NANOSCALE GRID BASED POSITIONING SYSTEM FOR MINIATURE INSTRUMENTED ROBOTS

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Abstract

To position an autonomous wireless robot (NanoWalker) over a sample's single atom so it can be imaged or manipulated, a Scanning Tunnelling Microscope (STM) is to be mounted on the robot itself. To do so a custom-built positioning system is developed. This requires the use of two sub-systems. The first to provide coarse positioning of the mobile unit in the micrometer range over a sample. To enable sub-micron range positioning of the NanoWalker, a second system is developed. Two different concepts are described. The first regards the usage of a tri-dimensional binary code to identify a single square. The second uses a variable-width line grid to uniquely characterize every intersection within the working surface. Many materials are considered, and the present work focuses on the results obtained on a Highly Oriented Pyrolytic Graphite (HOPG) sample. A preliminary screening of the machining techniques available suggested the use of Focused Ion Beam (FIB); other techniques are also considered. Conclusions are drawn upon STM imaging.

Keywords: Nanorobotics, STM, HOPG, reference grid.

1. INTRODUCTION

This article discusses the fabrication and the first tests of a reference grid system with nanometer scale resolution for applications in NanoRobotics and nanotechnology. The goal of the proposed reference system is to enable atomic positioning of a Scanning Tunnelling Microscope (STM) tip over a sample's single atom.

The initial context in which this grid is constructed is the NanoWalker project previously described in [1], [2]. The aim of this project is to develop a wireless three-legged robot, called NanoWalker, equipped with an STM [3] for applications in nanotechnology. In the specific case of the NanoWalker, the complex problem of positioning its STM tip over an atom is tackled in three separate phases in which two distinct technologies interact. Firstly, due the shear number of atoms present on large surfaces, limiting the area in which to reference these atoms is essential. To do so, many sample-holders are embedded in a 0.8 x 0.8 m area; each of them contains a special surface on which many copies of the reference pattern have been etched. The necessity to limit the number of sample holders to a hundred or so is due to the robot's size and ability to move around on the aforementioned surface. With smaller robots, such as the one currently being developped in the Walking-Die project [4], many more sample holders could be embedded in the same surface, thus largely increasing the parallel treatment capabilities of the system.

Using a system based on a Position Sensing Device (PSD) [5], the robot is first instructed to move over one of the created patterns. This enables coarse positioning of the STM tip within a few square microns of the wanted atom. From there, the pattern etched on the scanned surface is used to further improve accuracy of the tip localization. An atom counting technique is finally to be employed to localize the individual atoms of the reduced area. This paper focuses on the second phase described. The proposed technique has the advantage to permitthe absolute localization of features within a large area without having to resolve to any optical means or human intervention.

2. GRID CONCEPTS

The first challenge of the proposed grid localization system is to fragment a large area into a multitude of smaller windows in which the STM-equipped device can work. Each of these smaller windows has to be uniquely identifiable in order to be used as a localization device. Therefore, every window is separated into two distinct parts: first, the actual work area which needs to be as flat and regular a surface as possible to facilitate future STM scans and second, a coding mechanism needs to be integrated in the pattern to distinguish the different windows composing the grid.

Two approaches were studied for the grid concepts. Both rely on the STM's main characteristic, i.e. to measure a surface's topography. The first concept is to etch on a material a matrix of work windows uniquely identified by a binary code. This code is composed of rectangular bits etched at different depths within the material. The reason behind this concept is that, by nature, the STM is better suited to take depth measurements than to measure width of features, so an encoding mechanism that relies solely on abrupt depth variations of the surface should be reliable.

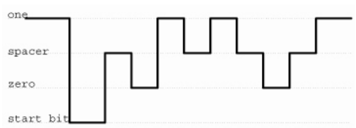

Fig. 1. “Binary code” concept cross-section

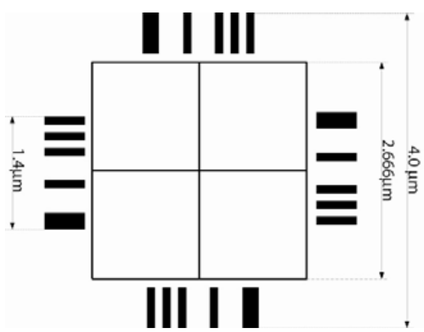

Fig. 2. “Binary code” concept window layout (code 40)

The main problem *a priori* with this code is that it is directional, meaning that the interpretation differs if the code is read from left to right or from right to left. To prevent this potential problem, a special feature is integrated to indicate the start of the code. To distinguish between two consecutive bits, a buffer zone is inserted in between. In total, three different heights are needed to fabricate the code. First, the ``start'' bit is etched at a great depth. Second come the zeroes etched slightly higher, followed by the bit spacers used to separate two consecutive bits. The ones are simply non-etched regions of the material (see Figure 1). Finding the binary code is the first to step to identify the work window. To maximize the chances of imaging a complete code with any random STM scan around the window's area, the same code is repeated four times around the square window. By dividing the window into four sub-windows, nine unique intersections are created. These intersections served as reference points from which to start the atom counting technique. Figure 2 is an illustration of a window layout, the black lines represent the surface to be etched. For clarity, the spacer bits are not represented.

