Creative Approaches on Interactive Visualization and Characterization at the Nanoscale

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Abstract. Visualizing and characterizing scientific data from observations at the nanoscale is a challenging task. We present creative approaches in the development of an interactive system to visualize and characterize nanopillar structures. This research is a result of a collaboration inside a team of scientists and artists, in the course of an artistic residency that occurred in a scientific institution. Before describing the development approaches, we will present a brief introduction to the thematic of nanotechnologies, media arts, and data visualization. This work arose from the need to observe and present nano visualizations during an artistic presentation, and to provide a software solution, that has been developed. The focus of this paper is to describe the technical and creative processes in the development of a reliable scientific visualization system.

Keywords: Nanoscale · Nanotechnology · Data visualization Characterization · Nanopillars · Automated SEM characterization Media art · Creative technologies

1 Introduction

Art offers science an essential store of images, ideas, metaphors, and language while methods of forming and patterning materials at the nano and micro scales are finding increased use as a medium of artistic expression [1]. Many organizations have initiated programs to bring together artists and scientists to stimulate collaboration and encourage the viewing of science as a means of public engagement. We have, as an example, the Leonardo Society, an international society promoting the cross-fertilization among the domains of art, science, and technology since the 60 s [2]. In this paper, we describe the technical and creative approaches developed in the context of an artistic residency at the

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International Iberian Nanotechnology Laboratory (INL) [3], in Braga - Portugal, during the last year. In dealing with state-of-the-art technology in nanotechnology, the creative team had to work with large number of observations and obtain visual outcomes to be presented in an interactive performance exhibitions [4, 5]. This process began a set of problem-solving practices while visualizing and understanding data from observations. Within the framework of this collaboration, a software was specifically developed to analyze and characterize patterns in acquired images at the nanoscale, within the manipulation of nanoscale observation instruments. The work took place at the INL's Micro and Nanofabrication Department as practice-based research. In the creative arts, including new media arts, the emphasis is on the creative process and the works that are generated, promoting new understandings that arise about practices, and visual arts training may strengthen such skills and thereby lead to improvements in geometry performance [6]. Therefore, the focus of this paper is the presentation of the visualization results, as well as the practices associated in the course of this development between multi-disciplinary teams. In this sense, practice and research, together, operate in such a way as to generate new knowledge that can be shared and scrutinized [7], and interdisciplinary, transdisciplinary, cross-disciplinary, intermedia, transmedia and multimedia are becoming ever more prominent within the sciences, technology and the arts [8].

2 Nanotechnology and Media Art

One nanometer is a unit of length in the metric system, equal to one U.S. billionth of a meter (0.000000001 m). The idea of nanotechnology first came from the physicist Richard Feynman who imagined the entire Encyclopedia Britannica could be written on the head of a pin [9]. The nanotechnology term was coined by Norio Taniguchi, a Professor of the Tokyo University of Science, to describe semiconductor processes [10]. From the viewpoint of technology and applications, the unique properties of the nanoscale mean that nano design can produce striking results that cannot be produced in any other way [11]. From medicine to computing, to sunscreens, implications of using nanotechnology are present in everyday life. Nanotechnologies play significant role in our life and society, and it spans a range of science and engineering disciplines. Mark Ratner emphasizes its advantages by mentioning that it might allow an aircraft to recover from the sort of fuel tank damage that downed Air France's Concorde flight 4590 or even the space shuttle Challenger [11]. Pioneer media artists Christa Sommerer and Laurent Mignonneau presented the interactive artwork Nano-Scape to bring the theme of nanotechnologies closer to the public awareness [12], by interacting with invisible self-organizing atoms through a magnetic force feedback interface. Victoria Vesna and James Gimzewski demonstrated compelling results when joining groups of scientists and artists outside the academic walls [13], providing a vision that we are all, from the bottom up, molecular in origin. Chris Turmey suggests a neo-cubist spirit for making and seeing nanoscale images [14]. Hawkins and Straughan presented Midas, an artwork that foregrounds the ongoing disassembly and reassembly of matter at the nano-scale [15]. Astrophysicists and nanoscientists, through visualized algorithms, receive pictures out of the depths of the macro-cosmos, and the micro-cosmos, respectively [16], and future applications for nanotechnology seem only to be limited by the creativity of researchers [9].

