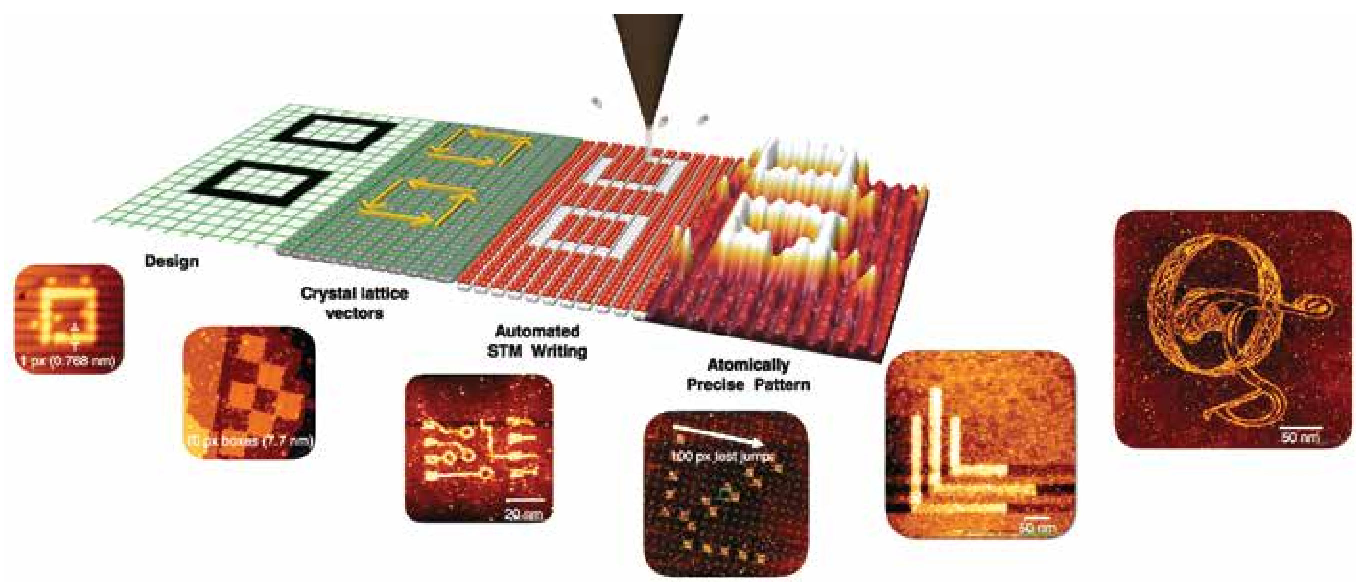
ZyVector™

STM Control System for Atomically Precise Lithography

Making Atomic Resolution Lithography a reality

- *Distortion-Free Imaging*
- *Automatic Lattice Alignment*
- *Digital Vector Lithography*
- *Precise Tip Motion with real-time position correction*
- *Automation and Scripting*



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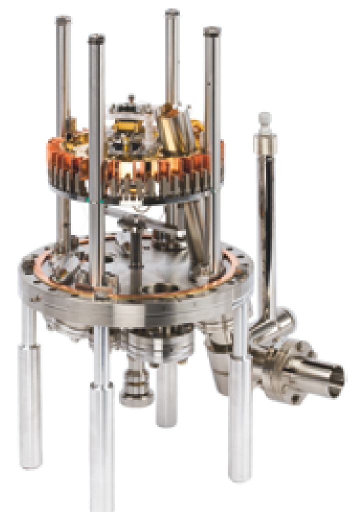
ZyVector™ | Atomic Scale Patterning Made Easy

At Zyvex Labs, our vision is to design, construct, and commercialize the world's most precise manufactured products.

For nearly 20 years, Zyvex Corp, LLC, has been at the forefront of developing tools and processes to create ultraminiaturized systems with atomic precision and unprecedented capability. Sister companies include Zyvex Technologies, the world's leading supplier of carbon nanotube polymers, and Zyvex Instruments, currently owned by ThermoFisher, which is the world leader in nanoprobe testing of integrated circuits.

Zyvex Labs is pursuing research and developing tools for creating quantum computers and other transformational systems that require atomic precision, towards its eventual goal of Atomically Precise Manufacturing. Developed as part of this effort, ZyVector turns the world-class ScientaOmicron VT-STM* into an STM lithography tool, creating the only complete commercial solution for atomic precision lithography.

**Adaptions for other STM systems possible.*



Scanz PC software for interface to user — USB — 20-bit Digital Control box for real-time control — ADC / DAC — High-voltage amplifier box — PIC / preamp — ScientaOmicron VT-STM

Digital Vector Lithography

- Takes atomic structure of surface into account
- Sub-nm pixel (4 surface atoms)
- Multiple Beam Widths available
- No partial exposure or proximity effects
- Automatic alignment of lattice

Built-In Metrology

- Nondestructive imaging mode available
- New Patterning can be aligned to old
- Pattern quality can be checked after writing
- Size of developed nanostructures traceable back to original pattern, with atomic precision.

Automation and Scripting

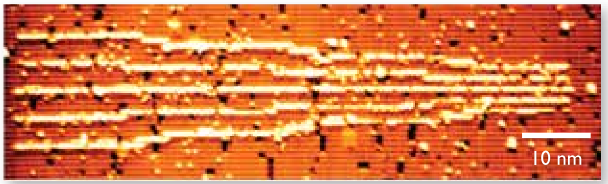
- Almost all actions can be automated.
- Command-line interface for single commands or scripts
- Script Menu for built-in and user-written scripts
- Multiple pattern input modes - as geometric shapes, vector lists, black/white bitmaps.

