Project I. 2: LITHOGRAPHY and PLASMA PROCESSING FOR NANO-PATTERNING

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External collaborators: A. Boudouvis (NTUA), P. Leunissen (IMEC), Th. Christopoulos (U. Patras), Y. Wang, J. Roberts (INTEL)

Projects Running:

- EU, 157 CRISPIES, Contract N^o: 30143
- EU, SOARING, Contract N^o: 35254
- INTEL-MoleEUV
- Nano2life EU Network of Excellence
- PHOTRONICS

Objectives:

During 2004 our nanopatterning activity focused in the metrology, characterization and simulation of Line Edge or Line Width Roughness (LER, LWR) for sub-100nm CMOS lithography and Etching. Our LWR metrology software is now friendly and robust, and it is thus used by other laboratories such as IMEC and INTEL. Our stochastic Lithography Simulator is also now a fast tool for investigation of process and material effects on LWR. In addition plasma etching of ultra thin photoresist films has proven that the etching rate drops as the photoresist thickness is reduced, thus alleviating some etch resistance demands of ultra thin films.

A significant advancement was also the completion of an integrated topography simulator for microelectronics and Microsystems fabrication. This work opens new possibilities in the simulation of plasma processes and process design and optimization.

During 2004 the group has also focused its activity in the fabrication of polymer-based microfluidics for biomicrosystems (Programme III. 2 led by Dr K. Misiakos). Polydimethylsiloxane as well as PolyMethylMethAcrylate were patterned both with soft lithography and classical lithography followed by plasma etching. We expect that this growing activity will soon become a program on its own.

Main results:

a) NANO-PATTERNING

i. Metrology and Characterization of Line Width Roughness using fractal concepts

V. Constantoudis, G. Patsis and E. Gogolides (Collaboration with P. Leunissen, Y. Wang, J. Roberts)

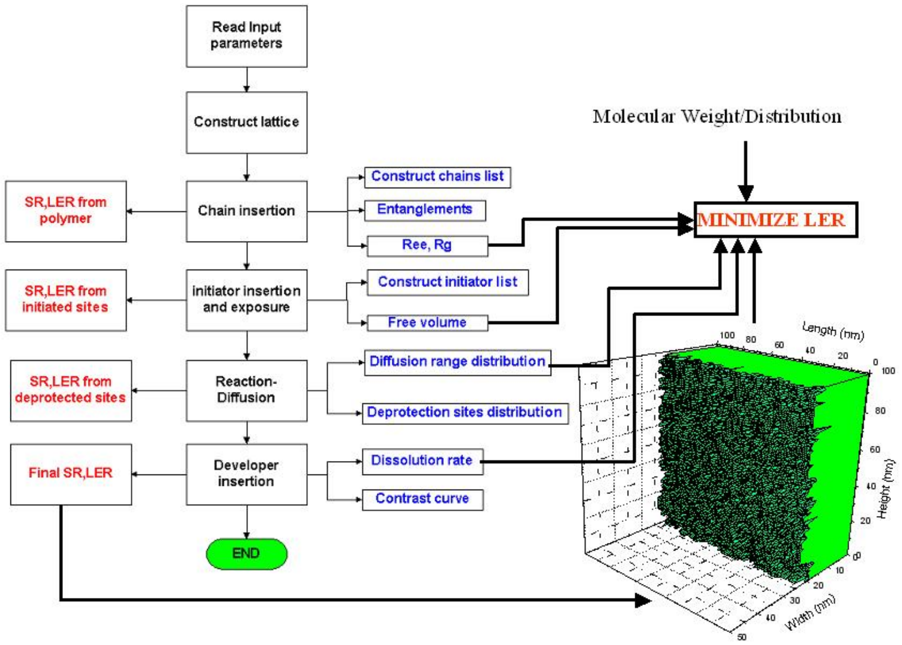
The resist Line Width Roughness (LWR) is one of the major obstacles to the development of new generation lithograpies since it causes local deviations of the gate length from the nominal value and thus degradation effects on transistor performance. The control and reduction of LWR necessitates first a reliable and complete methodology for its measurement and characterization.