3 INL Scale Travels – The Context of This Research

INL is the first intergovernmental organization in Europe in the field of nanoscience and nanotechnology [3]. In 2015, the Laboratory launched the Scale Travels initiative, that aims at fostering a multidisciplinary and hybrid approach between science, and one of its goals is to spark the discussion about the social, cultural and ethical impact of nanotechnology through media arts and to create novel media and digital objects based on nanotechnology, leading to original experiences and unexpected products, processes and services. The Scale Travels Residencies aims at bringing media artists and researchers into conversation and convergence embedded in a real laboratory environment inside INL's facilities [17–19]. This creative connection promotes the inclusion of new expert knowledge in the media arts and frames the discussion on the complexities underlying the nanoscience and nanotechnology research. INL is also hosting artistic residencies from the European Commission Starts initiative [20–22]. INL is located in the City of Braga, Portugal, which was included in the UNESCO Creative Cities Network. The title of UNESCO Creative City of Media Arts was attributed to the city of Braga on the 31st of October 2017 [23, 24].

4 Development

Using computer vision technologies [25], and creative programming open-source environments: Openframeworks (C++) [26] and Processing (JAVA) [27], we developed a series of software visualizations which achieve significant advances in the characterization of observations obtained by the Scanning Electron Microscope (SEM), an instrument that produces images of a sample by scanning the surface with a focused beam of electrons. Those visualizations were useful to produce data to understand and present artistic work at the 43rd International Conference on Micro and Nano-Engineering and INL Summit events in 2017 [4], and at the European Researchers Night in 2018 [5]. In the next section we will describe the techniques developed to better acquire, classify and characterize SEM observations in nanofabricated structures, specifically in the case of nanopillar structures, with different scenarios of observation.

4.1 Data Visualization in Nanotechnology

Advanced nanoscale observation instruments and pre-programmed sequential capture techniques offer the possibility of obtaining large amounts of images to analyze. As nowadays our ability to generate information far exceeds our capacity to understand it [28], it is important to have mechanisms to identify, classify and characterize features in those images. Scientists now require more from visualization than a set of results and a tidy showcase in which to display them [29], and because in nanotechnology even a small space measure can represent a lot of data, we based our approach in the principle of reduction and privileging of spatial variables [30], using graphical primitives such as lines, points and simple geometric shapes, focusing on feature-based approaches, very useful to reduce the amount of data which is shown at each instance of time [31]. Visualization research often involve finding innovative graphic and interactive techniques to represent the complexity of information structures [32], and sophisticated technologies of scientific visualization often require a departure from the standards of mimetic representation [33], as researchers constantly tweak them, altering parameters, changing color scales, substituting different algorithms with aesthetic and scientific conventions in mind [34] with the goal of obtaining a better understanding of the generated data, only possible if we collect, organize and characterize it. Artists, scientists and mathematicians are concerned with visualization in many different forms in order to better understand the true nature of reality [35]. Visual data exploration aims at integrating the human in the data exploration process, applying its perceptual abilities to the large datasets available in today's computer systems [36], and interface design for filtering and selecting data is also essential in this process. Eduard Tufte, pioneer in the field of data visualization, says that science and art share intense observing, and postulated principles of analytical design such as comparisons, causality, explanation, evidence, and multivariate analysis, which contributes effectively to a better understanding of a subject by different perspectives and combination of more than one characteristic [37], and suggests that repetition and change promotes comparison and surprise in visual communication [38]. In nano fabrication, observation and characterization, repetition and tiny micro and nanoscale differences are very common, but indeed crucial, and there are many essential variables to compare in repeated samples. Capturing images of nanostructures provided many engaging scientific visualizations with similarities to macroscale life forms and man-made structures [1]. In the next sections we present our approaches developed in the context of visualization and characterization from SEM observations.

