Atomically precise digital E-beam lithography

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ABSTRACT

Hydrogen Depassivation Lithography (HDL) is a version of electron beam lithography that uses scanning tunneling microscope (STM) instrumentation to expose a self–developing resist that is a monolayer of H chemisorbed to a Si (100) 2x1 H-passivated surface. Developed in the 1990s it has been largely a laboratory tool used in research for nanofabrication. The technique is capable of atomic resolution, the ability to remove single H atoms from the Si surface and has much higher precision than the best conventional e-beam lithography can possibly achieve exposing polymeric resists. However, its most promising attribute is that it can be used as a digital fabrication tool and is the first of a class of nanofabrication techniques that can be considered digital atomic scale fabrication technologies. Digital Atomic Scale Fabrication can be shown to have similar advantages over analog fabrication techniques that digital information technology has over analog information technology.

Keywords: Digital Atomic scale fabrication, Atomic precision, Hydrogen Depassivation Lithography, Scanning Tunneling Microscope, nanofabrication, scanning probe lithography

1. INTRODUCTION

Hydrogen Depassivation Lithography (HDL), developed by Lyding\textsuperscript{1} in the 1990s is a version of e-beam lithography that provides a very small spot size using electrons emitted from a cold field-emission source. The technique uses self-developing resist that is a monolayer of H chemisorbed to a Si (100) 2x1 surface; though recent work by Butera has demonstrated that a monolayer of Cl is also a viable resist\textsuperscript{2}. The technique uses scanning tunneling microscope (STM) instrumentation rather than the high-voltage electromagnetic optics and deflectors that are the usual for electron beam lithography.

The STM instrumentation, while delivering atomic resolution patterning capabilities has significant limitations in terms of reliability, accuracy, and programmability. These are common problems whenever a microscopy technology is first used to do lithography. Just as photolithography evolved from optical microscopy, and electron beam lithography (EBL) evolved from scanning electron microscopes (SEMs), HDL is evolving from STM technology. However, there have not yet been the industrial applications of semiconductor fabrication and mask making, which drove the development of photolithography and EBL, to drive the improvement of HDL. With support from government funding agencies\textsuperscript{3-10}, we have made and are making some significant improvements in STM technology for HDL.

The significant differences between the imaging and lithography modes, the fact that the H resist is self-developing, the exposure physics of HDL, and technological improvements to the STM technology that we have made, have allowed us to develop HDL into a digital fabrication technology\textsuperscript{11,12}. In this paper, we will describe the concept of Digital Atomic Scale Fabrication and present its commonality with digital information technology. We will describe digital atomic-scale fabrication’s advantages and present HDL as a specific example. We believe that digital atomic-scale fabrication is an approach to fabrication that could be used by a wide variety of fabrication techniques, both top-down and bottom-up. For many of the same reasons that digital information technology replaced analog information technology, we believe that digital atomic-scale fabrication will start another digital revolution and largely replace analog fabrication starting at the nanoscale, but over time, exponentially growing the physical volumes of digitally fabricated products.

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1.1 Hydrogen depassivation lithography is a version of electron beam lithography

Conventional electron beam lithography (EBL) is a serial write patterning process that uses a small spot of electrons deflected across a substrate to create a useful pattern. The vast majority of conventional EBL systems use high energy electron beams which are focused and deflected with electromagnetic optics to expose a thin layer of a polymeric resist. There are various implementations of EBL including shaped beam, variable spot size Gaussian beam, raster scan, and vector scan exposure approaches.

HDL, as currently implemented, is a variable-spot vector-scan e-beam lithography tool like most of the EBL tools used in research labs. However, it has some very significant differences as shown in the table below.

Table 1. Comparison of conventional EBL and HDL

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Conventional EBL</th>
<th>HDL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>1-200keV</td>
<td>4-100V</td>
</tr>
<tr>
<td>Beam Current</td>
<td>10-100pA</td>
<td>1-10nA</td>
</tr>
<tr>
<td>Optics</td>
<td>Large expensive electromagnetic</td>
<td>No optics</td>
</tr>
<tr>
<td>Deflection</td>
<td>electromagnetic</td>
<td>mechanical</td>
</tr>
<tr>
<td>Resist</td>
<td>Thin polymer</td>
<td>Self-developing monolayer of H</td>
</tr>
</tbody>
</table>

The differences are fairly dramatic. Compared to conventional EBL, in HDL the beam energy is lower by ~ 3 orders of magnitude and the beam currents are higher by 2 orders of magnitude. HDL has no optics and mechanical scanning. Another major difference is what HDL uses for a resist, a monolayer on H chemisorbed on a Si (100) 2x1 surface. At this point the pattern transfer methods for HDL are limited to a few cases of selective deposition, but there are already some very valuable applications including quantum computing qubits.