As an alternative to this three-dimensional structure, a single-depth pattern was engineered. This more ``analog'' encoding scheme consists of a grid pattern with gradually increasing line width. The non-etched region encompassed between two intersecting pairs of parallel lines forms
the NanoWalker's work window. The size of these windows is kept constant throughout the grid (see Figure 3). This concept maximizes the surface usage by not requiring any dead space between the coding mechanism and the work area. By measuring the width of a vertical and horizontal etched line, the NanoWalker will be able to uniquely determine where his STM tip is over the pattern. Each intersection of the pattern is unique and, from one, atom counting can be started.

In the current implementation context, the grid dimensions need to be tailored in such a way to support the NanoWalker's constraints. Since the PSD-based system has a predicted precision of ±15µm [6], the whole grid pattern must be at least 30µm wide to allow the STM to reach a coded part of the sample. Furthermore, the piezo actuating the robot's STM has a maximum deflection of ±1.6µm [7], the coding mechanism used to identify each work window composing the pattern must be within the range of any random 3µm STM scan executed by the NanoWalker.

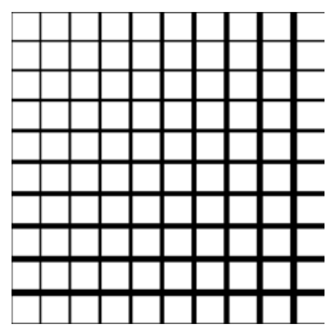

Fig. 3. Variable line width grid pattern

3. MATERIAL & FABRICATION

Scanning Tunnelling Microscopy relies on the conductivity of the scanned surface, the material used to fabricate the grid must therefore be conductive. Furthermore, a very regular atomic lattice is mandatory for the atom counting plan to succeed. Since the NanoWalker is not meant to operate in vacuum, the material used needs to be resistant to oxidation. Out of the many materials available for STM applications, Highly Oriented Pyrolytic Graphite (HOPG) [8] has been chosen. This artificial material has a layered structure such that cleaved properly, large areas of HOPG can be atomically flat, making this surface ideal for the fabrication of the proposed grid.

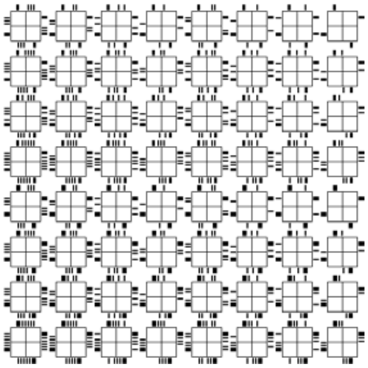

Fig. 4. Binary code 8 x 8 matrix

There are numerous techniques for etching HOPG, such as oxygen plasma etching [9] and Focused Ion Beam (FIB) etching. FIB was chosen because of its very accurate machining capabilities [10]. The time required to etch the sample with this technique may be longer than with other lithography techniques such as dry-etching, chemical etching or other additive techniques, but these all share the common drawback of having a minimum feature size not as precise as the FIB. To obtain such precise features, X-ray or Extreme-UV [11] is required. Although those techniques have not yet been completely ruled out, literature review has not uncovered any etching attempts on HOPG.

FIB has another advantage over other lithography techniques that made it ideal for these first tests: it does not
require any master mask fabrication. By feeding it a simple bitmap image, a complex pattern can be reproduced efficiently. The FIB machine used was an Ga+ ion Hitachi FB-2000A. The goal of these first tests is to study the effect of the FIB parameters on the pattern quality. The M0-20 beam has the smallest aperture size available in the *vector scan controller* mode and was used in each test.

The binary code etching requires three passes, one for each depth of the code. The line pattern can be done in only one pass. The FB-2000A can etch in one single pass material sizes of 4µm, 32µm and 256µm using a 512x 512 monochrome image. Since the grid needs to be larger than 30µm, the 32µm setting is used. This yields a maximum resolution of 62.5nm per pixel.

The binary code is etched as a matrix of 8 x 8 windows (see Figure 4). A 6-bit code identifies the 64 windows starting from the bottom-left to top-right. The line pattern on the other hand is a 10 x 10 matrix. Each window is 2.788 x 2.788µm, the thinnest line is 187.5nm and the thickness increment between each line 62.5nm.

Prior to the FIB machining, the HOPG samples were cleaved with regular 3M™ scotch tape.

