PROGRAM I
MICRO and NANOFABRICATION

Project I. 2: LITHOGRAPHY and PLASMA PROCESSES for ELECTRONICS, MICROFLUIDCS, and SURFACE Nano-ENGINEERING

Key researchers: E. Gogolides, A. Tserepi

Collaborating researchers: K. Misiakos, I. Raptis, P. Argitis, C.Tsamis, S. Chatzandroulis

Permanent Researcher: V. Constantoudis

Researchers on Contract: G.P. Patsis, G. Kokkoris, N. Vourdas

PhD candidates: P. Bayiati, M. Vlachopoulou, G. Boulousis, K. Tsougeni, A. Malainou, D. Kontziampasis

MSc Students: K. Kontakis, D. Papageorgiou, K. Ellinas, H. Christoyianni

Engineer: K. Kontakis

External collaborators: A. Boudouvis and M. Kalantzopooulou (NTUA, Greece), N. Hadjichristidis and E. Iatrou (UoA, Greece), S.Garbis and A. Vlahou (IIBEAA, Greece), S. Kakabakos and P. Petrou (IRRP, NCSR-Demokritos, Greece), G. Kaltsas (TEI Athens Greece), K. Beltsios (U. Ioannina, Greece), E. Gizeli and K. Mitsakakis (Univ. of Crete-FORTH, Greece) C. Cardinaud (U. Nantes, France), I. Rangelow and B. Volland (Univ. Ilmenau Germany), M. Cooke and A. Goodyear (Oxford Instruments Plasma Technology, UK), S. Daniels (DCU, Ireland), A. Erdmann (Fraunhofer, Germany), S. Tedesco, E. Pargon (CEA-LETI, France)

Projects Running:

- IEU NMP NoE Nano2Life, Contract No 500057, 1/2/2004-31/1/2008
- EU NMP2 STREP Nanoplasma, Contract No 016424 , 1/4/2006-31/3/2009
- GSRT, PENED 03 ED 202, 1/12/2005-30/06/2009
- DHMOEREUNA-2005, 1/1/2007-30/9/2008
- MD3, IT 214948, 1/12/2007-30/11/2009

Objectives:

Lithography and plasma etching are used as enabling technologies not only for electronics and MEMs, but also for microfluidics and lab-on-a-chip fabrication and modification. We are developing deterministic and stochastic microfabrication processes for a broad range of applications including life sciences using top-down fabrication and plasma directed assembly. Process simulation is a key activity to understand and predict the phenomena explored experimentally:

- For nano-electronics our work focuses on Line Edge Roughness (LER) prediction using molecular simulation, LER noise-free measurement from SEM images, and LER transfer during plasma etching (see section A).
- For microfluidics we use Deep Plasma Etching, and plasma assisted bonding to fabricate PDMS, PMMA, PEEK and Si microfluidic devices, such as chromatography columns. We also demonstrate novel plasma-based micro array fabrication process (see section B).
- We have developed promising nano manufacturing processes for stochastic nano-texturing of polymers, and found that protein adsorption is greatly enhanced on such smart surfaces. In addition we have discovered that plasma directed assembly of periodic nanodots can take place during etching of polymers, thus paving the way to plasma based lithography-less nanofabrication. Finally we propose a fast in-situ method to measure surface roughness during etching using spectroscopic ellipsometry (see section C).
- In order to understand the phenomena induced from plasma processing we are also developing the components of a total multi scale plasma simulator, comprising gas phase kinetics, surface kinetics, microstructure etching, and nanoscale etching simulation. Gas phase kinetics of common gases (C4F8 and SF6) and profile simulation are modeled, as well as nanotexturing of porous films during etching (see section D).

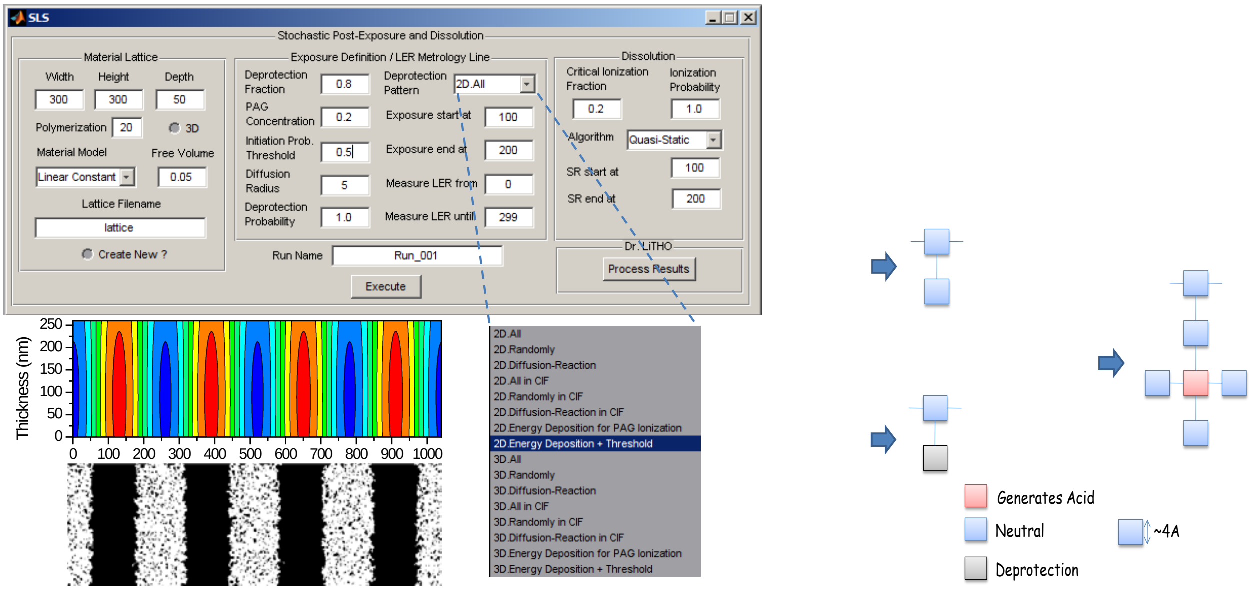
RESEARCH RESULTS in 2008:

