

Review article

Digital atomic scale fabrication an inverse Moore's Law – A path to atomically precise manufacturing



John N. Randall^{a,*}, James H.G. Owen^a, Ehud Fuchs^a, Joseph Lake^a, James R. Von Ehr^a, Josh Ballard^b, Erik Henriksen^c

^a Zyvex Labs, United States

^b University of Indiana, United States

^c Washington University in St. Louis, United States

ARTICLE INFO

Article history:

Received 22 October 2018

Received in revised form 5 November 2018

Accepted 7 November 2018

ABSTRACT

There is an exciting opportunity to start a second digital revolution that will supersede the first digital revolution in information technology (IT) as the primary driver of scientific, technological, and economic growth. This new revolution will be digital fabrication technology. The digital IT revolution has been largely driven by digital algorithms such as error detection and correction and Moore's Law which has given us an exponential trend in product capabilities. However, the longstanding trend in improving manufacturing precision which has enabled Moore's Law simply cannot be continued much longer because we are running into the limits imposed by the quantized nature of matter. At this scale, matter can no longer be treated in an analogue fashion i.e. as an infinitely divisible medium, but must be treated as an integer number of discrete atomic distances, i.e. in a digital fashion.

By embracing this digital nature of matter, we can conceive of a digital fabrication technology, where the digital processes are the making and breaking of chemical bonds, there is a digital address grid that is spatial in nature, and error detection and correction processes can be developed. This digital fabrication technology will have the similarly huge advantages over analog fabrication that digital IT has over analog IT. We remind the reader that effective digital technologies are not exclusively digital in their operation. Digital electronics is carried out by analog transistors that are embedded in circuitry designed to accept their output in a digital fashion. Digital fabrication technology is not synonymous with Atomically Precise Manufacturing (APM) but should lead to that important capability. Furthermore this digital fabrication technology will start a new exponential manufacturing trend that will replace Moore's law and will not be just for information processing and therefore will have an even larger impact than Moore's Law. Like any exponential trend Digital Fabrication will start slowly in a few niche markets, but the time for investing in the development of this new technology is now.

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1. Nanotechnology has generally failed to deliver on its promises

Zyvex Corporation was founded in 1997 by Jim Von Ehr to develop what we now call Atomically Precise Manufacturing (APM) in order to deliver on the exciting opportunities promised for nanotechnology as first suggested by Richard Feynman in his "Plenty of room at the bottom" speech [1] and later in significantly greater detail by Eric Drexler in his books *Engines of Creation* [2] and *Nanosystems* [3]. Zyvex Labs

has been working to develop APM and nanotechnology applications and products since its inception. A few years after the founding of Zyvex, the National Nanotechnology Initiative (NNI) was funded and billions of dollars have been spent on research to achieve the two main aspects that were promised: ultra-miniaturization and taking advantage of the emergent properties of materials at the nanoscale. Today, it pains us to admit it, but in our opinion Nanotechnology has failed to live up to its promises. Worldwide there has been some wonderful nanoscience accomplished that continue to point to some exciting applications, but we are significantly underperforming in producing Nano technology.

* Corresponding author.

E-mail address: jrandall@zyvexlabs.com (J.N. Randall).

We and other companies have developed some nanotechnology products that have been worthwhile, such as carbon nanotube enhanced polymer composites [4] developed by Zyvex Technologies, as well as a number of other useful nanotechnology products. However, virtually all of these products are relatively simple, many of them involving nanoscale additives to improve material properties, and not complex nanosystems with high reliability. It is not as if these complex nanosystems have not been designed. Rob Freitas has written a series of books on Nanomedicine [5] where he has worked out the details of a large number of potentially very useful products that have yet to be produced. My favorite is the Respirocyte [6] which is an artificial red blood cell which could store 236 times the oxygen as a normal red blood cell. An artist's rendition of Respirocytes in the blood stream is shown in Fig. 1. The physics of the Respirocyte is sound and yet it has not been created as of 2018.

The first author (John Randall) spent roughly ten years (1986–1996) at Texas Instruments Central Research Laboratories working to try to bring quantum resonant tunneling integrated circuits to market. Texas Instruments produced a large number of prototype devices that had excellent device characteristics [7] including a simple integrated circuit that operated satisfactorily at room temperature [8] but failed to develop successful products. The reason that Respirocytes, quantum resonant tunneling electronics, and a number of other potentially very complex and useful nanotechnology products that have been either designed or even prototyped have not made it to market is because we lack the manufacturing precision to mass produce them.

2. The semiconductor industry as a counter example

A significant exception to my claim that we don't have complex and yet reliable nanosystems, is the semiconductor industry. This industry is unquestionably doing nanomanufacturing and producing information processing products that have revolutionized life on earth with ridiculously complex and yet extremely reliable information processing systems. Moreover they have created an exponentially improving manufacturing capability that has been driving the world's technology, science, economy and standard of living for close to five decades. The exponential nature of this remarkable industrial revolution is what we have come to know as Moore's Law which is depicted in Fig. 2. It is instructive to consider why this nanotechnology has succeeded where others have failed.

While there are a large number of factors that have led to the amazing success of Moore's Law and the information age that it has enabled, the two cogent factors that we will refer to are:

- Digital information technology
- Avoiding the emerging properties of materials at the nano scale

The reason that integrated circuits can be created, or even designed, with the extreme complexity that includes 10 billion transistors on a

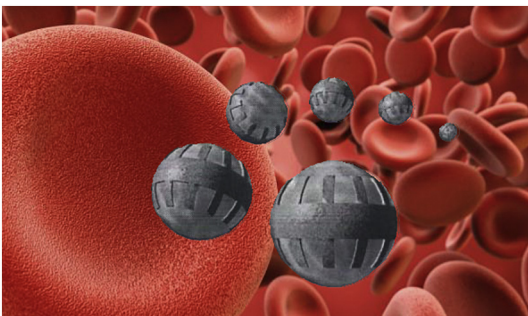


Fig. 1. A rendition of Respirocytes among red blood cells.

single chip, is that the process that these chips carry out is digital information processing. Digital IT has developed many advantages, as will be discussed in a subsequent section, but the two primary advantages to integrated circuit manufacturing are the immunity to noise of the digital signal, and the impact of that immunity on the physical tolerances of the transistors. While the absolute precision of semiconductor manufacturing is extremely impressive, a few nm, because they are now producing features approaching 10 nm, the relative precision is poor. Two decades ago the relative precision was roughly $\pm 5\%$. It is closer to $\pm 10\%$ today. While this sort of relative precision is acceptable for digital electronics, it does not work well for many other applications. Imagine trying to design an internal combustion engine with $\pm 5\%$ precision.

This poor relative precision has forced the semiconductor industry to avoid taking advantage of the emerging properties of materials at the nanoscale, because those properties depend very sensitively on the size. Because semiconductor manufacturing processes lack good relative precision, digital electronics cannot take advantage of these emerging properties because they cannot control them. This is the principal reason that Texas Instruments failed to commercialize quantum resonant tunneling devices. The energy levels of the discrete electronic states are directly affected by the size of the quantum confinement structure. Texas Instruments could make structures small enough to have quantized states, but could not control the sizes well enough to match the energy levels in any given device to another making it difficult to combine them into complex circuits. Even worse is the control of tunnel barrier widths which exponentially control the tunneling rate of currents flowing through the devices; small variability in manufacturing leads to large variability in performance. In the VIP NSF/DARPA program at UCLA and HRL Laboratories (1998–2001), for example, the required control over the interface roughness between the InAs and AlSb layers was less than 1 atomic layer.

The semiconductor industry has been extremely effective in developing tools and processes that work very well for making digital electronics, and because of the self-fulfilling prophecy of Moore's Law and the benefits it has provided have had the resources to dramatically improve manufacturing precision. The disconnect with the rest of nanotechnology and in fact micro technology, is that poor relative precision does not work well for most other applications, and yet it is tools developed by the semiconductor industry that are the majority of the tools in our nanofabrication research facilities. We will come back to the

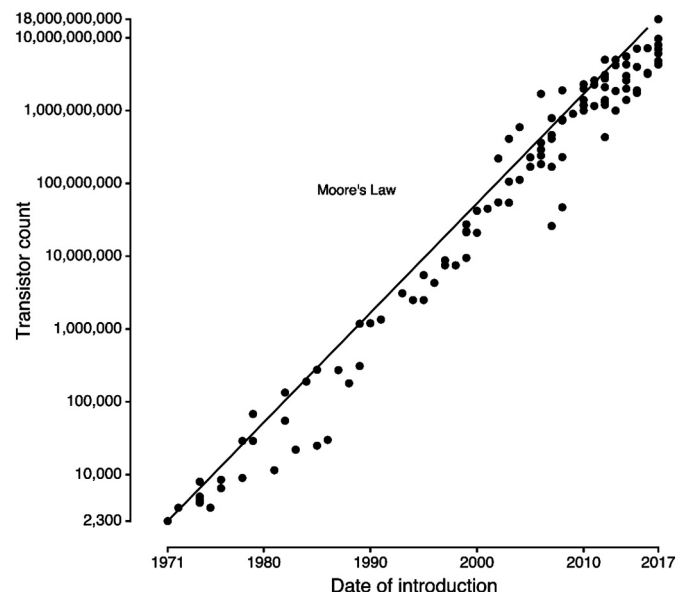


Fig. 2. A graphical representation of Moore's Law.

mismatch between semiconductor manufacturing and other nanotechnology manufacturing in a subsequent section.