Precise Tip Positioning and Motion

- Real-time creep and hysteresis correction enables atomic-precision motion over limited areas; reduced errors over large distances.
- Automatic alignment to fiducial marks allows for correction of residual errors.
- Distortion-free imaging for precise tip location.

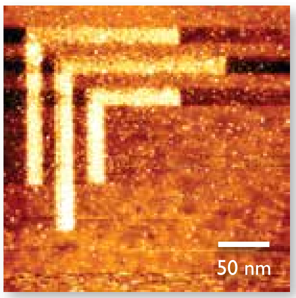
Applications

Dangling Bond Patterns, Quantum Dots, Wires.

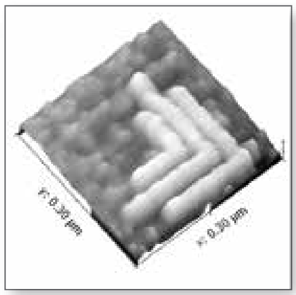


Sub-nm Lines at 3.8 nm–1.5 nm Pitches

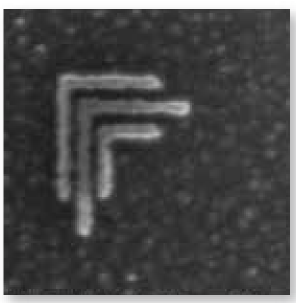
NanoImprint Templates



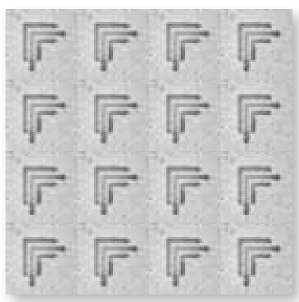
Patterning



Area-Selective ALD



Dry Etch



NanoImprint (Simulated)

Patterned ALD of TiO_2 hard mask in STM pattern
RIE of TiO_2 hard mask to create 3D Si structure
Replication of 3D structure using NanoImprint Lithography.

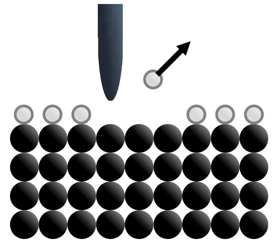
Ballard *et al. J. Vac. Sci. Technol.* B 32 041804 (2014),

Other Applications

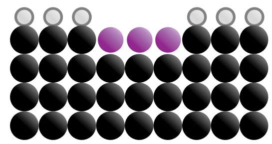
Patterned ALE of Si, Ge.

Selective Placement of many molecules.

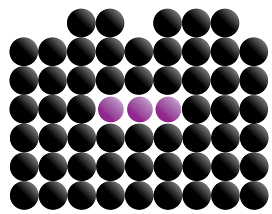
Dopant-based Electronics



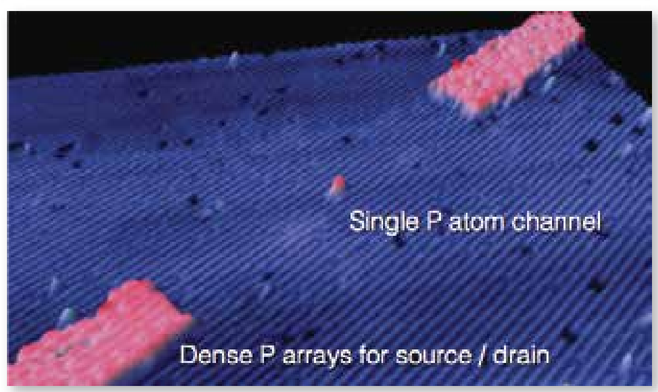
Hydrogen Depassivation Lithography



PH_3 Dose & P incorporation



Encapsulation with epitaxial Si



Deposition of PH_3 into STM pattern. Overgrowth of P to create embedded dopant layer for quantum computing devices.

Fuechsle *et al. Nat Nano* 7 242-246 (2012),

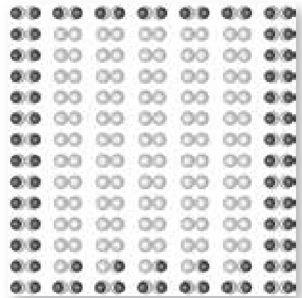
Digital Vector Lithography

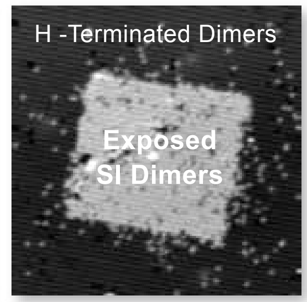
Unlike conventional optical or e-beam lithography, STM lithography takes into account the atomic nature of the surface. In ZyVector, writing is done as vectors, moving along the surface lattice directions, rather than a raster scan across the surface as used for STM imaging.

Hydrogen Depassivation Lithography (HDL)

Lyding et al.* first showed that at a positive sample bias, an STM tip can be used to inject electrons into a surface Si-H bond, until the bond breaks, exposing a chemically reactive Si dangling bond. Other materials are then selectively reacted with the dangling bonds, forming atomically precise nanostructures.

