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Technical report

Manufacturing at nanoscale: Top-down, bottom-up and system engineering

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Abstract

The current nano-technology revolution is facing several major challenges: to manufacture nanodevices below 20 nm, to fabricate three-dimensional complex nano-structures, and to heterogeneously integrate multiple functionalities. To tackle these grand challenges, the Center for Scalable and Integrated NAno-Manufacturing (SINAM), a NSF Nanoscale Science and Engineering Center, set its goal to establish a new manufacturing paradigm that integrates an array of new nano-manufacturing technologies, including the plasmonic imaging lithography and ultramolding imprint lithography aiming toward critical resolution of 1–10 nm and the hybrid top-down and bottom-up technologies to achieve massively parallel integration of heterogeneous nanoscale components into higher-order structures and devices. Furthermore, SINAM will develop system engineering strategies to scale-up the nano-manufacturing technologies. SINAMs integrated research and education platform will shed light to a broad range of potential applications in computing, telecommunication, photonics, biotechnology, health care, and national security.

Introduction

Current semiconductor manufacturing is at a cross-road: optical lithography will face tremendous difficulty as it approaches 50 nm critical dimensions, and projection tools become prohibitively expensive. In addition, to match the continually shrinking critical dimensions and increasing complexity, three-dimensional (3D) multi-level nano-device architecture becomes a necessity to increase the speed and to reduce the budget of power consumption and communication delay (ITRS, 2001). These challenges call for a fundamental change in the nano-manufacturing paradigm.

Along with the development of photo-lithography process, continuous efforts have been devoted to explore the alternative nano-manufacturing technologies. Several key technologies, such as X-ray lithography (Hartley & Malek, 1999), e-beam lithography (Tseng et al., 2003), near-field optical lithography (Yin et al., 2002; H'Dhili et al., 2003), and multi-photon optical lithography (Kawata et al., 2001; Yin et al., 2002), have been developed but yet to be matured before large-scale industrial applications, due to the inherent drawbacks of high cost or low throughput of these technologies. Imprint lithography is targeting to solve the cost and throughput issues of the nano-manufacturing (Chou et al., 1996; Sreenivasan et al., 2002). It has been developed to allow patterns on a wafer to be stamped from a master with high resolution and throughput. This well-developed technology has been used to fabricate nanoscale devices and circuits (Chen, 2002). However, the intrinsic drawbacks of imprinting are apparent: it is hard to achieve reliable resolution down to <20 nm (for soft lithography, the resolution is even poorer due to the elastic nature) and more importantly, nanoimprint is mostly limited to 2D fabrication, due to the high pressure involved during the imprinting. A competing approach, bottom-up fabrication (Whitesides & Grzybowski, 2002) such as chemical self-assembly, is based on molecular recognition and uses molecules/nano-dots rods as 'building blocks'. Two main drawbacks of the self-assembly process are evident: it is a homogeneous process and cannot make complex patterns for devices, and it generates defects due to its thermodynamic nature.

To tackle the above mentioned challenges, the Center for Scalable and Integrated NAno-Manufacturing (SINAM) sets its goal to establish a nano-manufacturing paradigm that will combine fundamental science and technology in nano-manufacturing, and will transform laboratory science into industrial applications in nano-electronics, biomedicine, and in traditional industries. Clearly, the wide range and high complexity of nano-engineered systems and products requires an integrated multidisciplinary nano-manufacturing research strategy. To embark on this important mission, SINAM is founded among six partner institutes – including UCLA, UC Berkeley, Stanford, UCSD, UNCC, and HP labs (Figure 1) – and the center has developed a strategic network with other participants from industry, government laboratories/institutes, other peer NSF centers, professional associations, as well as business analysis firms. On the basis of the strategic network, SINAM will further establish a consortium to closely interact with industry partners. SINAMs research efforts will not only focus on top-down nano-manufacturing