Such a methodology has been developed during last years in the Institute and has been realized in a software written in MATLAB platform. The methodology is based on off-line analysis of top-down CD-SEM images of the resist patterns and, in fact, consists of two steps. First, through an image analysis algorithm the edges of the lines contained in the image are extracted, and then their roughness (LER) is characterized using a set of parameters.

ii. 3D Stochastic Lithography Simulator incorporating a Modified Dissolution Algorithm based on Critical Ionization Model

G. Patsis, V. Constantoudis, V. Sarris and E. Gogolides*

A fast (quasi-static) dissolution algorithm was developed based on the concept of critical ionization, and added in the simulation flow of the other modules of the general lithography simulator we have been developing. Specifically, our objective is to obtain the suitable set of material and process parameters that minimize the line-edge roughness (LER) for a given material and process conditions.



iii. Simulation of electron beam exposure for EUV mask fabrication

G.Patsis and N. Glezos

Extreme-ultraviolet- (EUV) mask *fabrication (fig. I.2.1)* using electron-beam lithography has to eliminate the proximity effect defects, for the accurate representation of the patterned features. One special characteristic of EUV masks is that they contain a multilayer stack of repeated Si/Mo thin layers. This has to be considered explicitly in the simulation of electron-beam energy dissipation calculation using Monte Carlo methods *(fig. I.2.2)*. In a first approximation to the problem of electron scattering in a multi-layer substrate, the continuous slowing down approximation utilizing the Rutherford differential cross section is used in order to describe the electron inelastic energy loss mechanism and determine the amount of deposited backscattered energy, in the resist film on top of the multi-layer substrate. Three-dimensional modeling is used and in a first approximation, no secondary electron generation or other excitation processes are considered. The effect of the number of layers and their relative thickness in terms of incident electron energy is investigated *(fig. I.2.3)*.

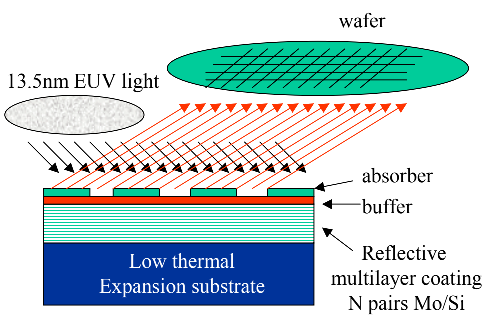


Fig. I.2.1: *Simplified picture of the lithographic process in EUVL. The main characteristic of the mask is that it is reflective rather than transmissive, because in the specific radiation wavelength all components of the mask absorb.*

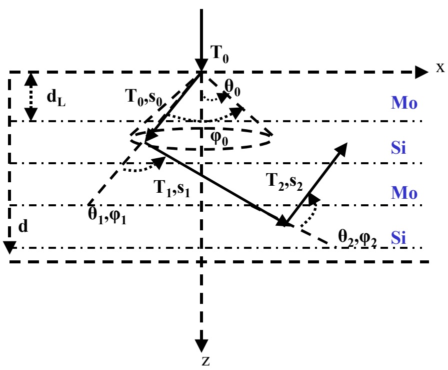


Fig. I.2.2: *Coordinate system used in the electron track simulation. Between successive scattering events, energy loss is calculated from the continuous slowing down approximation.*

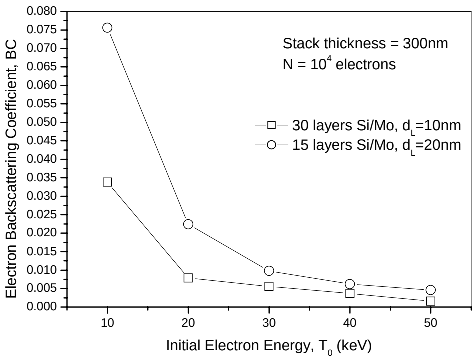


Fig. I.2.3: *Backscattering coefficient vs. electron beam energy as obtained from the simulation of $N=10^5$ electrons penetrating a 300nm multiplayer Si/Mo stack on top of a Si-substrate.*

