting spin textures are fully reconfigurable, i.e. they are stable at room temperature, but can be simply re-written by performing tam-SPL again on the same spot, or erased by heating the whole sample above the blocking temperature in the presence of the re-writing magnetic field.

Recently, tam-SPL patterning was demonstrated on complex magnetic systems comprising multiple ferromagnetic layers called synthetic antiferromagnets (SAF), which are extremely interesting for data storage and computing[3].

EXAMPLES

2D DOMAINS, 1D DOMAIN WALLS AND 0D QUASIPARTICLES

Spin-textures, such as magnetic domains, domain walls or vortices, are promising as active components



Schematic of a spin wave and local changes in magnetization.

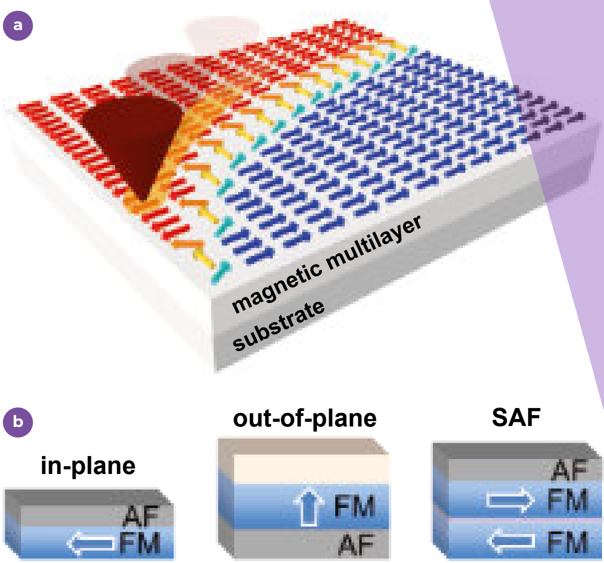


Fig. 2, a: Sketch of tam-SPL; b: Different exchange bias systems where tam-SPL has been demonstrated.

[1] S. T. Howell et al., "Thermal Scanning Probe Lithography — A Review", Microsyst. & Nanoeng. 6, Art. n. 21, 2020.
[2] E. Albisetti et al., "Nanopatterning magnetic landscapes", Nature Nanotech., 11, pp. 545–551, 2016.
[3] E. Albisetti et al., "Nanopatterning spin-textures — a route to reconfigurable magnonics", AIP Adv. 7, 055601, 2017.

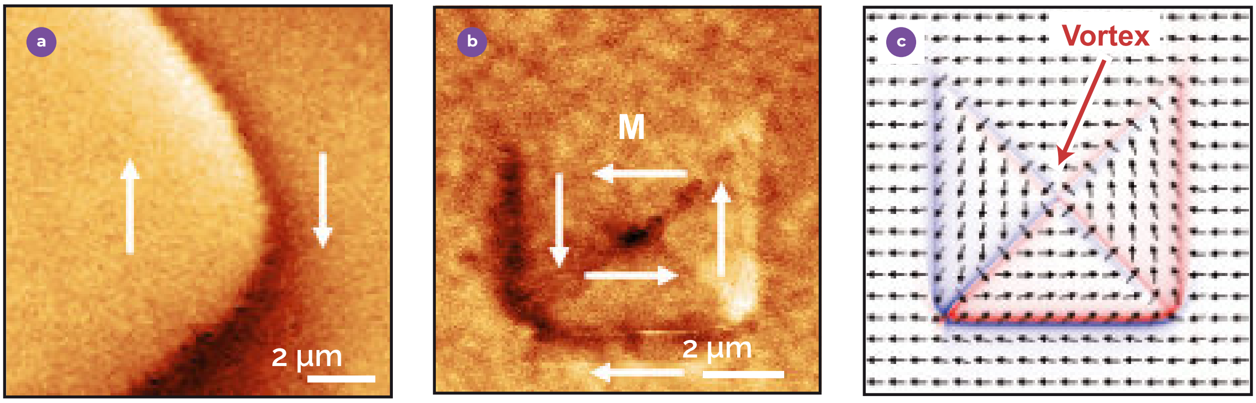


Fig. 3. Experimental MFM image of a curved wall (a) and a vortex magnetization configuration (b) patterned via tam-SPL. White arrows indicate the local direction of the magnetization. c: Micromagnetic simulations of the vortex show the local direction of the magnetization (black arrows).[4]

in a wide range of applications, from data storage, to processing, to biomedical devices. The main reasons for increased interest towards such structures are:

- They can be scaled down to nanoscale size.
- They can be manipulated via external stimuli, such as magnetic fields or electric currents.
- They are reconfigurable.

Spin textures are promising for various applications. A "racetrack memory" is a notable example. It uses densely packed and moveable domain walls or skyrmions (topological magnetic quasiparticles) as bits of information. Another application is a "vortex oscillator" which emits microwave signals when excited by a DC current. In biomedicine, magnetic nanoparticles with vortices are extremely interesting in anti-tumor hyperthermia treatments.

tam-SPL is a flexible and straightforward way to create and precisely control complex spin-textures with different dimensionality and properties (position, topology, and dimension). Here, we show a few examples of such systems patterned in prototypical CoFeB/IrMn exchange bias bilayers magnetized in the film plane.

Dimensionality	Examples
2D domains	Magnetic domains of different shapes (square, diamond, triangle)
1D domain walls	Straight and curved domain walls
0D topological textures	Magnetic vortices stabilized within domain walls, antivortices, Bloch lines

THE CANTILEVER'S HEATER TEMPERATURE is well-calibrated and can be accurately controlled between room temperature and 1100°C. The actual temperature at the tip of the scanning probe in contact with a sample is lower than that of the heater. This temperature is difficult to determine precisely because it depends on the various parameters like the thermal conductivity of the sample, interface thermal resistances and the actual tip shape. As a rule of thumb, the tip has 1/4–1/3 of the integrated heater temperature.