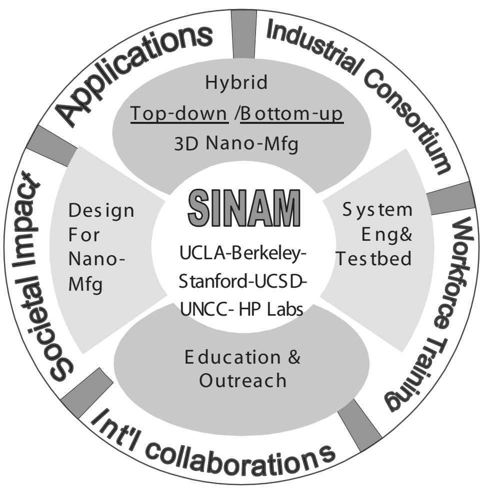

Figure 1. Theme organization of SINAM.

aiming toward critical resolution of 1–10 nm, but also emphasize on exploring novel hybrid approaches, in combining the top-down and bottom-up technologies to achieve massively parallel integration of heterogeneous nanoscale components into higher-order structures and devices. As the ultimate goal, SINAM will develop system engineering strategies to scale up the nano-manufacturing technologies.

Top-down nano-manufacturing

Amazingly surface plasmons at visible frequencies can have wavelengths down to nanometers. SINAM will develop a revolutionary approach, plasmonic imaging lithography (PIL). In PIL, surface plasmon optics and lenses open up an exciting avenue for ultrafine resolution imaging. These plasmonic lenses convert free space waves into surface waves, thus allowing unprecedented resolution of 1–10 nm in the final optical image. In effect, the plasmonic elements will act as the final objective lens for imaging a mask in a geometrical optical imaging system. These surface plasmonic waves can then be used to expose photoresist at resolution of 10–50 nm. SINAM will develop 3D nano-manufacturing based on layer-by-layer PIL approach for various materials and structures.

It is well established that the resolution is determined by the wavelength of the light used in the lithography. However, less recognized is the fact that optical wavelength can be changed; for example, in glass wavelength is shorter than in vacuum. Moreover, it can be much shorter indeed when light forms a surface wave (plasmon) on metals. We could be misled into believing that the Rayleigh optical resolution criterion is limited by the vacuum wavelength, but it is actually the modal wavelength of the propagating lightwave that is decisive. Frequency *versus* wave-vector and wavelength for surface plasmons are indicated in Figure 2.

The preliminary feasibility of plasmonic lithography with 150 nm resolution has been demonstrated in Figure 3 (Werayut et al., 2003). Given a modest writing speed of 200 μm/s, we expect the PIL will be capable of producing 20–40 wafers of 12 in. diameter per hour, compared with 10–20 wafer/h throughput in today's optical lithography in semiconductor foundries. This will make the PIL a highly competitive nanofabrication technique of high-speed, high-resolution, and low-cost compared with other techniques.

In addition, an ultra-molding and imprinting (UMIL) technology is proposed which promises the

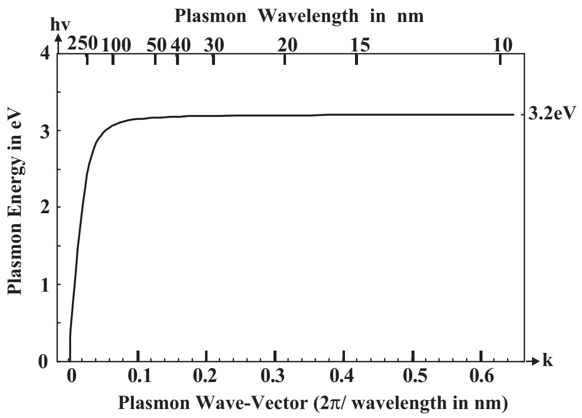

Figure 2. Frequency *versus* wave-vector and wavelength for surface plasmons.