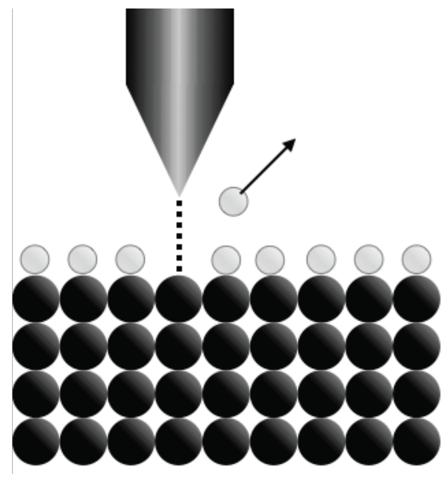
*Applied Physics Letters 64 2010-2012 (1994)





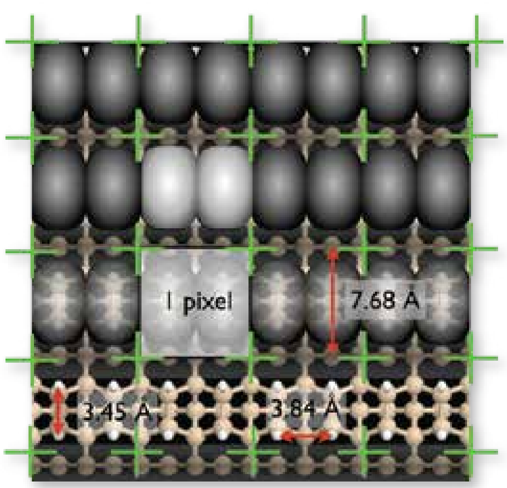
Atomic-scale lithography pixel

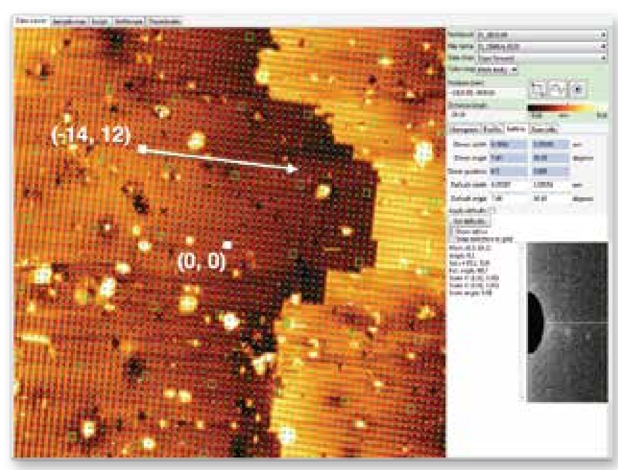
For the Si(001): H surface, we use a standard pixel size of 2 dimers on a single dimer row, giving a lithography pixel size of 0.768 nm. Patterns are typically generated from integral numbers of pixels, although for some special cases, such as the 3-dimer pattern used to place single P dopant atoms, half-pixels can be used.



Writing to the lattice

In order to write atomically-precise patterns, the location of the surface dimer rows are identified from the Fourier Transform of an STM image, and a pixel grid is overlaid onto the image.
To perform lithography, the tip is then instructed to move to a particular pixel, change to lithography conditions, and write a line along or across the dimer rows of the desired length.

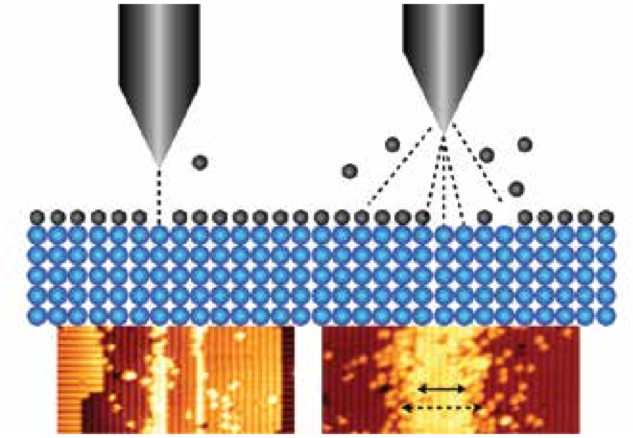




Variable Spotsize Lithography

STM lithography is digital because it causes the breaking of a Si-H chemical bond by electron excitation. There is no equivalent of partial exposure, because either the bond is broken or it is not. Likewise, there are no proximity effects.

Similar to e-beam lithography, with different settings of bias voltage and tunnel current, multiple line widths are available, from 1 px width up to several nm. Under low-voltage lithography conditions, around +4 V, 4 nA, with a dose of 4 mC/cm, the line width of STM lithography is one dimer row. This is known as Atomically Precise or AP mode. Above about 6 V, the tip moves out of tunneling range into Field Emission (FE) mode with much wider line widths, but also with rough edges to the lines. Use of the FE mode is useful to minimize write time for larger patterns, particularly where there is less need for absolute precision. For large patterns which do require precise edges, the modes can even be mixed within a single pattern, writing slowly around the perimeter, and quickly filling in the centre.