4.2 Visualizing Large Arrays of Nanostructures on Large Area Wafers

Nanopillars is a technology within the field of nanostructures placed together in lattice like arrays. Nanopillars set themselves apart from other nanostructures due to their unique shape and get their attributes from being grouped into artificially designed structures that promote different behavior far away from their natural properties. Each nanopillar has a pillar shape at the bottom and a tapered pointy end on top. This shape, in combination with nanopillars' ability to be grouped together, exhibits many useful properties, having many applications including efficient solar panels [39, 40], high resolution analysis [41], antibacterial surfaces [42] and water reduction [43].

Dense and large-area arrays of nanometric scale structures are regularly fabricated at INL Cleanroom (Figs. 1 and 2). The characterization of sub-micron structures (below 500 nm) at large scale and its post data analysis is a very challenging task [44]. The observed subject consists of approximately ten U.S. billion (10.000.000.000) pillars of 1 μm height and 500 nm diameter, with 1 μm period equally distributed among a diameter of 110 mm (Figs. 3, 4 and 5). To have a more real comparative notion, if you imagine a text with 10 U.S. billion words, this would form a book with 18 million A4 pages and with 5 million kilograms in weight. This is a huge amount number of pillar structure to analyze and characterize at a very small size, only possible through challenging and creative tasks with a controlled autonomy. A 110 mm diameter fully nanostructured area has been fabricated by electron beam lithography (EBL) and deep reactive ion etching. Circular pillars of 500 nm diameter have been distributed in 1 μm pitch was patterned. EBL (EBPG 5200 from Raith) exposure using a negative resist was carried out operating at 100 kV. For this EBL experiment, several approaches were used to reduce the exposure time for large-scale nanofabrication process.

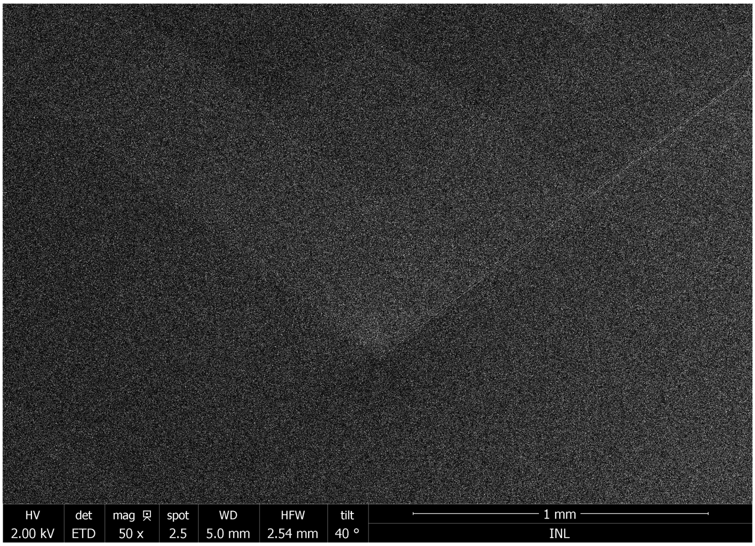

Fig. 1. Nanopillar formations, observed from a very far distance.

Automated routines for high and low magnification SEM imaging have been successfully developed. The images have been acquired using a SEM (NanoSEM from FEI) with the IFast scripting software [45], which allows to take large amounts of images from nanometric structures covering multiple regions of the wafer in few hours.

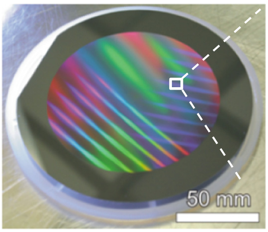

Fig. 2. Photography of the wafer containing the large array of fabricated nanopillars characterized automatically in this work.

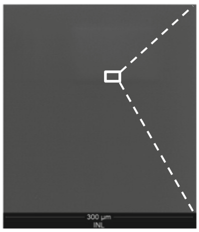

Fig. 3. Low magnification SEM image of part of the array.

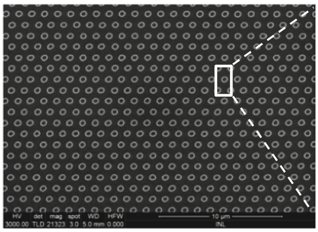

Fig. 4. High magnification SEM image.

