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Direct-laser writing of silicon microstructures: Raman microprobe diagnostics and modeling of the nucleation phase of deposition

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Two topics vital to the analysis and applications of direct-laser writing of silicon microstructures are addressed here: optical diagnostics and modeling. The use of real-time and postprocessing Raman microprobe analysis of laser-written doped polysilicon microstructures on CMOS gate arrays is shown to be a useful diagnostic tool. Also, the results of a Monte Carlo simulation of adatom migration and desorption are applied to the study of nucleation effects in direct-laser writing, with specific reference to the deposition of silicon.

I. INTRODUCTION

Photolithography has been quite successful in fabricating the intricate patterns required for manufacturing integrated circuits. This approach typically consists of more than a hundred independent steps with exceedingly tight quality control requirements, and is particularly well-suited for large-volume manufacturing of circuits. The increasing demand for limited-volume, application-specific integrated circuits warrants the consideration of alternate, more economical means of semicustom and custom microelectronics fabrication. One promising approach to address the stringent quality control requirements and fast turnaround times necessary for limited-volume production of integrated circuits combines elements of direct-laser writing and conventional photolithography. Research into the potential applications of direct-laser writing in microelectronics fabrication and repair, such as the interconnection of gate arrays, is becoming quite active.^{1,2} There is a corresponding interest in understanding the physics and chemistry of the laser-induced surface-localized microreactions involved in direct-laser writing.²

This article focuses on two aspects of localized laser deposition of silicon microstructures which can help gain insight into the physical basis of direct-laser writing and may impact the fabrication of integrated circuits using these techniques. Specifically, Raman microprobe analysis of silicon microstructures fabricated on CMOS gate arrays by direct-laser writing^{3,4} is performed. Also, an atomistic description of features of localized laser deposition by computer simulation is presented.

The observation of the Stokes Raman scattering radiation emitted during the direct-laser deposition of polysilicon microstructures on germanium and vitreous carbon has been reported recently.5 That report also included a study of the Raman spectrum observed during localized-laser heating of these microstructures after deposition. This paper explores the characterization of doped polysilicon interconnect structures on CMOS gate arrays using these Raman microprobe methods. Topics of interest here include investigating the temperature profile induced during laser deposition on gate array substrates, the dopant concentration in laser-deposited silicon, and the potential practical application of these techniques for real-time and in situ characterization of laserdeposited microstructures.

The results of a Monte Carlo simulation of high-speed, nonlocal deposition of adsorbate atoms on a surface are also presented. This computer simulation describes an experimental regime that is very different from those of earlier studies⁶-which were instead directed towards conventional, large-area thin film deposition with relatively slow vertical growth rates. Specifically, this model provides insight into the importance of adatom cluster formation and nucleation for different adatom/substrate combinations (and associated adhesion energies) during direct-laser writing of materials in general, and of silicon in particular.

II. EXPERIMENTAL METHODS

The Raman microprobe analysis was performed in an experimental setup which included a laser microscope⁷ that introduced the 5145 Å argon-ion laser to the substrate and permitted on-line viewing with a vidicon. The position of the focused laser on the substrate was varied by translating the stage holding the mounted substrate/reaction chamber up to a maximum scanning speed of 0.2 mm/s. Raman analysis was performed both on samples prepared in this facility by pyrolytic deposition of silicon from silane mixtures^{3,8,9} and on gate arrays interconnected using a similar procedure in a separate facility.⁴ In the former case, the same laser could be used simultaneously to locally heat the sample and induce laser-chemical vapor deposition (CVD), and also to provide photons for spontaneous Raman scattering. The Raman scattered radiation was collected, prefiltered to remove 5145 Å, dispersed by a 1 m single monochromator, and detected by an intensified/diode array/signal averager assembly.⁵

CMOS gate array wafers were prepared as in Refs. 3 and 4. As supplied by the vendor, the gate array wafer is covered with a thin film of aluminum. The aluminum layer was etched by photolithography leaving some features such as the aluminum power distribution lines; these were important in the Raman studies reported here. After patterning, a thin film of undoped amorphous silicon (a-Si) was deposited on the substrate to cover the exposed interlevel dielectric insulator (SiO₂/Silox), vias and remaining aluminum structures, to ensure laser absorption and heating at the surface.