For all of its successes and immense resources to continue, Moore's law is clearly grinding to a halt [9]. While it is an oversimplification, we need look no farther than Norio Taniguchi's chart [10] of the trends in manufacturing precision to see the problem confronting continued downscaling.

Norio Taniguchi (who first coined the term “nanotechnology”), a Japanese academic, studying the semiconductor processing industry realized the importance of manufacturing precision and plotted its historical trend as shown in Fig. 3 which shows the bleeding edge of manufacturing precision, which is a subset of his originally published data. We wish to point out that in the past 100 years the improvement in precision has been an impressive factor of approximately 100,000× and that the trend started long before Moore's Law. We assert that manufacturing precision is one of the primary rate limiting factors on human technological progress. Taniguchi's extrapolation has been remarkably accurate predicting decades ago that we would reach “Atomic Distance” accuracy in the second decade of the 21st Century which we have at least in terms of thin film deposition.

The problem embedded in Tanaguchi's data is that, to misquote Feynman: “We are running out of room at the bottom”. We are clearly running into the quantized nature of atomic-scale matter. This fact, we contend, is at the heart of the demise of the remarkable exponential progress of Moore's Law and in fact presents a major problem in technology advances in general. This is because one of the principal ways of advancing technology has been to improve manufacturing precision, and there is not another 5 orders of magnitude improvement in manufacturing precision to be had in the next 100 years. We contend, however, that there is a very attractive path to creating a new exponential trend in manufacturing that can effectively replace Moore's Law and give us a different path to technology advancements in areas more general than information processing.

3. Digital atomic scale fabrication

We believe that nanotechnology today is roughly where information technology was shortly before digital information technology replaced analog information technology. Analog information technology was quite useful, providing us with telephones, radios, and televisions for communication and vinyl records, video and audio tapes, photographs and films for information storage. However, when digital media, digital communication, and digital computation replaced the analog information technology, the entire world was changed in profound ways. The advantages of digital information technology are dramatic and account

for a rapid replacement of the older analog technology. The list below is not exhaustive, but captures some of the remarkable features of digital information technology:

- Immunity to noise
- Higher signal transmission rate
- Less required bandwidth
- Easier encryption (more secure)
- Simultaneous multi directional transmission
- Compression (lossless and otherwise)
- Error free reproduction Error detection & correction
- Outrageously complex systems with extremely high reliability

A key factor is error free reproduction which is enabled by error detection and correction. These advantages have allowed for the extremely complex digital information technology systems, such as the internet, to exist and to possess extremely high reliability.

a. Analog Fabrication

We have listed some of the advantages of digital information technology because we believe many of these advantages will be realized in a digital nanofabrication technology. We will first assert that the vast majority of top-down nanofabrication processes that we are now using are in fact analog fabrication processes. This includes, lithography, wet and dry etching, thin film deposition, chem-mechanical polishing, etc. These processes are analog fabrication because they treat matter as if it was infinitely divisible. *Current nanofabrication processes take advantage of the chemical nature of atoms and molecules but do not take advantage of the wonderfully invariant size of specific atoms and molecules.* There are a few exceptions. Atomic Layer Deposition (ALD) and di-block copolymer lithography do take advantage of the size of atoms and molecules, but they have not yet been fully developed as a digital fabrication technology.

We are asserting that a digital approach is one that will produce superior manufacturing precision. Let us provide a specific example. Consider the requirements for producing excellent precision in thin film deposition with some form of physical vapor deposition on some substrate and compare that to a more digital approach. To have excellent control of the thickness of a physical vapor deposited film, you will need:

- A uniform flux of the material across the entire area of the substrate
- A highly accurate flux monitor
- Very careful metrology to calibrate the flux monitor
- Multi directional flux if there is significant topography on the substrate

Let us then consider a more digital thin film deposition technology, Atomic Layer Deposition (ALD). ALD is a cyclic self-limiting chemical vapor deposition (CVD) process [11]. After an initial few cycles to establish nucleation, the deposition per cycle is extremely well controlled and uniform across the sample. Because of the self-limiting nature of the deposition, a uniform flux is not required [12]. To achieve a very reproducible, very accurate thin film thickness across the entire substrate, one simply has to turn the ALD crank a certain number of times. Also because the deposition is extremely conformal [13], maintaining excellent thickness control, even in the face of significant substrate topography, is easily achieved. We are not claiming that ALD is always the correct choice for thin film deposition. There are material quality and economic considerations that may favor other thin film deposition methods. We are saying that the digital nature of ALD makes it much easier to have extremely high manufacturing precision.

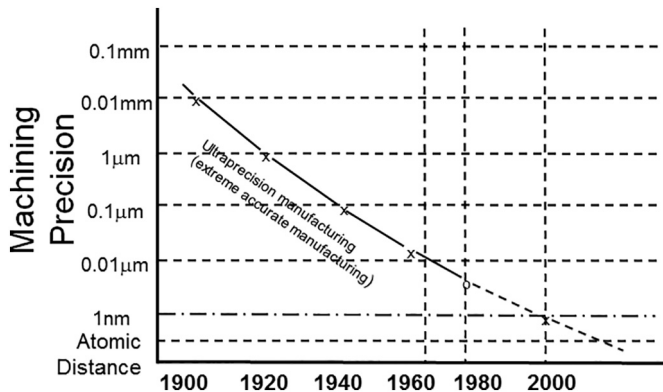


Fig. 3. A modification of Norio Taniguchi's Chart [10] on Machining Precision where only the ultraprecision manufacturing data is shown.

b. A generic digital process

Let us define a generic “digital process” as one that meets the following criteria:

- Lends itself to being interpreted as a digital (binary or multi-valued) result
- Whose digital output can be an input for another digital process
- Has a method of digitally addressing where the process takes place
- Has an “acceptably” low error rate (has some tolerance between digital results)
- Has error detection process(es)
- Has error correction process(es)

We will ask the reader to keep in mind when considering this generic definition a digital process that: The transistors in a digital electronic chip do not really have a digital output. They have an analog output that can be interpreted as a digital output by an appropriately designed circuit. To build complexity, it is required to have a digital output to be an input for a subsequent digital process. A digital address of where the digital process will take place is also a path to a process that can create complexity. There is always some error rate in any process. However, the error rate must not be so high that the error detection and correction processes cannot economically keep up with that rate. The error correction techniques can include the rejection of the output of a process. An acceptable outcome of a multi-step digital process is one that always completes successfully but accepts less than 100% yield of its constituent digital sub-processes. This is certainly the case of modern digital information processes.

c. A working definition of Digital Atomic Scale Fabrication

With this generic description of a digital process in mind, we propose the following definition of a Digital Atomic-Scale Fabrication process. Such a process will have the following characteristics:

- Makes or breaks chemical bonds (serial or parallel) – as a digital result
- A series of digital processes can be executed to fabricate useful complex structures
- Can digitally (spatially) address specific chemical bonds or bonding sites for making or breaking
- Has an acceptable error rate (**Requires some tolerance**)
- Has error detection methods
- Has error correction methods

A hallmark of a Digital Atomic Scale fabrication process is that it will take advantage of the quantized size of atoms and molecules and will improve manufacturing precision over analog fabrication techniques. It is also a promising path to Atomically Precise Manufacturing. But will it, as we assert, be able to take advantage of some of the same digital techniques that have made information technology so successful? Let us provide one example.

d. Borrowing concepts from digital information technology

Consider the transmission of digital information over a noisy communication channel. Typically a data packet (a string of binary bits) will be followed by a shorter string of parity bits. The parity bits are typically a lossy compression of the data packet bits produced by some algorithm. At the receiving end of the transmission, the same algorithm is used on the data packet and its results are compared to the received parity bits. If there is a disagreement then there has been an error in the

transmission and the data packet is discarded and a request for the transmission to be repeated is sent to the transmission station.

