Effects of heat generation during electron-beam-induced deposition of nanostructures

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(Received 19 October 2004; accepted 4 May 2005; published online 27 June 2005)

To elucidate the effects of beam heating in electron-beam-induced deposition (EBID), a Monte Carlo electron-solid interaction model has been employed to calculate the energy deposition profiles in bulk and nanostructured SiO$_2$. Using these profiles, a finite element model was used to predict the nanostructure tip temperatures for standard experimental EBID conditions. Depending on the beam energy, beam current, and nanostructure geometry, the heat generated can be substantial. This heat source can subsequently limit the EBID growth by thermally reducing the mean stay time of the precursor gas. Temperature-dependent EBID growth experiments qualitatively verified the results of the electron-beam-heating model. Additionally, experimental trends for the growth rate as a function of deposition time supported the conclusion that electron-beam-induced heating can play a major role in limiting the EBID growth rate of SiO$_2$ nanostructures. © 2005 American Institute of Physics.

[DOI: 10.1063/1.1942627]

I. INTRODUCTION

The phenomenon of electron-beam-induced deposition (EBID) involves the interaction of an electron beam with a substrate in the presence of a precursor vapor. The electron beam initiates the decomposition of an adsorbed precursor molecule into a volatile and a nonvolatile component. The volatile species leaves the surface and the nonvolatile species is then deposited onto the substrate.

The technological implications of a well-controlled, highly robust EBID process are far reaching in scope. Clear defect repair of an extreme ultraviolet (EUV) mask has been performed using a focused ion-beam (FIB) technique. However, the ion implantation inherent to FIB mask repair can disrupt the highly sensitive optical properties of the transparent region. Electron bombardment is less likely to have these adverse effects; therefore, EBID can be used as a damage-free clear defect repair technique. EBID also holds the potential for use in a high-resolution resistless lithography technique in which a masking layer is deposited via EBID. Additionally, EBID can be used as a direct-write technique for depositing nanostructures for use in microelectromechanical systems (MEMSs) as well as rapid device prototyping and repair.

While a plethora of materials has been effectively deposited by EBID, a high level of control over feature size and/or geometry has been elusive. Ukte et al. were able to deposit gold using a variety of gases including carbon-free and organometallic precursors. Molhave et al. reported on the deposition of gold to produce freestanding nanowires. The deposition of a TiCl$_4$ film from a TiCl$_4$ precursor was shown to occur at low temperatures (100 K). In addition, ZrO$_2$, copper, SiO$_2$, and carbon, have all been deposited by EBID. Tungsten is perhaps the most commonly studied material deposited by EBID. Matsui et al. reported on the deposition of elemental tungsten from a WF$_6$ precursor vapor. They were able to fabricate a 15-nm diameter tungsten rod in a transmission electron microscope (TEM) using a 120 keV electron beam. Tungsten has also been successfully deposited from W(CO)$_5$ vapor. Of particular importance to this study is the deposition of SiO$_2$ from a tetraethoxysilane (TEOS) precursor as reported by Sánchez, et al. An extensive list of EBID precursor gases from which many of these materials may be deposited was compiled by Silvis-Cividjian.

Despite the numerous EBID studies reported in the literature, there is still only a limited understanding of the physical phenomena that dominate the EBID process. For the capabilities of EBID to be fully realized, a greater understanding of the fundamental mechanisms is necessary. Several publications have focused on elucidating the effects of experimental parameters on the process. Fujioka et al. successfully deposited iron on a SiO$_2$ substrate by using an Fe(CO)$_3$ precursor gas. They studied the influence of primary electron energy on the deposition process. By scanning a $50 \times 100$-$\mu$m$^2$ area for 60 min, they determined that the deposition rate increased for lower beam energies. Hiroshima and Komuro reported on the deposition of conducting tungsten wires from a WF$_6$ precursor. Their studies showed an increase in the wire height with increased electron dose. They also were able to determine that multiple fast line scans were more effective for depositing wires than was a single slow scan. Platen et al. obtained a similar result for the deposition of tungsten in which the deposition rate increased for short pixel dwell times.

