Physical properties of nanostructures grown by oblique angle deposition

J. P. Singh, T. Karabacak, D.-X. Ye, and D.-L. Liu
Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, 110 8th Street, Troy, New York 12180-3590

C. Picu
Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, 110 8th Street, Troy, New York 12180-3590

T.-M. Lu and G.-C. Wang
Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, 110 8th Street, Troy, New York 12180-3590

(Received 27 April 2005; accepted 15 August 2005; published 20 September 2005)

Isolated three-dimensional nanostructures were grown on templated or flat substrates by oblique angle deposition with or without substrate rotation where the physical shadowing effect dominates and controls the structures. The mechanical and electromechanical properties of Si springs and Co coated Si springs were measured by atomic force microscopy. The electrical property of β-phase W nanorods were measured by scanning tunneling microscopy. Examples of measurements of the elastic property of springs, electromechanical actuation, field emission of electrons, and field ionization of argon gas are presented. Potential applications and improvements of growth of uniform nanostructures are discussed. © 2005 American Vacuum Society. [DOI: 10.1116/1.2052747]

I. INTRODUCTION

There has been an intense drive to advance computing and communication technologies beyond Si scaling, which is expected to end in about one decade. Over the last decade, many new electronic devices that operate at the molecular level have been proposed and tested in nanoelectronics. On the other hand, nanomechanics has received less attention and has not caught up with the level of activities in nanoelectronics. However, future nanomechanical devices such as nanoelectromechanical systems (NEMS) may have as important an impact on our lives as nanoelectronics. Many challenges need to be overcome before important nanomechanical or nanoelectronic devices can be practically realized. Challenges include: (a) the growth and control of these nanostructures; (b) the assembly of these nanostructures onto a substrate platform; and (c) the characterization of the mechanical, electromechanical, thermal, and other properties of these nanostructures.

In this paper we will present the growth of novel three-dimensional isolated nanostructures such as springs or rods on patterned or flat substrates using an oblique angle deposition. These nanostructures are isolated to each other and positioned vertically or inclined with respect to the substrate. The unifying theme is that this makes the measurements of fundamental mechanical or electrical properties of these isolated nanostructures under external driven forces (mechanical force, electrical current, applied voltages, etc.) using atomic force microscopy or scanning tunneling microscopy relatively easy compared with that of nanostructures laying down flat on a substrate. The results allow us to test physical properties of materials at the reduced length scale.

II. GROWTH OF NANOSTRUCTURES USING OBLIQUE ANGLE DEPOSITION

The oblique angle deposition has been known for more than a century. A renewed interest among many groups worldwide has occurred in recent years. Experimentalists have varied the angle of incident flux, the rotational speed of the substrate, the angular range of the rotational speed to grow various nanostructures. Theoretically, atomistic modeling and Monte Carlo simulations have been used to predict the formation of the nanostructures and the results were compared with experimental findings to better understand the growth mechanism. Figure 1 (left) shows the deposition configuration during an oblique angle deposition. The flux strikes the substrate with an angle θ normal to the substrate surface. Various sources including thermal, sputter, and e-beam depositions can be used for the deposition. The substrate can be rotated around the substrate normal with an angular speed ω. The substrates can be flat or templated. A variety of nanostructures have been grown on substrates depending on the deposition rate, substrate temperature, and how and what speed one rotates the substrate. If the substrate is templated with periodic arrays of pillars, then ordered 3D structures can be formed. Figures 1(a) and 1(b) show scanning electron microscopy (SEM) images of slanted Si rods and Si springs on templated substrates with regularly spaced W pillars, respectively. Three dimensional structures with a very large aspect ratio, porosity, shape and symmetry can be grown by changing the template spacing, rotational speed, and deposition angle. The isolated nanostructures are results of the geometrical shadowing effect in which the collinear flux is shadowed by the tall islands and cannot reach behind the tall islands. These nanostructures cannot be obtained by any advanced lithographic techniques. The oblique angle deposition technique is robust so practically any mate-
materials or combination of materials can be grown. The fact that these structures can be integrated onto a substrate platform makes them practical for many realistic applications. In addition, conformal nanocoating of a different material onto these nanostructures can be achieved by the chemical vapor deposition (CVD) technique\(^2\) to form complex and unique structures that possess intriguing new properties.