A comparison of the digital information technology process and a similar process in the digital fabrication technology domain are compared in Fig. 4. Now consider some Digital Atomic Scale Manufacturing process is producing a nanoscale widget of some sort. This widget could be the end product but as likely could be a subcomponent of a larger system. The design of this widget is completely known in terms of the number and type of all the atoms in the widget and their chemical bonding. Even if each chemical bond breaking and making required to build this widget could be checked at the time of the construction, this might be overly time consuming and expensive especially if the error rate in these digital processes was very low. Instead the entire widget could be fabricated without error checking. But how then, could errors within the 3D nanoscale widget be detected?

The physical manifestation of the widget would contain compressed information about the entire structure. For instance, it would have specific optical, electrical, and mechanical resonances. Since the design of the widget is known exactly, these and other properties would be very specific. Any variation from the expected response would indicate an error and the part could be rejected in a manner very similar to the digital information technology example above. Subsequently, examples of error correction that does not go to the extreme of rejection will be presented.

e. Assembly size limitations and hierarchical assembly

There is another important aspect of creating complex yet reliable systems that applies to any fabrication process whether digital or analog, but does play to the strength of digital fabrication. Complex systems are typically made of numerous components. As pointed out by DARPA Program Manager, John Main, in his conception of his “Atoms to Product” program [14], both biology and human manufacturing when assembling any particular complex structure from component parts generally does not create anything larger than 3 orders of magnitude larger than the parts that make up the structure. Main’s argument for this limitation, which is illustrated in Fig. 5, is that even with a very fast assembly rate of 10,000 parts per second, that creating 3D structures three orders of magnitude larger than the constituent parts is simply too long to be practical. The error rate, particularly in early realizations of Digital Atomic Scale Fabrication will also place size constraints on the output of any one fabrication process. So does this mean that the nanotechnology products that can be produced by Digital Atomic Scale Manufacturing will be limited to sub-micron size? The answer is no, because hierarchical assembly can be used to build larger more complex systems which is consistent with modern manufacturing processes.

InfoTech – Transmission over a noisy channel:

Data Packet Parity Bits
(01011011001001 . . .) (11010. . .)

Lossy Compression

Build a nanoscale widget to an exact specification:

The widget inherently has **lossy compressed data** about its exact structure: mass, resonances, etc.

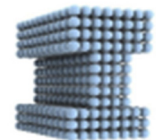


Fig. 4. – Error detection in Digital IT and a similar approach in Digital Fabrication. In each case a lossy compression of the digital structure comes along with the digital output. Inspecting this compressed data will indicate whether there is an error or not. If there is an error the digital output can be repaired or rejected.

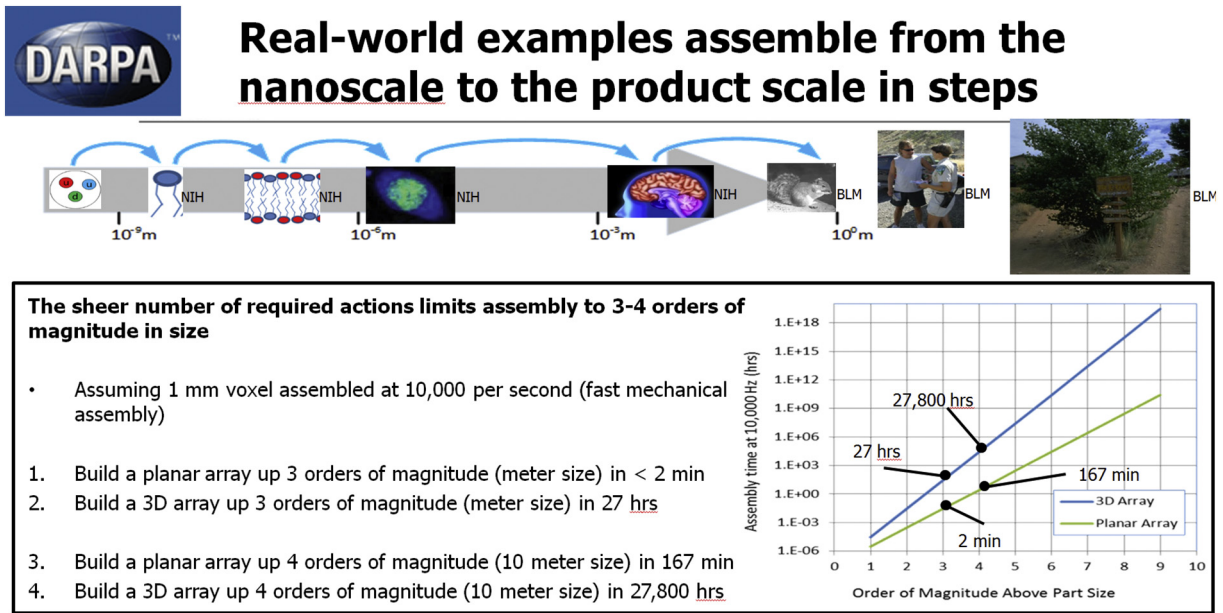


Fig. 5. Slide used by Dr. John Main, DARPA Program Manager describing the limits of assembly when introducing the Atoms to Product (A2P) program.

f. Digital Atomic Scale Fabrication is a broadly applicable concept

While we will present a specific Digital Atomic Scale Fabrication process that is a top down approach, we believe that the concept is valid for a wide variety of nanofabrication processes including self-assembly processes. In fact, we believe that biology is a great example of Digital Atomic Scale Fabrication.

- Biology makes and breaks chemical bonds in processes that create extremely complex structures.
- It controls where chemical bonds are made and broken with local structural/chemical addressing schemes. These processes are controlled by a digital chemical program stored in genetic material.
- It has chemical bond making and breaking processes that have significant tolerance but still make some errors.
- Biology employs numerous error detection and correction processes [15].

Currently there is a lot of excellent work on self-assembly, some of the most exciting of which is using the programmable self-assembly of DNA. We consider this immature Digital Atomic Scale Fabrication. Private discussions with and presentations made by James Alex Little of NIST on the limits of what can be effectively created with DNA self-assembly indicate that this process runs into size limitations not due to time, but due to errors [16]. Others have found similar limitations [17]. We assert confidently that these limitations could be mitigated if error detection and correction processes could be developed and employed.

4. Technical feasibility for a top down digital atomic scale fabrication technology

a. The tolerances of chemical bonds

A concept can provide interesting discussions, but if its implementation is not technologically feasible at present or at least in the foreseeable future, it is not of significant value. We submit that the technological infrastructure does exist to create a top down Digital Atomic Scale Fabrication technology that can be scaled into a

manufacturing technology. We also assert that there are now relevant incentives to do so.

A critical issue to deal with is the tolerances associated with making and breaking chemical bonds. Accessible tolerances are required in chemical bond making and breaking if we expect to create a viable digital technology. Let us consider the tolerances provided by chemical bonds.

Spatial:

- Chemical bond lengths are typically on the order of a few tenths of a nm.
- Chemical bonds will typically break with a roughly 10% strain
- Chemical bond capture distances are on the order of the bond length
- We will present a bond breaking process that has a tolerance on the order of the bond length.

These are challenging length scales, but within the range of available technological infrastructure. For instance, there are displacement sensors with picometer scale resolution.

Energy:

- Chemical bond energies are on the order of eV
- The relevant energy can be the difference between the ground state and anti-bonding state

These energy levels and differences are certainly accessible and we can easily exploit them.

b. Incentives and resources

Just because something is technologically feasible, does not mean that it will or should be produced. However, beyond the promise of enabling the manufacturing of successful nanotechnology products, there are recent events that are likely to create the incentives, and therefore the resources from government funding agencies that will enable Digital Atomic Scale Fabrication technology to be developed. The most compelling is quantum computing and communication. Government agencies all over the world have been funding quantum computing research for more than a decade and recently private investments in quantum computing companies have begun [18]. While there are many different implementations of quantum computing possible, all

will require ultra-high precision, and one of the most promising is the donor spin qubit being developed at the University of New South Wales [19]. This approach has the smallest qubits and the longest coherence times (by orders of magnitude on both counts) and the advantages of being realized in silicon. It does however have the most challenging fabrication approach and one that we believe will be significantly improved by Digital Atomic Scale Fabrication. There is also significant interest in developing quantum materials [20] and an exciting opportunity to at the very least create analog quantum simulation devices and the potential to create quantum metamaterials that could be created by Digital Atomic Scale Fabrication.

Finally, at least in the United States, a government funding agency, the Department of Energy's (DOE) Advanced Manufacturing Office is funding the development of Atomically Precise Manufacturing. Because of the definition of APM by the DOE:

“Atomically precise manufacturing is the production of materials, structures, devices, and finished goods in a manner such that every atom is at its specified location relative to the other atoms, and in which there are no defects, missing atoms, extra atoms, or incorrect (impurity) atoms.” [21].

Digital Atomic Scale Fabrication with its error detection/correction processes is not only a viable pathway, it may be required.