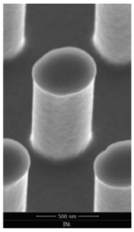

Fig. 5. High resolution 40° SEM image with 1 nanopillar.

With the obtained raw data, geometric parameters were extracted from the images with the development of our custom software using computer vision algorithms. A metrological analysis has been performed to determine the patterning accuracy in the xyz dimensions. A method was developed and established to automatically determine the diameter of each pillar in each observation. For this, a large set of SEM images at high and low magnification were obtained. For low magnification top view images (250 X), more than $2 \cdot 10^8$ pillars (corresponding to $\sim 2\%$) were analyzed revealing the absence of missing or broken silicon pillars.

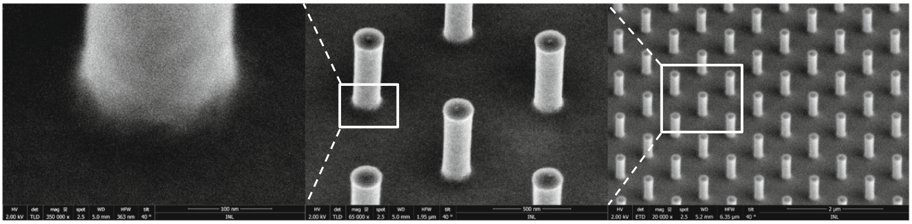

Fig. 6. Tilted SEM nanopillar observations.

High resolution tilted images (75 kX) (Figs. 5 and 6) were analyzed to determine the height of the pillars. More than 1000 SEM images at 5 kX were acquired to characterize the diameter and period along the wafer.

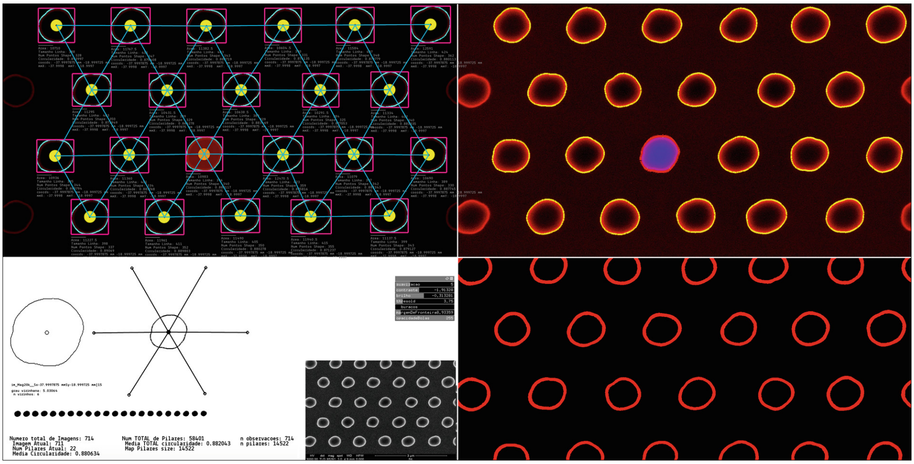

Fig. 7. Computer vision techniques to characterize the nanopillars. Real-time interface to adjust visual parameters. Top-left: neighborhood representation in blue lines, with selected pillar in red; Top-right: in yellow, characterizable pillars inside the image; Bottom-left: information about selected pillar and adjustment controls; Bottom-right: edge detection. (Color figure online)

The period, height and diameter of the fabricated structures were 1.038 ± 0.03 μm, 1.05 ± 0.025 μm and 520 ± 12 nm in the analyzed regions of the wafer demonstrating very little variation of the dimensionality along the wafer. Our code applies the correct contrast and brightness and blurs the image to reduce noise artifacts and have a perfect shape capture (Fig. 7). The software finds contours and selects the fully visible pillars in each observation. Each pillar is classified with its position in the wafer, center of mass, diameter, and a high-resolution circular shape (with more than 150 points) is extracted. Figure 8 shows 60 representations of pillars from the top view in a sequential order, each one with its different forms and sizes, which means that this individual characterization applies to all observed pillars, being thousands or millions, and having this detail for large quantities, in such a fast process, turns possible an efficient and effective large-scale study. Structural analysis of each pillar is performed with shape descriptors [46], including the level of circularity. In this sample, circularity it's important to analyze and get a global idea of the nanofabrication process quality. Neighborhood distance between nearby pillars it's also critical in the analyzed sample. Figure 7 (top left) shows six blue lines for each pillar representing its neighbors' positions.