The main technique used for characterizing the magnetic patterns at remanence is magnetic force microscopy (MFM). It shows the magnetic contrast associated with the regions of non-uniform magnetization, such as the domain walls surrounding a magnetic domain.

Panel 3a shows the MFM image of a patterned curved magnetic domain wall. This magnetic domain has opposite magnetization orientation with respect to the surrounding region. The domain wall — a region where the magnetization coherently changes its orientation — naturally forms at the boundary between two domains.

This approach can be extended to patterning of more complex textures. Panel 3b shows the MFM images of four triangular-shaped regions with a shared central apex and counter-clockwise rotation of the magnetization direction. Here, each triangular region was patterned with a different orientation of the external field. This magnetization configuration generates four 90° domain walls, with the vortex core at the apex.[4]

Panel 3c shows the corresponding micromagnetic simulation: black arrows indicate the local magnetization orientation, and the color contrast is related to the observed MFM contrast. The whirling direction of the vortex determines its topological properties. It is defined by the sense of rotation of the magnetization, which is defined via tam-SPL patterning. Such control is hardly achievable with conventional nanofabrication techniques.

WAVEGUIDES FOR SPIN WAVES

Spin textures are extremely promising in the field of magnonics. Magnonics operates on spin waves — perturbations in the spin texture which propagate in magnetic materials. It aims to implement the controlled spin wave generation, propagation and conversion in highly-integrated and energy-efficient computing platforms.

Spin waves can be a powerful mean for computing for the following reasons:

- Absence of Joule losses associated with their propagation.

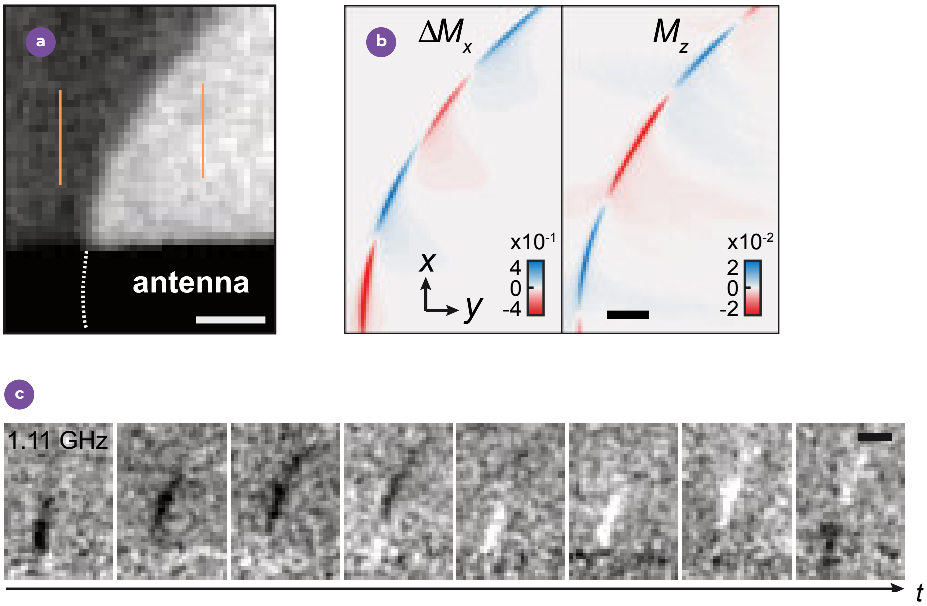


Fig. 4. a: Static STXM image of a curved wall; b: Micromagnetic simulation of spin waves propagating and confined within the curved wall, c: Sequence of STXM images showing the confinement, propagation and steering of spin waves within the domain wall. Scale bars: 500 nm.[5]

[4] E. Albisetti et al., “Stabilization and control of topological magnetic solitons via magnetic solitons via magnetic nanopatterning of exchange bias systems”, Appl. Phys. Lett. 113, 162401, 2018.

- The wavelength that can go down to a few nm (several orders of magnitude shorter than electromagnetic waves in the GHz-THz range)
- Rich phenomenology that can lead to new device architectures.

tam-SPL-engineered spin textures enable both fundamental studies and novel device concepts. Albeit the approach is still at the early stages, it has already reached some milestones. Here, we show two examples in two different magnetic systems.

Tailored domain walls act as nanowaveguides: They confine and steer spin waves in spin-wave circuits. Straight and curved domain walls are patterned via tam-SPL in a CoFeB/IrMn system.

Spin waves are excited via microstrip antennas fabricated on top of the patterned samples using optical lithography. X-ray microscopy (STXM) is used to observe the confined spin-wave modes propagating along the domain walls.

Panel 4a shows the static image of a curved 180° Néel domain wall, obtained by patterning two domains with opposite magnetization orientation. Orange arrows indicate the direction of the magnetization in the two domains. At the bottom of the figure, one can see the edge of the antenna used for spin-wave excitation.

Panel 4c shows the propagation of spin waves along the domain wall on a sequence of STXM images. The black and white contrasts correspond to the oscillating out-of-plane component of the magnetization, corresponding to the propagation of spin waves confined within the domain wall. Panel 4b shows the x and z component of the magnetization associated with the spin-wave propagation, obtained from micromagnetic simulations.

Domain walls can also form reconfigurable nanocircuits. Here, we show two domain walls patterned via tam-SPL at some distance (dashed white lines on the static STXM images in Panel 5a top). A small external field can modulate the distance between them. When the field decreases, the two domain walls are brought closer: in panel 5a bottom, they share a common apex.