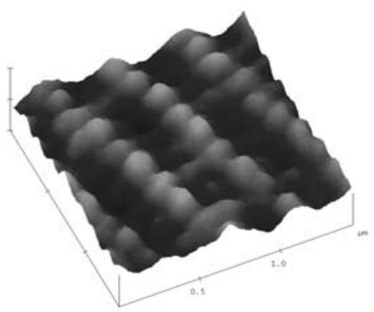

Figure 3. AFM image of a dot array pattern fabricated by PIL with 150 nm resolution.

nano-manufacturing at 1 nm resolution. The key to investigate UMIL is the usage of epitaxially grown superlattices to make 1–10 nm molds in 2D applications that require molecular level resolution. A multi-layered Si/SiGe superlattice can be deposited sequentially onto the substrate followed by a CMP planarization on the side wall. SiGe layers are then selectively etched back from a Si/SiGe superlattice, leaving the silicon fins as an imprinting mold. The advantage of UMIL technique is that the width and pitch of the lines are precisely defined by the epitaxial layer with thickness ranging from 0.5 to 20 nm. As shown in Figure 4, the preliminary results of 4–8 nm imprinted feature has been demonstrated.

Hybrid top-down and bottom-up manufacturing

Concurrent to the development of top-down nano-manufacturing technology, SINAM will develop a

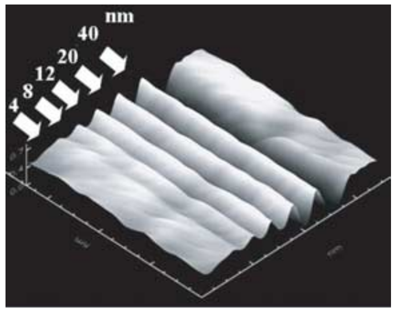

Figure 4. The UMIL process using a selectively etched Si/SiGe superlattice as a master to achieve 4 nm resolution.

unique technology, hybrid top-down and bottom-up process (HTBP), that combines the best aspects of top-down and bottom-up techniques for massively parallel integration of heterogeneous nano-components into higher-order structures and devices. HTBP assembles by ‘pick-and-place’ the nanoscale functional components, namely nano-LEGOs, into a defined pattern (a top-down approach); then the functional molecules attached to the nano-LEGOs can start to ‘glue’ the adjacent nano-LEGOs by self-assembly, thus forming a stable structure (a bottom-up approach). Depending on designed functionalities, the nano-LEGOs can be in the form of nano-wire, quantum dots, DNA, protein, and other functional entities.

HTBP technology has distinct advantages. First, it provides a massive parallel assembly of nano-LEGOs with a high production rate, in addition to the ability to organize the nano-structures into a desired pattern. Second, HTBP can integrate heterogeneous nano-structures. Third, it allows precisely controlling the destiny of the nano-LEGOs, therefore minimizing the generation of defects commonly found in self-assembly. Finally, HTBP promises a multi-scale assembly technique by linking the dimensions from nano- and micro- to macro-world (Figure 5). Therefore, HTBP has the potential to lead to cost-effective manufacturing of more complex structures.

To bond or ‘glue’ nano-LEGOs into a structure after ‘pick and place’ on the assembly motherboard, we need to employ a set of versatile molecular protocols attached to these LEGOs and use them to perform self-assembly between adjacent LEGOs. Bioengineering protocols and tethers such as specific DNA (oligonucleotides), proteins, and other biological entities will also be employed. Using the surface chemistry mentioned above, SINAM will devise means to allow core nano-LEGOs such as the nano-wires or quantum dots