iv. Plasma Etching of Ultra Thin Photoresist Films for Nanolithography

N. Vourdas, E. Gogolides

Recently, the requirements of microelectronics fabrication and nanotechnology imposed the thorough study of thin and ultra-thin films. Several set of experiments have already advocated that properties of thin films can be completely different from those of the bulk material. We focused on the plasma etching behavior of thin polymeric films, and shown a clear dependence of etch rate on the initial polymer thickness: etch rate decreases as the initial polymer thickness decreases, i.e. the etch resistance of thin polymeric films is higher than that of bulk polymer. In order to explain these results we correlated the etch rate profile to the T_g profile vs. polymer thickness. It is shown that T_g of thin films is different, in general, from the T_g of the bulk material. These differences in T_g indicate differences in structural and physical properties (conformation, orientation, density etc) vs. polymer thickness. These differences are reflected as different behavior during plasma treatment and subsequently as different etch rate. These findings, i.e. increased etch resistance of thin films, slightly alleviate the demands for etch resistance of ultra thin photoresist films of the next generation lithography. Finally, these results suggest that ER of thin films should be referred to specific thickness.

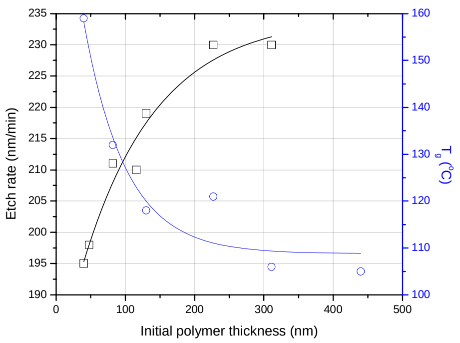


Fig. I.2.4: *ER and Tg variation of PMMA (M_n=15k) layers on Si as a function of initial polymer thickness.*

b) Integrated simulation of topography evolution during plasma etching of structures in MEMS and microelectronics fabrication

G. Kokkoris and E. Gogolides

A simulation framework has been developed for the topography evolution of features etched with plasma. This framework links the bulk plasma gas phase with the profile of the etched feature and constitutes of: a) The local flux calculation model. Shadowing and reemission of flux are taken into account. b) The surface etch model. This model includes the processes during the etching of SiO_2 and Si surface with fluorocarbon plasma. c) The algorithm for the topography evolution of the etched features. The level set method is implemented.

The aim of the simulation framework is to contribute to the profile control of the etched structures, which is necessary for the efficient operation of the corresponding microelectronic devices and MEMS. The simulation framework has been applied to SiO_2 and Si feature etching with fluorocarbon plasmas. Etching artifacts, such as RIE lag and microtrenching are predicted and explained in SiO_2 feature etching. The framework is also applied to *a)* the simulation of the multiple step, deep Si etch process (Bosch process, *c)* and *b)* the simulation of the roughness evolution of etched Si surfaces.

c) MICROFLUIDICS

i. Fabrication of Microfluidic channels on PMMA substrates

N. Vourdas, A. Tserepi and E. Gogolides (collaboration with Prof. Th. Christopoulos)

The fabrication of microfluidic devices with features of 10-1000um size are of great importance in many fields of analytical science, where a small quantity of sample is available, enhanced resolution and sensitivity in separation is needed and increased functional integration is desired (medical, chemical and biochemical analysis, microchemistry etc).

We explore a new method for fabrication of microfluidic devices based on the plasma etching of polymers using an appropriate mask (1. photosensitive silicon-containing polymeric mask (poly-dimethylsiloxane-PDMS), 2. aluminum mask). Plasma etching rates (ER) of PMMA were measured via in situ spectroscopic ellipsometry in order to achieve maximum ER_{PMMA}. Through this technique, an 80um-depth channel has been formed on PMMA, for application to DNA analysis device via capillary electrophoresis.

ii. Fabrication of PDMS Microfluidic devices

E. Vlachopoulou, A. Tserepi, K. Misiakos and E. Gogolides

Poly-Dimethyl Siloxane (PDMS) has been proved very popular elastomer material, widely used in the fabrication of microfluidic devices. For PDMS patterning, soft lithography has been overwhelmingly used, realized by means of thermal crosslinking of the material already shaped in molds made out of polymeric or other materials. Our work aims, through our familiarization with the current state-of-the art in soft lithography, at the development of alternative PDMS patterning technology based on plasma etching.