Since the propagating spin waves are confined at the walls, they can be displaced with high accuracy by

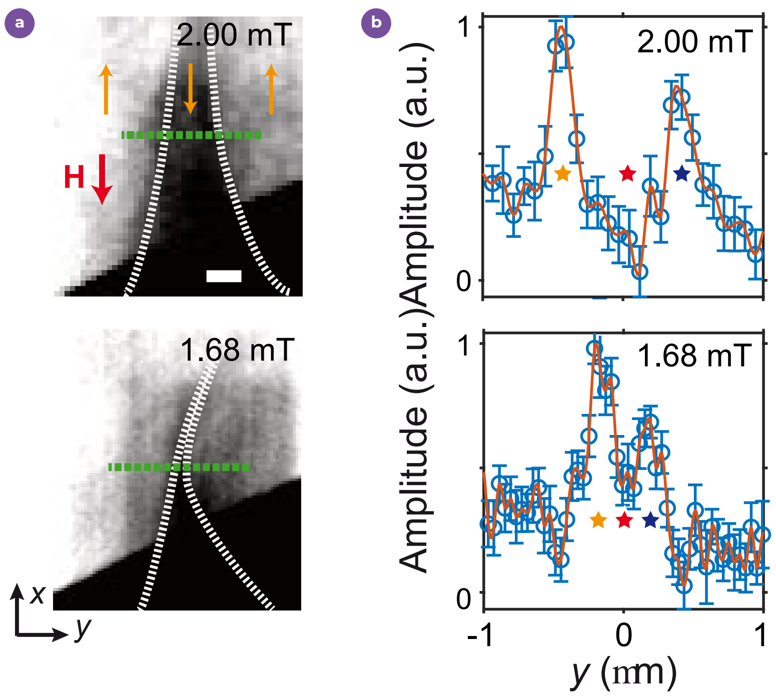


Fig. 5. a: Static STXM image of a circuit composed by two domain walls sharing an apex. By varying the external field the two domain walls are displaced from far (top) to close (bottom). Scale bar 500 nm; b: Corresponding spin-wave intensity along the green profiles of panel a.[5]

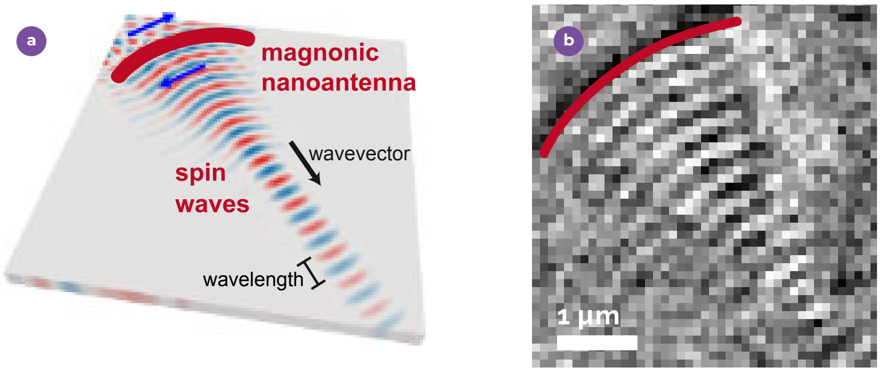


Fig. 6, a: Micromagnetic simulation showing the emission of focused spin wave beams from a domain wall based magnonic nanoantenna; b: Corresponding experimental data acquired via STXM.

controlling the position of the walls. This way, the interference of the spin waves is also controlled, as shown in panel 5b: the location of the peaks marks the position of the two spin-wave modes (green profile in panel a) displaced with the external field. The control of the interference of the confined modes via external stimuli, such as fields or currents, enables reconfigurable logic devices based on spin textures, such as Mach-Zehnder-type spin-wave interferometers.[5]

NANOANTENNAE FOR SPIN WAVES

"Magnonic nanoantennae" are a nanoscale optics-inspired application of tam-SPL-created spin textures in synthetic antiferromagnets. They generate and focus spin waves and let them interfere in a controlled fashion.

Magnonic nanoantennae are made by patterning domain walls and vortices, as described above, in an IrMn/CoFeB/Ru/CoFeB synthetic antiferromagnet.

A micromagnetic simulation (panel 6a) and corresponding experimental data (panel 6b) show the concept of magnonic nanoantennae based on a curved domain wall. The domain wall oscillates due to an external magnetic field generated by a nearby strip-line. As it does so, it emits spin waves that travel more than 10 times further than their wavelength, which is on the 100 nm-scale.

The wavefront retains the shape of the domain wall. This means that by controlling the shape and type of spin texture, it is possible to generate and direct focused beams, radial wavefronts (like the ones generated by a stone in a pond) or planar wavefronts (like the sea-waves on the beach).

When combined, multiple nanoantennae generate complex interference figures "on demand". This capability is a necessary condition for developing integrated computing systems based on spin waves.[6]

Exchange bias systems combined with tam-SPL constitute a versatile platform for precise engineering of spin-wave circuits and for studying the rich physics of spin-wave transport. The main requirement is that it is an "exchange bias system" (which is the effect we use for patterning spin-textures): so it should have at least a ferromagnet / antiferromagnet bilayer. (SAF has this + another ferromagnetic layer). Other systems are "out-of-plane" systems, where the magnetization points out of the plane of the films instead of in the plane.

[5] E. Albisetti et al., "Nanoscale spin-wave circuits based on engineered reconfigurable spin-textures", Comm. Phys. 1, Art. n. 56, 2018.

[6] E. Albisetti et al., "Optically Inspired Nanomagnonics with Nonreciprocal Spin Waves in Synthetic Antiferromagnets", Adv. Mater. 32, 1906439, 2020.

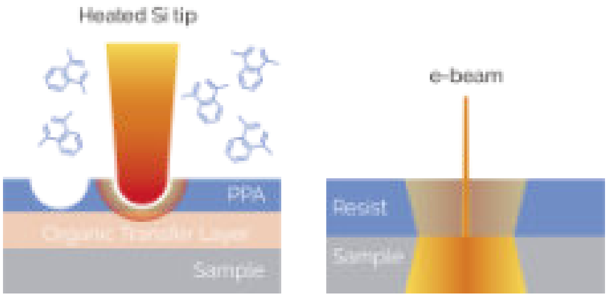
Experts' Know-how: Non-invasive Lithography

Enabling Superior Device Performance

Anya Grushina, Heidelberg Instruments Nano
(SwissLitho AG)

Quantum devices come in different shapes, types and materials, hence fabrication methods vary greatly. In most cases, the patterning process strongly influences the devices' performance. While the progress in sample preparation and patterning never stops, the devices often suffer from the residues and damage accumulated from multiple steps of nanofabrication.