In this paper, we will give some examples of the growth and measured properties of individual amorphous silicon springs and metallic tungsten rods. For mechanical property measurements we use atomic force microscopy (AFM). The AFM is used for imaging and applying force in the nano-Newton to micro-Newton range on the individual nanostructures. A conducting AFM tip is used to pass a current through the nanostructures to examine the electromechanical actuation effect. For the electrical field effect on nanostructures we used scanning tunneling microscopy (STM). The SEM provides both side and top views of the nanostructures. X-ray diffraction provides structural information such as amorphous or crystalline orientation. In some instances the work is supplemented by finite element analysis.

III. EXPERIMENTAL RESULTS

A. Growth of amorphous silicon springs on templated substrates

Well-separated Si helical spring samples were prepared on a templated substrate at room temperature by the oblique angle deposition technique with substrate rotation. The template consisted of two-dimensional arrays of W posts in square and triangular patterns on which springs were grown. The W posts have a diameter of 150 nm. The height of an individual post is about 450 nm. The post-to-post distances are 1000 nm and 600 nm for the square [Fig. 2(a)] and triangular patterns [Fig. 2(b)], respectively. Four-turn springs were grown on these W posts. The deposition was performed in a high vacuum chamber with a base pressure of 5 \(\times 10^{-5}\) Pa (\(~4 \times 10^{-7}\) Torr). The Si source (99.999%, Alfa Aesar, USA) was evaporated from a graphite crucible by electron bombardment heating. The substrate was mounted 32 cm above the source. The vapor flux arrived at a fixed oblique incidence angle of 85° from the substrate normal. The deposition rate determined from a quartz crystal monitor was carried out at room temperature. Figures 2(a) (spring A) and 2(b) (spring B) show the SEM cross section images of the springs on templates. In Fig. 2(b), not all the springs are in the same plane (depth) because of the triangular symmetry of the template (every other spring is behind).

B. Examples of measured mechanical properties

1. Spring constant of individual amorphous silicon springs on templates

Noncontact mode AFM was used to image the sample surface.\(^3\) This allowed us to precisely target the application of the compressive load onto a single spring and apply the load with the same tip. The conical AFM cantilever tip used in this experiment is a monocrystalline silicon and has a spring constant of 17 N/m based on manufacturer’s specification. The tip height is nominally 5–7 \(\mu\)m, and the tip radius of curvature is about 10 nm. The compression was achieved by controlling the vertical movement \((z)\) of the substrate against the AFM tip. The amount of compression or displacement, \(d\), of the spring was equal to the difference between \(z\) and the deflection of the cantilever. No permanent indentation occurred and the indentation was in the Hertzian range. The depth associated with Hertzian indentation was much smaller than the measured \(d\). There the value \(d\) obtained from the experiment was totally due to the spring compression. The force applied was evaluated as the product of the cantilever spring constant and its deflection. The force vs spring displacement curves for 20 individual springs for each pattern shown in Figs. 2(a) and 2(b) were measured. Representative curves of loading (filled triangles) and unloading (open squares) for each type of spring are shown in Fig. 3. The loading speed was 100 nm/s. The loading and unloading curves are seen to be linear and reversible, indicating linear elastic behavior within this range of displacement. Hence, no rate effects have been observed in this ma-

---

**Fig. 1.** Left: A schematic of the oblique angle deposition setup. Right: Examples of amorphous Si structures grown on templated Si wafers using oblique angle deposition. Right: SEM sides views of (a) tilted rods and (b) helical springs. The scale bars are one micron.

**Fig. 2.** Scanning electron micrographs (cross sections) of the Si helical springs on (a) square patterned substrate or spring A and (b) triangular patterned Si substrate or spring B. A cartoon represents the applied force by an AFM cantilever.
The average spring constant of the type shown in Fig. 2(a) was measured to be 10.2 N/m with a standard deviation of 1.5 N/m, while for the type shown in Fig. 2(b) it was 2.8 N/m with a standard deviation of 0.6 N/m.