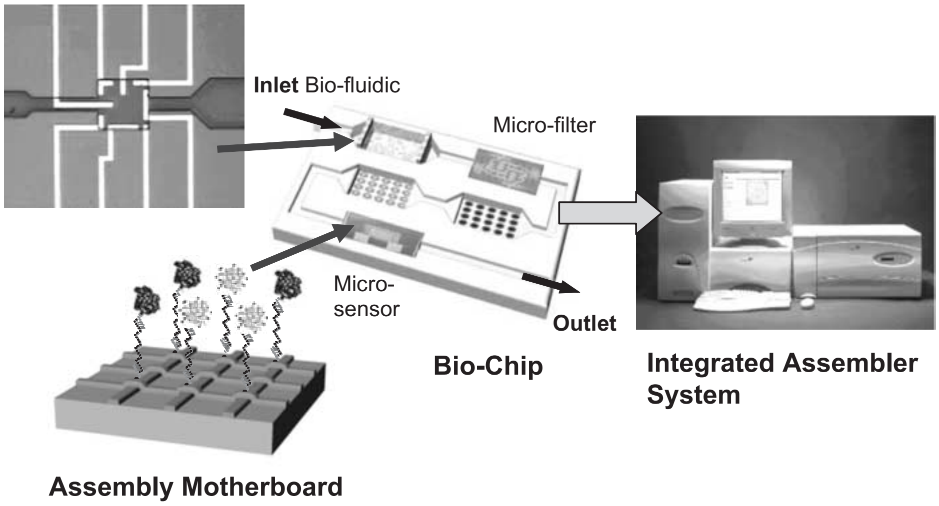

Figure 5. Integrated assembler system will bridge the multifunctional nano-LEGOs onto bio-MEMS devices and lead to scalable and cost effective manufacturing at macro-world.

to be independently modified at specific positions. Such modification will allow different nano-LEGOs to be assembled in a more precise manner, for creating heterogeneous higher-order nano-structures.

System engineering and design for nano-manufacturing

To make the innovative nanoscale processes commercially viable, manufacturing tools and systems must be developed to scale-up these processes with high throughput and high yield. SINAM will develop system engineering strategies and a nano-manufacturing testbed to address these challenges. The testbed, which will include PIL, UMIL, and HTBP manufacturing cells, and embed CAD/CAM and metrology, involves the process optimization, machine tool sensing and control, and system engineering practice. The testbed will also serve as a collaborative platform with our industrial partners for product development.

New fabrication processes can only mature through gradual adoption by a small but growing user community. SINAM will develop a novel design interface: 3D nano-CAD (Figure 6). This interactive CAD approach will allow efficient interactions between product design and process development. First, the initial 3D nano-structures will be integrated with the materials properties to build a 3D geometrical model. Then the fabrication simulators and performance simulators will be employed to predict the device performances. After fabrication, the nano-structures' performance are characterized and compared with the simulation predictions by the nano-CAD simulators. This comparison will create feedback to the designer as guidance towards the final optimization of material selection, geometric configuration, and process control parameters of the 3D nano-structures. Tolerance Design issues will be addressed from the structure level to the device performance level (Hahn & Shane, 1983).

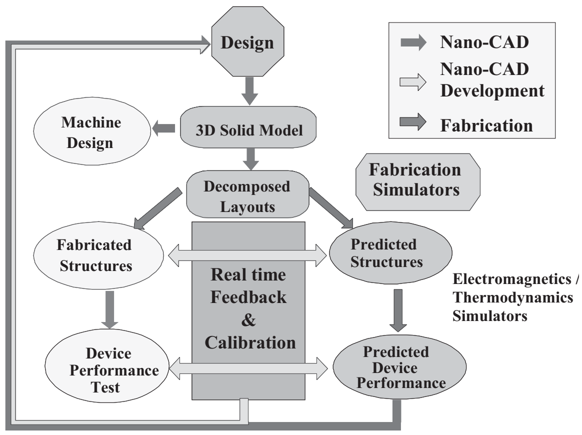

Figure 6. 3D nano-CAD development.