Here we demonstrate how thermal scanning probe lithography (t-SPL) enabled by NanoFrazor helps to avoid many problems associated with typical nanofabrication steps. The resulting devices show a superior performance due to the non-invasive patterning principle and gentle processes with respect to the sensitive sample materials.



Comparison of heat distribution from an e-beam and a heated NanoFrazor tip in a resist stack and the sample during patterning.

The key t-SPL capabilities for relevant to quantum devices fabrication:

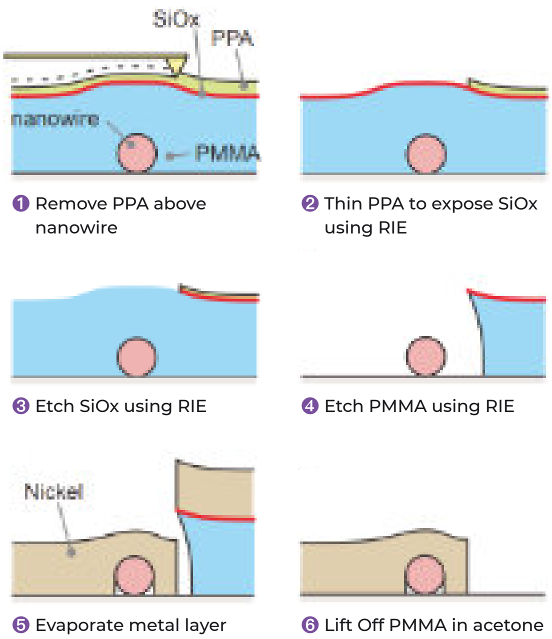
- t-SPL is free of charged particles.
- High-resolution patterning (8 nm half-pitch[1])
- Highly localized heat from the tip does not reach sample material through the resist stack.
- In-situ markerless overlay by topology scanning;
- No charge accumulation in insulating substrates and layers (e.g. gate dielectrics);
- Glove-box-compatible system for patterning ambient-sensitive samples in a controlled inert atmosphere.

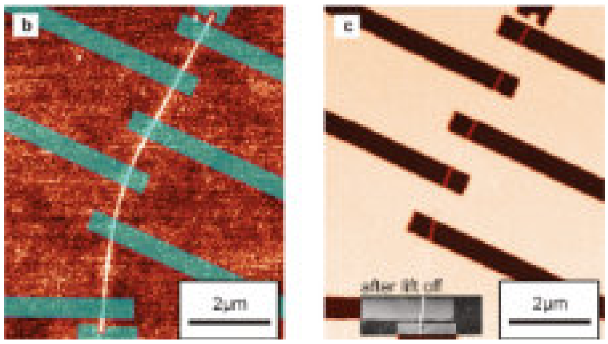
PROCESS FLOW

1. Spin-coat the sample with a suitable resist stack
2. Use the NanoFrazor's cold tip to image the flake or the nanowire for markerless overlay[2]
3. Pattern the sample in the desired location
4. Create an undercut using wet developer or reactive ion etching.
5. Evaporate and lift-off contacts.

REMARKS ON THE PROCESS DETAILS:

- During patterning, the tip is heated for a few microseconds only. The direct evaporating of the resist (no redeposition of volatile moieties) is an endothermic reaction, which ensures that the heat is highly localized. Our experiments show that the substrate heating by t-SPL is much less than the soft bake of the resist (minimum 80°C required)
- Water-free sample fabrication process is possible with a certain combination of resist stack and developers (consult us for details).
- NanoFrazor Scholar can be placed inside a glove box to pattern and image samples that are sensitive to the environment.

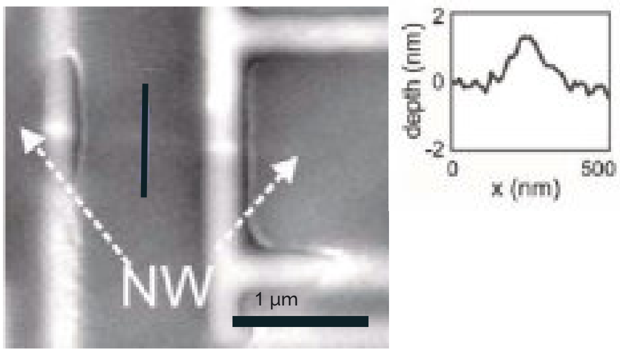




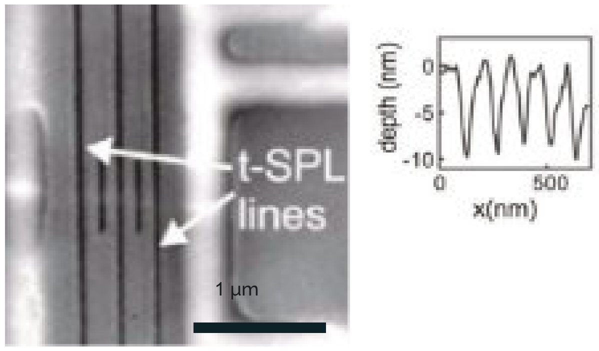
Markerless overlay. Left: 27 nm-thick nanowire under the resist stack: botom PMMA (61 nm), SiOx (4 nm), and PPA (20 nm). The NW is imaged by the cold NanoFrazor tip for overlay, the designed electrodes shown in cyan; Right: written electrodes after the pattern transfer into PMMA by reactive ion etching; the inset shows metallic electrodes after the lift-off.[2]

[1] Yu Kyoung Ryu Cho et al., "Sub-10 Nanometer Feature Size in Silicon Using Thermal Scanning Probe Lithography Using Thermal Scanning Probe Lithography", ACS Nano 2017, 11, 12, 11890–11897.