III. RAMAN MICROPROBE ANALYSIS

During the deposition of silicon via the reaction of silane with a laser-heated surface most of the incident laser beam is absorbed or reflected, while a relatively small fraction is inelastically scattered by spontaneous Raman scattering. Since this Raman spectrum contains real-time information concerning the deposited material composition, free carrier type and concentration, crystallinity, strain, and temperature, this signal may be of use in characterizing the deposited materials; in some cases, it may be useful for controlling processes such as the interconnection of gate arrays. During deposition a second laser, possibly at a different wavelength and at lower intensity, can also be focused at or trailing the reaction zone, to better characterize the deposit. Furthermore, after deposition a laser can be focused on the fabricated microstructure for in situ characterization. Real-time and in situ Raman analysis during laser writing were first discussed in a previous report⁵ for the deposition of undoped polysilicon from silane on germanium and vitreous carbon substrates. In this section Raman microprobe analysis is used to characterize doped and undoped polysilicon microstructures on CMOS gate arrays.

For uniformly heated samples, the Raman shift of c-Si monotonically decreases from 520 to about 480 cm⁻¹ as the temperature increases from ambient (298 K) to near melting (1690 K).^{10,11} Over the same temperature range the width of the spectrum monotonically increases from 3 to about 25 cm⁻¹.^{10,11} The relation of the width and shift of the Raman spectra for uniformly heated silicon is plotted as curve e in Fig. 1 for oven temperatures from 300–1450 K. Strain and variations in crystallinity can also alter these shifts and widths.



FIG. 1. Peak width (FWHM) vs frequency shift is plotted for the Stokes Raman spectrum of silicon for different conditions. The range of data in each plot corresponds to a range of incident laser powers (a)–(d) or oven temperatures (e), starting from a minimum in the implicit variable (a few mW for a–d; 300 K for e) at 520 cm⁻¹ shift and increasing along the curve to the right. Plots a, c, and e are presented for comparison purposes and are derived from Refs. 5 and 10. The Raman data in plots b and d were obtained in postdeposition analysis of *n*-type polysilicon interconnects deposited on gate arrays in Ref. 4. (a) Local laser-heated *c*-Si wafer from Ref. 5. (b) Laser-probed polysilicon lines written on aluminum structures on gate arrays. (c) Laser-probed undoped polysilicon on Ge from Ref. 5. (d) Laserprobed polysilicon lines on gate array insulator region (*a*-Si/SiO₂). (e) Oven-heated *c*-Si from Ref. 10.

The Raman spectrum of a substrate locally heated by a focused laser which also serves as the Raman probe, is derived by summing the contributions from different regions maintained at their respective temperatures. Consequently, for equal maximum temperatures the Raman spectrum of a locally laser-heated substrate can be broader and less shifted in frequency than the corresponding spectrum of a uniformly heated substrate. The width/shift relation for a laser-heated Si wafer is displayed as curve a in Fig. 1, where the power of the probe laser is an implicit variable along the curve.⁵ The corresponding relation for laser-heated silicon microstructures can fall anywhere in the range between curves a and e, depending on the specific conditions. For example, the temperature profile for a thermal conductor microstructure on a thermal insulator will tend to be flat¹² and therefore the width/shift relation should more resemble curve e. For deposits on thermally conducting substrates, the temperature profile will be more inhomogeneous¹² and the Raman relation should tend to resemble curve a. Furthermore, the width/shift relation of the probed microdeposit will tend to more resemble curve e rather than curve a when the deposit and substrate are different materials and therefore will have different Raman shifts, and will also more resemble curve e as the diameter of the laser focus becomes larger than the width of the microstructure. Because of the spatially varying material characteristics on a gate array, the Raman spectrum of polysilicon microstructures on the gate array should reflect these differences. This dependence of the Raman spectrum on the underlying substrate is of potential use in discovering defects in gate array wafers.

Figure 1 shows the width/shift relations for a series of postdeposition Raman analyses of the phosphorus-doped polysilicon structures of a gate array interconnected in a separate facility.⁴ The data points along these curves (from left to right) were obtained from Raman spectra taken with increasing laser power, as illustrated in Fig. 2(a) of Ref. 5. A typical high-laser power (75 mW), postdeposition Raman spectrum of a silicon microstructure on a gate array insulator is displayed below in Fig. 2 (curve b, thin solid line). Plot d in Fig. 1 represents the Raman width/shift relation for n-



FIG. 2. Real-time (a, bold line) and post deposition *in situ* (b, thin line) Raman spectra of the same laser-deposited, undoped Si line at the same laser power (75 mW) and scan speed ($\sim 0.1 \text{ mm/s}$) on an insulating region of a gate array. Silane was used for silicon deposition.

