QSi

Silicon Reinvented

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QSi is a tradename of Quantum Silicon Inc.

QSi is reinventing silicon semiconductor technology.

Our mission is to enable the semiconductor industry to continue its Moore's Law path without discarding the enormous investment it has in silicon. Little more performance can be realized by following the current roadmap – certainly not while containing costs.

QSi provides a transition path that is fully compatible with end-of-roadmap CMOS on the same chip. In the near term, we will replace bottleneck processes with a faster and more efficient binary technology that can mate and work naturally with CMOS. Thereafter, we offer a smooth transition to a new path as the atom-defined technology takes over more of the CMOS turf, creating ever more capable devices.

For many years, automated and scalable atom-scale manufacturing processes evaded research organizations around the world. QSi has developed both the unique tools and the physical processes that allow error-free, automated and scalable atomically precise manufacturing. Our unique capabilities derive from our world leading atom-perfect silicon lithography. These processes work on ordinary silicon substrates and are CMOS compatible.

Using our atomically precise lithography, QSi creates switchable dipoles within exactingly and reproducibly defined structures. These devices allow information transmission and logic operations to be performed without use of any conventional electrical current. The result is very low energy consumption, extremely high operation rates (~ 100 GHz) and a miniscule bit energy (~ 10^{-20} J). Our devices are stable at temperatures ranging from conventional CMOS operating temperatures all the way down to extreme cryogenic temperatures.

Our first product, a comparator of an unequaled power-delay product, is being developed with the participation of Texas Instruments Kilby Labs. This is envisioned as both a standalone device and as an important component of a fast, energy efficient analog-to-digital converter.

Other products are designed and in development – a hardware random number generator, a quantum magnetometer, and a neural network training accelerator among them.

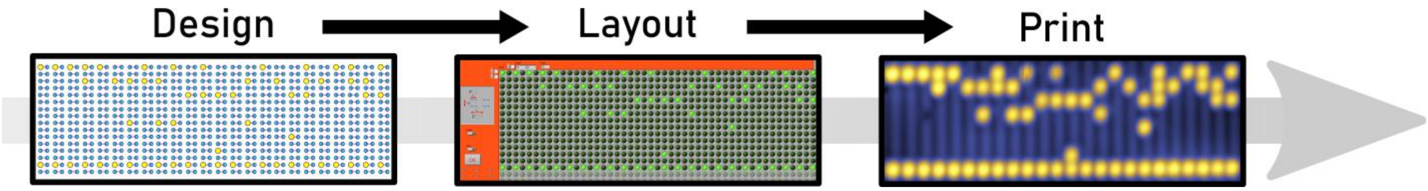
This document provides a high-level introduction to our company, our technology, our products and our business. There is a lot to explore beneath what we present here. We invite deeper discussion.

QSi uses proprietary scalable atomically precise manufacturing technology to develop all-silicon, energy-efficient, fast, atom-scale binary computing devices. Our electronic devices are based on QSi's unique Atomic Silicon Quantum Dots.

Atomically Precise Lithography

QSi's lithographic techniques for atomically precise manufacturing are the best in the world. We use adapted Scanning Probe Microscopes for manufacturing purposes. QSi has developed these microscopes into economically scalable manufacturing tools. Machine learning techniques detect and correct errors, re-form the tips when necessary, and locate and avoid defects on the silicon surface. The process proceeds without the need for operator monitoring. Our patented control systems and user interfaces create a fully automated and scalable atom-scale production process.

Using unique design and simulation CAD tools, device designers lay out and test the circuit, which is then automatically printed. The microscope image on the right is 9nm wide, and each yellow feature is a single, exactingly positioned Silicon Quantum Dot. These structures are entirely stable at temperatures up to 200 C.



Computing Devices and Business Model

We use our manufacturing techniques to make computing devices formed from patterns of Atomic Silicon Quantum Dots (ASiQDs). Within those patterns, our devices use electrostatic fields to rearrange patterns of electrons. We call this technology Field Controlled Computing. So instead of loading millions of electrons from a power supply and then dumping them to ground with each clock cycle, we rearrange a fixed number of electrons, thus using orders of magnitude less energy than conventional CMOS. Our ASiQDs have made it possible for us to develop atomically small, extremely fast and energy efficient devices that are made entirely of silicon and fully compatible with conventional CMOS on the same chip, preserving the semiconductor industry's enormous half-century silicon investment.