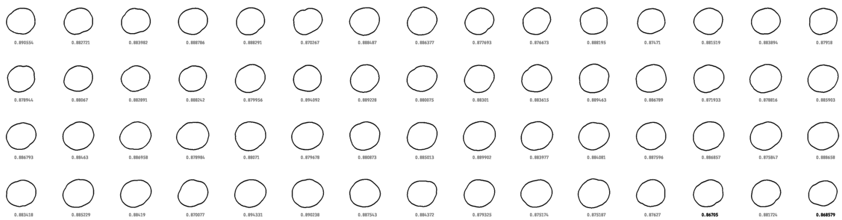

Fig. 8. Representation of pillars from the top view in sequential order of observation. A circularity value (from 0 to 1) is calculated and presented for each nanopillar. 1 means a perfect circularity.

Figure 9 shows an overlayered representation of a large amount (more than 80000) neighborhood positions. A perfect 6-point star would represent perfect equidistant pillar positioning. Histograms of neighborhood distance are also presented (right side bar and gradient graphs) showing that the sample equidistance's level is near perfect values.

Making use of the low opacity, and with the shape superposition, we obtain a good visual reference of the circularity (Fig. 10). As we have a good resolution in the shapes, we can still color the most repeated vertices along all individual observations, and thus have a global notion of the nanofabrication process. This approach visually presents a possible solution to one of the major problems in the area of scientific visualization: the

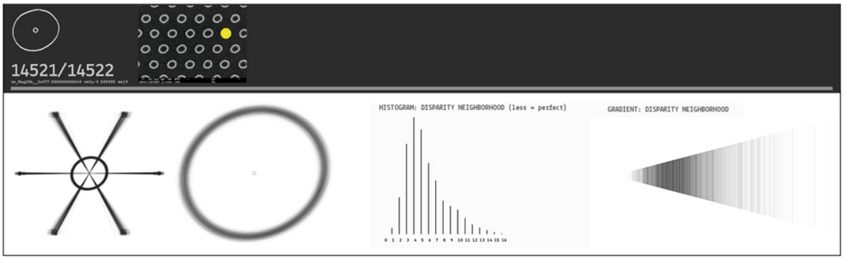

Fig. 9. Neighborhood distances between pillars (0 means the desirable distance in this sample, and greater than 14 goes out of specifications). General circular shape is also presented.

representation of error or uncertainty [29]. Having this result at the level of each pillar, and having calculated its specific position, we can graphically show the variation of the values along the wafer, as shown in Fig. 11, where circularity is plotted in the left and neighborhood equidistance in the right.

After having perfect position patterns, a possible characterization of the equidistance can be achieved if we overlay neighborhood lines by applying negative color effects. In a perfect positioning situation, we would have a clear and straightforward mesh. In non-perfect patterns, we will have color sets that react to differences in the nanopillar positioning (Fig. 12). Nanotechnology is mostly based on physical processes, and it is interesting to note that this more analogical effect causes interesting visual outputs, similar to generative images, usually produced by computational noise or even random effect. After all, neutral analysis is not the only important task in life [47].

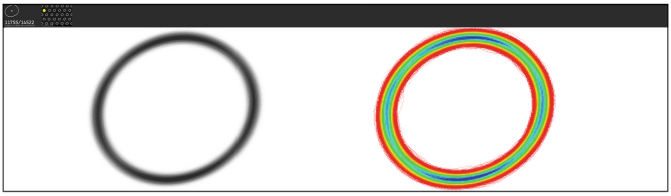

Fig. 10. General view of pillar circularity. In the right-side visualization, color gradients from red to blue represent the most common vertices in each nanopillar in crescent order. Red means less common and blue means most common vertices. (Color figure online)

The proposed visualization system is also interactive, and presented as a software application, meaning that it can characterize different sample sets, and computer vision parameters can be adjusted in real-time. It also stores these configurations for multiple uses over time.