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type silicon lines written on the thick, thermally insulating interlayer dielectric, while plot b represents lines written on the (thermally conducting) aluminum transmission lines. For reference, the relation for laser-deposited undoped Si microstructures on Ge from Ref. 5 is also plotted, curve c. As expected, the Raman spectra of the lines written on the structures with high thermal conductivity (plot b) more closely resemble the case of the laser-heated substrate with large temperature inhomogeneities (plot a), while the plot for the polysilicon-on-insulator case (plot d) more closely resembles curve e for uniformly heated silicon. The maximum temperature of these Si structures during Raman analysis appears to be within a few hundred degrees of melting. At very low laser power the Raman shift of each n-type polysilicon line was 519 cm⁻¹, with a width of \sim 4–5 cm⁻¹, as found for undoped Si on Ge in Ref. 5.

The temperature profiles for isolated silicon dots written on insulator regions of the gate array are expected to be flatter than for corresponding polysilicon lines because of the additional thermal conduction path along the Si line in the latter case.¹² This was examined here by depositing undoped silicon spots by laser writing, followed by *in situ* Raman analysis. As expected, the postdeposition Raman profiles of approximately 5 μ m diameter laser-deposited spots effectively fall on the uniform-temperature plot e of Fig. 1 (not shown in the figure).

The influence of dopant atoms on the Raman spectra of doped polysilicon microstructures can be significant. At high dopant concentrations the distinct peaks due to local Si–P or Si–B local modes can quantitatively determine the total concentration of substitutional dopant atoms; for example, the Si–¹¹B mode near 620 cm⁻¹ can be used to measure boron doping levels.¹³ In some regimes the concentration of untrapped free carriers from activated dopants can also be determined because free carriers tend to "soften" the crystal¹⁴ and hence, alter the Raman spectrum of silicon.^{14,15} Only this latter effect is examined here. Since P and B dopants induce relatively small changes in the absorption spectrum of silicon at room temperature,¹⁶ the Raman scattering probability is not expected to be a strong function of doping.

Further experiments were conducted with the deposition of doped polysilicon microstructures on CMOS gate array interlevel dielectric and the subsequent Raman analysis performed in the same chamber. The same n- and p-type reactant mixtures used to interconnect gate arrays in Refs. 3 and 4, i.e., a few percent phosphine (n-type) or diborane (ptype) mixed with silane and disilane at several hundred Torr pressure, were also used here. Some representative data obtained in these studies are plotted in Fig. 3. In all these studies the Raman shift measured at low laser power was independent of total reactant pressure and dopant type. Also, no significant variation in Raman scattering probability with doping was observed in any of these cases. There was also no observable difference in the width of the Raman spectrum probed at low laser power for undoped and n-type silicon, as is clear from Fig. 1. However, the low laser power Raman spectrum of laser-deposited boron-doped polysilicon was consistently broader than that for phosphorus-doped polysilicon; the width of this p-type material was typically rough-



FIG. 3. Peak width and frequency shift for the *in situ*, postdeposition Raman spectra of *n*- and *p*-type polysilicon microstructures on an interlayer dielectric insulator portion of a CMOS gate array. As explained in the Fig. 1 caption, the power of the laser probe is an implicit variable. The deposition conditions (reactant pressure, laser power, dopant gas) are given in the figure. The sparsely spaced dashed line is a fit to the PH₃ run, while the closely spaced dashed line is a fit to the data from all three B_2H_6 runs.

ly 8 cm⁻¹, which is ~ 2 cm⁻¹ wider than for *n*-type silicon, as seen in Fig. 3. As the laser power used in the Raman analysis was increased, the difference in *p*- and *n*-type Si Raman peak widths did not increase and may have even become smaller than the low-power difference of 2 cm⁻¹.

The self-consistent interaction of the k = 0 optical phonon with free electrons in the conduction band of n-type silicon induces an optical frequency-dependent perturbation of the phonon frequency in second order.¹⁴ For 4880 Å excitation, the free electron-dependent frequency shift is small $(-0.5 \text{ cm}^{-1} \text{ per } 10^{20} \text{ electrons/cm}^3)^{14}$ relative to undoped material, while the additional broadening is small¹⁵ or zero.14 The perturbation of the Raman spectrum for borondoped silicon is much more severe because of the first-order interaction between the optical phonon with valence band holes in p-type silicon.¹⁴ For example, for 4880 Å excitation the relative Raman shift is about -1.7(-3.1) cm⁻¹ and broadening is about 7.5 (9.9) cm^{-1} for a hole concentration of $5.9 \times 10^{19} (1.4 \times 10^{20}) / \text{cm}^{3}$ ¹⁴; the profile is very asymmetric at higher doping levels.¹⁵ At 5145 Å, the corresponding shift is expected to be much smaller and the broadening is expected to be somewhat smaller than at 4880 Å.15 The frequencies and widths of the n- and p-type silicon Raman spectra measured here are consistent with these cited Raman data^{14,15} and the doping concentrations of the laser-deposited polysilicon deduced from resistivity measurements, i.e., $\sim 10^{20}$ /cm^{3, 3,17} More precise determination of doping levels is possible using 4880 Å radiation. Note that Ref. 5 suggests that photoproduced carriers do not contribute significantly to the properties of the Raman spectra obtained here.