High process resolution is essential for EBID to be considered a useful nanofabrication technique. Platen et al. discussed the resolution limits for the deposition of tungsten needles. They showed that the deposit diameter increased for low energy and high current, in accordance with the in-
increased beam diameter. Their studies showed that the base diameter as well as the height initially increases rapidly followed by a transition into a lower growth rate regime. It was found that the diameter eventually saturated to a maximum value while the height achieved a steady-state growth rate. Secondary electron-induced deposition can reduce EBID resolution by the lateral thickening of a growing column and by contributing to growth at the pillar base. Silvis-Cividjian et al. developed a model to simulate the effects of secondary electrons on the process resolution. The results of the simulation suggested that secondary electrons generated within the deposit are scattered out and contributed to the broadening of the feature. Using the knowledge gained from this model, Silvis-Cividjian et al. fabricated a 10-nm carbon line in a scanning transmission electron microscope (STEM).

While the observed two-regime growth rate behavior has yet to be fully explained, some of the previous literature alludes to the fact that beam-induced heating may be involved. Platen et al. suggest that a beam-induced surface temperature increase could be responsible for a reduced precursor sticking coefficient, thereby limiting the deposition rate. In order to determine the thermal effects of electron bombardment, it is necessary to either model or experimentally confirm the local temperature profile. Monte Carlo simulation of electron scattering in a tip structure and the subsequent energy deposition have been investigated, but was not integrated into a thermal model. Mirkarimi developed a finite element model to study electron-beam-induced heating on a planar Mo/Si multilayer film. This model utilized an analytical function to describe the energy deposition profile as a function of the radial position, current, voltage, and material parameters. They found that at high current density (2.2 MA/m²), a 10-keV beam induced a surface temperature of 833 K. However, private communications with the authors revealed that their commercial software package had mishandled the thermal conductivity data leading to an artificially high temperature (the actual temperature rise was on the order of 15 K). Experimental evidence of beam-induced heating was reported by Chu et al. in this study, a thermocouple was used to determine the temperature rise of a photoreist under electron bombardment. They reported that a 70-K increase in temperature occurred for a 15-keV electron beam and a current density of 0.5 MA/m².

Experimental and simulated results support the fact that electron bombardment can cause significant temperature increases at sufficient current densities. However, there is still a need for a more specific model that simulates electron trajectories in a nanostructure and is capable of integration with a thermal predictor model. This work describes a Monte Carlo simulation that is coupled with a finite element thermal model to simulate the local temperature rises that occur when a nanostructure is irradiated by an electron beam. The results of the simulated temperature rises are then correlated with observations made by previous authors as well as our own experimental results. This provides a greater understanding of the physical phenomena controlling EBID, thus leading to greater process control, reliability, and performance.

II. METHODOLOGY

A. Experiment

All experimental work was carried out in a Hitachi 4300-SE/N variable pressure scanning electron microscope equipped with a thermal field-emission electron source. The precursor vapors used for EBID are typically corrosive to thermionic emitter filaments. This normally results in constant emitter degradation and continual loss of emission current. The interlocked, differentially pumped column of the Hitachi 4300-SE/N allows for gases to be introduced into the system at low pressures (<10⁻² Pa) while the SEM is maintained in high-vacuum mode. This stable emission current allowed for greater experimental control and reproducibility. While the actual probe diameter was not determined for these experiments, the SEM is generally capable of probe sizes on the order of a few nanometers.

In order to deliver a higher localized vapor flux, the SEM was fitted with a gas injection system. The injection system consisted of a wobble stick capable of three-dimensional positioning inside the chamber. Precursor vapor was delivered through a hypodermic needle that was positioned directly at the substrate surface as discussed in a previous publication.