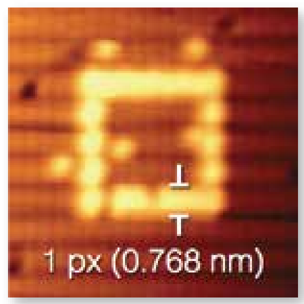
AP mode:	FE mode:
4.5 V, 4 nA,	8 V, 1 nA,
2 mC/cm	0.1 mC/cm
20 nm/s	100 nm/s
Liinewidth: 1 px	Linewidth: 4 px
26 px/s	520 px/s

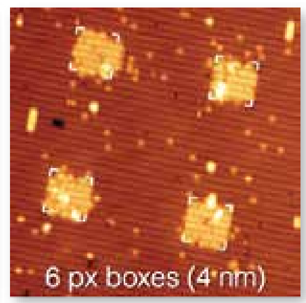
Writing Simple Patterns

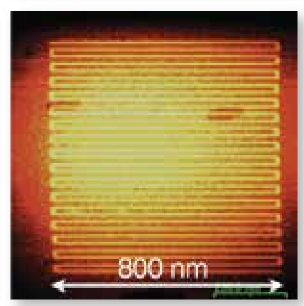
Simple shapes can be selected in the Litho tab and written with just one or two clicks.

In the Script Menu tab, geometric patterns can also be called, with editable parameters, such as dimensions and angles. Here, alignment to the lattice can be turned on and off as required.

Current, voltage and electron dose parameters are selected in the Litho tab. Preset groups of parameters giving different linewidths can be saved, and quickly selected.





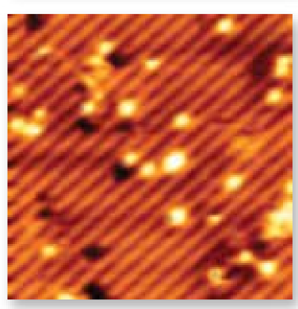


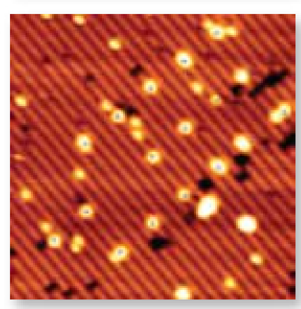
Removing single atoms

For removal of single H atoms, or single dimers, Feedback Controlled Lithography (FCL) is more reliable than simply drawing a very short line.

The Litho trap settings in the Litho tab allow for the litho mode to be exited immediately when a sharp change in the tunnel current, or other trigger, is registered.

This sharp change indicates the removal of one or two H atoms under the tip. Single dots, lines or arrays of single dimer patterns can be produced using scripts incorporating Feedback Controlled Lithography.





Precise Tip Positioning and Motion

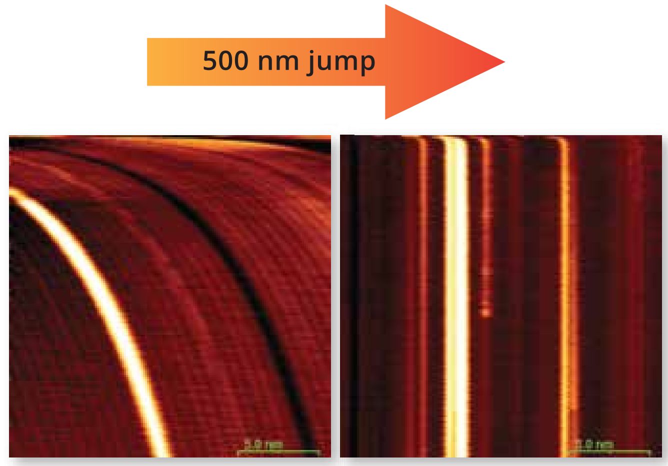
Unlike commercial STM systems designed for imaging, in ZyVector we wish to have the tip move arbitrarily across the surface with atomic precision. Therefore we must achieve real-time accuracy and precision in the tip position, so that STM images are undistorted, and lithography vectors follow their desired path.

Piezo Creep and Hysteresis Correction

Standard piezo actuators exhibit two types of position error:

1. Creep is a time-dependent error, whereby the last 10% of any motion does not happen instantaneously, but occurs over tens or hundreds of seconds.

2. Hysteresis is a position-dependent error; if the tip moves away from zero, and then back again, the tip will not return to the original location. The 20-bit controller in ZyVector adjusts the voltages delivered to the piezo actuators in order to correct these errors in real time, giving accurate and precise tip positioning. Corrections are applied to all four quadrants of the piezo tube, and therefore motions in x, y and z are all corrected.

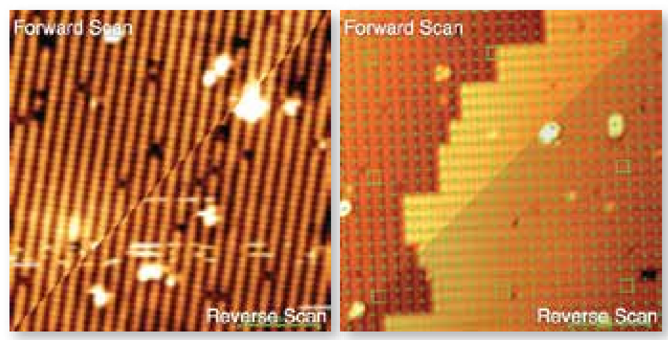


First 200 s after 500 nm jump

Uncorrected creep *Creep Corrected*

Distortion-Free Imaging

Creep also occurs on a millisecond timescale, and causes an offset between the forward and backward scans. This means that the tip is never really where it appears to be. With creep correction applied, the forward and backward scans overlap exactly, making precise tip positioning over a dimer row or other feature possible.