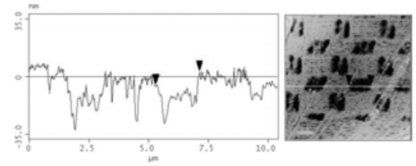

Fig. 5. Cross-section of binary code pattern on HOPG

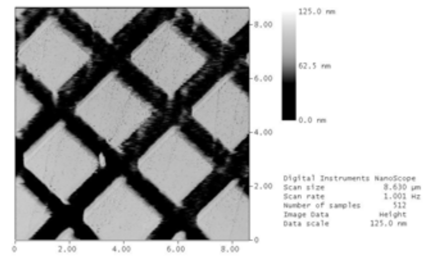

Fig. 6. 8.5µm scan of line pattern etched on HOPG

4. RESULTS

Through a comparative evaluation of numerous grids etched with an array of varying parameters, a first tuning of these parameters was possible. Several combinations of settings were tried, each resulting in deeper or lighter features. The fabricated grids were then observed with a commercial NanoScope IIIa STM.

Many images of the etched grids were taken with the following recommended parameters for HOPG when imaged with a NanoScope IIIa STM: bias voltage: 20mV, setpoint current: 2nA, Integral gain: 2.0, Proportional gain: 2.0, Derivative gain: 0. The objective was to find which FIB etching parameter combination produces the best results for STM observation. The preliminary results suggest that a lighter FIB etching is better suited for the STM imaging process than a deeper, more incisive machining. The latter, due to the higher depth and poorer definition of the features, affects the STM imaging with chronical overshoot, resulting in a pattern hardly readable.

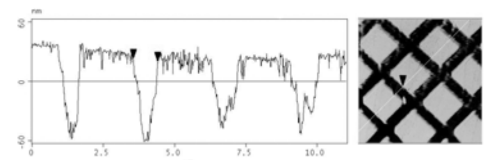

Fig. 7. Cross-section of line pattern on HOPG

The visual results of the binary code are poor. It is barely possible to distinguish the different work windows, yet the code alone. The cross-section of one line of the bit code reveals no clear pattern from which to identify the window's code (see Figure 5). It is believed that this is mainly due to the three separate etching steps needed to fabricate this pattern. The code requires small features with a very precise alignment of multiple etchings, both of these cannot be easily achieved with the ion bombardment machining process that FIB involves. When numerous etchings take place in the same area, the walls of the depreciations so created seem to collapse on themselves and overlap each other to create one large hole instead of creating a multi-steps structure.

The line pattern, on the other hand, seems to show promise, providing that the right etching parameters are used. As seen in Figure 6, the pattern edges appears sharper and more defined than with the binary code, thus resulting in a more comprehensible codification. A cross-section analysis confirms this impression: the much more regular topography of the latter can easily be followed by the STM controller, and thus, the noise embedded in the measurement does not affect as profoundly the encoding of the information on the surface as in the former method.

5. CONCLUSION

From the images taken, it seems clear that the FIB etching of the binary code pattern does not yield very good result, conversely, the line pattern approach may be a more viable solution. Using this proposed reference grid system, it is possible to uniquely identify each intersection of the pattern. Doing so enables localization of an STM tip within a 2.788μm area without any need for optical systems. Applications for this system are expected in the field of nanorobotics, such as in the NanoWalker project. Further work needs to be put into the optimization of the FIB etching to obtain a more precise grid. One possible avenue worth trying is to segment the etching of the 32μm grid by sequentially etching neighboring areas of 4μm squares. This would yield a theoretical resolution eight times higher than with the one-pass etching. The beam alignment and the sample placement would be critical for such a fabrication strategy since any minor misalignment of the grid segments would result in breaking the increasing line width pattern on which the whole localization concept relies. The obvious trade off for this benefit would be the increased time and complexity required to fabricate one grid.

Trying out other techniques to fabricate this pattern would also provide insightful information. Techniques such as nanoimprint lithography [12] advertise sub-50nm pattern fabrication. It would also be interesting to try to see if building a three-dimensional structure such as the binary code would yield better results with this type of technique where a multi-depth master stamp can be created.

The next step in the implementation of this new nanometer scale positioning grid is the image analysis of the cross-section obtained from the STM. An algorithm capable of reliably identifying the intersection from a robot's scan size of 3.4μm must be implemented. With this algorithm working, localization at a even lower scale within a single work window can start. In the case of the NanoWalker, this atom counting strategy will rely heavily on its STM scanning capabilities and will constitute the third and final step of the referencing system here-described.

Acknowledgements

This work is supported by the Canada Research Chair (CRC) in Conception, Fabrication, and Validation of Micro/Nanosystems and by the Natural Sciences and Engineering Research Council of Canada (NSERC). The authors also acknowledge the support of the CM^2 Laboratory at École Polytechnique de Montréal for providing access to their FIB facility and to the LCM Laboratory of the University of Montreal for permitting the use of their STM.

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