The experimental work focused on the use of a TEOS precursor vapor to deposit SiO₂ nanofibers. The nanofibers were deposited on a silicon substrate coated with a 2-μm layer of SiO₂ topped by a 500-nm sputtered tungsten film. The tungsten film was photolithographically patterned in order to simplify location of the experimental region. The SEM was operated in point analysis mode, which fixes the beam in a stationary position. Typically, the main chamber ambient TEOS pressure was ~1.8 × 10⁻³ Pa during the deposition process. It has been estimated that the localized vapor flux may be 100 times greater than that specified by the ambient pressure based on capillary flow equations. Temperature-dependent measurements were carried on an Emitech K25X Peltier Cooled Stage. The stage is capable of stable operation in a temperature range of 243–348 K.

B. Simulation

A Monte Carlo-based electron trajectory simulation was developed in the MATLAB® computing environment. The code was based on a single-scattering electron interaction model described in detail by Joy. In this model, collisions are governed by the Rutherford screened cross section,

\[ \sigma_E = 5.21 \times 10^{-21} \frac{Z^2}{E^2} \frac{4\pi}{\alpha(1+\alpha)} \left( \frac{E + 511}{E + 1024} \right)^2, \]  

(1)

where \( Z \) is the substrate atomic number, \( E \) is the electron energy, and \( \alpha \) is given by

\[ \alpha = 3.4 \times 10^{-3} \frac{Z^{0.67}}{E}. \]  

(2)

From these relationships and additional material properties, energy-dependent mean free paths can be calculated for each electron. A random number generator was utilized in computing the scattering angles, which allowed for calculation of
the electron trajectory. The energy deposition, \( \Delta E \), was determined for each scattering event. The electron trajectories were converted from Cartesian coordinates to cylindrical coordinates under the assumption that the electron distribution is radially symmetric. The spatial distribution of electrons was then discretized into a uniform grid of 3-nm units in the radial and axial directions. The energy deposited by each electron was collected and sorted into the spatial grid and allowed for the calculation of the total-energy deposition distribution (W/m³). The electrons used in the simulation were assumed to emanate from a point source at the center of the nanofiber tip. This is a reasonable approximation because the 3-nm-grid radial dimension is on the order of the achievable beam diameter in the SEM. The use of a Gaussian-shaped spot is necessary only in the case of a large spot size (>3 nm) or if a finer grid size is used. Therefore, the simulation may become inaccurate at the extremes of high current and low energy due to the large probe sizes inherent to these conditions. In order to precisely determine the magnitude of the temperature rise, it would be necessary to know the beam diameter and its functionality with condenser lens setting and beam energy.

This matrix of energy deposition data was converted to a text format compatible with the FLEXPDE® finite element modeling software, which is capable of accepting the data as input and using it as an energy source term in the heat equation,

\[
\kappa \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) + H(r,z) = 0, \quad (3)
\]

where \( \kappa \) is the thermal conductivity, \( r \) is the radial position, \( z \) is the axial position, \( H(r,z) \) is the energy source, and \( T \) is the absolute temperature. The solution of the heat equation with appropriately applied boundary conditions yields a simulated temperature profile of the nanofiber. Figure 1 is a representative illustration of the axisymmetric model used to approximate experimentally-observed EBID geometries. The boundary condition applied for surfaces 1 and 3 as shown in Fig. 1 was \( \partial T / \partial z = 0 \). The boundary condition applied to the symmetry axis (6) and the nanofiber radial boundary (2) was \( \partial T / \partial r = 0 \). The outer radial (4) and axial (5) boundaries of the substrate were assumed to be semi-infinite and constant at \( T = 300 \) K. As determined by prior simulation, the electron-beam-heating process reaches thermal equilibrium on the order of nanoseconds, which is much less than the experimental growth time. Therefore, the heat equation was solved in steady-state \( (\partial T / \partial t = 0) \) as given by Eq. (3) in order to lower the computation time. The thermal conductivities of SiO₂ and tungsten used in the simulation were 1.4 and 174 W/m/K, respectively.