Figure 2, trace a (thick solid line) shows a typical Raman spectrum obtained during laser deposition of (undoped) polysilicon from SiH_4 on a gate array dielectric insulator. The associated postdeposition Raman signal is depicted in trace b (thin solid line), which was obtained by analyzing the same line at the same laser power (75 mW). As demonstrated in Ref. 5 for Si on germanium and vitreous carbon, the real-time peak here is smaller and shifted to higher fre-

quency vis-a-vis the postdeposition peak. The integrated real-time Raman signal for silicon on germanium⁵ (a good thermal conductor) is only about 10% smaller than the postdeposition probe signal; whereas the real-time signal appears to be relatively much smaller than the postdeposition signal ($\sim 20\%-40\%$) for silicon on thermal insulators, such as on interlayer dielectric (SiO₂) in this study and on vitreous carbon in Ref. 5. This suggests that the differences in the real-time and postdeposition spectra may be predominantly due to the different temperature profiles (and possibly phase) during writing vis-a-vis postdeposition reading, and only to a lesser extent due to differences in material morphology and strain.⁵

The value of Raman microprobe analysis for real-time or *in situ* analysis of polysilicon structures depends on the desired scanning speeds and microstructure dimensions. For a $5 \,\mu$ m wide polysilicon line and a 1 mm/s scanning speed,³ data collection and analysis must occur in 5 ms to provide useful feedback during deposition. High-laser power Raman profiles, with the signal and noise as shown in Fig. 2, typically require 5–15 s collection time. With improved photon collection, and decreased wavelength dispersion and resolution, collection times may be lowered to perhaps 100 ms. Still, this would probably not be fast enough for real-time analysis of high-speed deposition. However, for real-time monitoring of slower deposition and for *in situ*, postdeposition analysis with (more slowly scanning and perhaps multiple) probing lasers these techniques are potentially useful.

IV. NUCLEATION EFFECTS IN DIRECT-LASER WRITING

Models of direct-laser writing have proven to be quite useful in understanding the underlying physics of experimental observations. In one such model of localized-laser CVD¹⁸ the Arrhenius-type behavior of local surface chemistry was coupled with the gas transport of molecular reactants and products to predict the rate of local material growth for a given laser intensity and gas pressure. In this model, each deposit adatom produced at the surface was presumed to stick, with no surface migration or desorption. For relatively low growth rates, deposition was found to be limited by the rate of surface reaction as determined by the (Arrheniustype) reaction rate constant and the laser-controlled local temperature rise; whereas at relatively high deposition rates the surface reaction was limited by gas transport.

The current work examines the importance of surface nucleation during the initial stages of material growth for the high deposition rates and high temperatures encountered in direct-laser writing. In both conventional deposition¹⁹ and direct-laser writing the early phases of growth are known to be hampered until critical nuclei form, which can then grow and coalesce to form thin films. Details concerning surface nucleation (and not the details of the surface chemistry) can be the main factor limiting the growth rate in some experimental regimes. In the model presented here the importance of adsorbate atom/substrate atom adhesion in direct-laser writing is specifically addressed, while gas transport effects, localized surface chemistry, and variations in local temperature and molecular flux to the surface are ignored. (These effects will be considered elsewhere.²⁰) Simulation conditions, such as the flux of deposit atoms impinging the surface, are chosen to reproduce conditions in the laser CVD of polysilicon on a variety of substrates, which have different adhesion energies with Si.