Soft lithography based on the SU (8) resist and a thermally-crosslinked PDMS, in combination with plastic bonding techniques have been developed at IMEL for the fabrication of PDMS microfluidic devices.

At the same time, plasma-based PDMS patterning was optimized to proceed with high speed and to yield properly designed wall profiles for the etched structures. The evaluation of both techniques, soft lithography and plasma-based patterning, are to be compared on a simple microfluidic device consisted of a channel extending between two circular receptors for the external tubing used for fluid delivery to the microfluidic device (see figures below). This device is expected to be used for biological solutions delivery on a bio-sensor developed at IMEL.

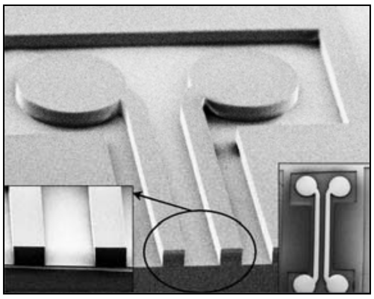


Fig. I.2.5: *SEM image of the lithographically-defined SU-8 structure. Thickness 100 μm, width of lines 150 μm. The vertical profile of the lines is clearly shown at the inset on the left, while a top-down SEM of the whole structure is shown at the inset on the right.*

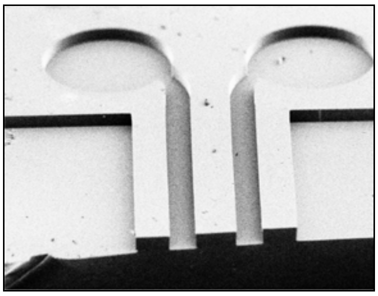


Fig. I.2.6: *SEM image of the replica PDMS structure, fabricated by soft lithography. Depth of micro-channels 100 μm, width 150 μm. Diameter of the reservoirs: 800 μm.*

iii. Electrowetting-based technology for actuation in microfluidics

P. Bayiati, A. Tserepi, K. Misiakos and E. Gogolides

Hydrophobic polymeric films deposited on various surfaces (by plasma deposition or by spin-coating of teflon-like commercial products) can be used for the fabrication of microfluidic devices based on electrowetting. Such surfaces can be varied from hydrophobic to hydrophilic with voltage application and thus they can be used for actuation of fluid transport in microchannels. For the plasma deposition of the hydrophobic films, fluorocarbon gases, such as C_4F_8, are used and the plasma parameters are investigated in order to obtain films with high hydrophobicity and low contact angle hysteresis. However, such hydrophobic films have poor dielectric properties, a problem which can be overcome by the use of composite multilayer structures, where the hydrophobic film is combined with a material of good dielectric constant and strength, such as Si_3N_4. Reversible, low voltage electrowetting has been achieved with the use of a composite film consisted of a thin hydrophobic fluorocarbon material deposited on a Si_3N_4 film *(Figs. I.2.7)*. Furthermore, electrowetting experiments were conducted *(Fig. I.2.8)* using protein solutions on Teflon spin-coated surfaces and exhibited significant and reversible dynamic contact angle modulation indicating that such hydrophobic films can be used in microfluidic channels for biological fluid transport based on the electrowetting on dielectric effect.