III. RESULTS AND ANALYSIS

A. Experiment

Several experiments were performed in which silicon dioxide nanofibers were deposited from a TEOS precursor. Figure 2 is an electron micrograph of typical nanofiber structures that result from operation of the SEM in point analysis mode during EBID. Similar nanofibers were grown in a series of experiments in which the deposition time was varied in order to determine the transient behavior of the growth rate, the results of which are displayed in Fig. 3. The experiments were performed at 20-keV beam energy, \( 1.8 \times 10^{-3} \) Pa, and two different beam currents. The data presented in Fig. 3 show that while the nanofiber height increases with time, the rate of the increase (as depicted by the Fig. 3 inset plot) in height actually decays. Therefore, as the nanofiber becomes taller, the growth rate decreases to a steady-state value and eventually the height begins to saturate, as shown in Fig. 3.

Another interesting result from Fig. 3 is the observation that the initial and steady-state vertical growth rates are higher for lower incident-beam current. It can be seen that at 10 min, a 107-pA beam current yields an \( \sim 750 \) nm-tall nanofiber, while at 530 pA the height is less than 500 nm. The response of the deposition rate to increased current suggests that there is mass-transport limited growth in these ex-
Experiments. In such a case, reduction in the availability of adsorbed TEOS precursor is expected to decrease the overall deposition rate. The precursor flux was constant for these experiments as the pressure was constant; therefore it is assumed that any decrease in precursor population is due to factors other than pressure. Electron-beam-induced heating (EBIH) is one phenomenon that can be used to explain the aforementioned results. Electron bombardment results in a finite amount of energy being deposited in the substrate, which can result in a temperature increase. The precursor availability as governed by the surface population of an adsorbate, $n_a$, is given by

$$n_a = \left[ \frac{p}{\sqrt{2\pi MRT}} \right] \tau_0 e^{-\Delta H_{des}/RT}, \tag{4}$$

where $p$ is the pressure, $M$ is the molecular mass, $R$ is the universal gas constant, $\tau_0$ is the inverse of the attempt frequency, and $\Delta H_{des}$ is the enthalpy of desorption.$^{26}$ Equation (4) is strongly temperature dependent and thus significantly influenced by changes in temperature as can result from EBIH. Tedder et al. studied the surface population of TEOS interacting with a SiO$_2$ surface.$^{27}$ They reported that at temperatures above 100 K, a large portion of the bound TEOS enters a physisorbed state, which reaches a maximum surface density at 250 K. Molecular desorption of TEOS was found to be enhanced by increased surface temperature in the range of 250–450 K, above which decomposition from TEOS to siloxane species occurred. Therefore, if electron bombardment induces a surface temperature increase for room-temperature experiments, it is expected that higher currents—which result in higher surface temperature—will reduce the TEOS surface coverage and thus reduce the deposition rate. Therefore, the reduced deposition rate observed at higher beam current displayed in Fig. 3 is in agreement with the idea of EBIH-limited TEOS surface population.

To experimentally verify that increased surface temperatures reduce the deposition rate, additional experiments investigating the effects of substrate temperature on the EBID process were performed. A hot/cold stage was installed in the SEM in order to perform temperature-dependent EBID growth experiments using the TEOS precursor. Deposition of silicon dioxide nanofibers was performed under the constant conditions of 20-keV beam energy, 120-s deposition time, and a pressure of $1.7 \times 10^{-3}$ Pa. The exact beam current was not specifically recorded as the hot/cold stage is not electrically connected to our metering port, but the condenser lens and aperture settings were consistent with a previously measured ~200-pA beam. For this experiment, deposition was performed in the temperature range of 295–345 K. For each temperature adjustment, there was a necessary sample stabilization time of ~5 min in order for the specimen to reach thermal equilibrium after which no noticeable beam drift occurred. Figure 4 is an Arrhenius plot of the natural logarithm of the deposition rate versus the inverse of the substrate temperature. This plot illustrates that the growth rate is a strong function of substrate temperature and that higher rates occur at lower surface temperatures. This observation confirms that for these experimental conditions, the surface population of TEOS plays a limiting role in the deposition process. From the Arrhenius plot, the measured activation energy of the process was determined to be ~0.23 eV. While the desorption energy for TEOS on SiO$_2$ was not reported in the work by Tedder et al., desorption energies typically vary from 0.15 eV for physisorbed species to 0.65 eV for weak chemisorption and physisorbed organic species.$^{26}$ Additionally, Wise et al. determined that the thermal activation barrier for deposition of SiO$_2$ from diethylidioxyxilsane (DEDEOS)—a species similar to TEOS that may also be used as a precursor for high-pressure chemical-vapor deposition (HPCVD) of SiO$_2$ deposition—was approximately 0.5 eV, and noted that this was similar to the reported value for TEOS.$^{28}$ This provides evidence, albeit indirect, that under the aforementioned experimental conditions, the surface population of TEOS controls the vertical deposition rate of SiO$_2$.