[2] C. Rawlings, et. al, "Accurate Location and Manipulation of Nanoscaled Objects Buried under Spin-Coated Films," ACS Nano, vol. 9, no. 6, pp. 6188–6195, Jun. 2015.



Left: NanoFrazor image of the 30 nm-thick InAs NW with Au contacts under 200 nm of the resist; Right: line scan along the line on the left.



Left: NanoFrazor image of the top gates patterned in the PPA resist; Right: line scan along the nanowire.

EXAMPLES

TOP GATES ON A 30 NM-THICK INAS NANOWIRE[3]

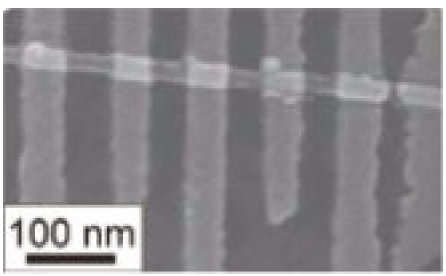
Nanowire-based devices offer a convenient platform for studying quantum confinement phenomena. Due to small dimensions of nanowires and sensitivity of dielectric materials to damage from charged particles, fabrication of such devices is challenging. Here, we demonstrate a top-gated InAs nanowire device fabricated using the NanoFrazor technology. The location of the 30 nm thick nanowire under 200 nm of resist was precisely identified using imaging mode with a cold tip. After that, a precisely overlaid top gates were patterned using t-SPL. The heated tip directly sublimated the resist, preventing charge accumulation in the Al_2O_3 gate dielectric, which resulted in superior device performance.

At room temperature, the device shows a sub-threshold swing of 60 mV/dec, close to the theoretical limit predicted for such devices. This performance is significantly better than that of similar devices with top gates defined using EBL.

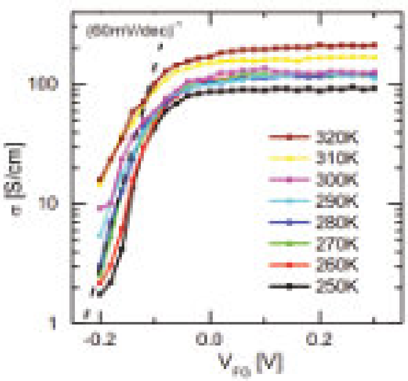
CONTACTS WITH VANISHING SCHOTTKY BARRIERS ON 2D MATERIALS[4]

Single-layer MoS2 field-effect transistor

Devices on 2D materials and Van der Waals heterostructures often suffer from resist residues and damage introduced by charged particles during

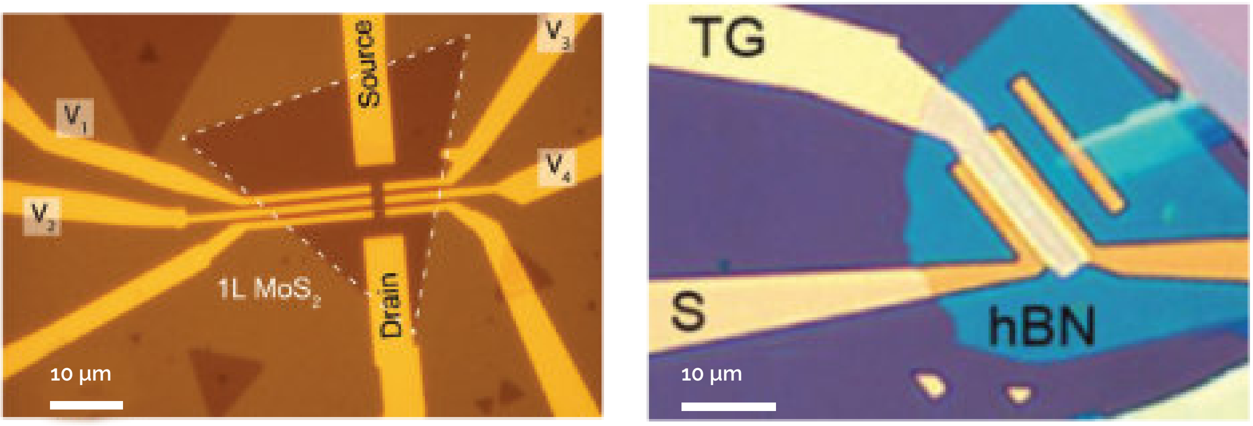


SEM view or the InAs nano-wire with top gates patterned using t-SPL.



Device performance of InAs-based field-effect transistor at different temperature shows the subthreshold swing of 60 mV/dec.

[3] H. Wolf et al., “Thermal Scanning Probe Lithography (t-SPL) for Nano-Fabrication,”, Pan Pacific Microelectronics Symposium 2019, pp. 1–9.



a: Optical image of a single-layer MoS2 flake with Hall bar FETs patterned on it; b: Top-gated MoS2 FET with h-BN as a gate dielectric. Both devices show exceptional performance due to improved source-drain charge injection.[3]

e-beam. t-SPL avoids both of these problems: PPA resist evaporates without redeposition on the sample surface, and the heat does not reach the sample. Recent work on 2D materials confirms superior quality of devices fabricated this way.

- Linear I-V curves even at low temperatures.
- Record-high on-off ratio of 10^9–10^{10}.
- Ohmic contacts with vanishingly low Schottky barrier of ~0mV.
- Very low subthreshold swing of 64 mV/dec.

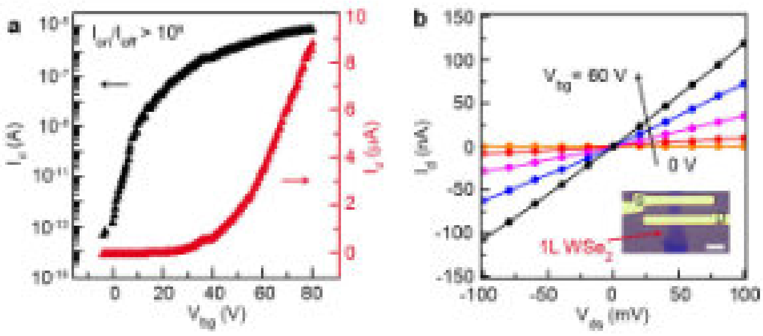
Single-layer MoS2 field-effect transistor

- Linear I-V curves across wide drain voltage range highlight vanishingly small contact resistance.
- Record-high on-off ratio of 10^9–10^{10}.