5. A specific example of a digital atomic scale fabrication technique – hydrogen depassivation lithography

a. Description of HDL

Joe Lyding at the University of Illinois developed Hydrogen Depassivation Lithography (HDL) in the mid-1990s [22]. HDL is a Scanning Tunneling Microscope (STM) based technique that actually does lithography rather than, push, pull, or pick and place atoms on a surface. It is in fact a version of electron-beam (e-beam) lithography in that it has an electron source (the STM tip) that delivers a very small spot of electrons on a surface and exposes (actually self-develops) a resist. The resist is the limit of a thin resist, a monolayer of H on a silicon (100) 2×1 surface. The tip/beam is moved around mechanically rather than by electro or magnetic deflection. There are other similarities and some counter intuitive differences, but HDL is certainly related to conventional e-beam lithography tools that are ubiquitous in top down nanofabrication facilities and the industrial tools that make photomasks for the semiconductor industry. Zyvex adopted HDL as an important path to APM in the early 2000s, first published on our progress in 2009[23] and from the start were interested in a digital approach to patterning.

HDL, as we have developed it, is a variable-(not really Gaussian)-spot, variable-energy, vector-scan, e-beam lithography tool. The H resist is self-developed by electron stimulated desorption. HDL is performed on a Si (100) 2×1 H passivated surface [24]. The surface preparation includes a short high temperature anneal followed by a H passivation process where atomic H is deposited on the Si surface at ~ 350 °C. The surface reconstruction provides dimer rows of Si atoms as shown in Fig. 6.

Fig. 7A shows a ball and stick model of the Si 2×1 surface. Since we are developing a digital patterning system, we can use this quantized surface to define pixels. Almost every lithography process defines pixels. What is unique with our approach is that our pixels are directly related to the structure of the Si surface lattice. We have chosen two dimers along a dimer row (4 surface Si atoms) to be our square sub-nm (0.768 nm) pixel. The energy tolerance of the Si–H bonds allows us to image the surface at low bias (either positive or negative) and low current (normal for imaging) without doing any lithography. As is shown in Fig. 7B we can identify the surface lattice and therefore the pixel grid that we use as a digital address grid for the patterning.

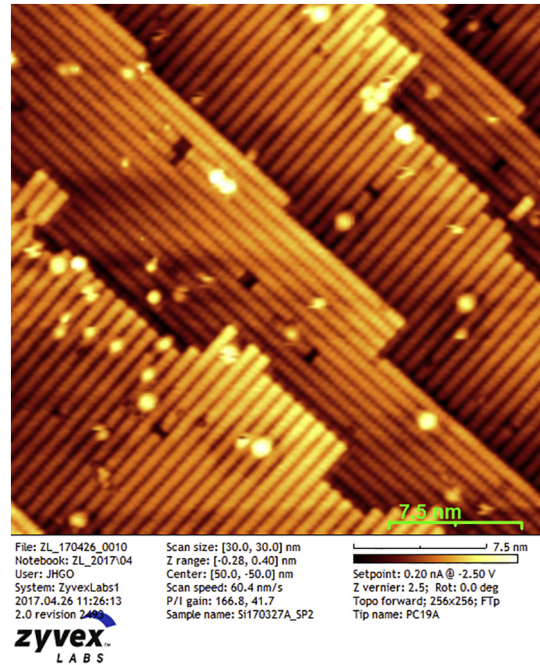


Fig. 6. STM image of Si (100) 2×1 H passivated surface with dimer rows, step edges, Si vacancies and missing H atoms (dangling bonds).

b. Error detection and correction in HDL

This ability to have distinct imaging and lithography modes has advantages beyond imaging the address grid. It also allows HDL to inspect the surface before exposing, make its own alignment marks and later register to them, carry out lithography and then inspect the pattern (error detection) and subsequently, if required, repair the pattern (error correction). We currently can only repair opaque defects (H atoms not removed) by coming back and exposing them. However, Wolkow has demonstrated that clear defects (H atoms inadvertently removed) can be repaired at low temperature by picking up a H atom (from some other area) and placing it back down on the Si atom [25].

c. Exposure modes in HDL

There are two distinct exposure modes as shown in Fig. 8. The low bias or Atomically Precise (AP) mode (2–5 V) is actually a multi-electron exposure mode where electrons tunnel directly from the tip to the sample. A single electron impact does not impart enough energy to the Si–H bond to break it, but can move the bond up the vibrational ladder of states toward the anti-bonding state where it will then desorb. However there are competing phonon-assisted processes which relax the excited bond back down the ladder of states to the ground state. These two competing processes result in an exposure efficiency which is very low, and has a very large dependence on current [26]. This creates an extremely small exposure zone directly under the tip which allows for atomic resolution patterning [27].

In Fig. 8A a sub-nm (two atoms wide) line is exposed in the resist. This extremely small and high contrast exposure zone is the result of two exponential processes: first the tunneling current falls off exponentially with distance resulting in a very sharply defined electron beam spot and then the depassivation exposure efficiency varies with the 8th power of the current [27]. The current, even at atomic resolution is typically several nA. The exposure zone is more than an order of magnitude smaller than the limits of conventional e-beam lithography and has much higher contrast [27]. The bright line in Fig. 8A is where the H has been removed from the surface. A common nomenclature for

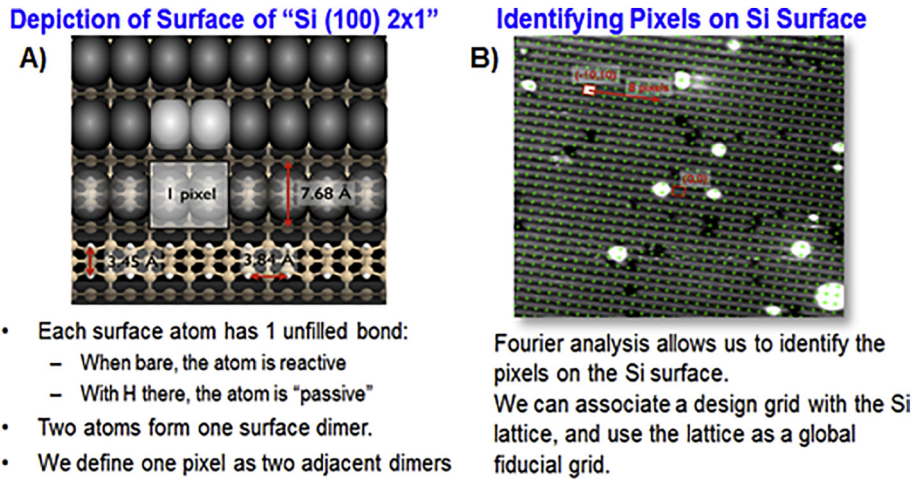


Fig. 7. A) Ball and stick model of Si (100) 2 × 1 H passivated surface showing dimers and our 4 Si atom pixel. B) Identification of positions of pixels (greenes cross at pixel corners) in STM image obtained by image analysis.

the missing H atoms in a H passivated surface is "dangling bonds" indicating where there is an unsatisfied covalent bond.

The high bias mode 8–50 V is a single electron exposure mode where the electrons are Fowler-Nordheim field emitted from the tip and the exposure spot is on the order of a few nm wide and produces some line edge roughness (though effectively less than you would think based on the Fig. 8B image). We refer to this as the Field Emission (FE) mode. Similar to conventional e-beam lithography we fracture the desired pattern into regions to be exposed by the fine beam (AP mode) and the larger spot (FE mode). These lithography modes are both used with positive sample bias. We have determined experimentally that there is up to a +/- 0.13 nm tolerance in tip position in the AP mode when passing down a dimer row and exposing (removing) all H atoms along the dimer row.

In addition to electron stimulated desorption by either exposure mode, there is another process that can remove H from the Si surface and form what we refer to as "spurious dangling bonds". These can be seen in Figs. 8B and 9A as single white dots that are dangling bonds

made some distance from the desired pattern. We believe that these are caused by liberated H atoms that make it back down to the surface and form an H₂ molecule with a bound surface H resulting in a liberated H₂ molecule and a dangling bond [28]. While there is now technology to correct this patterning error [25], as we will point out subsequently there is tolerance to this sort of defect. While there are some advantages of performing HDL at cryogenic temperatures, we do all of our HDL at room temperature and occasionally at elevated temperatures (~250 °C)[29]. Because the clean Si, where the H has been removed is very reactive, we operate HDL at Ultra High Vacuum (UHV) so that the Si remains clean until we dose the surface with a desired species to make chemical bonds in a subsequent Digital Atomic Scale Fabrication process.