In addition to exposure time and beam current, the incident-beam energy was also expected to play a significant role in the SiO$_2$ deposition process due to changes in reaction probability (as governed by the precursor vapor dissociation cross section), the volume over which energy is deposited, and the secondary and the backscattered electron distributions and yields. The effects of beam energy were examined using an 80-pA incident beam current, a 60-s deposition time, and a chamber pressure of $1.8 \times 10^{-3}$ Pa. Figure 5 depicts the results from this experiment and illustrates that the
deposition rate increases with increased energy up to a maximum at 20 keV. Beyond 20 keV, an increase in energy decreased the deposition rate. Since the dissociation cross section decreases with increasing energy in this energy regime (greater than 3 keV), this result was not anticipated. In a process governed by the electron-mediated dissociation of TEOS, it would be expected that the deposition rate would continuously decrease with increased beam energy due to the reduced dissociation probability. The fact that this is not observed indicates that a phenomenon other than dissociation controls the deposition rate for the given experimental conditions. Since it was previously shown that in this pressure-current regime, the surface population of TEOS controls the deposition rate, the lower beam energies must lead to a reduction in precursor surface coverage, thus limiting the deposition rate. While this result is not fully understood, it may be partially explained by simulating the effects of EBIH as a function of beam energy. The results of these simulations will be discussed in the following section.

B. Simulation

Experimentally, it was found that increased surface temperature resulted in reduced deposition rates due to reduced precursor coverage. In addition, the growth rate was shown to decrease at higher current, which is likely due to higher nanofiber tip temperatures produced via EBIH. In order to verify that the EBIH can result in sufficient nanofiber tip heating to produce these results, a simulation was developed to determine the magnitude of EBIH.

The initial simulations were used to investigate the effects of increased current on the nanofiber tip temperature. Since the rate of heat generation is proportional to the incident current, the change in nanofiber tip temperature, ΔT, for constant energy, radial position, and nanofiber geometry is linear with increased current.

Subsequent to determining the effects of beam current, the effects of beam energy on nanofiber tip temperature were simulated and are shown in Fig. 6. A beam current of 500 pA and variable beam energy were used for the simulation. Also in Fig. 6, the differences between a SiO2 thin film (500 nm thick) and a 500-nm-tall nanofiber under electron bombardment are illustrated. In the simulation, the SiO2 film was deposited on an effectively semi-infinite silicon layer, while the nanofiber was deposited on an effectively semi-infinite slab of tungsten on SiO2 (used to mimic experimental conditions), as shown in Fig. 1. Importantly, it was determined that the thermal conductivity of the semi-infinite substrate has very little effect on the nanofiber tip temperature as the heat generation is localized in the region of irradiation. In contrast, the thermal conductivity of the nanofiber has a profound effect on the steady-state nanofiber tip temperature. For the thin film, the maximum surface temperature of 304 K is realized at 1 keV (the lowest-energy simulated). As the energy is increased to 30 keV, the film surface temperature is observed to decay to a value slightly above room temperature. Higher temperatures are observed at low energy because of the inherent reduction in the electron interaction volume. While the total energy deposited by the low-energy electrons is of course smaller, it is distributed over a much smaller volume. Consequently, the energy density for low beam energies is much higher, and leads to higher temperatures in the case of thin-film irradiation.