Niemeyer-Dolan bridges

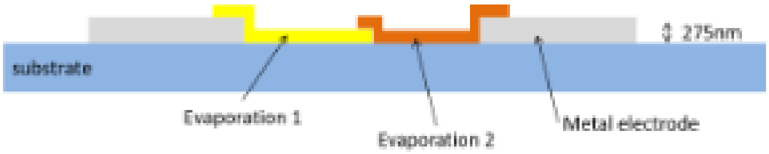
Superconducting qubits similar to those shown on the cover often rely on superconducting tunnel junctions (STJs) formed between two thin superconducting electrodes separated by a tunneling barrier. STJs are typically fabricated on insulators (e.g. sapphire or thick silicone oxide). They are measured at ultralow temperatures to remove ambient noise. Charges trapped in the insulator can be detrimental to measurements.

The Niemeyer-Dolan technique, or shadow evaporation, is based on suspending a resist bridge structure with a large undercut, then depositing Al (superconductor) at one angle, allowing AlO2 (insulator) to form, and a subsequent Al deposition at a different

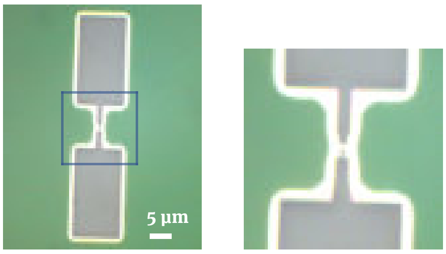


Characteristics of FETs fabricated via t-SPL on exfoliated 1L WSe2 flakes. Top: Transfer curves acquired at room temperature with Vds = 2 V for back-gated FETs fabricated on monolayer exfoliated WSe_2, featuring an Ion/Ioff > 10^8. The transfer curve is shown both in the linear scale (red triangles) and log scale (black triangles). Bottom: Corresponding room temperature output curves at different gate voltages (Vbg). In the inset, optical image of the t-SPL device. Scale bar: 2.5 m

[4] X. Zheng et al., “Patterning metal contacts on monolayer MoS2 with vanishing Schottky barriers using thermal nanolithography,” Nat. Electron., vol. 2, no. 1, pp. 17–25, 2019.



Niemeyer-Dolan bridge geometry: metal electrodes such as Nb sputtered on Si substrate with Al/AlO2 deposited in Evaporation 1 and Al deposited on top in Evaporation 2 form a Josephson junction in the area where the deposited materials overlap.



a: The optical image shows the formation of an undercut after resist development;
b: The zoom-in of the area denoted by the square.

angle without taking the sample out of the evaporation chamber. This approach leaves the interface perfectly clean and produces an STJ in one evaporation step (or, more precisely, the following sequence of steps: evaporation + venting to form the oxide + tilting to a new position + another evaporation). The advantage of this technique is that the extent of the overlap is tunable by adjusting the tilt angles during evaporations.

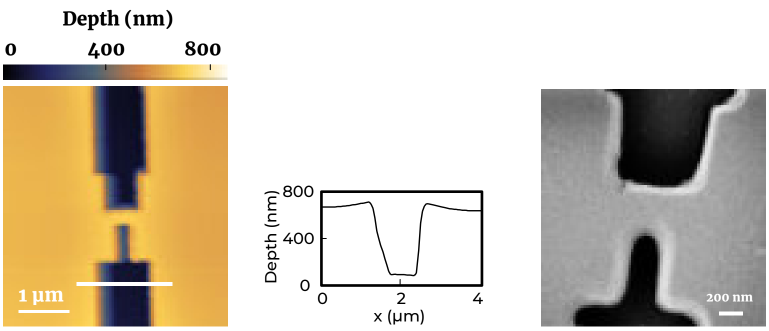
Niemeyer-Dolan bridges are usually fabricated by means of an electron-beam, but thermal scanning probe lithography (t-SPL) can also be used to pattern such structures. t-SPL has an advantage for fabricating these devices, because it avoids permanent charging of the substrate.

PROCESS FLOW

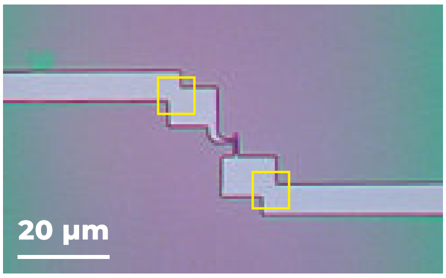
1. Resist stack: 500 nm LOR 3A (Micro Chemical Corp.) baked 5 min at 180 °C + 100 nm thermally sensitive PPA (Allresist GmbH) baked 2 min at 110°C.
2. Pattern the contacts and the bridge using tSPL.
3. The LOR is developed with AZ400K developer (Micro Chemical Corp., diluted 1:4 in deionized water) for 45 s to form a suspended resist bridge.
4. Lift-off is done in TechniStrip Micro D350, a DMSO based resist stripper.

REMARKS ON THE PROCESS DETAILS

Contacts to pre-patterned Nb leads can pose a challenge to t-SPL patterning, because thickness of the electrodes (~350 nm) is large compared to the tip length, which is ca. 700 nm. However, starting the pat-



a: AFM scan of the suspended resist on a sapphire substrate before evaporation, showing the structure after patterning by t-SPL and developing the bottom-layer resist; b: Line-scan along the indicated white line on a shows the pattern depth. c: SEM image of the free-standing bridge covered with Au for contrast.



Optical microscopy image showing the overlay of the contact structures to the freestanding bridge (here, a different Niemeyer-Dolan bridge geometry is used).