While HDL is a version of e-beam lithography it is useful to consider just how different the HDL exposure process is from conventional EBL. Many of the differences will seem counter-intuitive for experienced EBL users. Consider the following differences.

- In EBL the higher beam energy leads to lower resist sensitivity while in HDL higher beam energy yields dramatically higher resist sensitivity.
- In EBL higher beam energy is required for small spot sizes while in HDL higher beam energy moves into the field emission regime which produces a larger spot size.

1.2 Resolution limits to conventional E-beam lithography

Since its inception in the 1960s, EBL has improved its resolution by reducing the E-beam spot size. This has been done by raising the beam energy to reduce its diffraction and by improving the electromagnetic optics to reduce distortion. A practical limit to the energy of the beam is around 250keV when high energy electrons can displace atoms. Using 200keV beam energy and aberration corrected optics, it is possible to produce spot sizes on the order of 0.1nm.

However, in conventional e-beam lithography where high energy electrons are focused to a small spot and scanned over a surface to expose a thin polymeric resist, the resolution is limited by other processes that are captured in the point spread function which describes the lateral spread of energy that exposes a resist from an infinitely small-diameter high-energy primary electron beam. The point spread function has the following components:

- Forward scattering – The scattering of primary electrons as they pass through the resist. This effect is diminished by using higher energy beams.
- Back scattering – Primary electrons that scatter from the substrate and then pass through the resist again spreading the exposure zone significantly though typically at a low level. The level of this effect is increased by high Z substrates and the lateral extent is increased by higher energy beams.
- Secondary electrons – low energy electrons generated by inelastic scattering from the primary beam
- Volume Plasmons – charge waves created by the high-energy primary beam passing through the resist.
Karl Berggren’s group\textsuperscript{19} sought to explore the limits of resolution in conventional e-beam lithography. To minimize the spot size they chose an aberration corrected 200keV Scanning Transmission Electron Microscope. The high energy is required to get a very small spot size and it decreases forward scattering. Forward scattering was also reduced by using a thin (20nm) layer of hydrogen silsesquioxane (HSQ) resist. To minimize backscattering they used an extremely thin (10nm) SiN substrate. There was little they could do to reduce the number or range of secondary electrons or volume plasmons given their other choices. They both simulated the point spread function (PSF) and took experimental data to measure the PSF. Their data is shown in Figure 2 taken from reference \textsuperscript{19}.

![Figure 2](image)

Figure 2. Plot from reference \textsuperscript{19}. This figure plots the normalized resist exposing energy density in arbitrary units as a function of radius from the center of the electron beam. The different components (ignoring backscattering which was largely eliminated) of the PSF

The key take away from this paper and its figure is that even with the extraordinary efforts to minimize the components of the point spread function that accompanies a very small spot size, that the deposited energy density is still at about 10% of the maximum under the beam at 4nm radial distance and there are long tails to the PSF.

1.3 HDL process

HDL is carried out on a Si (100) 2x1 H passivated surface in Ultra High Vacuum (UHV) usually at room temperature. The Si (100) 2x1 reconstructed surface forms dimer rows as shown in Figure 3, which change direction by 90\degree wherever there is a single-height step edge at the boundaries of a terrace. For our digital lithography process we choose two dimers (four surface Si atoms) along a dimer row to be our pixel. Each pixel is a sub-nm (0.768nm) square. Figure 4 shows a ball-and-stick figure of the Si (100) 2x1 surface and our choice of a 4 atom pixel. It also shows an STM image with significantly lower resolution than in Figure 3, where we have used a Fast Fourier Transform image analysis to define where our pixels are in spite of the low resolution. We use this pixel identification to align to the Si lattice and guide our tip vectors to expose (remove) the H from the Si surface.