A. Micro & Nanopatterning: Micro and Nano Lithography and Line Edge/ Line Width Roughness (LER, LWR)

A1 Molecular simulation of photoresists for double exposure 193nm Lithography

(G. P. Patsis, D. Drigiannakis, I. Raptis)

Increasingly smaller feature sizes emphasize the importance of the molecular properties of the materials comprising the resist film itself. The material size and architecture effects on LER need to be quantified for accurate LER control. The stochastic lithography simulator (SLS) developed by our group, provides mesoscopic models for the simulation of statistically important effects during the post exposure bake and development of the photoresist (Fig.1). This enables the simulation of line edge roughness related phenomena which become increasingly important in nanolithography.



Width 300
Height 300
Depth 50
Polymerization 20
Material Model Linear Constant
Free Volume 0.05
Lattice Filename lattice
Deprotection Fraction 0.8
PAG Concentration 0.2
Initiation Prob. Threshold 0.5
Diffusion Radius 5
Deprotection Probability 1.0
Deprotection Pattern 2D.All
Exposure start at 100
Exposure end at 200
Measure LER from 0
Measure LER untill 299
Critical Ionization Fraction 0.2
Ionization Probability 1.0
Algorithm Quasi-Static
SR start at 100
SR end at 200
Run Name Run_001

(a) (b)

Fig. 1: (a) SLS interface. (b) Discrete representation of the molecular structures of typical 193nm resists in the SLS

Mesoscopic models of the resist film need to be highly detailed in order to capture and quantify the effects on LWR, and must consider polymer chain, PAG, and quencher molecule contribution to LER (Fig 1b). Such mesoscopic resist models specify the material in terms of the chemical groups contained in the molecule on an angstrom scale. The SLS can handle 3D lattices with resist, PAG, and quencher molecule descriptions and interaction in the same computational lattice.

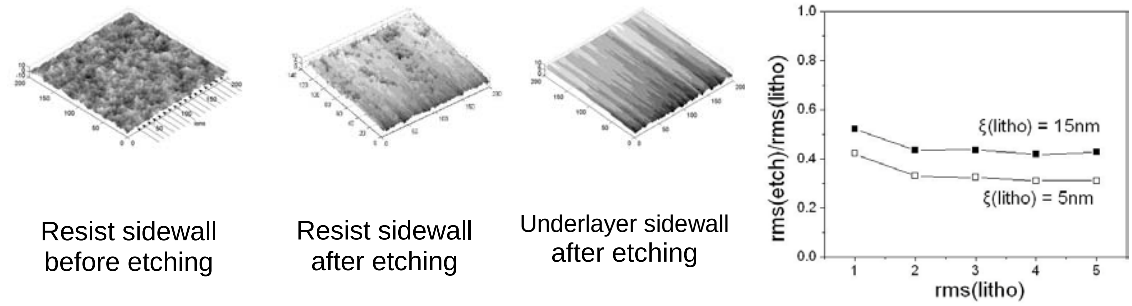
C. T. Lee et al, (Proc. SPIE 6519 (2007) 65191E) proposed the use of polymer-bound and polymer-blend PAG chains, in order to minimize acid diffusion degradation of resist edge. Models of such molecular structures (Fig. 1b) were simulated with the 3D SLS for a typical 32nm exposure scenario. The resulting resist profiles were analysed with the off-line SEM-image-metrology software also developed by our group.

According to these simulations, the polymer – PAG-blend resist has a much higher LER than the resist with polymer bound PAGs. This is in good agreement with the experimental data. It also supports the intuitive explanation that a bounding of the PAG to the polymer chain allows for a high PAG concentration and therefore low acid diffusion and lower LWR.

A2 LER transfer during plasma etching
(V. Constantoudis, G. Kokkoris, E. Gogolides)

A lot of work has been devoted to the investigation of the material and process origins of Line Edge Roughness (see subtask A1). However, what actually affects device operation is not lithography induced resist LER, but the sidewall roughness of the final pattern transferred by etching to the layers (polySi, $SiO_{2...}$) beneath the resist film. We model LER transfer to underlayer taking into account the roughness of the resist sidewalls and assuming totally anisotropic etching. A 3D semi-analytical model is implemented, which mainly considers the effects of the shadowing of the anisotropic flux of incoming ions caused by resist roughness on underlayer LER.

Figure 2a,b,c shows the outcome of the model regarding sidewall morphology evolution. We can see that both resist (Fig. 2b) and underlayer sidewall (Fig. 2c) exhibit striations along ion direction, according to experimental results [e.g. D.L. Goldfarb et al., *J. Vac. Sci. Technol. B* 22 (2004) 647, X. Hua et al., *J. Vac. Sci. Technol. B* 24 (2006) 1850].