QSi's approach results in logic devices that use orders of magnitude less energy than wholly transistor-based computers. As computer use has become more ubiquitous, the amount of energy that the ICT sector uses has increased to the point where computing today is responsible for greenhouse gas emissions as large as those of the airline industry. QSi’s binary products are at least 100 times more energy efficient than the best of what is projected for end-of-roadmap transistor-based technologies, with speeds that are 100 times greater.

We are developing a semiconductor IP business around our classical device designs, licensing both the circuit design and the atomic scale manufacturing technologies used to produce them.

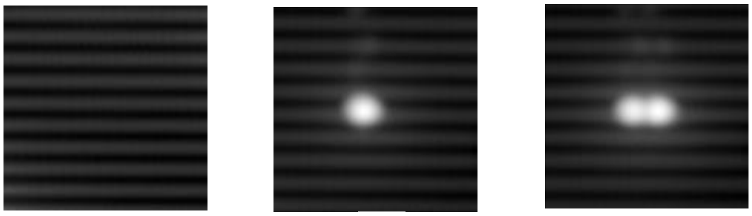
Atomically Precise Manufacturing Products: We are licensing for non-competitive uses the tools that we have developed for tip-based manufacturing. QSi is in a development agreement with one of the world’s largest instrument manufacturers to incorporate our unique, proprietary single atom tips into a new instrument that is expected to ship in 2022. The device we use to move our tips for manufacturing is proving to be an attractive product for other markets. We booked initial development revenue in 2019, and project first product revenue from those devices in 2021.

Technology

Atomic Silicon Quantum Dots

At the center of QSi’s approach to building atom-scale electronics sits a remarkable, proprietary structure – the Atomic Silicon Quantum Dot (ASiQD). Made on entirely ordinary hydrogen-terminated silicon, each ASiQD consists of a single silicon surface atom with its capping hydrogen atom removed. This creates a “quantum dot”, a zero-dimensional dot capable of holding two, one or zero electrons. Because these electron states are in the silicon band gap, we achieve isolation from ordinary silicon conduction pathways. Each ASiQD is identical to every other and precisely positioned relative to the underlying silicon lattice, an enormous advantage for scalability.

The Scanning Tunneling Microscope images below show ASiQDs on a hydrogen-terminated silicon surface. The grey horizontal bar-like features are regions of the silicon wafer surface that are hydrogen terminated. The bright spots in image frames “b” and “c” are Atomic Silicon Quantum Dots fabricated by automated removal of single hydrogen atoms.



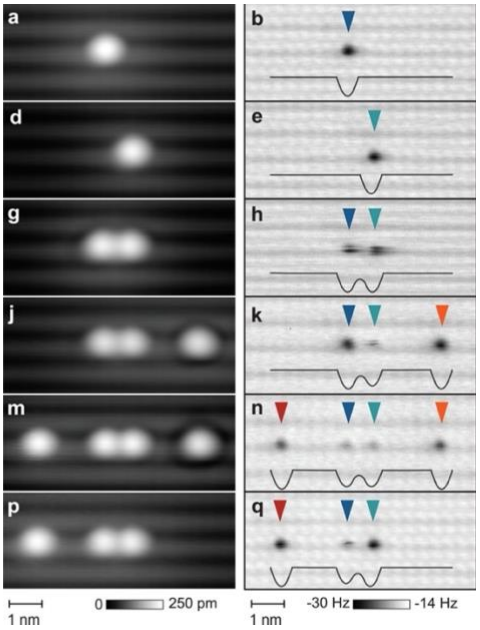
a b c

The pair of dots in frame (c) above is the basic QSi logic cell. It is two adjacent ASiQDs with one shared electron. Because the positions of the atoms cannot deviate from those defined by the crystalline silicon wafer, atom placement is perfectly regular and reproducible. There is no variance among our building blocks, unlike transistors. Likewise, single electron occupation of atom pairs occurs spontaneously and without variation. Single electrons naturally, instantly come to rest in our paired-atom binary units.