The spring constant of the two types of springs was evaluated using classical equations and geometrical parameters measured from Fig. 2. The rising angle $\alpha$ (or pitch angle) of the springs is 28°. The pitch is $h = 950$ nm. The wire thickness ($d$) of the springs was measured to be $350 \pm 20$ nm and $225 \pm 10$ nm for spring A and spring B, respectively. The mean coil diameter ($D$) is $570 \pm 30$ nm and $590 \pm 10$ nm for spring A and spring B, respectively. The computed values overestimate the measured spring constant by more than 100%. In order to elucidate the origins of this discrepancy, the springs were modeled by finite elements (FEM). When the force was applied along the direction of the axis of the coil or axial force in the model, the FEM overestimates the experimental spring constant. Only when the force is applied directly on the wire of the spring, as in the actual experiments, is the structure subjected to axial compression as well as bending. The displacement of the point where the force acts is rather large in all directions. However, the effective spring constant may be evaluated by dividing the force (oriented in the direction of the axis of the coil) to the displacement component in the force direction. This loading mode gives the effective spring constant much smaller than that evaluated for axial loading and is in reasonable agreement with the experimental results. Therefore it is concluded that the linear elasticity may be used to predict the response of these structures provided that the geometrical parameters and loading conditions (on the axial or on the wire) are properly represented in the model. The scaling of force constant for amorphous Si holds to the length scale of springs that we measured.

2. Electromechanical actuator from metal coated individual amorphous silicon springs on a template

In this example we present the results of electromechanical actuation of Co coated individual helical Si springs. The four-turn amorphous Si springs that were grown on a template that consists of a two-dimensional array of W posts arranged in a square pattern template as described in the previous section. The average substrate rotational speed was 2 h/turn and each turn was divided into four discrete steps instead of 32 discrete steps in the previous sample. That is, the rotational angle was fixed at an angle for half-an-hour growth and then rotated to 90° for the next 1/2 h growth. The Si springs were rendered conductive with a metallic coating deposited by the chemical vapor deposition (CVD). The source was dicobalt octacarbonyl, $\text{Co}_2(\text{CO})_{12}$ and the deposition was performed in a vertical reactor. The sample was heated up to 80 °C during deposition. The base pressure of the reactor was about $2 \times 10^{-11}$ Pa ($1.5 \times 10^{-3}$ Torr). The total reaction time was 5 min. The thickness of the Co layer was determined to be 10 nm by Rutherford backscattering spectroscopy of the blanket coated Si substrate placed next to the Si spring sample as well as the transmission electron microscopy image of a nanospring. This 10 nm coating limits the maximum current (about 25 mA) that can be applied to the spring. The conductivity is lost if a current exceeds 25 mA probably due to the loss of the Co coating.

The topography of sample springs was first imaged by using the noncontact AFM mode. This allowed us to precisely select a position on a well-isolated single spring. Then, the AFM mode was changed from noncontact to contact mode and the preset constant force was chosen at 1 nN to avoid spring overloading while insuring good electrical contact between the tip and the structure for passing a current. A dc current is passed through the spring by a conductive AFM tip with a cantilever spring constant of 17 N/m [see Fig. 4(a)]. The conductive coating on the AFM tip is sputtered Pt. The radius of curvature of the tip is about 60 nm. This dc current $I$ passed from the conducting AFM tip to the isolated spring generates a magnetic field $\mathbf{B}$ that produces a magnetic force $\mathbf{F}$ between the coils of the spring. For small pitch size $h$ the electromagnetic force in the coil puts the spring in compression. The total deformation of the spring is measured with the same AFM tip held in contact mode at the top of the spring. The plot of $I^2$ versus the total deflection of the spring $d$ measured with the AFM is shown in Fig. 4(b). Each data point is the average of ten different measurements on the particular nanospring. The error bars for the measured spring displacement $d$ represents the standard deviation of the measured value. As expected, the magnetic force experienced by the spring is proportional to the $I^2$. At steady state equilibrium, this magnetic force is balanced by the spring elastic force $F$. The estimated thermal expansion associated with 25 mA current passing through a spring is in the range of sub-nm which is much smaller than the magnetic force induced compression. The sub-nm expansion under about 20 mA passing current was experimentally verified from a straight Si nanorod (no electromechanical effect).

In order to evaluate the electromagnetic forces acting on the structure, the actual spring was modeled as a coil of pitch $h$ and diameter $2R$ equal to those of the physical structure, and of vanishing wire diameter. This is equivalent to assuming that the whole current flows through an infinitesimally thin wire that follows the geometry of the real spring. It should be noted that a certain uncertainty exists with regard to the exact path over which the current flows. The approxi-
mation made in the evaluation of the electromagnetic force according to which the whole current flows through an infinitesimally thin wire \((r\to 0)\), may induce errors. We propose that an upper limit of the electromagnetic force may be evaluated by assuming that the relevant pitch, corresponding to the distance between two neighboring conductive paths, is \(h/\ell\), i.e., the distance from the upper surface of the wire at polar angle \(\theta=0^\circ\) to the lower surface of the wire at \(\theta=2\pi\). With this assumption and for the small value of the geometrical parameter, \(\xi=h/2\pi\ell=0.18\), the bending may be neglected with respect to the effect of the axial force. The total deflection of the structure results as \(d=-8.1A/\kappa\), where \(A=\mu_0\mu_rF^2/4\pi\) (in units of force) and \(\mu_0\) is the permeability of free space, and \(\mu_r\) is the relative permeability of Co for which we assume a value of 200 (the values reported in the literature range from 70 to 250). Requiring the compatibility with the data in Fig. 4, the spring constant results to be \(\kappa=12\ \text{N/m}\).