Resist sidewall before etching (a)

Resist sidewall after etching (b)

Underlayer sidewall after etching (c)

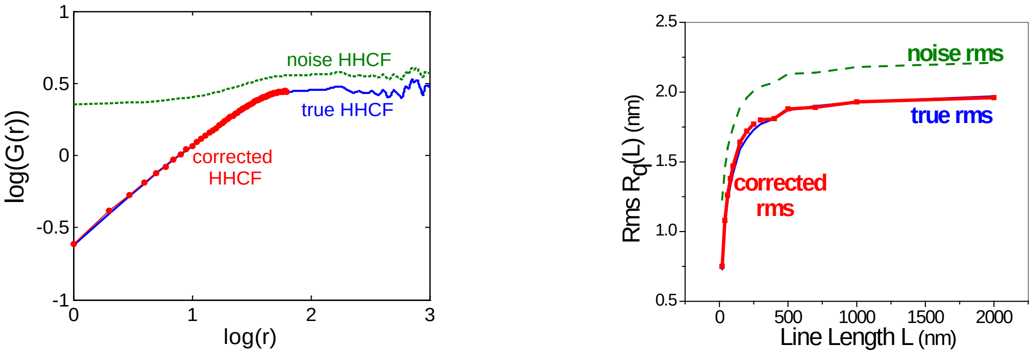
(d)

Fig. 2

The impact of resist LER on underlayer roughness parameters is displayed in Figure 2d, for two different initial resist correlation lengths (ξ(litho)=5 and 15nm). The model predicts that anisotropic etching significantly reduces the rms value of the underlayer sidewall (ratio of etch/litho less than one). Comparison of these predictions with experiments is the subject of ongoing work of our group.

A3 Noise free spatial LER/LWR metrology from top down SEM images
(V. Constantoudis)

The control and reduction of LER requires accurate measurement of LER. Up to now, despite the recent advances in scatterometry and CD-AFM techniques for LER/LWR measurement, the most widely used and mature method is based on the analysis of top-down CD-SEM images of line space structures. However, this method suffers from the presence of noise on CD-SEM images. Here we to focus on the noise free estimation of the spatial LER parameters. We showed that, by appropriately extending the methods of other groups [(see J. Villarubia and B. Bunday, SPIE 5752, 2005 and A. Yamaguchi et al. SPIE 6152, 2006)], we can obtain a) a formula for noise free calculation of the HHCF and b) an algorithm for noise free rms vs L curve using, in both cases, the measurements with image noise. The noise free spatial LER parameters of correlation length and roughness exponent can be straightforwardly extracted by these functions. Also, we tested the efficiency of these noise free estimations by using model edges and lines. Fig. 3a shows the HHCF of the true edge (blue solid line), of the measured edge including the image noise (green dashed line) and the corrected noise free HHCF (red line with full square symbols) provided by this work. One can easily notice the astonishing coincidence of the corrected HHCF with the true one. Fig.3b displays the same results but for the rms vs L curve. One can also observe the very good reproduction of rms vs L curve provided by the corrected result.



(a) (b)

Fig. 3: Height-Height Correlation Function HHCF (a) and rms vs L curve (b) of the true edge points (blue solid line), of the measured edge points with the image noise (green dashed line) and the corrected estimation using our methodology (red line with full squares). Notice the very good reproduction of true curves by the corrected ones.

B. Microfluidic and Microarray Fabrication for Life Sciences (see also project III.3)

B1 Plasma etching of PMMA and PEEK microfluidics

(K. Tsougeni, K. Kontakis, N. Vourdas, D. Papageorgiou, E. Gogolides)

We demonstrate a new mass production amenable technology for fabrication and surface modification of plastic disposable microfluidic devices, namely direct lithography on the plastic substrate followed by deep polymer etching. This year we applied plasma processing to fabricate polymeric microfluidics in Poly(methyl methacrylate) (PMMA) and Poly(ether ether ketone) (PEEK). Deep anisotropic O_2 plasma etching was utilized to etch (pattern) the polymeric substrate via an in situ – high etch resistant – Si-containing photoresist such as photosensitive Polydimethylsiloxane or inorganic–organic hybrid polymer (ORMOCER). Etch rates were optimized to minimize the process time and surface roughness was controllably adjusted from very rough (high aspect ratio nanocolumns) to smooth channels, by choosing appropriate plasma conditions (see below B2). After engraving the PMMA and the PEEK, a bonding step was done to seal the channels and provide their fourth wall. Fig. 4a demonstrates a PEEK plate, after the plasma treatment and after sealing with a pressure adhesive. Demonstration of a mixer was also done on PMMA (Fig. 4b).

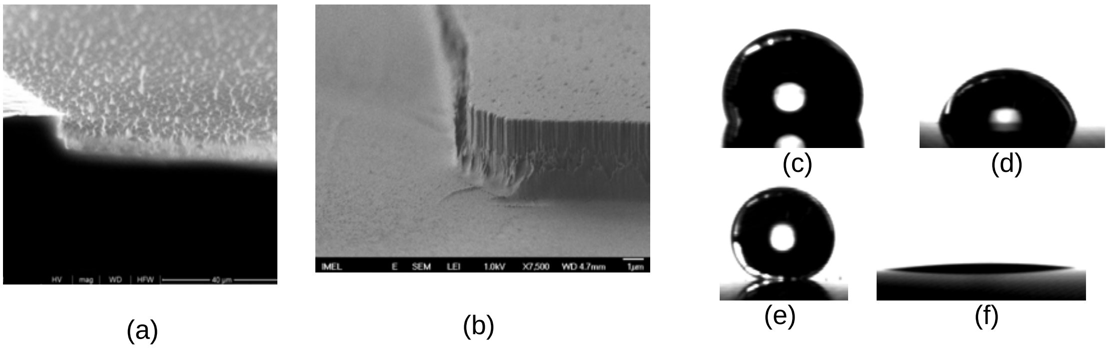
(a) (b)

Fig. 4: (a) The microfluidic channel of PEEK and details in SEM of the cross section after the sealing. (b) Mixing of two liquids in PMMA plasma etched microfluidic mixer.