The two atoms form a double well potential that traps the electron over one atom or the other. These positions form a natural basis for logical binary states “0” and “1”.

Field Control: The image below illustrates how our perfect control over atomic patterns leads in turn to control over electrons and therefore over logical binary state.

In addition to a pair of ASiQDs, Frame j below shows a third atom placed to the right of the pair. That third atom is charged with one further electron of fixed position. Image k is taken over the same area as image j, but it is tuned to reveal as black dots the electrons within that pattern. The black line in frame k is an approximation of the spatially varying potential energy experienced by electrons. Image k reveals that the electron marked by the red arrow pushes the single electron trapped within the pair to the left side. In image p, the controlling charged atom has been moved to the left side. Image q shows that the electron with the pair

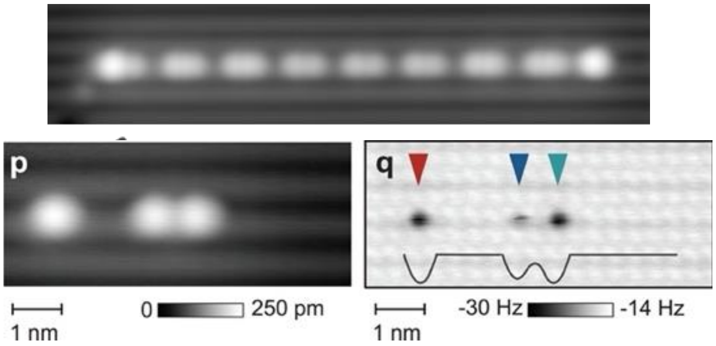


has responded to this field change by moving to the right. Measurement and *ab initio* calculation show that the bit energy, that is the energy required to change binary state is roughly 10^{-20} Joule. Taken together, these data show our unique, unprecedented ability to represent and control information using very little energy.

Fast, Energy-efficient Binary Computing

For over half a century, electronic computing has been implemented using transistor-based logic. By design, transistor circuits draw a burst of electrons from a power supply to charge gates then sink those electrons to ground with every cycle of the clock. This produces heat. QSi's approach, by contrast, uses only the energy required to rearrange a fixed set of electrons under field control to represent, create and transmit information. This method does not use conventional current and produces almost no heat. When we place a charge near a two-quantum-dot cell the electron is localized at one of the two quantum dots making it possible for the two-dot pair to express binary state – a zero or a one.

When placed in a row, a series of these two-quantum-dot structures interact with each other, forming a "binary wire" that communicates binary information from one terminus to the other. without the use of conventional current. The image below shows a binary wire. The top image shows the atom placements. The lower frame shows the left polarized electron positions within each sub-unit.

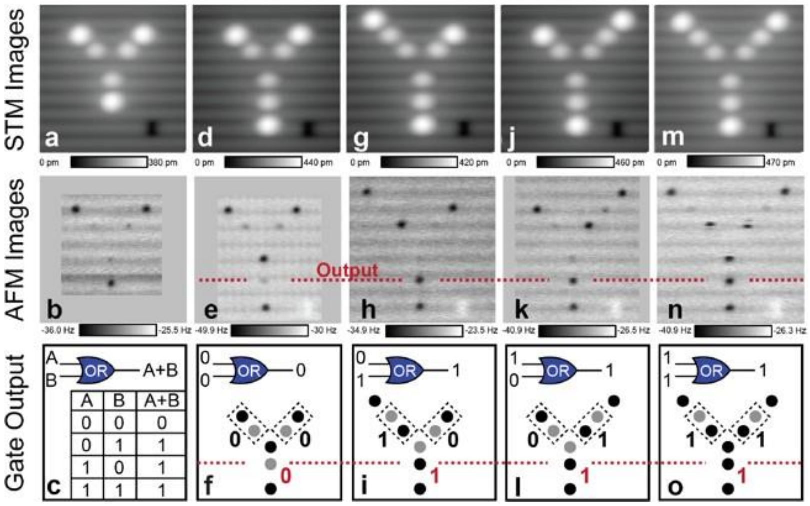


Binary state propagation speed is as yet too fast to measure with our nanosecond time resolution. Computational modeling indicates typical propagation times in the picosecond range.