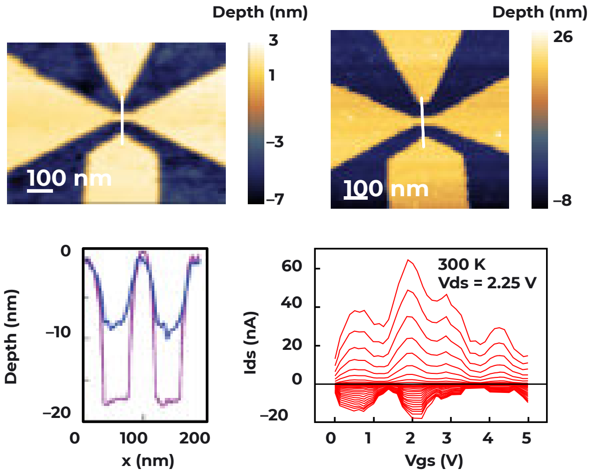
terning on top of the thick electrode and moving down the step provides a continuous electrode pattern.

The in-situ imaging capability is very helpful to ensure precise overlay of different parts of the structure.

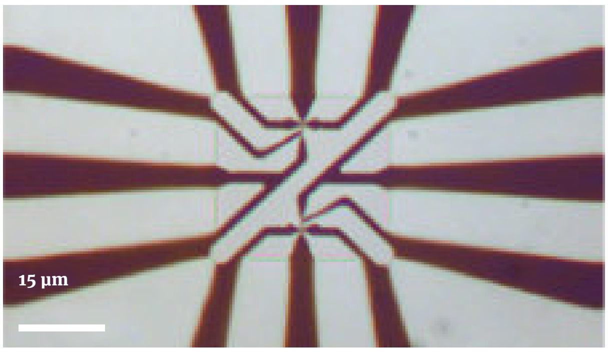
Single electron transistors fabricated using mix & match t-SPL and direct laser writing

Single-electron transistors (SETs) comprise a quantum dot and two contacts separated from it by a barrier, through which electrons can tunnel. Fabricating such devices requires very precise high-resolution patterning of the contacts.

A mix-and-match approach helps to avoid multiple painstaking fabrication steps. t-SPL can be combined with direct laser sublimation of resist for rapid fabrication of high-quality SETs[5]. First, high-resolution features are written by the thermal probe; then, the coarse features (>1 µm) are patterned by the laser in the same resist layer. Note that the laser also sublimates thermal resist (as opposed to conventional photolithography processes). The resulting device is a quantum point contact tunnel junction that forms a single electron transistor operating at room temperature.



Silicon point-contact quantum-dot SETs.
a: AFM topography scan of thermal resist after high-resolution patterning by t-SPL. Quantum point contacts form a ~25 nm wide channel with a side gate spacing of 55 nm; b: AFM topography scan of the same pattern transferred into silicon by reactive ion etching; c: AFM line-scans taken along the white lines on a and b show the pattern profile after t-SPL and after etching into Si; d: I-V gate characteristic at 300 K measured at different values of the source-drain voltage shows clear Coulomb peaks. Image courtesy: Armin Knoll, IBM Research Zürich.



Mix-and-match approach: coarse electrodes written using direct laser sublimation and the fine structure in the center using t-SPL in the same fabrication step. Image courtesy: Armin Knoll, IBM Research Zürich.

PROCESS FLOW

1. Prepare the resist stack for high-resolution patterning (top layer PPA)
2. Measure the offset between the laser focus and the cantilever tip for calibration
3. Locate special features on the sample for precise alignment
4. Write high resolution features using heated cantilever tip (resolution down to 8 nm)
5. Write low resolution features using the integrated laser writer (less than 30 sec for 30x30 µm2)
6. Transfer the pattern into the substrate using reactive ion etching or evaporation followed by lift-off.

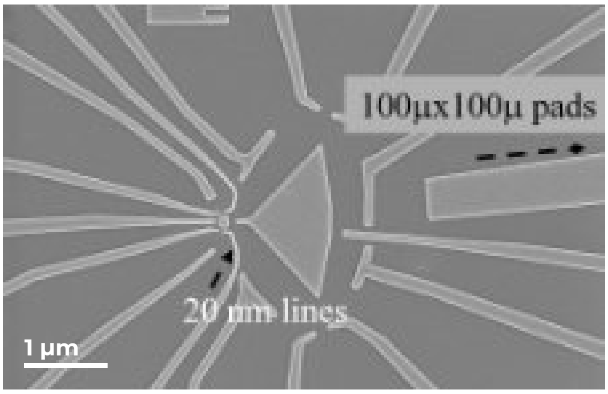
[5] C. D. Rawlings et al., “Fast turnaround fabrication of silicon point-contact quantum-dot transistors using combined thermal scanning probe lithography and laser writing”, Nanotechnology, 29, 50, 505302, 2018.

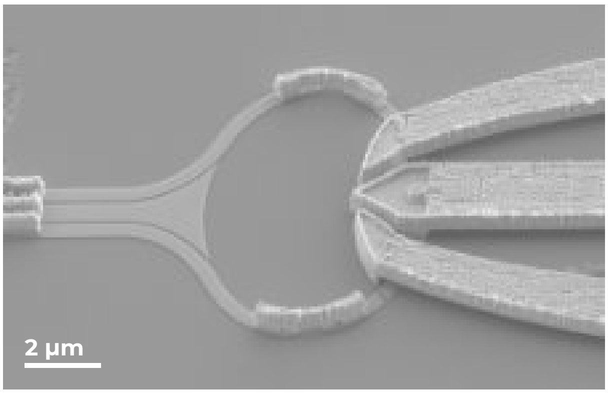
Experts' Know-how: BEAMER — Electron Beam Lithography Software

Enabling Quantum Devices

The research of quantum devices is one of the most popular and at the same time most challenging research areas for electron beam lithography (EBL). The capability of EBL systems to form nanometer-size spots and to position them with nanometer accuracy is essential for "printing" complex shapes with sufficient accuracy and in reasonable time.