An independent evaluation of the spring constant using mechanical measurements similar to those reported in our previous example was performed.\(^{25}\) In these measurements, no electrical current is passed through the structure, and rather the springs are loaded in compression using the AFM tip. Representative loading and unloading curves were obtained for a single spring. The response of the structure is linear and the loading and unloading curves overlap. No indentation was observed on the surface of the spring after testing. The spring constant is determined from the slope of (best fit to) the characteristic curve to be about \(8.75\pm0.04\ \text{N/m}\). Note that the mechanical force from the AFM tip applied on the wire of the spring is loaded off-axis. We have also performed finite element analysis. Considering the uncertainty in the dimensional parameters, the apparent stiffness for loading with a force applied on the wire ranges from 5.2 to 17 N/m. Therefore our force constant measured by AFM is consistent with the modeling. When the force is applied axially, the computed spring constant ranges from 10 to 32 N/m. The difference is due to the fact that off-axis loading produces both spring compression and bending, while axial loading produces compression only.

C. Growth of \(\beta\)-phase tungsten nanorods on a flat substrate

Next, we consider the growth\(^{29,30}\) and characterization of properties of tungsten nanorods.\(^{31,32}\) Tungsten films have been intensely researched due to their importance in various technological applications, for example, field emitters, photonic crystals, diffusion barriers in semiconductor interconnect structures, absorbing layers in x-ray mask, and x-ray mirrors. Depending on the growth conditions and thickness of the films, normal incidence sputter deposition (NISD) of tungsten films can give rise to either the \(\alpha\)-phase \(W\), which has the equilibrium bcc structure with a lattice constant of 3.16 Å, or the metastable \(\beta\)-phase \(W\), which has an A15 (cubic) structure with a lattice constant of 5.04 Å, or a mixture of both phases. These two phases have very different properties. For example, the measured resistivity of \(\beta\)-W film is an order of magnitude higher than that of the \(\alpha\)-W film. It was suggested that oxygen incorporation might play a role in the formation of the metastable \(\beta\)-W.

Using oblique angle sputter deposition we are able to grow \(\beta\)-phase \(W\) in nanorod form. Our tungsten nanorods were grown by a dc magnetron sputtering system with a base pressure of \~\(1.4\times10^{-6}\) Torr. The films were deposited on oxidized \(p\)-Si(100) substrates \(\sim2\times2\ \text{cm}^2\) size) using a 99.95% pure Ar cathode (diameter \~7.6 cm). The substrates were RCA cleaned and mounted on the sample holder located at a distance of \~15 cm from the cathode. The vapor flux arrived at an oblique incidence angle \(\theta\) from the substrate normal. The angle \(\theta\) has been repetitively changed from large to smaller angles to obtain a layered structure in vertical direction: 85° (40 min), 75° (10 min), and 60° (5 min) for the first layer and then three layers of 88° (10 min), 85° (10 min), 80° (5 min), 75° (10 min), and 60° (3 min). The substrate rotation speed was set to 0.5 Hz (30 rpm). In all the deposition experiments, the power was 200 W at an ultrapure Ar pressure of 1.5 mTorr. The maximum temperature of the substrate during the deposition was measured to be \~80 °C. The thickness of the films was determined by a step-profilometer and also verified by SEM cross-sectional images. See the inset in Fig. 5. The
Deposition rates were measured to be $\sim 7.0-10$ nm/min for the oblique angle sputter deposition. The SEM top view image (not shown here) reveals that the areal density of W rods is about $10^{13}$ rods/m$^2$. The top of W rods has fourfold symmetric (110) facets. These sides of a pyramid were inclined with respect to the square base by an angle of about 45° as can be seen from the inset in Fig. 5. X-ray diffraction (XRD) $\theta$-2$\theta$ measurements using a Sintag diffractometer with a Cu target and operated at 50 keV and 30 mA show that the W rods of length $\sim 760$ nm has a $\beta$-phase with a strong W(200) peak of a $\beta$-phase W (see Fig. 5). During the oblique angle sputter deposition, due to the extreme shadowing effect we expect that the islands that grow taller in the vertical direction will shadow a considerable amount of surface area in the film. We expect a faster growth of the lower mobility $\beta$-phase W.