ASiQDs can also be arranged to form logic gates. These can be connected together with binary wires to form computing circuits that operate at normal CMOS operating temperatures. Very good stray charge immunity has been demonstrated.

Energy consumption is roughly 100x less than end of roadmap transistor gates.

The images below show operation of an atom defined OR gate. The top row of images show atom positions and the images just below those show electron positions within those ensembles.



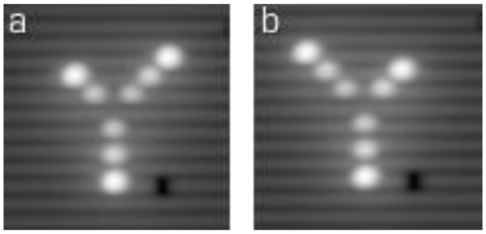
Scalable Hydrogen Lithography

All of QSi's devices are made by selectively, rapidly, accurately and predictably removing hydrogen atoms from a hydrogen-terminated silicon surface to create electronic circuits. This technology was dubbed "hydrogen lithography" by developers at IBM. QSi is the best in the world at Hydrogen lithography, greatly surpassing what our colleagues at IBM, or any competitors can do.

Our hydrogen lithography methods require atomically sharp metal tips in Scanning Probe Microscopes. While standard methods can reliably produce sharp tips outside the STM, inevitably as they are used the quality of their apex degrades. Until now, correcting this has required a skilled, PhD-level operator to notice features that indicate that the apex of the tip no longer has a single predominant atom and intervene to restore the tip. Because of this, probe -based hydrogen lithography had not been scalable and was not commercially viable.

We have developed and patented a machine-learning based system to automate our lithography: tip conditioning, error detection and correction, identifying and avoiding defects on the silicon surface are all automated. Our system automatically recognizes when a tip has become degraded and automatically sharpens it, all without operator intervention. This is a pivotal advance, allowing efficient and parallelized atom scale manufacture for the first time.

In addition to our advanced capabilities in rapidly and predictably creating ASiQDs by removing H-atoms from the H-terminated silicon surface, we are also able, again rapidly and predictably, to replace individual H-atoms after they are removed. Dubbed “Atomic White-Out”, this gives us the ability to perfectly correct fabrication placement errors, or simply to edit circuits at will during circuit development. We have developed and patented the artificial intelligence methods that recognize when the wrong H-atom has been removed and automatically replace it. The image below shows an eight-atom pattern with an ASiQD “moved” by erasing the one at the top right (a) and creating a new one at the top left (b).

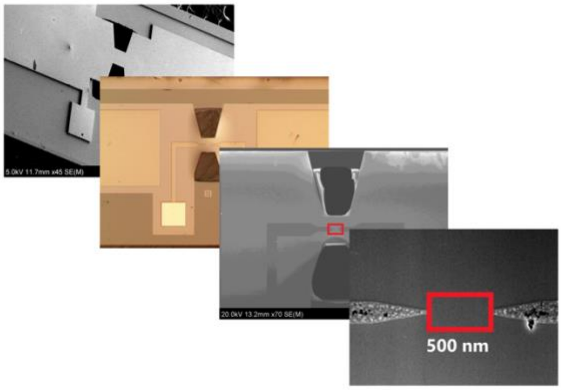


Similarly, we have automated the process of selecting the defect-free segments of the silicon surface for optimal placement of our atomic patterns.

In short, we have made tip-based atomic lithography a scalable, commercial manufacturing process.

Macro- to Atom-scale Interface

Atom-scale devices are of little use if they cannot be controlled. Constructing an interface between the atomic scale and the normal lithographic scale is a complex challenge that we approached by developing a platform chip that is made using conventional optical and electron beam lithography. The chip bridges the scale gap between macroscopic contacts and nanoscale structures, providing a platform for controlling atom-scale devices. This approach allows working CMOS device and our atom scale entities to be co-located on the same chip. An Electron Microscope image of a macro-to-atom connection chip is shown below.



Atomic CAD tools: We design and make patterns of ASiQDs using a unique CAD tool to control the movement of the tip. The images below show the tool's GUI used to design the multi-atom device on the right.