B2 Plasma etching of PDMS microfluidics

(M.–E. Vlachopoulou, A. Tserepi)

Plasma etching of PDMS by SF_6 plasma has been explored as a route for the fabrication of microfluidic devices made of PDMS with simultaneous control of surface properties (chemistry and topography). PDMS structures with vertical profile were obtained at high plasma powers and bias voltages, appropriate for high etching rates. We demonstrated control on the topography of the etched surfaces, depending on the etching conditions; either smooth surfaces or very rough columnar-like surfaces were obtained (Fig. 5 (a,b)). Further control of the surface topography can be achieved by treating the etched surfaces with wet etchants. Control of the wetting properties of PDMS surfaces has been also achieved, through tuning of the plasma conditions and plasma chemistry (Fig. 5 (c-f)).



(a) (b) (c) (d) (e) (f)

Fig. 5: PDMS microchannels 10 μm deep etched for 15 minutes (a) under conditions appropriate for creation of high nanoroughness on the bottom, and (b) under conditions ensuring smooth etched surfaces. Water droplets on (c) an untreated PDMS surface (CA=110°), (d) a fresh SF_6 treated PDMS surface (CA=75°), (e) a three-month aged 6-min SF_6 treated PDMS surface exhibiting superhydrophobicity (CA=145°) and (f) a 6-min SF_6 treated PDMS surface, after a subsequent O_2 plasma treatment for 1 min under mild conditions exhibiting superhydrophilicity (CA=5°).

B3 Plasma etching of silicon microfluidics

(G. Boulousis, S. Garbis, A. Tserepi, E. Gogolides)

We fabricated microfluidic devices in silicon substrates for chromatographic applications such as phosphopeptide separation. The stationary phase that we use is Titanium dioxide for affinity chromatography coupled with electrospray ionization mass spectrometry in collaboration with the Foundation of Biomedical Research of the Academy in Athens. Silicon [100] n-type substrates have been etched in an Alcatel helicon plasma reactor. The microfluidic devices have been etched with the gas chopping process (BOSCH process) (power 1800 Watt, pressure 5.25 Pa, -55 V bias, temperature 15 ^oC).Two different geometries were fabricated, one with 32 parallel channels and the other with posts as shown in figure 6 (a, c). After engraving the Si substrate, a bonding step with a pressure adhesive or with a PDMS film was done to seal the channels and provide their fourth wall. Fig. 1(b,d) demonstrates a Si microfluidic device after the plasma treatment in a tilted SEM view.

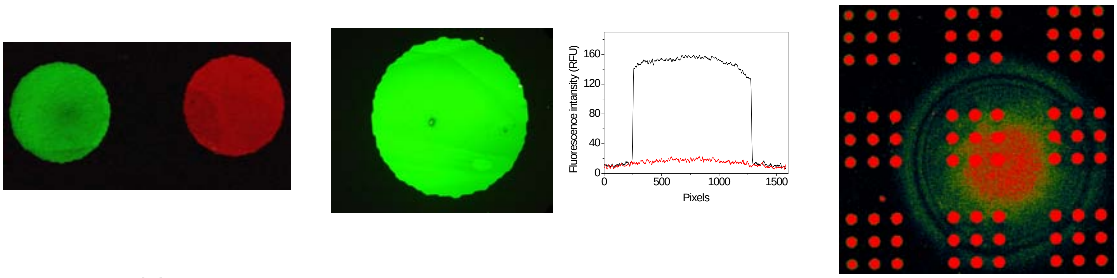
(a) (b) (c) (d)

Fig. 6: Photos of the mask layout of the different geometries (a) the parallel channels and (c) the posts. The Silicon microfluidic devices, (b) the parallel channels and (d) the posts.

B4 Method for fabrication of protein microarrays through plasma treatment of patterned substrates

(P. Bayiati, A. Malainou, A. Tserepi, P. S. Petrou, S. E. Kakabakos)

Microarray technology has become an invaluable tool for large scale and high throughput bioanalytical applications. In the last year, the progress we have made concerns on one hand refinement of the already proposed method for protein patterning through plasma selective FC deposition on patterned SiO_2/Si substrates. The capability to immobilize two different proteins on such substrates was demonstrated (Fig. 7(a)), while the stability of protein binding on C_4F_8 plasma treated surfaces was also investigated and was found comparable to commercial PS microtitration plates. Therefore, with the proposed method, high density and high quality (signal to noise 25:1, Fig. 7(b)) protein microarrays can be fabricated exhibiting very good intra-spot homogeneity and inter-spot repeatability. On the other hand, progress achieved during the last year concerns the expansion of our method to low cost substrates, specifically on glass substrates patterned with a photoresist. We have demonstrated selective immobilization of proteins on glass areas surrounded by photoresist (AZ5214), after treatment of such substrates in O_2 plasmas (Fig. 7(c)).