We have developed a highly automated tool that performs HDL on various CAD file formats including binary bitmaps where the bitmap pixel is directly related to the four atom pixels on the Si surface. The tip vectors for exposure of the pattern are determined and the order arranged to minimize total tip motion. Examples of HDL

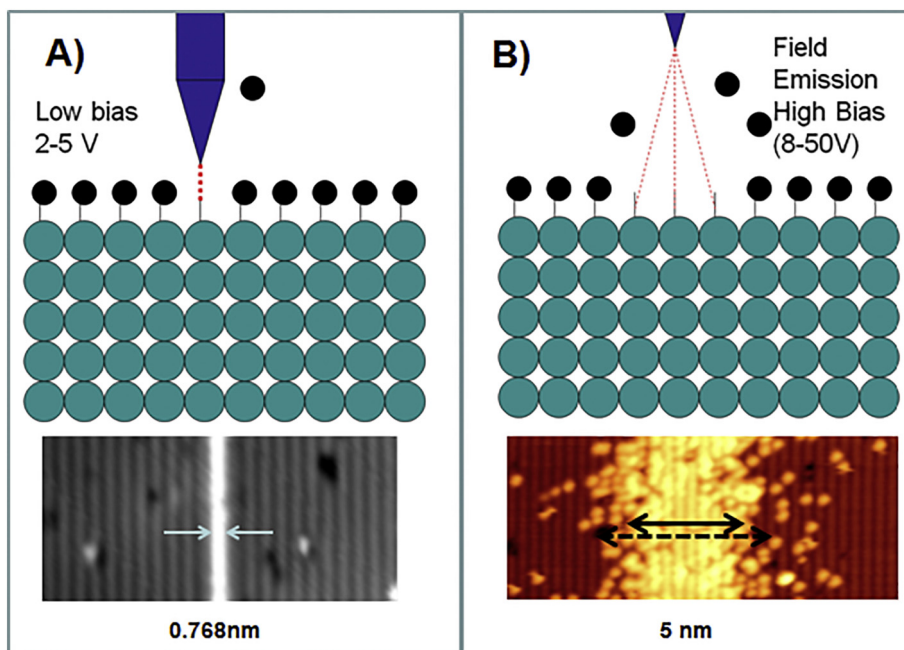


Fig. 8. A) low bias (AP Mode) B) High Bias (FE Mode).

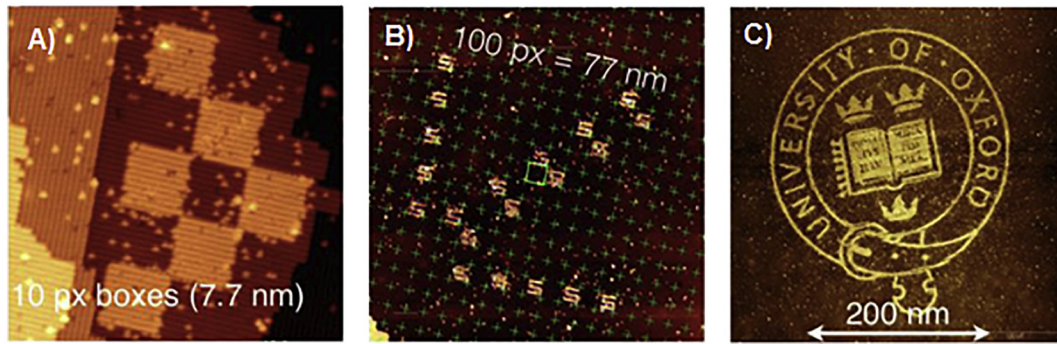


Fig. 9. Examples of atomic precision HDL: A) six 7.7 nm squares B) Alignment test showing sub-nm alignment precision C) Oxford Logo written by Oxford lad, James H.G. Owen DPhil.

accomplished in an automated process at Zyvex Labs are shown in Fig. 9.

d. Utility of HDL – What can you do with a patterned H resist on a Si surface.

We have continually referred to the monolayer of H on the Si surface as a resist. It is a resist because we can pattern it with an electron beam, but will it “resist” an etch process? As far as we know the answer is no. It is not a physical resist. However, it is a chemical resist in that it will resist some chemical vapor deposition processes. For instance we have demonstrated selective epitaxial growth of Si using disilane as the precursor gas [29], selective ALD of TiO_2 [30], and selective deposition of the donor dopant P using PH_3 as the precursor gas [31]. In each case these deposition processes can be considered Digital Atomic Scale Fabrication techniques.

The most technologically interesting of these at present is the patterned deposition of donor dopants. Michelle Simmons at the University of New South Wales has been using HDL to place P atoms selectively on Si surfaces. These donor dopant atoms can be incorporated into a single Si (100) plane and buried in epitaxial Si that can be isotopically purified, which eliminates the unpaired nuclear spin in the ^{29}Si isotope providing for extremely long coherence times of the nuclear and electronic spins in the P atoms. Fig. 10 depicts this process and the method of making metallic Ohmic contacts to the buried electrodes. The ability to place single donor atoms with atomic precision while at the same time with a HDL pattern create the gates that set the spin state of the qubits, control the interaction between qubits, and create the Single Electron Transistors (SETs) that can read out the spin states, makes this a very attractive approach to quantum computing [32]. A company, Silicon Quantum Computing [33], has been formed to commercialize this technology and has received initial funding of 83 M\$(Australian dollars)[34].

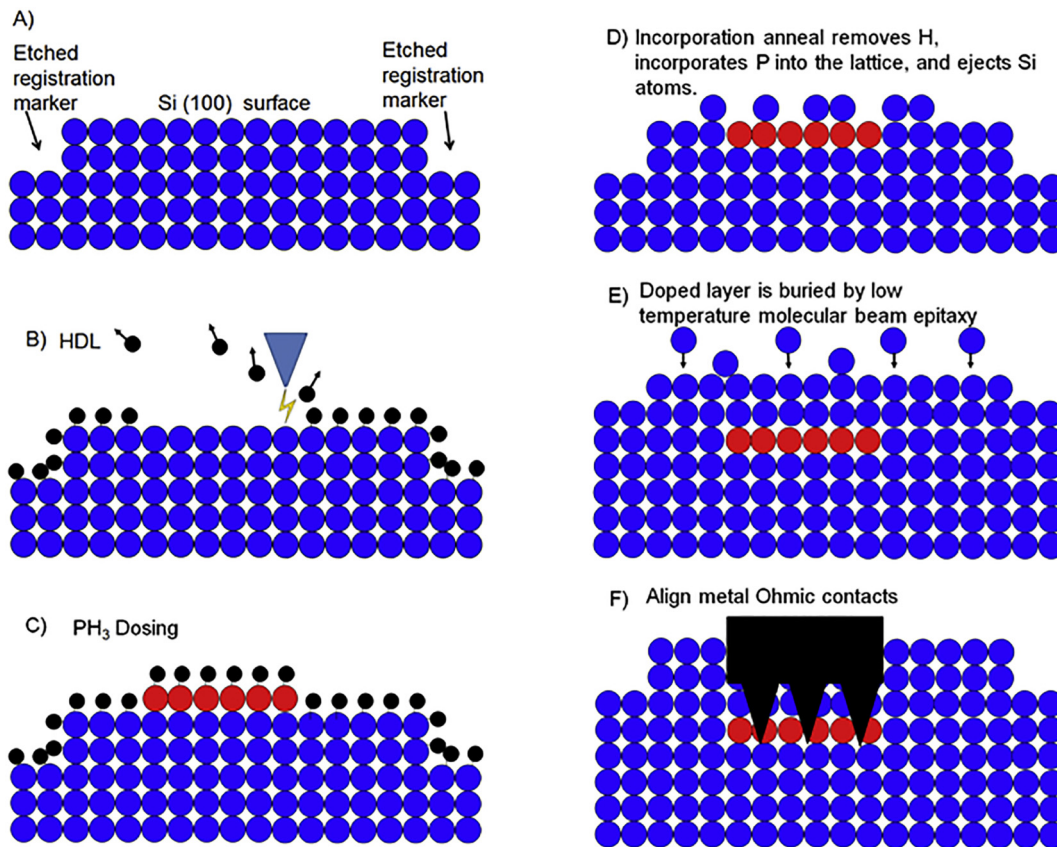


Fig. 10. Illustration showing the fabrication process for delta doped devices a) preparing the Si surface and placing etched alignment markers b) H passivation applied and then patterned with HDL c) phosphine dosing, d) P incorporation, e) Low temp Molecular Beam epitaxy of Si e) Align to registration markers and deposit metallization to make Ohmic contact with P doped electrodes.

Using essentially the same process, periodic patterns of dopant atoms can be used to create 2D super lattices, tunneling contacts, and electrostatic gates. These structures have the potential to create analog quantum simulation devices that can be used to better understand solid state quantum physics. Fig. 11 shows a generic device of this type. The freedom to design the atomic distribution of the dopant atoms in a plane creates significant opportunities to explore a wide range of physics.