Distortion-free Imaging

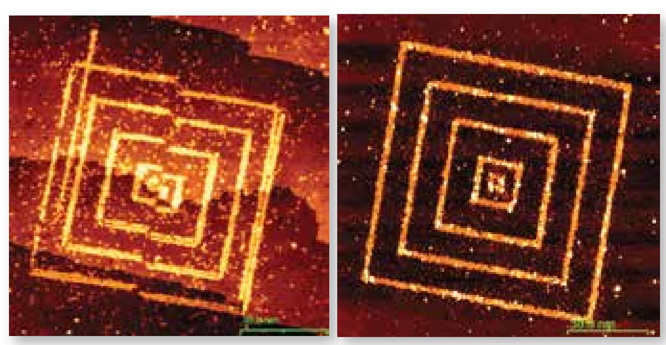
Creep Correction Off *Creep Correction On*

The effect of Creep on Lithography Precision

We use test lithography patterns to measure the effectiveness of the creep correction. The test pattern shown is a set of concentric boxes, which is defined using two bitmaps, one for the left half of the pattern, and one for the right half.

Without creep correction, the rectangles are not concentric, are not square, and the pairs of lines are not adjacent. There is also an offset between the two half patterns.

By running this and other test patterns, we can obtain quantitative data for the precision of the motion. The average error after 10 repetitions on this test pattern was less than 1 nm.



Lithography Test Pattern

Creep Correction Off *Creep Correction On*

For larger motions, Scanz can use a combination of real-time creep and hysteresis correction, and alignment to surface fiducial marks to maintain accurate positioning.

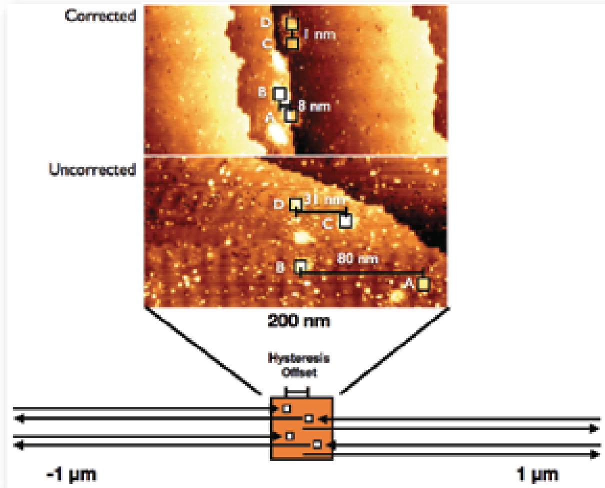
Accurate navigation across the surface with creep and hysteresis correction.

For larger motions, Scanz can use a combination of real-time correction of creep and hysteresis, and alignment to surface fiducial marks to maintain accurate positioning while making large jumps across the surface.

Testing Hysteresis Correction: In this test, the tip makes large jumps back and forth, and draws a box after a rightwards jump, and then after a leftwards jump, as indicated by the arrows. The hysteresis offset is measured as the distance between the second and third boxes. This offset is then put into Scanz, to correct the hysteresis.

Uncorrected: In the first set of boxes, the distance between boxes after a 1 µm jump is 80 nm, which is a mixture of creep and hysteresis. In the second set, the tip waited a few minutes before drawing a box, and the offset is now 30 nm, which is mainly hysteresis.

Corrected: A similar data set after applying creep and hysteresis correction. Now the boxes are all almost perfectly aligned, even after a 1µm jump.

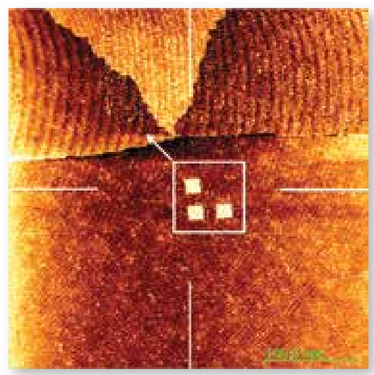


Results of a hysteresis test script. The hysteresis is measured from the distance between the 2nd and 3rd boxes of each set.

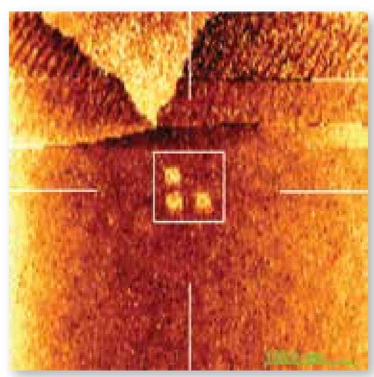
Automated Fiducial Mark Alignment

Over larger distances, effects such as thermal drift and uncorrected creep and hysteresis can still cause errors in the tip position. With STM, the surface can be imaged without affecting the H layer, using the same probe as for writing. This allows for direct alignment to a previously written pattern, or to a deliberately written fiducial mark.

A series of scripts are provided in Scanz, giving the capability to search for, identify, and automatically align to fiducial marks on the surface, so that accumulated position errors can be zeroed. In this way, residual position errors can be minimized.



A fiducial mark is located, by comparison to a previous image of the mark taken after writing.



The scan centre is relocated to the fiducial mark, even using low resolution, fast imaging.

Automation and Scripting

The ZyVector software, Scanz, enables automation and user scripting of almost every part of the software, including imaging, movement across the surface, and writing.