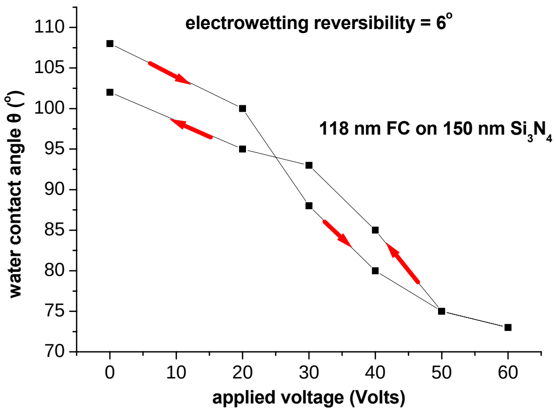


Fig. I.2.7: *Water contact angle of fluorocarbon plasma deposited film in combination with a Si_3N_4 film versus applied voltage (first increasing and then decreasing).*

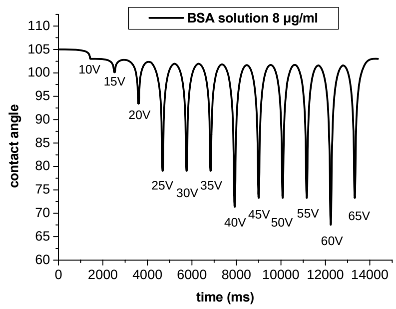


Fig. I.2.8: *Contact angle modulation of a teflon spin-coated surface on Si_3N_4 during application of pulses of increasing voltage, using a bovine serum albumin solution.*

PUBLICATIONS in INTERNATIONAL JOURNALS

1. "Line Edge Roughness (LER) investigation on chemically amplified resist (CAR) materials with masked helium ion beam lithography", S. Eder-Kapl, H. Loeschner, M. Zeininger, O. Kirch, G. P. Patsis, V. Constantoudis, and E. Gogolides, Microelectronic Engineering, 73-74, 252 (2004)
2. "Photoresist line-edge roughness analysis using scaling concepts", V. Constantoudis, G. P. Patsis, and E. Gogolides, J. Microlithogr. Microfabrication, Microsyst. 3, 429 (2004)
3. "Effects of photoresist polymer molecular weight on line-edge roughness and its metrology probed with Monte Carlo simulations", G. P. Patsis, V. Constantoudis, and E. Gogolides, Microelectronic Engineering 75(3), 297 (2004)
4. "Line edge roughness and critical dimension variation: Fractal characterization and comparison using model functions", V. Constantoudis, G. P. Patsis, L. H. A. Leunissen, and E. Gogolides, J. Vac. Sci. Technol. B (22), 1974 (2004), and Virtual Journal of Nanoscale Science & Technology- August 30, 2004, Volume 10, Issue 9
5. "Si etching in high-density SF_6 plasmas for microfabrication: Surface roughness formation", E. Gogolides, C. Boukouras, G. Kokkoris, O. Brani, A. Tserepi, V. Constantoudis, Microelectronic Engineering 73-74, 312 (2004)
6. "Oxygen plasma modification of polyhedral oligomeric silsesquioxane (POSS) containing copolymers for micro and nano fabrication", N. Vourdas, V. Bellas, E. Tegou, O. Brani, V. Constantoudis, P. Argitis, A. Tserepi, E. Gogolides, Plasma Processing Of Polymers, pp. 281-292, (2004)
7. "Simulation of SiO_2 and Si feature etching for microelectronics and MEMS fabrication: a combined simulator coupling modules of surface etching, local flux calculation, and profile evolution", G. Kokkoris, A. Tserepi, A. G. Boudouvis, and E. Goggolides, J. Vac. Sci. Technol. A 22, 1896 (2004)
8. "Si etching in high-density SF_6 plasmas for microfabrication: surface roughness formation", E. Gogolides, C. Boukouras, G. Kokkoris, O. Brani, A. Tserepi, and V. Constantoudis, Microelectron. Eng. 73-74, 312 (2004)

9. “Selective Plasma-induced Deposition of Fluorocarbon Films on Metal Surfaces for actuation in microfluidics”, P. Bayiati, A. Tserepi, E. Gogolides, K. Misiakos, J. Vac. Sci. Technnol. A 22(4), 1546-1551, (July/August 2004)