Today's optical microlithography step-and-scan systems (Zwart et al., 1997) are capable of 20 nm overlay. As the proposed nano-manufacturing processes strive to reduce the critical dimension, new machine capabilities with substantially higher level of precision and accuracy at sub-10 nm will be required. Therefore the

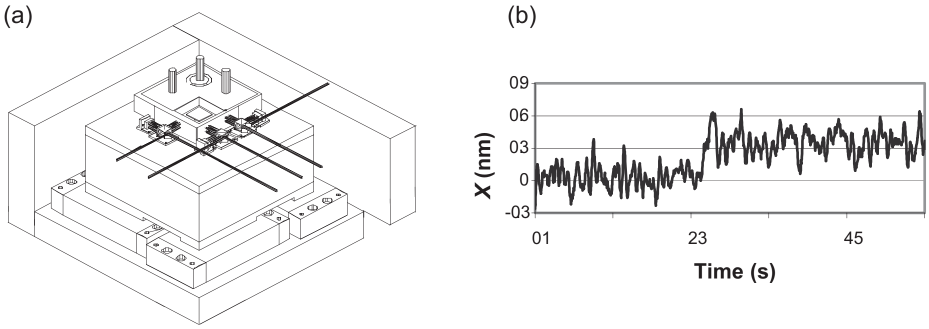

Figure 7. SAMM developed in UNCC: (a) CAD design for SAMM; (b) experimental results indicate 0.3 nm precision.

most challenging issue for nano-manufacturing is the accuracy and speed of alignment and motion (parallelism, gap width, scanning rate, etc.) required by the lithographic processes (Rai-Choudhury, 1997). The key to sub-100 nm nano-manufacturing lies in synergistic integration of precision engineering and control engineering under a multi-scale system architecture. As shown in Figure 7, A prototype 6-DOF magnetically suspended 3D-subatomic measuring machine (SAMM) has demonstrated a static precision of 0.3 nm using PID control and 1 nm relocation precision has been achieved over the entire 25 × 25 μm area (Holmes et al., 1995). It will be used in the initial phase of the project to further address the dynamic precision required by the processes.

At the system level, process scalability and reliability will be our major driving force. Our initial process development and integration efforts will be dedicated to the established failure mechanisms such as stress concentration, adhesion and fracture, electrical parasitic capacitance and thermal shock. To overcome the proven failure mechanisms, we will identify the optimal process sequence and conditions based on the physics driven process and on the performance simulators. The above research will form the basis of the prototype nano-manufacturing system. The multi-scale architecture will allow us to seamlessly integrate SINAMs system with existing industrial capabilities. Thus, our die-to-die nano-manufacturing process will be readily scaled-up to wafer level production.

Education

A recent report from the Council of Competitiveness, 'The Quiet Crisis', points to the current serious workforce crisis in the high-technology sector. According to this report, a quarter of the current science and engineering workforce will retire by the end of this decade. In addition, this workforce no longer mirrors the national profile. These are critical issues, made all the more serious by the paradigm shift in science and technology to the nanoscale. The crisis produced by the discontinuity between the national need and current profile of US scientists and engineers will be conceivably amplified by the coming revolution in nano-manufacturing.

SINAM identifies its educational mission in addressing critical high-tech work force needs, through an integrated education program with SINAM's research. SINAM will take special efforts with California schools to reach out to minority and female students as following: (1) Grades 7–12 Discover Nano-technology: Traditionally, K-12 education rarely offered any exposure to engineering. SINAM researchers will create an inquiry module on nano-technology for this community. (2) Nano-Manufacturing Summer Academy will provide a 10-week summer training for undergraduates students, K-12 grade school teachers and students. We plan to develop an introductory course (4 credits) of nano-manufacturing at SINAM. (3) 'Graduate Young Investigator (GYI)' and Industrial Internships for Graduate Students: We will experiment with a novel concept. We will award a small grant to the best proposal from graduate students who not only propose innovative ideas, but who involve in the proposed research at least two faculty members from different fields. This will provide an excellent experience for the GYI as a 'driver and boss' in research and will also endow them with an interdisciplinary research spirit. (4) SINAM will actively build a Nano-manufacturing Graduate Internship Program with our industrial partners from SINAM Industrial Consortium. SINAM will work with California Science Museums and the California State Economic Strategy Panel to build awareness of the opportunities and impact of nano-manufacturing.

Acknowledgement

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