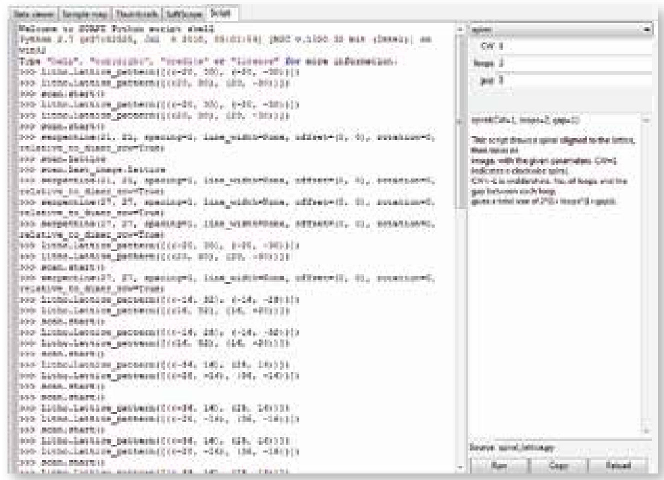
The simplest form of automation is the queuing of commands in the user interface. A series of actions can be queued up, and are shown in the Info Panel at the bottom of the Scanz window. Individual items can be cancelled with the 'x' button, or the whole queue is cancelled with the Cancel action button.

To extend the capabilities of ZyVector, users can write their own scripts, typically in a text editor outside Scanz, and then uploaded to the software.

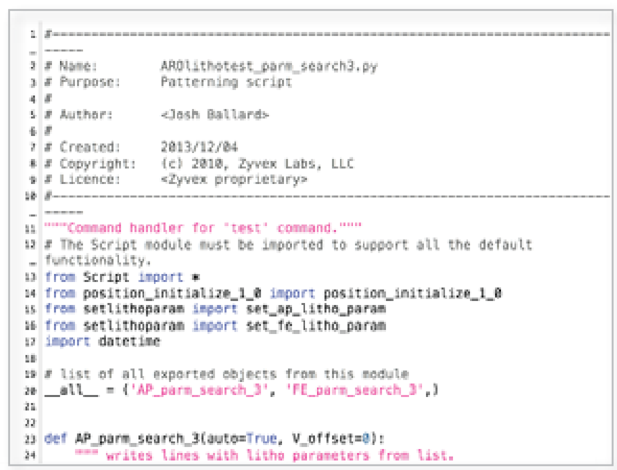
Scripts for ZyVector are written in a Python-based script language and can be a simple list of commands all the way to a complex set of instructions describing all the moving, imaging, writing, and other tasks required for generating a pattern for a whole device.

Many built-in scripts are provided, to perform tasks such as calibration of the default lattice parameter, determination of lithography parameters, writing simple shapes, etc.

The Script view tab provides both a command line interface to commands and scripts, and also a Script Menu to provide a GUI to easily find and run scripts. Many scripts have various input parameters, such as dimensions, rotation angles, etc. and the Script Menu tab provides a convenient way to edit the desired values for these parameters.



The Script tab, showing the command line interface, and the script menu panel.



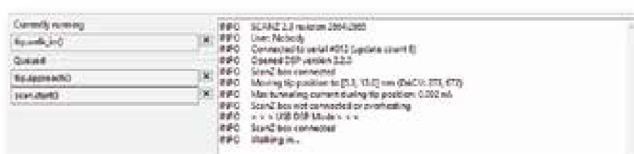
A ZyVector script

Bitmap Input

Any arbitrary pattern can be input as a black and white bitmap. The white pixels will be written with one bitmap pixel corresponding to the standard 0.768 nm lithography pixel.

The Multimode_VectorGen script parses the bitmap, producing a list of tip vectors organized in the order of writing. For large patterns, both AP mode and FE mode vectors are used to achieve an optimal write time. The edges are written using AP to achieve atomic precision. The larger patterns are filled in quickly with FE mode vectors. The pattern can then be written.

All of these standalone methods for writing patterns can also be incorporated into a script. Thus ZyVector is capable of very sophisticated automated patterning tasks.

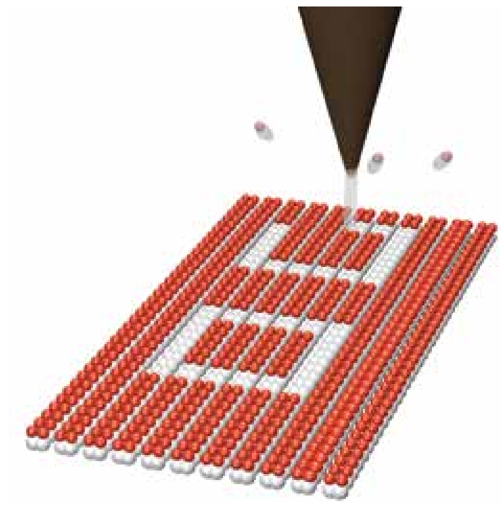


Queued actions in the Info panel

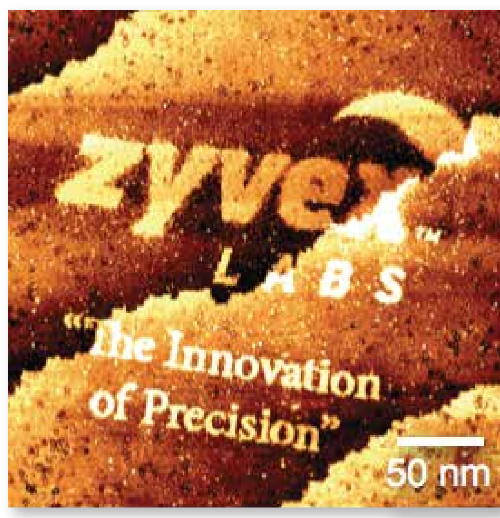
ZyVector has great flexibility in the methods for pattern definition; either as geometric shapes, or as arbitrary bitmaps. There is a special script, Multimode_VectorGen, which reads bitmaps and writes them out as patterns.