(a) (b) (c)

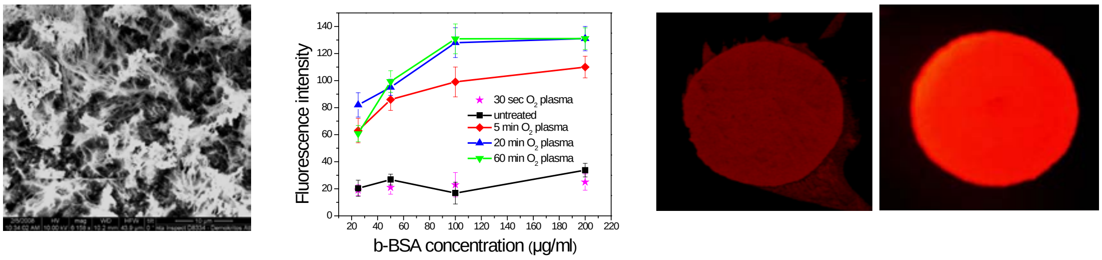
Fig. 7: (a) Fluorescence image of fluorocarbon modified Si substrate bearing SiO_2 spots after immobilization of two different proteins, gamma globulin IgG (green spot) and b-BSA (red spot), (b) high quality IgG spot on C_4F_8 plasma treated SiO_2/Si substrates, as demonstrated by the fluorescence intensity plot obtained across the image in (b), and (c) fluorescence image of a modified glass substrate patterned with AZ photoresist, demonstrating selective (10:1) protein adsorption on 100 μm glass spots after treatment in O_2 plasmas

C. Plasma nanotexturing and plasma-directed assembly on polymer surfaces: Fabrication, wetting and Bio applications

C1 Plasma nanotexturing of PMMA for increased protein adsorption

(K. Tsougeni, P. S. Petrou, S. E. Kakabakos, E. Gogolides)

We demonstrated fabrication of random columnar/filamented-like, low and high-aspect ratio micro or nano-structures based on O_2 plasma-induced roughening (nanotexturing) of poly(methyl methacrylate) (PMMA) (Fig. 8). The effect of topography and protein adsorption capacity was investigated. Conditions (plasma treatment, ageing) are sought for maximum and uniform protein adsorption on nanotextured PMMA surfaces. Specifically, adsorption of biotinylated-BSA was found to increase with plasma duration. A 2x to 4x times increase in protein adsorption (depending on the protein concentration) was observed on aged surfaces prepared following 5-60 min O_2 plasma treatment compared to untreated PMMA surfaces (Fig. 8b). Highly homogeneous bright protein microspots on such optimized plasma-nanostructured surfaces are also shown (Fig. 8c, d).



(a) (b) (c) (d)

Fig. 8: (a) top down SEM images of PMMA surfaces after 25 min O2 plasma etching. (b) Variation of fluorescence intensity after coating with biotinylated BSA and reaction with AF548 labeled streptavidin, on O_2 plasma treated surfaces, for different plasma exposure time. Fluorescence images of b-BSA spots on a (c) flat untreated, (d) 5-min O_2 plasma-treated PMMA surface.

C2 Plasma nanotexturing of PDMS for increased protein adsorption
(M.–E. Vlachopoulou, P.S. Petrou, S.E. Kakabakos, A. Tserepi)

Effect of SF_6 plasma induced nanotexturing on protein adsorption has been explored (Annual Report 2007), revealing increase in protein adsorption with plasma treatment time. This year, this work was continued by studying the effect of ageing of SF_6 treated surfaces on protein adsorption in detail and by using automated protein spotting (nanoplotter) and digital reading of fluorescence intensity by utilizing a scanner (Fig.9).

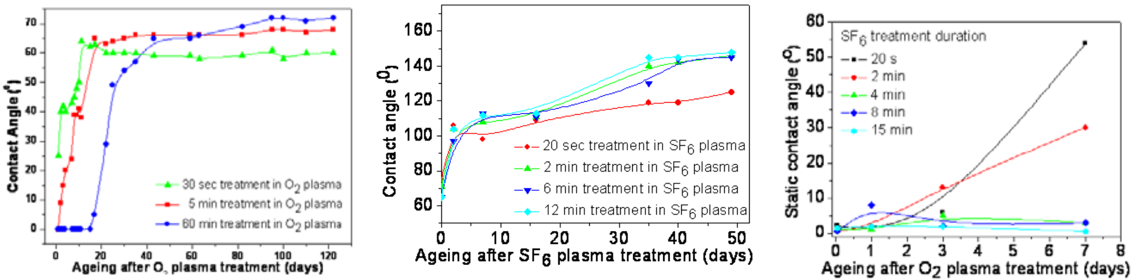
(a) (b) (c)

Fig. 9: Spotting of b-BSA on fresh SF_6 treated surfaces with a nanoplotter. Fluorescence images of spots of 200 μg/ml b-BSA (a) on an untreated PDMS surface, (b) on a 6 min SF_6 treated PDMS surface and (c) on a 20 min SF_6 treated PDMS surface.

Furthermore, the effect of the subsequent O_2 plasma treatment under mild conditions and its ageing, on protein adsorption was explored. Fresh or aged SF_6 treated surfaces become super-hydrophilic after subsequent treatment with O_2 plasma. Ageing is necessary for spotting on such surfaces, in order to increase the deposited protein concentration. Thermal treatment of such surfaces at 120°C, after wash in deionised water, results in rapid hydrophobic recovery to 90°, without affecting surface topography. Such rapidly recovered hydrophobic surfaces resulted in increased protein adsorption capacity and spots with good homogeneity.