Zyvox Labs is receiving funding from the DOE and DARPA to fabricate and test these types of devices. We also have support from the National Science Foundation to develop approaches for selective deposition of acceptor dopants to complement the donor dopants. We envisage the possibility to create quantum metamaterials formed by arrays of dopant atoms placed in silicon with these methods.

The ability to controllably tailor dopant lattices opens an entirely new front in the synthesis of meta-materials that can be used as analog quantum simulations of many interesting systems. Indeed one of the long-standing problems in condensed matter physics is how theoretical predictions of intriguing phenomena can be difficult to realize in ‘real’ materials where unwanted interactions may arise, atomic bonds may vary slightly in strength, character, or direction just sufficiently to spoil the physics being pursued, or the materials synthesis may simply be difficult or impossible. In recent years a key advantage has been developed in cold-atom work where artificial lattices can be induced to mimic many condensed matter systems of interest, from Anderson localization to topological insulators and quantum Hall systems.

The system that can be realized in a Digital Atomic Scale Fabrication process with HDL and selective deposition of P and other dopants controllably placed in a background of Si, arguably comprises a brand new quantum simulator system with the advantage that dopants may be placed *anywhere*, not just purely on a lattice (enabling e.g. disorder effects to be explored); located in one, two, and perhaps even three dimensions. Also, changing the dopant species may introduce new ranges of on-site energies, coupling strengths, and even intrinsic spin-orbit interactions. The relative distance between dopants is a convenient knob for controlling interaction strengths, and extrinsic fields may be imparted relatively easily, including electric fields (by gating), magnetic fields, temperature, and even pressure gradients may be imparted via strain gauges. Indeed, these Si-dopant-based quantum meta-materials have all the advantages of being *materials* that may be readily explored using standard electronic and optical measurement schemes, while enabling the realization of virtually any lattice given one’s patience in building atom-by-atom.

This is an incredibly exciting prospect. There are many ideas for physics in condensed matter systems that have been difficult or impossible to realize in ‘real’ materials that may be possible to explore in

meta-materials. We consider several examples here: First, arranging dopant atoms in honeycomb lattices should enable access to the Dirac physics of graphene [35], black phosphorous [36], or silicene [37], in which a linear dispersion with a spinor structure arises from the physics of electron hopping between two interpenetrating triangular sublattices. Distortions of this lattice mimic magnetic fields and can produce artificial fields up to 100 s of Tesla [38,39], possibly enabling a room temperature quantum Hall effect. Second, by employing atoms with a strong intrinsic spin-orbit coupling, the basic model of a quantum spin Hall insulator may be realized [40], in which gapless spin-polarized states flow at the perimeter of a gapped bulk insulator. This is the regime of topological insulators [41], which are promising candidates for spintronics (through the native spin-polarized currents) and are key ingredients in many schemes to realize topological quantum computation [42]. Alternatively, one may explore the physics of quantum spin liquids in a regime where electron hopping is negligible and only spin interactions remain. Using triangular, honeycomb, or Kagome lattices, it may be possible to induce a frustrated magnetic state [43,44]; in low-spin systems at low temperatures, these can lead to highly entangled and degenerate quantum spin liquid states whose fundamental excitations—differing in various models—can include spin analogs of Majorana particles that may also lead to topologically non-trivial systems for quantum computation [45–47]. Finally, one might construct quasicrystal lattices with no long-range order [48,49] which are thought to manifest unusual electronic transport including interesting topological phases [50,51].

Nanoimprint templates: The most important industrial application of conventional e-beam lithography tools is making photomasks for the semiconductor industry. While the throughput of HDL is presently far too low to even make photomasks, there is an opportunity to make use of HDL and selective ALD to make extremely high precision and resolution nanoimprint templates for specialized applications. This combination is ideally suited for the periodic placement of high-precision patterns where the long range periodicity is not important. An attractive target is ultra-precise filtration with nanopore membranes. There are many industrial applications where ultra-precise separation through filtration could lower costs and energy use [52]. Working with S.V. Sreenivasan at the University of Texas at Austin, we have a proof of principle that HDL followed by selective ALD of TiO₂ and reactive ion etching can produce nanostructures that can be replicated by nanoimprint [53]. A small area of highly uniform pillars, that could be used to pattern a dense array of nanopores, could be stepped out over a much larger area (where the stitching of fields would not require a tight tolerance) to make a daughter nanoimprint or perhaps even a roll to roll template that could produce large areas of very precise filters very cost effectively.

e. HDL qualifies as a Digital Atomic Scale Fabrication technology.

We now consider whether HDL would qualify as a Digital Atomic Scale Fabrication technology. Comparing with the previously listed criteria, HDL breaks Si–H chemical bonds and subsequently chemical bonds of other molecules adsorbing selectively into the patterns are reformed, allowing us to make more complicated structures. We can spatially address the specific bonds that we want to break. We have a fairly low error rate because we have spatial tolerance in tip position. We have error detection and correction methods. In other words, HDL fully qualifies as a Digital Atomic Scale Fabrication technology.

f. The tolerances of HDL

A hallmark of a good digital process is that it has significant tolerances. We have already mentioned the ± 0.13 nm tolerance in tip position. This is a direct result of the well-ordered, quantized Si lattice and the extremely small and high contrast exposure zone of the low bias exposure mode.

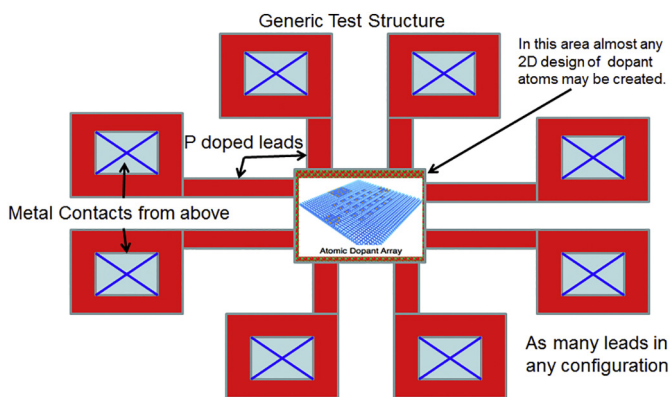


Fig. 11. is a schematic of a 2D super lattice device where the design of the dopant array is only constrained by the sub-nm pixels on the Si lattice. As many tunneling contacts and electrostatic gates as required can be designed in. The entire design is accomplished with a single patterning step.

If the motion control of the tip fails to maintain the required tolerance, errors can be made in the patterning in the form of missing some H atoms or inadvertently removing extra H atoms. Also there can be spurious dangling bonds formed by liberated H atoms making it back down to the surface. As pointed out these defects can be detected and repaired.

The exposure dose has a huge tolerance in that there is no overexposing the resist. Once the H is desorbed from the surface, additional electron dose in UHV does nothing. There is no partial exposure of the resist, the Si—H bond is either broken or it is not. This is definitely a digital response.

There is no accumulated partial exposure of the resist. There can be excitation by an electron dose that moves the Si-H bond up the vibrational ladder of states, but fails to reach the antibonding state. However, in the absence of continuous electron bombardment, this excited state quickly relaxes back down to the ground state.

Because there is no accumulated partial exposure of the resist, there is no proximity effect. The proximity effect in conventional e-beam lithography can dramatically reduce dose tolerances and impairs patterning accuracy and is problematic to correct for.

For the spurious dangling bond defects that can be formed there is significant tolerance to this sort of defect for subsequent digital processes that make chemical bonds in the intended patterns. For all of the selective self-limiting CVD processes that we are aware of, there is no reaction with single dangling bonds [54]. It takes at least two adjacent dangling bonds for molecular chemisorption of the currently used precursor molecules to occur.

g. Microscopy to Lithography evolution.

The capabilities that we have achieved with HDL have only been possible because we have been systematically improving STM technology. The transition from microscopy to lithography is one that has been made before with optical microscopes to photolithography and from scanning electron microscopes to conventional e-beam lithography tools. The requirements for accurate lithography are much more stringent than are required for imaging. The microscope technologies have also benefited significantly as the improvements in optics and associated technologies have migrated back to microscopes.

There has been a knee jerk reaction of significant skepticism whenever we suggest that STM technology could be used in a manufacturing environment. This is because STMs are widely (and deservedly) known as difficult and unreliable instruments that users put up with only because of their atomic resolution imaging capabilities. It is true that STM technology has been relatively static since their invention in 1982. However, that is primarily because there has not been a compelling use for a lithography tool to be developed. Because of the potential of quantum computing and some other highly desirable applications mentioned in this paper, Zyvex Labs has been working, with some key government funding from DARPA, ARO, DOE, and the NSF to improve STM technology so that a reliable and effective atomic resolution lithography tool can be developed.