D. Examples of measured electrical properties

1. Cold field emission from $\beta$-phase tungsten nanorods on a flat substrate

Cold field emitters have been researched due to their energy saving in technological applications, for example, flat panel display and vacuum electronics. We have used an STM to study both the field emission character and topography of individual $\beta$-phase tungsten nanorods. Figure 6(a) shows an STM image of pyramidal nanorods surface obtained in a constant current mode using a Pt–Ir tip with a radius of curvature about 10 nm, a set current of 1 nA and a negative bias voltage of 0.5 V applied to the W nanorods surface. On some nanorods we highlighted dotted lines along dark boundaries and we can see the boundaries do not intersect to one point. Instead an area that looks like pyramidal apex geometry exists. Figure 6(b) is a schematic diagram of a W nanorod showing the square-based pyramidal apex oriented in the [100] direction and bound by four (110) facets.

The field emission measurements were performed on these pyramidal nanorods in a vacuum chamber with a base pressure better than $1 \times 10^{-8}$ Torr. The STM tip is used to image the nanorod and then the tip was withdrawn from the nanorod apex and the feedback was disconnected so that current-voltage curves were obtained at a fixed separation of about 280 nm. The electrical connection from the W nanorods cathode to the STM tip anode was made by a copper wire attached to the top surface of W film and by-passed the metal/semiconductor diode that minimizes the voltage drop across the interface. The voltage was increased up to a burn-out voltage value where the emission current dropped to zero due to the emitter-tip failure. The plots of typical electron emission current ($I$) versus applied dc voltage ($V$) characteristics measured by STM for a W nanorod having a pyramidal apex (open triangles $\triangle$) are shown in Fig. 7 for a comparison. The turn-on voltage was observed to decrease from $\sim 510$ V for the conventional film surface to $\sim 145$ V for the pyramidal apex geometry. An important ex-
experimental finding is that an extremely stable high emission current of \( \sim 23 \, \mu A \) with \(<3\%\) fluctuations over \( \sim 2\) h at a low extraction voltage of \( \sim 260\) V and \( \sim 280\) nm cathode-anode distance was measured. This is due to the very sharp pyramidal apex W nanorods grown by glancing angle deposition technique. The conventional film gives a lower emission current of \( \sim 0.7\, \mu A \) having \(<5\%\) fluctuations at a higher voltage of \( \sim 720\) V.

The Fowler-Nordheim (F-N) plot for pyramidal nanorods and the conventional film are given as the inset in Fig. 7. The curve from the conventional film surface exhibits a straight-line behavior, whereas the F-N curve for a pyramidal W nanorod is nonlinear. The nonlinear behavior of the F-N curve that we observed from the pyramidal nanorod (very sharp tip) pointed out that F-N theory based on a planar model of a tip (blunt tip) with a constant field outside the tip does not apply to a very sharp tip. The local geometry of the tip and the spatial variation of field need to be considered.\(^3\)\(^3\)\(^5\)

In addition, our observed high current density and low field for electron emission compared with that measured form the continuous W film are consistent with an early high field emission detected on submicron size metal cathodes.\(^3\)\(^4\)

2. Field ionization of gas using \( \beta \)-phase tungsten nanorods on a flat substrate

The field ionization process is the subject of intense research because of its technological applications in ionization sensors and field ion microscopy (FIM). The field required in ionization of gases is very high and can be of the order of few V/Å. Therefore, several kilovolts are applied to a sharp tip in order to draw any useful ionization currents. In this example, we show the efficient ionization properties of \( \beta \)-phase W nanorods having pyramidal apexes for argon gas. The high pressure region automatically builds up near the sharp pointed W tips apex because of the induced polarization of gas atoms. These W nanorods provide a large number of individual field ionization sites for a gas.