C3 Ageing properties of nanotextured PMMA and PDMS
(M.–E. Vlachopoulou, K. Tsougeni, K.G. Beltsios, A. Tserepi, E. Gogolides)

Design and control of wetting properties of PMMA and PDMS surfaces has been achieved (see Annual Report 2005, 2006, 2007) utilizing appropriate plasma treatment. This year, ageing of such plasma treated surfaces was studied in detail. Ageing of O_2 plasma treated PMMA surfaces is presented in Fig.10(a), while ageing of SF_6 treated PDMS surfaces is shown in Fig.10(b), followed by the ageing of such surfaces after a subsequent O_2 plasma treatment under mild conditions in Fig.10(c). In all cases, plasma induced nanoroughness is revealed to delay hydrophobic recovery. Super-hydrophobic PDMS surfaces are obtained after appropriate ageing of SF_6 plasma treatment, while super-hydrophilic PDMS surfaces obtained after, the subsequent to SF_6 plasma, O_2 plasma treatment, are sufficiently stable when treated in SF_6 for at least 4 min.

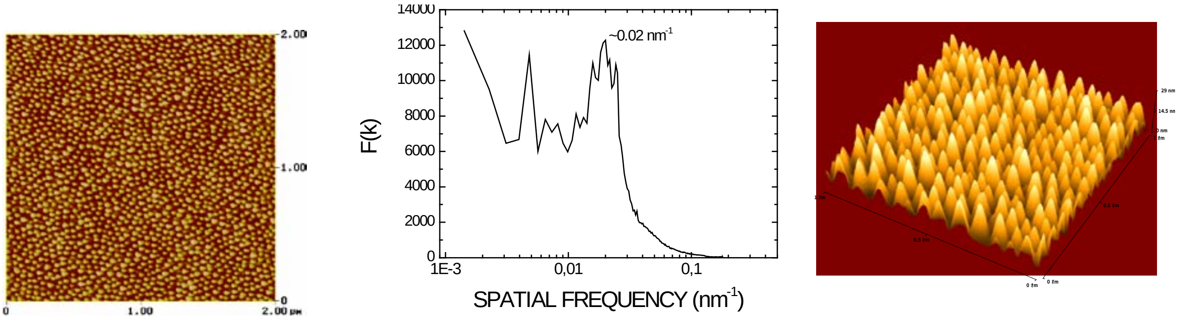


(a) (b) (c)

Fig. 10: Hydrophobic recovery of (a) O_2 plasma treated PMMA surfaces and (b) SF_6 treated PDMS surfaces depends on treatment time, as plasma induced nanoroughness delays their hydrophobic recovery. Similar conclusion has been obtained for the case of SF_6 treated PDMS surfaces after a subsequent O_2 plasma treatment under mild conditions (c).

C4 Nanodot formation with plasma etching: Towards plasma directed assembly
(N. Vourdas, D. Kontziampasis, E. Gogolides)

Plasma etching is used to transfer a lithography pattern on to an underlayer (see B1-B4) or to nanotexture a surface as described in C1-C3. The first is a deterministic pattern-transfer process producing ordered structures with dimensions defined by lithography, while the second is stochastic process producing randomly placed and sized nanostructures. Can the plasma be used to produce lithography-less, and ordered nanostructures? Periodic, well-defined, features in the nano-scale are essential in several fields, such as photonics, optical applications, nanoelectronics, high-density information storage media, catalysis, bioanalytics, medicine etc. We discovered a new, fast, low ion energy, plasma-assisted method of fabricating periodic nano-structures with controlled geometrical characteristics on polymer/plastic materials under appropriate plasma conditions (patent application filed). Figure 11a is a 2x2 um^2 Atomic Force Microscopy (AFM) image, where the morphology of the plasma treated PMMA plate is unveiled; a mound-like surface of uniformly spaced and sized nanodots. The peak of F(k) function in Figure 11b at 0.02 nm^{-1} shows 1/0.02=50 nm periodicity. Figure 11c is a 3D AFM image of a PMMA film, unveiling the periodic nano-dots that are formed also on films.



(a) (b) (c)

Fig. 11: (a) 2x2 um2 AFM image of PMMA plate surface after O2 plasma treatment. RMS is 10.2 nm. (Nanoscope III AFM, tapping mode from Digital Instruments). (b) Circularly averaged fast Fourier transform of the AFM image (a). (c). 2x2 um2 AFM image of PMMA film surface after O_2 plasma etching down to Silicon substrate. RMS is 6.6 nm. (CP-II AFM, tapping mode, from Veeco)

C5 A method to measure plasma-induced surface roughness of polymeric films
(N. Vourdas, G. Kokkoris, E. Gogolides)

A method is proposed to measure the root mean square surface roughness (h_{rms}) of thin polymeric films on hard substrates during plasma etching. It utilizes in situ monitoring of the film thickness versus etching time by spectroscopic ellipsometry to extract the height distribution and h_{rms} at the corner point. The corner point is the time instant where etching rate starts to gradually drop; it depends on the initial film thickness, and denotes the gradual exposure of the hard substrate to the plasma due to the advancement of the rough etch front. The h_{rms} is found equal to approximately half of the remaining thickness at corner point. The method compares well with atomic force microscopy measurements.

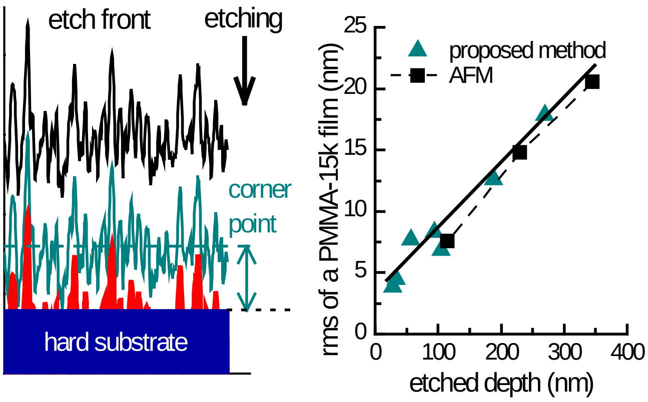


Fig. 12: The simulated evolution of an etch front under anisotropic etching at three time instances t0, tCP (corner point), and t>tCP. hrms versus etched depth according to the proposed method (empty triangles) and from AFM measurements (filled triangles). The material is PMMA-15k.