HDL is currently realized as a variable-spot-size, vector-scan system with two distinct exposure modes as shown in Figure 5. The small spot, atomically precise mode is at a low bias (2-5V) and electrons tunnel from the tip to the sample and cause the H to be desorbed from the surface. As explained below, the effective “spot size” or exposure zone diameter is on the order of 0.4 nm. This allows the STM tip to be guided along a dimer row removing both Si atoms. Patterns may be fractured as in conventional EBL and the field emission mode can be used to pattern “Larger” areas much more quickly not only because the spot is bigger, but also because the exposing efficiency is much greater.
Figure 3. An STM image of a Si (100) 2x1 H passivated surface. The distinct rows on the surface are two Si atoms wide and are called dimer rows. The dimer rows change direction by 90° at atomic step edges. The step edges are going down from the bottom left to the upper right. The bright spots are missing H atoms (dangling bonds). The dark areas are missing Si atoms.

Figure 4. Left - Depiction of surface of “Si (100) 2x1” Right - Identifying pixels on the Si(001) surface

Figure 5. Left – Low bias tunneling mode can expose a single pixel line. Right – Higher bias field emission mode has a bigger spot size and has much higher exposure efficiency.
The monolayer of H atoms, which serves as a resist, is self-developed by electron stimulated desorption. At these low biases there is not sufficient energy to electronically excite the Si-H bond into the anti-bonding state directly and the exposure process is a multi-electron process which causes vibrational heating moving up the vibrational ladder until the kinetic energy is high enough to break the Si-H bond. However, there is a competing phonon-driven process that moves the Si-H bond back down to the cold ground state. The fact that this is a multi-electron process and the fact that the cross-section for inelastic collisions imparting energy to the Si-H bond is very small leads to a very inefficient self-developing process. However, this inefficiency is one of the reasons that the resolution of HDL is atomic scale.

While the atomic resolution of HDL is well established, and the multi-electron process is supported by experiments the electron distribution and the effective spot size or exposure zone of HDL has not been well studied until recently. It seems counter-intuitive that with no optics a tip roughly 1 nm away from the surface would be able to pattern with sub-nm accuracy. To better understand this, we created a simple model as shown in Figure 6.

The tunneling current distribution is fairly sharp, but not sharp enough to explain the resolution that we see experimentally. Previous theory and experimental work shows that the multi electron exposure process is highly non-linear with respect to current. This is due to the competing phonon process that reduces the kinetic energy moving the bond back down to the cold ground state. The lower the current, the more electrons it takes to win the race against the phonons to get the kinetic energy high enough to break the bond. This is also why the desorption efficiency is also highly non-linear with respect to bias, as it takes fewer electrons at higher energy to beat the kinetic energy lowering phonon process. Beneath a certain current threshold at a particular bias, the phonons always win. This is why the imaging mode, which is typically at much lower currents, does not cause H desorption even with positive sample bias.

The previously published theoretical work suggested that the depassivation efficiency, that is the number of electrons required to desorb H atoms (depassivate the Si), goes with roughly the 8th power of the current. The experimental work from the same publication showed considerable scatter in this sensitivity.

We carried out some additional experimental work to determine the depassivation efficiency as a function of dose. The results of those experiments are shown in Figure 7. The method of those experiments are as follows: We exposed a series of small patches on H passivated Si (100) 2x1 surfaces at different currents and different scan speeds using our usual positive sample bias of 4V. Since the depassivation process is somewhat stochastic, there was not a clean threshold of dose, determined by scan speed, at a specific current that separated the removal of all H atoms in the patch from no depassivation in the exposed patch. We took the minimum dose at which roughly half of the H atoms in the patch remained to calculate the depassivation efficiency. These experiments were repeated several times and the H/e data was averaged for each current. A power law fit to the averaged data yielded an exponent of 4.91. This result falls within the range of the experimental data in reference 20.

With this non-linearity of H/e quantified, we can apply this function (exposure efficiency is the current to the power of 4.91) to the calculated current distribution from Figure 6 and see the spatial distribution of the effective exposure efficiency as depicted in Figure 8.
Figure 7. A plot of the depassivation efficiency, or the number of H atoms removed per electron (H/e) which is the Y axis of the plot as a function of the set-point tunneling current from the STM tip which is the X axis with units of nm.

Figure 8. Normalized radial distributions of tunneling current and depassivation efficiency. The Y axis has arbitrary units and is in a logarithmic scale. The X axis is radial distance from the center of the exposure spot and has units of nm.