The field ionization experiments\(^3\)\(^2\) were conducted in an ultrahigh vacuum (UHV) chamber with a base pressure better than \( 5 \times 10^{-9}\) Torr. A schematic of the setup for the measurement of argon gas field ionization is shown in Fig. 8. The anode is the W nanorods sample and the cathode is a 1 \( \mu m \) thick continuous Ag film deposited over \( p \)-Si(100) surface. A piezo driven Inchworm\(^\circ\) motor was used to control the distance between a W nanorods anode and Ag film cathode. High purity (99.9999\%) research grade argon gas was admitted to the UHV chamber through a leak valve to various pressures ranging from \( 10^{-5}\) Torr to \( 10^{-2}\) Torr. A positive voltage ranging between 0 to 400 V was applied to the W nanorods sample and the ionization current was collected at the Ag film cathode about 0.4 \( \mu m \) away from the W nanorods apex. We did try to measure the field ionization of Ar atoms from an individual W nanorod using a Pt-Ir scanning tunneling microscopy tip as the cathode. We were not able to detect any measurable current due to the extremely small size of the ionization collection region.

Figure 9 shows experimentally measured ionization current versus anode voltage for different Ar gas pressures ranging from \( 10^{-5}\) Torr to \( 10^{-2}\) Torr. The ion current fluctuations were observed to be \( \pm10\%\) for currents smaller than 100 nA and \( \pm50\%\) for higher current values. The ion current was found to increase rapidly with increasing positive voltage applied to the nanorods sample, which is visible from the logarithmic scale in Fig. 9. A current-voltage curve for the background current, i.e., in the absence of Ar is also shown in the same Fig. 9. Two findings from Fig. 9 are (1) the onset voltage for Ar gas is only 3–4 V whereas in the absence of Ar gas it is about 200 V and (2) the ion current collected with Ar gas (\( 10^{-2}\) Torr) present at about 25 V is two orders of magnitude more than the ion current collected from the background (\( 10^{-9}\) Torr) at about 350 V. This demonstrates an outstanding and unambiguous gas detection with a favorable signal to noise ratio for these pyramidal W nanorods ionizers. The strong voltage dependence of ion current in Fig. 9 is consistent with previous observations of field ion-
izations in metallic tips and was suggested to be due to a rapid increase in tunneling probability for electrons from impinging Ar atoms to the metal tip. In general, the ion current versus applied voltage shows a power law behavior, where the precise value of power depends on the form of the electronic density of states of the tip under a high electric field. From our data, the ion currents were found to increase on an average of about a third power of voltage with argon gas present.

E. Growth of uniform slanted nanorods using two-phase rotation

The above examples are from samples that were made by substrate rotation. In a conventional oblique angle deposition with no substrate rotation, nanorods grow faster along their widths in the direction perpendicular to the plane of incident flux or faster side way growth. This anisotropic growth on a templated substrate can result in “fan-out” shapes of nanorods that touch each other due to the faster growing widths. Asymmetric two-phase substrate rotation was designed to eliminate the side growth in oblique angle deposition. Within one complete revolution, the substrate rotates at a rotational speed $\omega_1$ in a phase sector $\phi$ and then at a higher speed $\omega_2$ in the rest phase sector $2\pi-\phi$. In this method, the growing rods are exposed to the deposition flux from all angles with some portion of a rod surface receiving more flux than the rest. We fabricated well-aligned Si nanorod arrays with uniform sizes from templates arranged in square and triangular lattices using this two-phase substrate rotation method. One example is shown in Fig. 1(a). Another method used to decouple the direction of incident flux and column growth in oblique angle deposition results in improvement of the uniform linear segment is called PhiSweep. In this method the substrate is swept from side to side with a sweep angle about a central axis defining the direction of the straight column. The sweep angle is defined as half of the sweep angle. We also presented measured properties of individual nanorods by AFM and STM and supplemented our understanding by finite element analysis. For mechanical measurement we are limited to applying force in either compression or tensile magnitude using the nanostructured compliant layer obtained by the oblique angle deposition. There are other basic electromechanical, magnetomechanical, magnetic, and thermal properties of these individual nanostructures that can be studied using scanning probe microscopy. One important lesson we gained from our study is that the nanostructure has to be uniform in shape and its size to be known accurately because when one extracts properties from the measurements using either finite elements or any other models the input parameter often is the size. If the size is not uniform one has to perform statistics of measurements from many individual nanostructures. The two-phase rotation method is one effort toward achieving more uniform sizes of these nanostructures.

ACKNOWLEDGMENTS

The work was supported by the NSF CMS-(0324492), SRC and RPI. The authors thank B.K. Lim for providing the templates and N. Koratkar for valuable discussions.