1. Pattern File comprises black-and-white bitmap input file.

2. ZyVector converts the pattern file into write vectors, following the Si(001) lattice.



3. STM tip moves along the write vectors removing H atoms.



4. The final atomic-resolution pattern of exposed Si dangling bonds.

Scanz User Interface

The Scanz software that controls ZyVector provides the fundamental functionality for STM imaging, but its true strength lies in the ability to automate almost all aspects of operation in order to perform atomically precise lithography most efficiently.

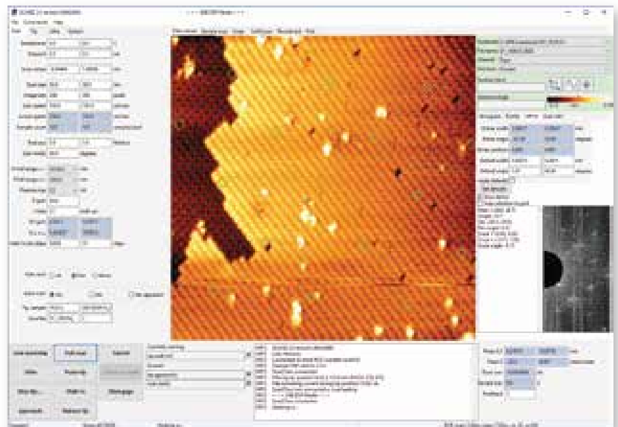
Scanz is contained within a single window - to the left are the Control Panels where settings are changed, and to the right are the View tabs, where STM images are viewed, and analysed, and from where scripts can be run.

Control Panel Tabs

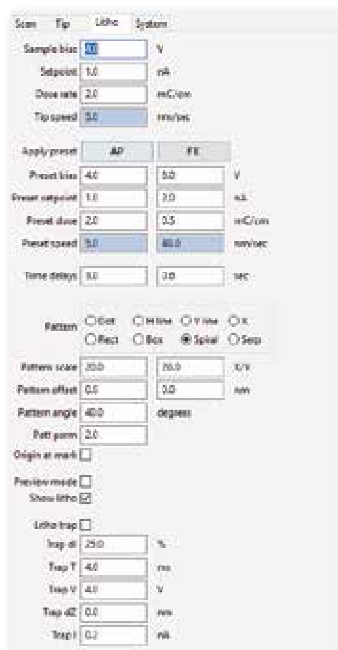
For routine imaging, the user will mostly make use of the Scan Tab, allowing for movement across the surface in x and y, settings for scanning such as image size and pixel resolution, and scan speed. The feedback control loop sensitivity is also set here.

The Litho tab contains controls for voltage, current and dose for different Litho modes. A menu of simple lithography shapes is also provided, and controls for Feedback Controlled Lithography.

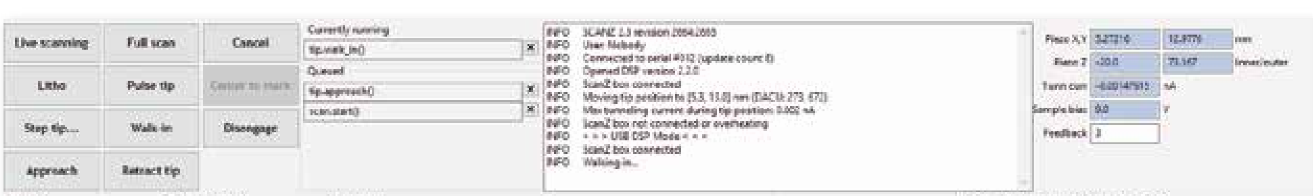
Below the Control Panels, are the Action Buttons, such as Scan, Litho and Cancel. Actions which are pending will appear in the Queue, from where they can be cancelled individually. Next to the Queue is the Information Panel, which provides feedback on the status, such as movements across the surface, activation or completion of commands etc.



The ZyVector software, Scanz, showing the main Scan control tab and the Data Viewer tab.



The Litho tab, for performing simple STM lithography.