A Monte Carlo simulation⁶ is used to predict the nucleation characteristics of material deposited under high temperature and high flux conditions. Deposit atoms are positioned in a three-dimensional $20 \times 20 \times 10$ grid on a perfect (100) substrate crystal plane. This 10-unit high grid (in the z direction) is more than sufficient to accommodate the height of the initial clusters. The simulation involves a repeated sequence consisting of one atom impinging on and initially sticking to the lowest unfilled site (minimum unoccupied zposition) at a randomly chosen x-y position; this is then followed by a surface relaxation cycle (with repeated adatom migration and desorption). In this surface relaxation cycle, there are repeated steps in which a randomly chosen adatom is permitted to relax; these steps continue until the average adatom has relaxed the expected average number of times, as detailed below. For each individual relaxation step, the probability for migration of the chosen adatom into each of the unoccupied 26 adjacent grid sites is computed. Then, depending on the random number chosen, the adatom either remains in its initial location or migrates to an adjacent site. If the atom migrates to a location where it is no longer bound to an atom in the adjacent 26 sites, it desorbs and is removed from the simulation. Adatoms laterally migrating out of the $(20 \times 20 \text{ grid})$ are reinserted at a randomly chosen site along the grid perimeter.

Adsorbate-substrate and adsorbate-adsorbate binding energies are input parameters, as is the ratio of the single adatom migration energy to desorption energy. The relative binding energies of deposit atoms with nearest-neighbors, next-nearest neighbors, etc., is assumed to obey a van der Waals-type $(1/r^6)$ scaling. The probability of migration is determined from these binding energies using a Boltzmanntype function, as detailed in Ref. 20.

The number of attempted migrations per second $(N_{\rm mig})$ by an adatom is given by

$$N_{\rm mig} = v_0 \exp(-E_{\rm mig}/kT), \qquad (1)$$

where ν_0 is the characteristic adatom vibration frequency, set equal to 10^{12} /s (a typical phonon-adatom collision frequency), and $E_{\rm mig}$ is the average energy required for single adatom site-to-site migration on the surface. The number of incident atoms per site per second is approximately given by

$$N_{\rm inc} = 3.7 \times 10^3 \, G,\tag{2}$$

where G is the growth rate in μ m/s. Thus the number of attempted events, including migrations and desorptions, per adatom per incident atom is given by $N_{\rm mig}/N_{\rm inc}$. The simulation program can permit collective migration of two-atom clusters in addition to solely single atom migration. Unless otherwise stated the results presented below assume that only single atom migration is allowed. The results of some simulations which include single atom migration as well as collective two-atom cluster migration are also presented.

In the simulations reported here the incident flux was set to simulate vertical growth rates of 10 μ m/s and 0.5 mm/s for silicon. Both rates are representative of very fast deposition of polysilicon by local-laser writing. For example, the vertical growth rate during the writing of $4 \mu m$ wide, $0.5 \mu m$ high Si lines at a 1 mm/s scanning rate (Refs. 3 and 4) is 0.125 mm/s. The adsorbate-substrate migration energy $E_{\rm mig}$ was varied to examine the dependence of nucleation on deposit/substrate adhesion. This variation also requires changing the average number of events per adatom per incident atom, in accordance with Eqs. (1) and (2). In this study the ratio of adatom migration energy to desorption energy, which is typically 0.2-0.6, was fixed at 0.5.21 The adsorbate desorption energy from a layer of adsorbate atoms was set at 3.2 eV, to simulate highly cohesive adatoms, and the substrate temperature was chosen to equal 1500 K, which is characteristic of local temperatures during local laser deposition of silicon.5

Figure 4 displays the results of this simulation obtained for the 0.5 mm/s deposition rate. The number of adsorbed surface atoms per site is plotted versus the number of incident atoms per site for various values of $E_{\rm mig}$. Several simulations were conducted for each condition; the averaged results are plotted. When significant, the run-to-run fluctuations are specified below. For $E_{\rm mig} > 0.35$ eV nucleation does not hinder the thin film growth. Essentially every atom incident on the surface is tightly bound and will not desorb. The case of silicon deposition on a silicon substrate falls within this category. Nucleation and thin film growth are expected to occur and indeed do occur instantly in this case. When the adsorbate-substrate migration energy drops to 0.35 eV, an average of 0.85 atoms per site must impinge the surface before any growth begins. (In the five simula-