PUBLICATION in CONFERENCE PROCEEDINGS

1. “Material origins of line-edge roughness: Monte Carlo simulations and scaling analysis”, G. P. Patsis, V. Constantoudis, and E. Gogolides, **Proc**. *SPIE Int. Soc. Opt. Eng*. 5376, 773 (2004**) (Poster)**
2. “Toward a complete description of linewidth roughness: a comparison of different methods for vertical and spatial LER and LWR analysis and CD variation”, V. Constantoudis, G. P. Patsis, L. H. A. Leunissen, and E. Gogolides, **Proc**. *SPIE Int. Soc. Opt. Eng*. 5375, 967 (2004) **(Poster)**
3. “Effects of different processing conditions on line-edge roughness for 193-nm and 157-nm resists”, M. Ercken, L. H. A. Leunissen, I. Pollentier, G. P. Patsis, V. Constantoudis, and E. Gogolides**, Proc**. SPIE *Int. Soc. Opt. Eng*. 5375, 266 (2004) **(Poster)**
4. “Increased plasma etch resistance of thin polymeric and photoresist films”, N. Vourdas, E. Gogolides, A. G. Boudouvis, ***Proceedings*** *of Micro & Nano Engineering (MNE)* 2004, Rotterdam-Netherlands, 19-22 September 2004
5. “Characterization of the roughness of structures and surfaces through SEM and AFM images”, V. Constantoudis, G.P. Patsis, E. Gogolides, A. Tserepi, E. Valamontes, and O. Brani, ***Proceedings*** *of the XIX Panhelenic Conference of Solid State and Materials Science*, 2004 (in Greek)
6. “Modification of the morphology of Si-contained polymer surfaces after plasma treatment”, A. Tserepi V. Constantoudis, G. Cordoyiannis, E. Valamontes, N. Vourdas and E. Gogolides, ***Proceedings*** *of the XIX Panhelenic Conference of Solid State and Materials Science*, 2004 (in Greek)

CONFERENCE PARTICIPATION

1. “Line Width Roughness (LWR) metrology, characterization, and simulation: Developing the software tools for understanding, describing, and predicting LER”, E. Gogolides, V. Constantoudis, G. P. Patsis, *EUVL Workshop 2004*, Roterdam, 23/9/04 **(Poster)**
2. “Calculations of electron-beam energy deposition in resist films over multiplayer Si/Mo substrates”, G. P. Patsis, N. Glezos, *Microfabrication, Microsystems and Nanotechnology (MNN)*, Athens, 2004. (Talk)
3. “Effects of polymer chain architecture on film surface and line edge roughness. Monte Carlo Simulations”, G. P. Patsis, and E. Gogolides, *Microfabrication, Microsystems and Nanotechnology (MNN)*, Athens, 2004. (Poster)
4. “Plasma etch rate measurements of thin PMMA films correlation with the glass transition temperature”, N. Vourdas, A. G. Boudouvis, E. Gogolides, *2nd Conference on Microelectronics, Microsystems and Nanotechnology* (MMN2004), Athens, Greece, November 15-17, 2004
5. “Patterning of thick polymeric substrates for the fabrication of micrifluidic devices”, M.E. Vlachopoulou, A. Tserepi, N. Vourdas, E. Gogolides and K. Misiakos, *2nd Conference on Microelectronics, Microsystems and Nanotechnology* (MMN2004), Athens, Greece, 15-17 November, 2004
6. “Electrowetting of plasma-deposited hydrophobic films as a means for fluid transport in microfluidics”, A. Tserepi, P. Bayiati, K. Misiakos, E. Gogolides, *4th Int. Meeting on Electrowetting, Blaubeuren,* Sept. 2004 **(poster)**
7. “Complexity in Science and Society” Patras, July 2004 (poster: “Fractal structures in nanoelectronics”) **(best poster award)**
8. “Fractal polymer surfaces after lithographic processing”, *XX Panhelenic Conference on Solid State and Materials Science*, Ioannina September 2004
9. “Profile evolution during SiO_2 and deep Si feature etching”, G. Kokkoris, A. G. Boudouvis, and E. Gogolides, *16th International Vacuum Congress*, Venice, Italy, June 28 - July 2, 2004

INVITED TALK

“Determining the impact of statistical fluctuations on resist line-edge roughness”, L.H.A. Leunissen, M. Ercken, G. P. Patsis, *Micro and Nanoengineering (MNE)*, Roterdam (2004) **(Invited talk)**