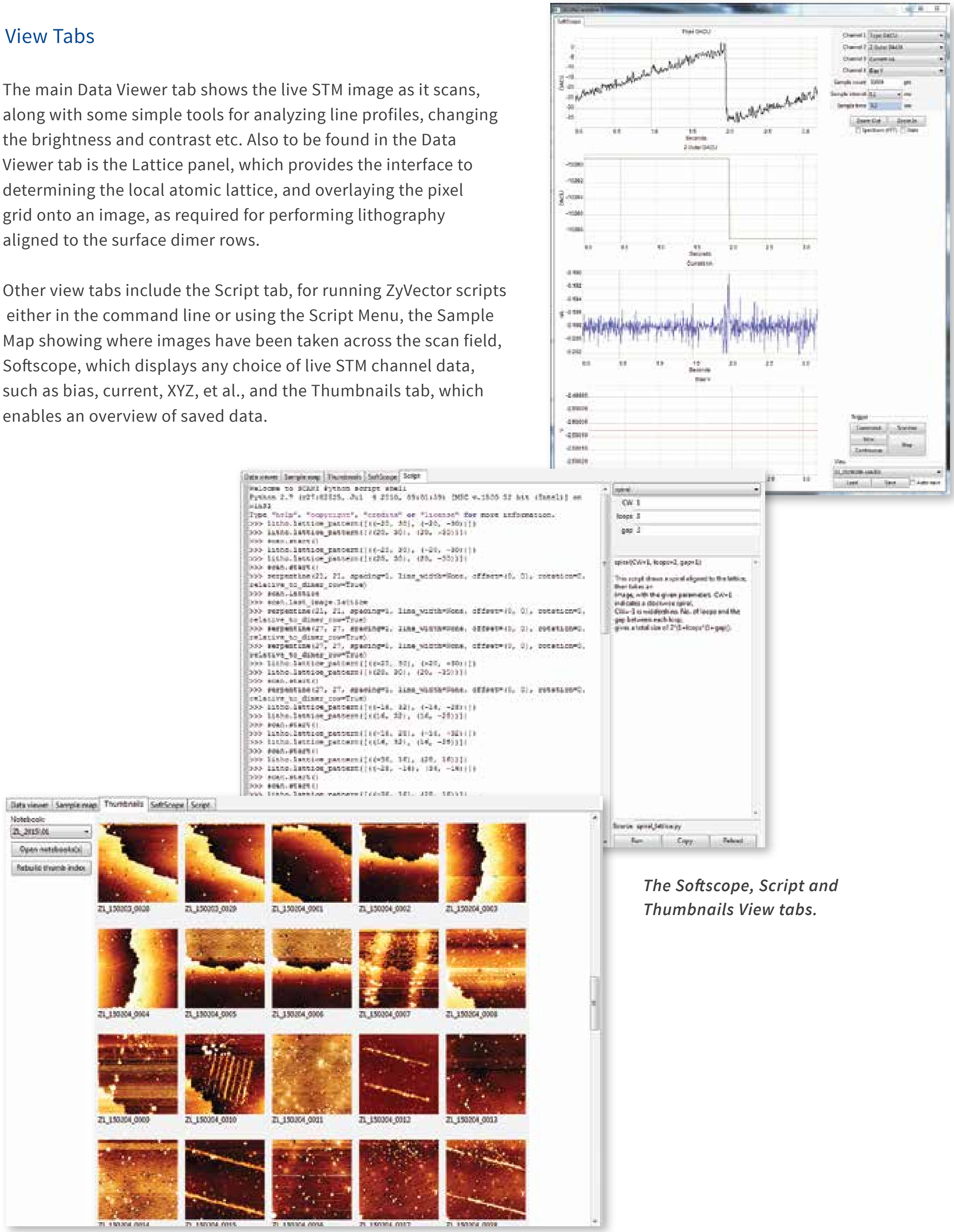


The Action Buttons, Queue and Information Panel

View Tabs

The main Data Viewer tab shows the live STM image as it scans, along with some simple tools for analyzing line profiles, changing the brightness and contrast etc. Also to be found in the Data Viewer tab is the Lattice panel, which provides the interface to determining the local atomic lattice, and overlaying the pixel grid onto an image, as required for performing lithography aligned to the surface dimer rows.

Other view tabs include the Script tab, for running ZyVector scripts either in the command line or using the Script Menu, the Sample Map showing where images have been taken across the scan field, Softscope, which displays any choice of live STM channel data, such as bias, current, XYZ, et al., and the Thumbnails tab, which enables an overview of saved data.



The Softscope, Script and Thumbnails View tabs.

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Technical Specifications:

ZyVector Hardware Controller

Provides:

- 4 fine x/y channels (± 135 V)
- 1 fine z channel (± 135 V)
- 3 coarse xyz channels (± 200 V)
- 1 tip bias channel (± 10 V)
- Pre-amp gain control, for Omicron preamp
- Pre-amp bias range control for Omicron preamp amplified current input
- Fits Omicron VT STM preamp and PIC cabling.

20-bit Digital Control Box

- Provides real-time control of the tunnelling feedback loop.
- Calculates creep and hysteresis corrections for precise piezo motion across the surface.

Scanning

- xy ranges depend on nm/V calibration.
- For Omicron VT system: 9500 nm.
- Z-range 1.3 µm
- Minimum scan bit size: 10 pm.
- Minimum vertical bit size: 1 pm.
- Fast scan direction arbitrarily defined between 0-359.9° relative to piezo tube axes.

Advanced Position Controls

- Local piezo tube calibration based on lattice recognition, including determination of lattice angle relative to piezo tube axes.
- Lattice phase recognition for precise lithography positioning.
- Creep and hysteresis correction in xy.
- Initial calibration of correction factors provided at installation. (Fine optimization by user required periodically)

Hydrogen Depassivation Lithography (HDL)

Two vector writing modes available:

- AP mode (single-dimer-row line width)
- FE mode (wider line width, rough edges)

For single-atom removal, automated Feedback Controlled Lithography mode available.

Advanced Scripting Capabilities

- We provide scripts based on Python for test HDL patterns, creep correction calibration, lithography parameter calibration, etc.
- User-written scripts can be easily incorporated and run using command line interface or drop-down menu.

For more information, please visit the Zyvex Labs Website: https://www.zyvexlabs.com/apm/products/zyvector

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The innovation of precision