Figure 6 shows that the temperature response of an irradiated nanofiber is quite different from that of the irradiated thin film. For the same incident current, the tip temperature of a nanofiber can be substantially higher than the surface of the thin film. This difference is due to the geometry of the nanofiber itself. Because the nanofiber is a raised feature, it represents the creation of a new surface with effectively insulating boundary conditions (convection and radiation through the vacuum are neglected in the thermal finite element model). In contrast with the thin-film simulation, there exists only a narrow path for thermal diffusion, as heat must travel the length of the nanofiber before it can be dissipated into the bulk. Therefore, the nanofiber effectively becomes a quasi-one-dimensional structure in terms of heat conduction—an effect that results in increased tip temperatures relative to a flat surface.

Upon further inspection of Fig. 6, another noteworthy trend is observed to occur as a function of energy. In the nanofiber, the tip temperature initially increases in the low-energy regime, reaches a maximum, and then steadily decreases with higher energy. This trend is due to the location of the energy source in relation to the nanofiber sidewall surface. At very low energy, the energy source is located well inside of the nanofiber boundary, so that the energy source is...
small compared to the volume of the nanofiber. As the energy increases, the energy deposition volume increases and approaches the insulating boundary, which leads to higher temperatures. As illustrated in Fig. 6, smaller diameter nanofibers will have a tip temperature maximum at lower beam energies. Beyond this maximum, the interaction volume increases to the point where a large portion of the electrons are scattered out of the nanofiber and the resultant loss of energy yields lower nanofiber temperatures. Therefore, the tip temperature of a nanofiber is primarily dictated by the location of the energy source relative to the outer nanofiber boundary. This effect is clearly observed in Fig. 7 in which the energy deposited at the near-tip region of the nanofiber is plotted as a function of radial position. It can be seen that at the lowest of energies, the majority of the energy density is located inside of the nanofiber. At higher energies, the energy source spans the full radius, but because of scattering out of the fiber, significant energy is lost and the overall energy deposition rate decreases. While the trends of the simulation at low energy are interesting, it is important to note that all of the experiments were carried out at 3 keV or higher energy. Therefore, the spike in nanofiber tip temperature shown in Fig. 6 would not be reflected in any of the experimental data presented, as this phenomenon only occurs at these lower energies. Future experiments are planned to explore this region.

Figure 8 is a typical contour plot that is generated following the solution of the heat equation. This simulation used a 1.5-keV beam, 500-pA incident current, and a 500-nm-tall, 100-nm-diameter nanofiber. From the isothermal contour lines in Fig. 8 it is clear that, except for the near-tip region, there is essentially no radial temperature gradient. Therefore, the nanofiber represents a quasi-one-dimensional structure in terms of heat flow. Again, this is in contrast with the bulk (thin-film) heating situation in which there exists a radial and axial temperature gradient.

Experimental evidence was presented that showed the nanofiber growth rate increasing up to a maximum at 20 keV as in Fig. 5. According to the simulation results in Fig. 6, the nanofiber tip temperature should decrease with increasing energy in the energy regime from 3 to 30 keV. It was experimentally observed that the deposition rate increased with increasing energy from 3 to 20 keV as in Fig. 5. Therefore, this result is consistent with the correlation between high beam energy and low nanofiber temperatures from 3 to 20 keV, where the low growth rates at low energy can be attributed to reduced surface coverage of TEOS as induced by higher nanofiber tip temperatures. While the model provides an adequate explanation of the observed energy dependence in the 3–20-keV range, the turnover in growth rate from 20 to 30 keV as shown in Fig. 5 cannot be explained by the EBIH model. While further experiments are needed to confirm this behavior, it is possible that at these high energies, the EBID process transitions to a dissociation-limited process governed by the dissociation cross section, which would decrease at higher, beam energy.