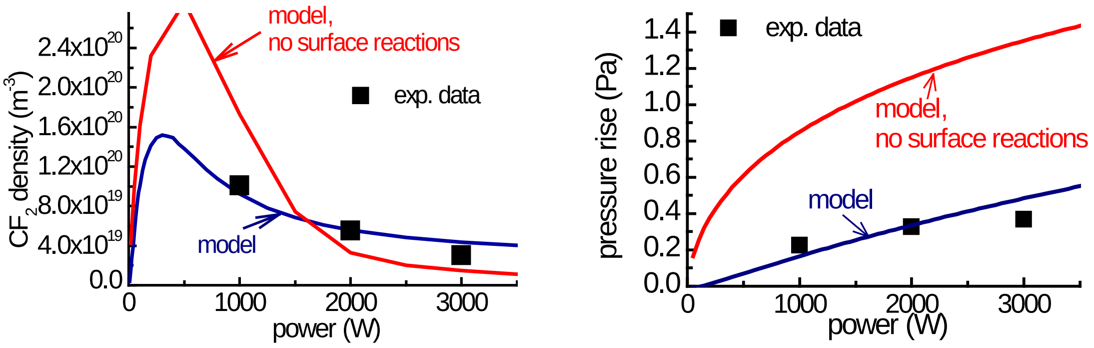
D. Plasma processes simulation

D1 Towards a complete multi-scale plasma simulator: Global plasma chemistry modules coupled to reactor kinetics for C4F8 and SF6 plasmas

(G. Kokkoris, E. Gogolides)

Revisited global models for C_4F_8 and SF_6 plasmas are formulated by coupling gas phase and wall surface reaction kinetics. The modules are part of our multi-scale plasma simulation effort. The contribution of this revisit is the inclusion of wall surface kinetics. In order to have a more detailed description of the plasma–wall interaction, a set of surface reactions, which follows experimental observations (e.g. production of CF_3 on the reactor wall during C_4F_8), is considered in the revisited global models. The rate coefficients of the surface reactions are adjustable parameters and are calculated by fitting the model to experimental data from an inductively coupled plasma reactor.

The major findings for C_4F_8 plasma are a) the vast dissociation of C_4F_8 and the dominancy of CF_4 even at low power conditions, and b) the net production of CF_3 and a net consumption of CF_2 at the reactor walls. Concerning SF_6 plasma, a loss mechanism for SFx radicals by deposition of a fluoro-sulfur film on the reactor walls is needed to predict the experimental data. (see fig. 13)



(a)

(b)

Fig. 13: Global model results (with and without wall surface reactions) and experimental data for a) C_4F_8 plasma (CF_2 density vs. power) and b) SF_6 plasma (pressure rise).

D2 Simulation of profile evolution during deep etching of Silicon nanostructures with neutral beams

(G. Kokkoris, A. Tserepi, E. Gogolides)

The potential of using hyperthermal neutral beams for etching high aspect ratio Si nanostructures is investigated through simulation. Advantageous aspects over the conventional plasma etching processes are predicted. Ultra high aspect ratio trenches with good anisotropy can be fabricated by neutral beam etching without (as necessary for conventional deep Si plasma etching) sidewall passivation. Sidewall bowing is a possible artifact. Inverse etching lag is predicted, and the neutral flux at the bottom of the structures, and consequently etching, can be sustained in structures with much higher aspect ratio compared with the case of conventional deep Si plasma etching.