Figure 8 can be used to understand the extremely high resolution of this exposure method. There are two extremely nonlinear functions that create this extremely small “exposure zone”. The physics of tunneling currents provides not only a small electron beam spot, but also extremely short “tails” compared with usual Gaussian tails of conventional EBL. The second highly nonlinear function of exposure efficiency with current amplifies the spatial confinement. At a radial distance of 0.5nm the tunneling current is down a little over one order of magnitude. But the exposure efficiency, because of the current non-linearity, is down almost 6 orders of magnitude at that same distance. While this distribution is based on a model, it explains reasonably well our experimentally determined patterning data. Because we are exposing a surface that is well ordered in pixels with such a sharp exposure zone, which can be adjusted (by changing the current), we actually have some tip position tolerance that still permits perfect patterning. At present we still have some errors because the tolerance is still challenging in the face of thermal drift and creep and hysteresis. Fortunately we can use the Si lattice as a global fiducial grid and keep these errors reasonably low.
1.4 HDL and EBL resolution and precision comparison

To understand just how much of an improvement in resolution and precision HDL represents, it is instructive to compare to the distribution of exposure efficiency of conventional EBL as described in reference 19. Figure 9 plots the normalized experimentally determined exposure efficiency of conventional EBL at or very near the limit of what is practically achievable with this technology with the spatial distribution of exposure efficiency of HDL.

![Figure 9. Comparison of the normalized radial distribution of the exposure efficiency of EBL and HDL. The Y Axis is the normalized exposure efficiency in arbitrary units. The X axis is radial distance from the center of the beams in units of nm.](image)

It is obvious from Figure 9 that HDL is a much sharper tool that will have dramatically better resolution and make much higher contrast images. However, the graph does not tell the entire story. Because of the digital response of the H resist there is no remaining partial exposure of the resist. If a neighboring H atom gets some exposure dose, but not enough to break the Si-H bond, once the electron flux stops hitting the Si-H bond the vibrational energy quickly decays back down to the cold ground state. With no residual partial exposure, there is no proximity effect that will change the dimensions of the exposed region depending on the level of exposure nearby. This makes HDL not only much higher resolution than EBL but also makes its precision and accuracy much better.

An additional advantage of HDL over EBL is that, as mentioned above, the imaging mode does not expose the resist so the completed lithography may be inspected. This means that HDL may write its own alignment marks, and in fact use previously written portions of the pattern as alignment marks allowing for much easier scan field stitching by aligning to design features that run across scan field boundaries. But an even more powerful advantage is the opportunity for error detection and correction. Since we can inspect the pattern and find errors, for instance when we fail to remove some H atoms that should have been removed, we can come back and remove them. Recently, Wolkow has shown the H atoms can be replaced on the Si surface with atomic precision presenting an opportunity for perfect patterns via error detection and correction. This is simply not possible with conventional EBL.

1.5 HDL is scalable

As a serial write tool, with extremely high resolution (0.768nm) HDL obeys the speed limit imposed by Tennant’s Law and has extremely low throughput. However, it is scalable in a way that conventional EBL simply is not. Several significant efforts have been made to parallelize e-beam lithography to make it viable as a direct write tool to manufacture devices, but they have all essentially failed due to Coulomb interactions of the electrons between the source and the sample which is stochastic and therefore defies correction. By replacing STM piezoelectric scanners with Micro-Electro-Mechanical System (MEMS) scanners, the footprint of a 3 degree of freedom MEMS positioner with electrostatic actuators may be reduced to the point that on the order of 7 million scanners could fit in the area of a 300mm wafer. Because the beam path is so short (a few nm at most) and the separation of tips is >10,000 times larger than the beam path, there is essentially no Coulomb interaction.

The other problem associated with this sort of massively parallel integration is that the wiring and crosstalk problem of routing analog signals into a large array of scanners would be a nightmarish problem. However, it would be possible to use local microcontrollers to control a small set (9-16) of MEMS scanners. In this way the MEMS and microcontrollers
could be put on a power bus and microcontrollers could be put on a data bus to receive high level instructions. This architecture would greatly simplify integration challenges.

Even with 6-7 orders of magnitude improvement in throughput, this technology would still be far too slow for consumer electronics. However, for high-performance, high-value products like solid state quantum devices that need atomic scale resolution and precision, but do not need billions of devices, this would be a viable manufacturing path. Moreover, this study assumed MEMS technology that is commercially available today, and there is still quite a bit of downscaling of MEMS that could push tip density quite a bit higher.

1.6 HDL as Digital Atomic Scale Fabrication
The following properties of HDL make it the first lithography technology that has the following attributes:

1. It has a binary process that is the breaking of a chemical bond.
2. This process has some technologically accessible tolerance which keeps errors reasonably low.
3. We have a digital (spatial) address grid which is the Si surface lattice.
4. Error detection and correction is possible.