Resolution requirements are comparable to high-end CMOS devices — both have feature sizes below 10 nm. However, in contrast to CMOS electronics which are mostly Manhattan layouts, quantum devices often require curved irregular shapes. To achieve such shapes with high resolution and smooth edges using e-beam lithography, one needs a uniform filling with electron beam shots.

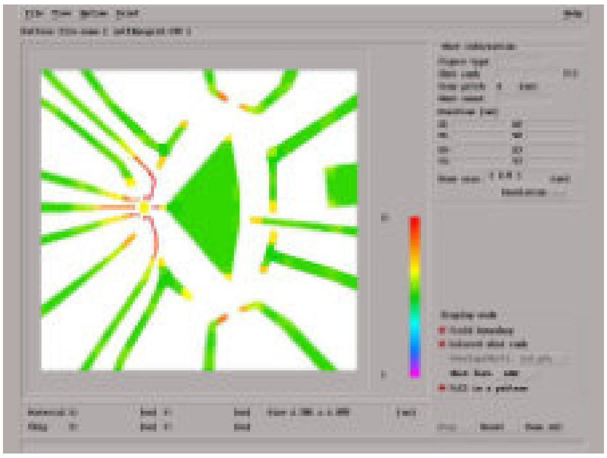




The pattern needs to be tiled into write-fields because exposure area accessible by electrostatic / electromagnetic deflection of the beam is limited to millimeter size. Given the nanometer dimensions of some parts of the devices, stitching errors at the write-field borders have to be as small as possible.

BEAMER is the software package for e-beam data-preparation and correction. It features sophisticated "curved-fracturing" that preserves the intended design in the machine format as close as possible, and field-position control technology. BEAMER is continuously optimized to achieve the most advanced quantum devices using electron beam systems.

Even when the electron beam is focused to nanometer range, the electron energy is spread over many microns by electron scattering in the material. This spread is manifested through the well-known proximity effect. It is especially strong for quantum devices made on high-density III-V (e.g. GaAs) substrate materials. Additional process effects from resist development and pattern transfer can further deteriorate the device quality. A powerful proximity and process correction (PEC) can mitigate the issue. Sometimes, high-resolution single-layer resist processes are followed by multi-layer processes that form interconnection with "bridges" and need special 3D proximity effect correction which takes into account the development of the resist.



BEAMER includes the most comprehensive and powerful PEC technology available. It has been developed over 15 years in strong co-operation with the leading nano-fabrication centers producing various quantum devices.

The TRACER software quickly simulates the point-spread-function (PSF) and calibration of process effects.

In summary, BEAMER takes care of organizing and optimizing the design onto the wafer to achieve the best exposure results. The researchers can focus on their devices.

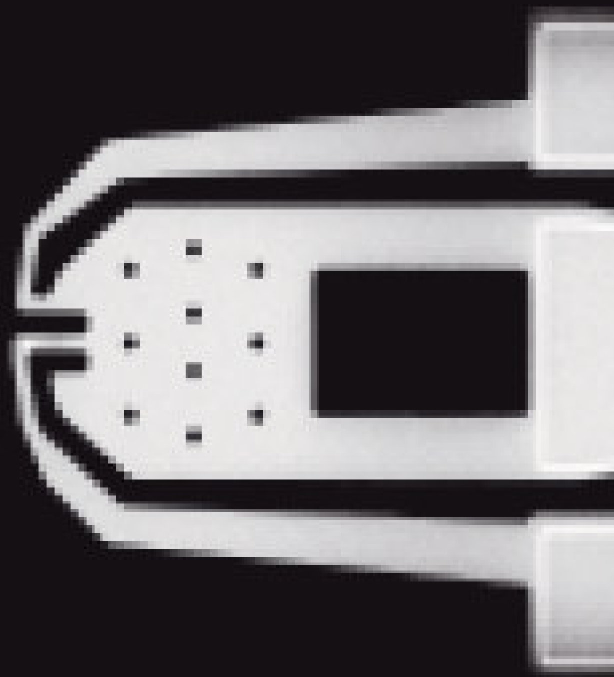
GenISys offers application support based on the cumulated knowledge and experience of leading nano-fabrication centers worldwide.

Images source: Weizmann Institute of Science, Israel.

HEIDELBERG INSTRUMENTS
The power of direct writing

IBM Research

7th Thermal Probe Workshop



17–18th November 2021 • Zürich

This 2-day workshop has grown into a small conference with around 25 talks and 70–100 attendees — experts from a broad range of nanosciences.

Registration and more information at tpw-zurich.com

Novel devices enabled by nanofabrication
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Advanced pattern transfer & materials
High aspect ratio structures and new materials

Thermochemical & additive manufacturing
Local conversion of materials and dip-pen nanolithography

Ultra-high-resolution patterning
Sub 20-nm nanofabrication and pattern transfer

Nanofluidics & nanomanufacturing
Lab-on-a-chip, engineering nano-landscapes, self-assembly

Large-area nanostructuring
Nanoimprint lithography, large nanostructures arrays

Nanoscale imaging & metrology
Advanced probe microscopy

Heated tips, MEMS & thermometry
New cantilever designs and thermal metrology

Industrial flash-session
Latest development in direct-write lithography tools and resists

Icons made by eucalyp and freepic from www.flaticon.com

20 μm (structure width)

OPTICAL IMAGE OF JOSEPHSON JUNCTION MASK ON TOP OF A BASE ALUMINUM LAYER (WRITTEN USING MLA150).

THE OVERLAP CONNECTS THE JUNCTION TO ITS CAPACITOR PADS WHICH ALSO FUNCTION AS ANTENNAE. TOGETHER, THE JUNCTION AND THE ANTENNA FORM A QUBIT THAT IS COUPLED TO THE ELECTROMAGNETIC ENVIRONMENT OF A 3D SUPERCONDUCTING CAVITY.

IMAGE: DAVID SCHUSTER, AKASH DIXIT, PHYSICS DEPARTMENT AND JAMES FRANCK INSTITUTE, UNIVERSITY OF CHICAGO.