While there are still many challenges ahead, we have made significant improvements. For example, we have developed a very effective creep and hysteresis correction technology to dramatically reduce the image distortions and positioning errors that have plagued STM users since the inception of STM technology [55]. We have developed automated alignment to the Si lattice significantly improving tip positioning and patterning accuracy [56]. We developed multimode lithography comparable to the variable spot-size technology prevalent in conventional e-beam lithography. We have developed the first significant improvement to the current feedback PI control loop that adjusts the PI parameters dynamically to adjust for changes in the local barrier height [57]. This control loop improvement is an extremely important step toward eliminating the most troublesome aspect of STM operation, frequent tip crashes. We have developed a control system designed

specifically for STM lithography that is a 20-bit system based on a powerful FPGA system on a chip that is very low noise and has very low latency allowing for better real time control as required for lithography [58].

h. Scalability of HDL

The other major obstacle in producing a viable industrial lithography tool is the extremely low throughput of any tool with such a high patterning resolution. Tennant's Law [59] has predicted the areal throughput of serial write tools as a function of their patterning resolution. The trend can be expressed as:

$$At = (R/23)^5$$

where: At is the areal throughput ($\mu\text{m}^2/\text{h}$) and R is the resolution in Angstroms

This means that if we improve the resolution by a factor of 2 the throughput is reduced by a factor of 32. According to this math, HDL with a resolution of 7.68 Ångstroms should have a throughput of 0.0042 $\mu\text{m}^2/\text{h}$. In fact at a current exposure rate of 104 atoms per second we are a little more than 10 times that throughput, and we are fairly sure we can get at least another factor of 10 increase in throughput with no resolution loss, but this is still a very low rate.

In an effort to dramatically improve the throughput of HDL, we have been working with DARPA [60] and DOE [61] support to develop a highly parallel exposure tool by replacing the large piezoelectric tube scanners with Micro Electro Mechanical (MEMS) scanners that are smaller and can be mass-produced as a dense array. A recent study we did suggests that as many as 7 million XYZ STM scanners could fit in the area of a 300 mm wafer [27]. While this is clearly a dramatic improvement in throughput, it could only be accomplished with significant resources and would still be orders of magnitude too slow to compete with the current Deep UV scanners that fabricate our CMOS digital electronics. But this was never our goal. We expect to use a highly scaled HDL as a Digital Atomic Scale Fabrication tool to be used at the beginning of the digital fabrication revolution which will be explained as an Inverse Moore's Law.

6. Other digital atomic scale fabrication processes

As we have indicated previously in this paper, there are a number of other nanofabrication processes that could benefit significantly from a digital fabrication approach.

a. Positioning of Atoms with Scanning Transmission Electron Microscopes

Excellent demonstrations of well controlled positioning of atoms have been demonstrated at Oak Ridge National Laboratories [62,63]. While not explicitly developed as digital fabrication, the demonstrated manipulations have all of the components that could lead to an excellent digital atomic scale fabrication technology.

b. Selective ALD, Atomic Layer Epitaxy, and other CVD processes

Selective Atomic layer deposition is already a process that nearly qualifies as Digital Atomic Scale Fabrication, it makes and breaks chemical bonds with a low error rate in a cyclic manner [64]. It can deposit on a selected address grid. It has significant tolerances. What are not firmly established are error detection/correction processes. Atomic layer epitaxy as actively driven by HDL has been demonstrated [29] but is not yet an effective and reliable process to create atomically precise 3D structures. Selective deposition of dopant atoms in HDL patterns is well established [31] and error detection is possible but currently lacks error correction.

c. Atomic Layer Etching

Various atomic layer etching processes exist [65] and are excellent candidates for turning into Digital Atomic Scale Fabrication processes.

d. Self-assembly processes

As mentioned previously, biology is already using numerous Digital Atomic Scale fabrication processes complete with error detection and correction. There is marvelous work being done in artificial self-assembly processes that are excellent candidates but have not yet developed error detection and correction.

e. Challenges

Most nanofabrication processes rely on chemical reactions that can be wonderfully parallel but are stochastic in nature. This affects both errors and precision. An example is the current process for depositing a single P atom after HDL patterning. It has only a modest yield for incorporating the P atom and a lattice spacing of uncertainty in where the P gets incorporated. Another example is in the patterned Atomic Layer Epitaxy that we have developed, where the disilane precursors only deposit $\sim 1/3$ monolayer per cycle resulting in difficulties in patterning the subsequent layer and a deposition process that is already slow being 3 times slower. We need better precursors and better surface chemistries. Atomic layer deposition and etching processes can be inspected for errors, but error correction processes have yet to be developed.

7. Digital atomic scale fabrication as the path to APM

For too long we have counted on the semiconductor industry to produce nanotechnology products (other than consumer electronics) or at least give us the tool set with which to produce nanotechnology products. We believe that Digital Atomic Scale Fabrication can lead to much improved manufacturing precision. These improvements will allow a number of nanotechnology products and applications to be successfully manufactured that need the precision to control the emerging properties of materials at the nanoscale or for other reasons. But to be successful, this manufacturing technology must find early applications and products that are niche markets with large margins. For this reason, and several others, we do not believe that the semiconductor industry will play a role. Their tools are too specialized, are designed to produce nanoscopic but not highly precise structures, and are too expensive to bother with niche markets.

a. Improved Precision and reduction of errors

We are not equating Digital Atomic Scale Fabrication with Atomically Precise Manufacturing, but we are saying that it is a path to APM. By approaching nanofabrication with a digital approach, we can make significant strides in improving manufacturing precision and reducing the errors that hurt both yield and precision. While the end goal should be atomic precision with as few errors as possible, we expect valuable manufacturing processes to be developed that have less than atomic precision and will include defects. We will provide a cogent example.

Consider the process described above that will produce nanoimprint templates with HDL, selective ALD and reactive ion etching to produce nanoimprint templates to make cost effective nanopore membranes. While the HDL can be atomically precise, selective ALD, while still a Digital Atomic Scale Fabrication process, will not produce atomically precise structures because of the stochastic nature of the initial nucleation of the ALD growth. Reactive ion etching that will produce the master template is not a digital process, nor is the nanoimprint process. However this will produce nanopore filters with unprecedented precision which will be used in the pharma and chemical processing industries.

Without some commercial successes of Digital Atomic Scale fabrication that is not yet APM, we will not have the resources to develop and improve the tools that will enable APM. However, given that there are a host of valuable nanotech products that can be produced with improved manufacturing precision (such as the nanopore filters mentioned above) but not yet APM, we fully expect investments in improving the technology to drive toward APM.

b. Digital benefits

In the longer term it is essential that we as a civilization develop Atomically Precise Manufacturing. The benefits will be dramatically more capable, reliable, efficient, and environmentally sustainable technology. We also must get to APM in order to fully realize the advantages of Digital Fabrication technology. At the same time the advantages of Digital Fabrication technology will help us get to APM.

Let us take a single example to try to make this point. One of the most valuable aspects of digital information technology is the ability to reproduce information exactly. This is because with digital information technology we can have a long string of operations that do not accumulate errors. As a simple surrogate example, we can add a huge number of digital numbers together without any error accumulation and be confident that the sum is correct.

On the digital fabrication side let us assume we have some nanoblocks that are a crystalline material and atomically precise. In other words they have a length that is an exact number of crystal lattice units and mating surfaces that are perfect crystal surfaces. If we bring two perfect matching crystal surfaces together with precision that is accurate to less than a bond length, then they will bond and essentially combine into a single crystal. This process is depicted in Fig. 12. This sort of combining clean surfaces together in vacuum to make extremely strong bonds is known as vacuum welding or cold welding [66]. There is a recent example of bringing two gold nanowires together in a TEM with nanomanipulation capabilities. After bonding the interface between the two previously separate crystals could not be detected by TEM imaging, mechanically testing, or electrical transport [67].

If any number of these blocks are assembled in this manner into a linear structure then the final structure will be exactly the sum of the lattice constant numbers of the constituent parts. In other words, we will have addition with no error accumulation. The sum of the parts will still be atomically precise. This example assumes that we can fabricate these blocks with atomic precision and no defects. However, in the experimental work mentioned above it is unlikely that the two crystal surfaces brought together were perfect. We will also suggest that this sort of bonding has a reasonable tolerance to defects.

Consider two mating surfaces that are each 100×100 atoms in size. Let us consider a 1% error on each of these surfaces resulting in a total of 100 ad-atoms on each surface. This is a very conservative estimate from several perspectives, because the 1% error rate would be high and we are ignoring the likely presence of vacancies. Nevertheless let's imagine that these two surfaces are brought together as suggested by the Fig. 13.

We assume that the 10,000 covalent bonds will overcome the resistance of 200 adatoms forcing some to the edge and out of the interface and forcing some atoms to interstitial sites. This will not be a perfect interface, but it will largely preserve the atomic precision of the complete structure.