We believe that these four attributes can be slightly abstracted to form a definition for a wide variety of nanofabrication processes that can be developed as Digital Atomic Scale Fabrication.

2. DIGITAL ATOMIC-SCALE FABRICATION

2.1 Nanotechnology has failed to live up to its promise
Zyvex is a nanotechnology company that has been pursuing nanotechnology products for over two decades. While we have had some successful products, we believe that Nanotechnology has significantly underperformed its potential. While there has been a lot of nanoscience and a number of worthwhile simple nanoproducts, with the exception of the semiconductor industry, there are no complex devices or nanosystems. The exception of semiconductors is an interesting example where digital electronics allow for poor relative precision in manufacturing. While thin film control is much better lithographic relative precisions are on the order of +/-10% at best at the minimum feature size. The fundamental reason that we see no complex nanosystem products is lack of manufacturing precision at the nanoscale.

2.2 Analog vs digital technologies
We believe that nanotechnology is about where information technology was when it was primarily analog. In the 1960’s and 1970’s we had telephones, televisions, radios, tape recorders, and plastic discs with wiggly grooves. This technology was certainly useful to store and transmit information, but the impact was nowhere near what it has become since our analog information technology was replaced by digital technology. There are a large number of technical reasons that digital information technology is superior to analog 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
- **Outrageous complexity with extremely high reliability at an ever decreasing cost!**

The advantage that I want to highlight is the error free reproduction, but it is important to point out that the lack of errors is only because of error detection and correction.

2.3 A new digital revolution
We believe that there is a fantastic opportunity to start a new digital revolution in fabrication manufacturing. We expect that this will start at the nanoscale but will eventually encompass all of manufacturing through an exponential manufacturing trend that I will refer to as an Inverse Moore’s Law. This will be described subsequently.
“Digital manufacturing” is an often used phrase and has been defined in many ways. We want to make a very specific definition about a class of manufacturing that we think will start this new digital revolution at the nanoscale and will take advantage of the digital nature of material at the nanoscale where matter is quantized. Digital Atomic Scale Fabrication is defined as a class of fabrication techniques which have the following characteristics:

1. **Binary functions** are making and/or breaking chemical bonds
2. There is some **technologically accessible tolerance** to the binary process
3. **Spatial - digital addressing** is possible to control where bonds are made and/or broken
4. **Error detection and correction methods** are developed

The astute reader will note that we have already indicated that HDL has these characteristics and therefore fully qualifies as a digital atomic scale fabrication technology. We believe that there are lots of other nanofabrication techniques that could be developed to incorporate these features and therefore significantly enhance their precision to allow them to eventually manufacture atomically precise structures. A key feature is the spatial digital addressing of the binary functions (making and/or breaking chemical bonds) which permits a large number of products to be made by the same manufacturing process simply by programming where the chemical bonds are made or broken. We note that evolution has developed a digital atomic scale fabrication technology that we refer to as biology, a technology that uses relative digital spatial addressing and lots of error detection and correction.

We note that virtually all of the manufacturing that we now do at the nanoscale is analog fabrication in that it treats matter as if it is infinitely divisible. Lithography, etching, deposition, chem-mechanical polishing, etc. are all essentially analog techniques.

We assert that digital atomic scale fabrication is a route to improve a wide variety of nanofabrication techniques including bottom-up, self-assembly techniques such as DNA origami and other self-assembly technologies which often, in their present forms, already have all of the attributes listed above save error detection and correction. I note that a number of DNA assembly researchers are beginning to talk about the need for error detection and Correction\(^\text{36}\).

### 2.4 Borrowing from digital Information technology

Many decades of developing digital information technology have produced useful processes that can be adapted to digital atomic scale fabrication. While there are many, I will point to one that deals with the important aspect of error detection and correction.

Consider the digital information technology approach to communicating digital information over a noisy communication channel. A data packet of some length of bits is transmitted that is followed by a packet of parity bits. The parity bits typically contain lossy compressed information about the bits in the data packet that are produced by a specific algorithm. The receiving station reads both the data packet and the parity bits and then runs the same algorithm on the data packet. If the results of the algorithm do not agree with the received parity bits then there has been an error. If an error is detected, then the received data is discarded and a request is sent back to the transmitting station for the datapacket/parity bits transmission to be repeated.