In addition to providing insight into the beam energy experiments, the simulations help explain the transient behavior of the EBID process. To understand the time-dependent growth rate behavior shown in Fig. 3, a 20-keV, 500-pA beam was used to simulate the tip temperature of a 100-nm-diameter nanofiber with varying nanofiber height. Figure 9 shows that as the nanofiber height increases, the tip temperature increases sharply. Therefore, as the nanofiber grows, the surface population of TEOS is continually reduced, resulting in the reduced growth rates that are observed for long deposition times (or tall nanofibers). However, as the solution of a partial differential equation is significantly influenced by the boundary conditions, it was necessary to perform diagnostics to verify that the model did not produce erroneous results due to boundary condition placement. A
series of simulations were performed to confirm that the location of the 300-K boundaries, as shown in Fig. 1, had no impact on the temperature profile solution. Placement of the boundaries 1000 nm closer to the fiber produced only a 0.1-K decrease in the tip temperature, which validated that the temperature increase with height was not an artifact of the increasing distance between the energy source and these outer 300-K boundaries.

Figure 9 suggests that the nanofiber tip temperature continuously increases with increased height. If this were the case, it would be expected that the growth rate would also continuously decrease if limited by TEOS coverage. Figure 3 shows that a continuous decrease in the deposition rate is not observed, but rather saturation to a steady-state value. We presume that the tip temperature and hence the TEOS coverage reach a steady-state value which leads to the observed steady-state deposition rate. The attainment of a steady-state tip temperature as opposed to a continuous increase with nanofiber height may be due to either the neglect of radiative heat losses that become significant at higher temperatures (proportional to \( T^4 \)) or to the simplified cylindrical model of the nanofiber used in the simulation.

**IV. CONCLUSIONS AND OUTLOOK**

The phenomenon of electron-beam-induced heating (EBIH) was used to explain common experimental observations associated with electron-beam-induced deposition. It was shown that a reduction in surface coverage of TEOS as controlled by elevated substrate temperatures reduces the EBIH rate. A Monte Carlo electron-solid interaction model integrated with a finite element model was used to simulate the tip temperature of a nanofiber as a function of current, beam energy, and nanofiber geometry. For typical experimental conditions, the simulation suggests that the nanofiber tip temperature decreases with increasing beam energy. Simulation results suggest that the nanofiber tip temperature depends strongly on the position of the electron interaction volume relative to the edge of the nanofiber, with the maximum temperature occurring when the interaction volume diameter is equal to the nanofiber diameter. It was also determined by simulation that the tip temperature increases as the nanofiber height increases. According to the model, typical experimental EBIH conditions are capable of generating tip temperature increases of 30 K—a temperature that was shown experimentally to dramatically reduce the deposition rate. The observation of the reduced deposition rate of nanofibers at longer times and higher currents was correlated with the increased nanofiber tip temperature inherent to these conditions that result in reduced surface coverage of the TEOS precursor. The experimentally observed energy dependence of the deposition rate was partially correlated with thermal effects, but is still not fully understood.

Based on experimental observations and simulated results—low current, high energy, and short nanostructures are conducive to low temperature and high deposition rates. Fortunately, these conditions are also favorable for high-resolution EBIH processing. Therefore, the thermal effects should only be significant when depositing high aspect ratio nanostructures. The strong geometric dependence of the temperature rise indicates that future EBIH models should involve more realistic models and simulations of bulk heating by irradiation should incorporate surface roughness. In addition, radiative heat losses should be taken into account in further EBIH simulations.

Currently, a direct-write EBIH-based lithography technique is under development in which the thermal effects are negligible due to small feature height. Also under development is a fully three-dimensional model of EBIH that incorporates vapor dynamics, surface diffusion, and EBIH to further elucidate the role of all of these in the deposition process. To further validate the EBIH conclusion in relation to EBIH, experiments are being performed that will allow for measurement of the average temperature of nanostructures under electron bombardment.

**ACKNOWLEDGMENTS**

The authors wish to thank David C. Joy for his valuable insight, as well as the members of his research group for their support. This research was sponsored by the Defense Advanced Research Projects Agency (DARPA) Advanced Lithography Program.

14. N. Silvis-Cividjian, Electron Beam Induced Nanometer Scale Deposition (Dimension, 2002).