The ability to engineer materials at the atomic scale will also permit a large amount of defect tolerance to be designed in. Although it is engineering of materials at the nanoscale rather than the atomic scale, the work of Julia Greer demonstrates that appropriately designed materials have a surprisingly large defect tolerance [68].

We have already pointed to a number of advantages of digital information technology that can be adapted to digital fabrication technology. We believe that there are a large number of other such concepts that are potentially adaptable. Some will probably not be translatable. We are

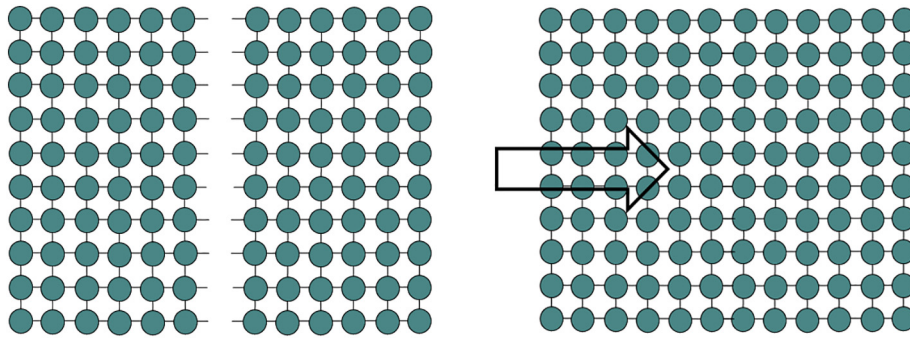


Fig. 12. Vacuum welding of two perfect covalent crystal surfaces.

likely to find other concepts that work well for digital fabrication that are not known in information technology.

8. APM creates the inverse Moore's Law

The end of the exponential trend known as Moore's Law will more or less coincide with the related but much longer exponential trend of improving manufacturing precision. The end of both of these trends will present some problems in that our technological progress and economies have been relying on both of these trends for quite some time now. We believe that there is a great opportunity to create a new exponential manufacturing trend that could be considered an Inverse Moore's Law. First of all, let us consider Moore's Law.

The Law itself predicts the doubling of the number of transistors every 18–24 months. It has done so primarily by improving manufacturing precision so that transistors could be smaller and more of them could fit on a single chip. The size of the chip has remained essentially the same. The function of the chip has remained the same, digital information processing. The complexity and capabilities has grown exponentially.

So basically Moore's Law:

- Downscaling
- Improving manufacturing precision
- Product size remains the same
- Product function remains the same
- Exponential growth in complexity and capability

If Digital Atomic Scale Fabrication enables Atomically Precise Manufacturing which achieves essentially absolute precision and starts manufacturing nano to microscale high valued products, it will start a virtuous circle of investments which improve the manufacturing efficiency which allows the physical volume of any one product to grow while maintaining the atomic precision. This will be product size upscaling of extremely reliable and increasingly complex products.

The products would not be restricted to any particular function. This would lead to a growth of the range of products produced by APM.

So basically APM via an Inverse Moore's Law:

- Upscaling
- Maintaining Absolute Precision
- Product size growth
- Product function growth
- Exponential growth in complexity and capabilities across a wide range of products.

A graph showing a representation of how we think that an exponential Inverse Moore's Law might progress in producing larger and larger products through upscaling the manufacturing process is shown as Fig. 14.

Fig. 14 is an attempt to describe a hypothetical trend over time of the increase in physical volume of products that could be cost effectively made by APM. The rate of increase in volume is based on an assumption that is inversely tied to the downscaling rate that drove Moore's Law.

In contemplating this exponential growth of products that have an ever increasing volume of first ultra-precise and then atomically (absolutely) precise structures, keep in mind that the total product may not need to be ultra or atomically precise. For instance, a nanoimprint template only needs a very small volume of material to be ultra or atomically precise. The complete product would be much larger than the precise portion.

9. Conclusion

As Moore's Law grinds to a halt and we run out of room at the bottom, there is an opportunity to create another digital revolution that involves fabrication at the atomic scale rather than processing information technology. Our proposal is that the making and breaking of chemical bonds will be the digital processes. While we present a specific top down fabrication method, we believe that digital fabrication is a

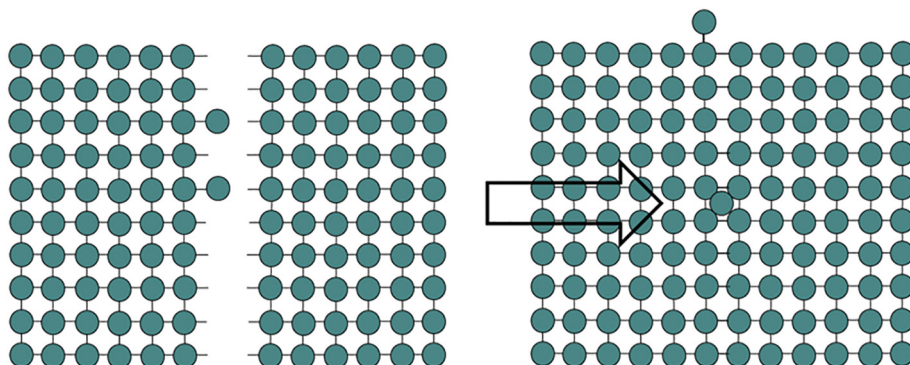


Fig. 13. Vacuum welding of imperfect covalent crystal surfaces.

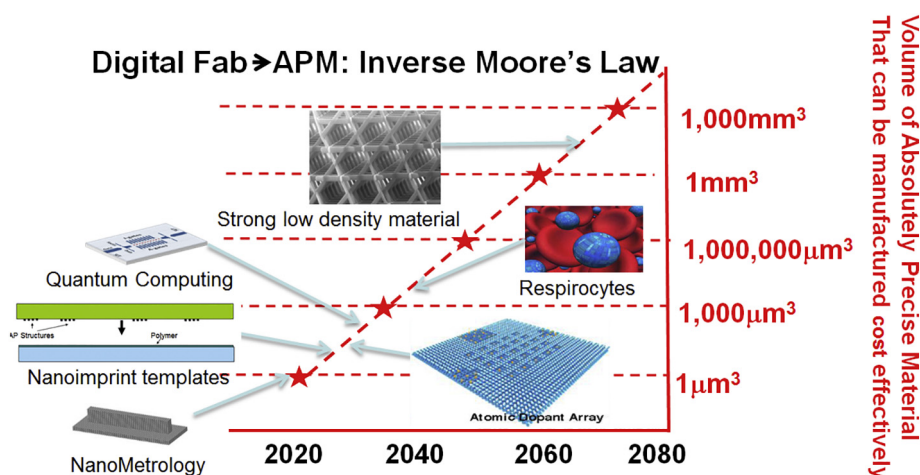


Fig. 14. A graphical representation is shown of the concept of an Inverse Moore's Law.

concept that will apply to many top down and bottom up nanofabrication technologies. Many of the same advantages that propelled digital IT to replace analog IT will be available to digital fabrication. A key process that must be developed is error detection and correction. Semiconductor companies and processing tools are ill-equipped to develop digital atomic scale fabrication. We believe that the technological infrastructure is in place, technological relevance of atomic scale engineering has emerged and funding opportunities are now in place which all create the environment to enable serious efforts to begin to develop this technology. Digital Atomic Scale Fabrication will start off by significantly improving the manufacturing precision at the nanoscale enabling many nanotechnology products in the near term, but will also enable Atomically Precise Manufacturing. All of this activity will start a new exponential manufacturing trend that can be considered an Inverse Moore's Law. This exponential trend will drive our technologies, and economies for the remainder of the 21st Century.

Acknowledgements

This paper attempts to capture a talk that John Randall gave at the 2018 Micro Nano Engineering (MNE) conference that was held in the great city of Copenhagen. John Randall would like to thank the conference organizers, particularly Anja Boisen who really knows how to run a spectacular conference and the wonderful inhabitants of Copenhagen who introduced him to Beer Towers.

This work has been supported by research contracts from the Defense Advanced Research Projects Agency, United States through the Air Force Research Laboratory, United States contract number FA8650-15-C-7542, the Defense Advanced Research Projects Agency contract number 140D6318c0072, and the Army Research Office, United States Contract Number W911NF-13-1-0470. This material is based upon work supported by The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office Award Number DE-EE0008322.

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Conflict of interests

Zyvox Labs has a product that it sells which is an STM controller specifically designed for Hydrogen Depassivation Lithography. We explicitly **do not** mention it by name in the text of this article, but do provide references to relevant information about the unit. Much of our research developing digital atomic scale fabrication is done on this tool and so to the extent that this work is discussed; it is relevant to the article. We also discuss several other approaches.

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