Consider a Digital Atomic Scale Fabrication process producing nanowidgets with an exact design of all atoms and chemical bonding between the atoms. Even if it is possible to inspect each chemical bond modification or creation during fabrication, that may be expensive. The end result can be interrogated. In this case, the equivalent of parity bits are not required. Inherent in the physical structure of the nanowidget is compressed data about its structure. For instance, it will have a specific mass and specific optical, electrical, and mechanical resonances. Interrogation of one or more of these properties will be able to detect an error. If there is an error the nanowidget can be discarded or its material recycled. There are many other digital information technology techniques that can be adopted by digital atomic scale fabrication.

### 2.5 We are running out of room at the bottom

Norio Taniguchi, who first coined the term nanotechnology in the mid 1970’s plotted the historical trends in manufacturing precision and extrapolated into the 21\(^{\text{st}}\) century\(^2\). A subset of his data, that of the bleeding edge of manufacturing precision is shown in Figure 10-A. This shows the remarkable improvement of approximately 100,000X improvement in manufacturing precision over the past 100 years. This improvement in manufacturing precision has driven our science and technology impacting many industries, but none more dramatically than the progress of the
semiconductor industry as captured in Moore’s Law, depicted in Figure 10-B. The predicted and fulfilled doubling of transistors on a chip has been accomplished largely by downscaling which is only possible by improving manufacturing precision.

![Figure 10 A – Taniguchi’s plot of the leading edge of manufacturing precision. B- Moore’s Law C- Inverse Moore’s Law](image)

However, considering Taniguchi’s plot, there is a warning inherent in the data. Note the annotation of “Atomic Distance” in the Y Axis of his plot, and the fact that he has correctly predicted that we would be, at least in thin film deposition, at this physical length scale in precision. The fact of the matter is that we do not have another 5 orders of magnitude in improvements of manufacturing precision because of the quantized nature of matter. Although not inherent in the Moore’s Law graph it is widely acknowledged that downscaling and Moore’s Law is grinding to a halt. While there are other paths to technological advancement, the exponential improvement in our manufacturing precision has been an extremely powerful enabler of technology progress and the advancement in our science that is enabled by advancing technology. If we do not do something different, we will have science and technology stagnation.

2.6 An inverse Moore’s Law

We propose that a new exponential trend in manufacturing is possible. We think that it is essentially Moore’s Law turned on its head. Consider the main features of Moore’s Law:

- Exponential increase in product complexity by downscaling
- The downscaling is enabled by improved manufacturing precision
- The product size has remained constant to first order
- The product function has remained information processing

We believe an Inverse Moore’s Law will create a new exponential manufacturing trend where:

- There is an exponential increase in product complexity by upscaling the physical volume of the products
- This is accomplished by first achieving and then maintaining Atomic precision while upscaling
- The product size increases exponentially
- The product functions can be diverse

Figure 10-C is a guess at an exponential trend in product physical volume and some of the early products. The manufacturing process will necessarily include hierarchical assembly of atomically precise sub-components. We believe that this new exponential manufacturing trend that will start with Digital Atomic Scale Fabrication can drive our economy, technologies, and standard of living through the rest of the 21st century.

3. CONCLUSIONS AND DISCUSSION

We have described an emerging version of electron beam lithography that is carried out with STM instrumentation that is referred to as HDL. This technology has dramatically better resolution and precision than conventional EBL. It’s resist is the limit of a thin self-developing resist, a monolayer of H chemisorbed to a Si (100) 2x1 surface. HDL achieves
atomic resolution at room temperature in UHV. The pattern transfer techniques are restricted to selective deposition. Its throughput is very low but it is scalable through massive parallelization.

HDL has been developed as a digital technique that is of a class of nanofabrication that we define as Digital Atomic Scale Fabrication. We believe that this represents a new digital revolution that can borrow quite effectively from digital information technology particularly in error detection and correction. We believe that Digital Atomic Scale Fabrication is a concept that is valuable to a wide range of nanofabrication techniques, Top-Down, and Bottom-Up alike. We also believe that nanofabrication techniques that utilize this concept will enable Atomically Precise Manufacturing which could provide a new exponential manufacturing trend to replace the continual improvement of manufacturing precision and its most widely known example of Moore’s Law, both of which are grinding to a halt because we are beginning to have to deal with the quantized nature of matter. We call this new exponential manufacturing trend the Inverse Moore’s Law.

4. ACKNOWLEDGEMENT

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