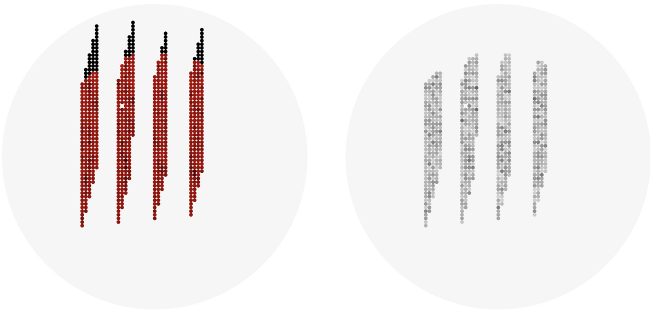

Fig. 11. Circularity and neighborhood equidistance values distributed by position in the wafer. Each point represents one observation and opacity color represents the average value of circularity (left) and average value of neighborhood equidistance (right). Lighter colors mean greater circularity or better equidistance in the neighborhood. (Color figure online)

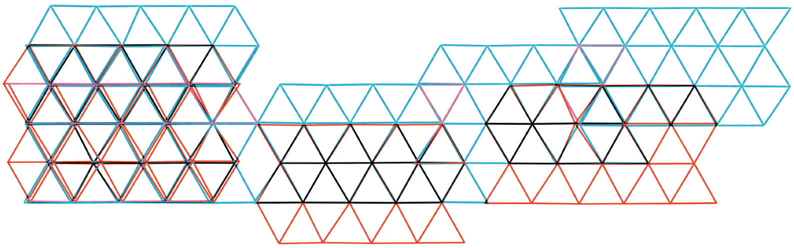

Fig. 12. Overlaying neighborhood distances from different samples and applying color pixel difference (negative overlayered effect) provides a view about the nanopillars positioning disparity. (Color figure online)

A set of visualizations presented in this publication were selected to integrate an interactive installation exhibition (Fig. 13), presented at the European Researchers' Night, in Porto, Portugal [5]. This result was achieved with interdisciplinary work where attention to detail was the most distinctive feature in the process, via creative activity and visual thinking [48]. Innovation happens when convergent thinkers combine forces with divergent thinkers, and art and science – once inextricably linked, both dedicated to finding truth and beauty – are better together than apart [49].

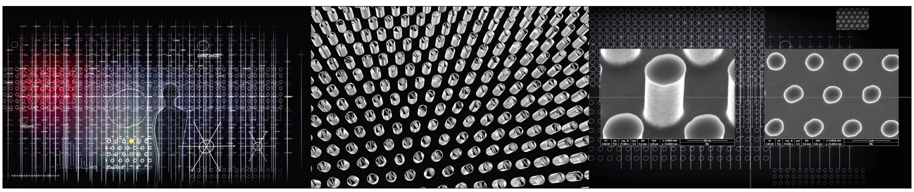

Fig. 13. Image excerpts of the exhibition *Nano Geometries*, at the European Researchers' Night, 28th September 2018, at Palácio das Artes, Porto, Portugal.

5 Conclusion

High-quality interactive visualization can help scientists to analyze data at the nanoscale. It is useful for getting great perspectives of subjects, as well as for querying small details in objects and, most of all, being able to characterize them. It is also useful to uncover hidden irregularities in the observations, very difficult to notice at such small sizes and significant quantities. Presenting scientific data in a human-observable form let the experts improve and tweak the nanofabrication processes. From the point of visualization, we also conclude that low-opacity overlapping, or color-gradient techniques, provide a better view of the general nanopillar patterns, and this is a particularly useful technique when it is critical to analyze tens of thousands, or even million observations. Interactivity is also important in visualization, to change values, conditions and operators during the characterization procedures. The software solution presented in this document can analyze and characterize large quantities of objects at the once, being limited only by the capabilities of hardware machine. Because the system was built from scratch, responding to a specific need, turns out to be quite efficient when compared to other general and multipurpose visualization systems, where tasks are made in separated steps with needed file transfers between different software solutions or platforms. An important aspect to conclude this paper is that although the initial goal of this work was to respond to specific needs for the presentation of an artistic work, the solution was posteriorly improved for specialized use.

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