FIG. 4. Average number of condensed atoms per site vs the accumulated number of incident atoms per site for a growth rate corresponding to 0.5 mm/s at 1500 K. The absorbate-substrate migration energy is: (a) 0.55 eV, (b) 0.45 eV, (c) 0.40 eV, (d) 0.35 eV, (e) 0.30 eV. Note the break in the abscissa axis. Each simulation was continued (i.e., atoms continued to impinge the surface) only until the surface was nucleated enough to ensure continued film growth. The plot for case e represents an average of three simulations, with the onset of nucleation occurring with 47 ± 22 atoms incident per site. This average dose of 47 atoms per site corresponds to a deposition time of 1.3 μ s, compared to the 1.0 ms needed to deposit 1 μ m of material. In these simulations the absorbate-substrate desorption energy of adsorbates from a layer of adsorbate atoms was set to 3.2 eV. Collective migration and desorption of two-atom clusters were not included in these simulations.

tions performed in this case nucleation began with a range from 0 to 3 atoms incident per site.) For this example, simulations were also conducted in which both single atom and two-atom cluster migration events were allowed. Nucleation occurred a little later in this case, only after an average of 2.4 atoms impinged at each site. (For the eight runs conducted, this number ranged from 0.8-5.8 atoms per site.) At this migration energy atoms tend to desorb before they can migrate toward each other and form stable clusters. Atoms in these clusters each have multiple bonds with the surface atoms and with other adsorbate atoms which are seldom broken at this temperature (1500 K). Since a 1 μ m thick silicon microstructure corresponds to a vertical height of about 3700 Si atoms, these nucleation conditions of 0.85-2.4 atoms incident/site in essence correspond to "instant" nucleation.

For $E_{\rm mig} = 0.3$ eV, nucleation plays a more important role in film growth. In this example a growing (supercritical) cluster of atoms is formed only after approximately 47 atoms have arrived per site. Three Monte Carlo simulations were performed for this condition to determine the statistical variation about this cited average value needed to form a supercritical cluster; the fluctuation is about 22 atoms/site. For even smaller adhesion energies nucleation and film growth becomes progressively less likely. With $E_{\rm mig} = 0.25$ eV, nucleation began only after an average of > 40 000 atoms impinged per site (not shown in Fig. 4). (40 000 atoms per site corresponds to about a 10 μ m high deposit, assuming no desorption.)

Curves similar to those in Fig. 4 are obtained for simulations conducted at the slower deposition rate of 10 μ m/s, with conditions otherwise identical to those used above. However, a given plot for 0.5 mm/s deposition corresponds to a 10 μ m/s plot obtained for an $E_{\rm mig}$ about 0.2 eV higher. Since adatoms impinge on the surface at a relatively slower rate in this case, adatom desorption prior to cluster formation becomes even more probable. For instance, whereas many atoms must arrive at each site before even a single critical cluster forms for adsorbate/substrate combinations with $E_{\rm mig} < 0.30$ eV for fast (0.5 mm/s) deposition, lack of suitable nucleation sites becomes important for a wider range of conditions, $E_{\rm mig} < 0.50$ eV, for the slower 10 μ m/s growth.

An upper limit of ~ 0.4 eV for the migration energy of silicon on SiO2 and Si3N4 surfaces has been determined from studies of chemical vapor deposition of polysilicon on the respective substrates.¹⁹ Though the present model does not take into account the amorphous nature of the silicon dioxide and silicon nitride thin films, it still suggests that nucleation may be the rate-limiting step in some instances of directlaser writing. Clearly, when depositing structures at a vertical growth rate of 0.5 mm/s (1500 K) nucleation may be difficult; while for the slower rate of $10 \,\mu m/s$ nucleation appears to be substantially more difficult. Experimentally, nucleation is sometimes seen to play a dominant role in direct-laser deposition of silicon on silicon dioxide and silicon nitride surfaces. In these cases, a thin overlaying film of (nonoxidized) a-Si is advantageous not only because it ensures localized laser-heating at the surface (due to its large

absorption coefficient and low thermal conductivity), but also because it serves as a site for fast nucleation of silicon atoms.

Future modeling will examine the importance of nonuniform temperature and nonuniform flux profiles, and surface chemistry on the nucleation and early stages of growth of thin films by direct-laser writing.²⁰

V. CONCLUDING REMARKS

This paper has described two topics of great importance in studies of direct-laser writing of microstructures in general and of polysilicon interconnects in particular. The Raman spectrum of polysilicon interconnects has been analyzed with respect to substrate properties and deposit doping. Raman microprobe techniques have been shown to be potentially useful for real-time and *in situ* diagnosis of laser-deposited polysilicon on gate arrays and other substrates. The surface nucleation model presented here illustrates the importance of deposit-surface adhesion energy and deposit growth rate in the nucleation and growth of rapidly deposited thin films, in general, and of laser-deposited polysilicon microstructures on substrates of interest, in particular. Work in these areas is continuing.

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