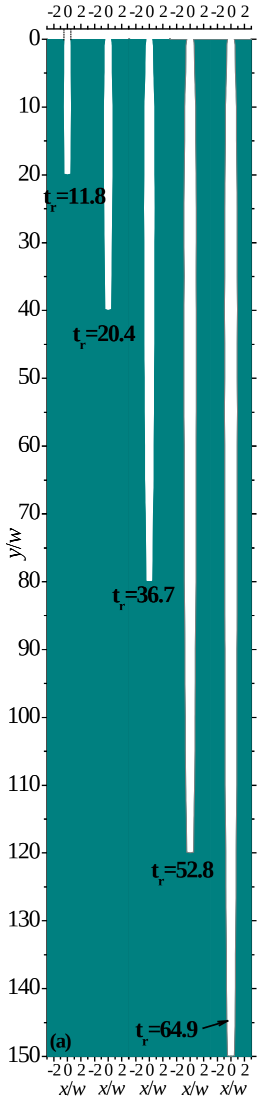


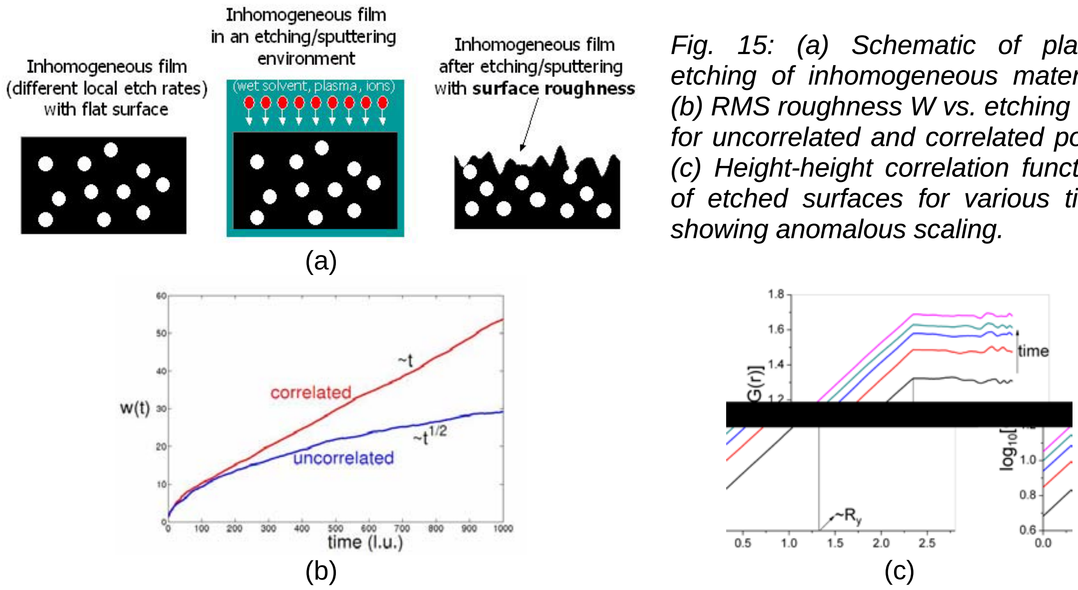
Fig. 14: Simulated Si trench profiles versus time (tr) for the case of Neutral Beam Etching with a monoenergetic (5 eV) and fully collimated beam of F atoms.

D3 Etching of inhomogeneous materials

(V. Constantoudis, H. Christoyianni)

During the recent years, films of inhomogeneous materials (porous or composite) are largely used in many areas of nano and microtechnology (e.g. as low-k dielectrics in semiconductor industry) due to their beneficial physicochemical properties. One of the major tools for patterning these films is etching, but experiments have shown that it induces noticeable surface roughness (much more important than that of homogeneous films) which obviously degrades their performance. We model the layer by layer (deterministic) etching of both porous and composite films in two and three dimensions and study the evolution of surface roughness and its dependence on pore and filler properties. A schematic representation of the roughness formation on an initially flat inhomogeneous film during etching is shown in Fig.15a.

We found that in both porous and composite films roughness evolution exhibits anomalous scaling behaviour indicated by the upward shift of the height-height correlation function with etching time at all scales (see fig.15b). A new universality class is defined by the critical exponents of this evolution characterized by the constancy of correlations and the square root time increase of rms roughness. Finally, it was shown that the presence of even slight correlations between pores or fillers have drastic effects on the evolution of rms roughness (see fig. 15c). The latter finding may be exploited for the detection of correlations between pores or fillers using roughness evolution as a diagnostic tool.



[redacted]

(a)

(b)

(c)

Fig. 15: (a) Schematic of plasma etching of inhomogeneous materials. (b) RMS roughness W vs. etching time for uncorrelated and correlated pores. (c) Height-height correlation functions of etched surfaces for various times showing anomalous scaling.

Publications in International Journals and Reviews

Microfluidics - Bioapplications

1. “Plasma processing for polymeric microfluidics fabrication and surface modification: Effect of super-hydrophobic walls on electroosmotic flow”, N. Vourdas, A. Tserepi, A.G. Boudouvis, E. Gogolides, Microelectronic Engineering, 85 (5-6), pp. 1124-1127, (2008)
2. “High-aspect-ratio plasma-induced nanotextured poly(dimethylsiloxane) surfaces with enhanced protein adsorption capacity”, Vlachopoulou, M.E., Petrou, P.S., Kakabakos, S.E., Tserepi, A., Gogolides, E., Journal of Vacuum Science and Technology B: Microelectronics and Nanometer Structures, 26 (6), pp. 2543-2548, (2008)
3. “Integration of microfluidics with a love wave sensor for the fabrication of a multisample analytical microdevice”, Mitsakakis, K., Tserepi, A., Gizeli, E., Journal of Microelectromechanical Systems, 17 (4), pp. 1010-1019, (2008)
4. “Fabrication of a micro-column for gas separation using poly(dimethylsiloxane) as structural and functional material”, A. Malainou, M. E. Vlachopoulou, R. Triantafyllopoulou, A. Tserepi and S. Chatzandroulis, J. Micromech. Microeng., 18, 105007 (2008)

Plasma Nanostructuring, Plasma Processing, Plasma Simulation

5. “Formation and metrology of dual scale nano-morphology on SF6 plasma etched silicon surfaces”, G. Boulousis, V. Constantoudis, G. Kokkoris, E. Gogolides, Nanotechnology, 19 (25), art. no. 255301, (9pp), (2008)
6. “Oriented spontaneously formed nano-structures on poly(dimethylsiloxane) films and stamps treated in O2 plasmas”, Tsougeni, K., Boulousis, G., Gogolides, E., Tserepi, A., Microelectronic Engineering, 85 (5-6), pp. 1233-1236, (2008)
7. “The potential of neutral beams for deep silicon nanostructure etching”, Kokkoris, G., Tserepi, A., Gogolides, E., Journal of Physics D: Applied Physics, 41 (2), art. no. 024004 (2008)
8. “A global model for C4F8 plasmas coupling gas phase and wall surface reaction kinetics”, Kokkoris, G., Goodyear, A., Cooke, M., Gogolides, E., Journal of Physics D: Applied Physics, 41 (19), art. no. 195211, (2008)
9. “High-density plasma silicon oxide thin films grown at room-temperature”, Vlachopoulou, M.E., Dimitrakis, P., Tserepi, A., Vamvakas, V.Em., Koliopoulou, S., Normand, P., Gogolides, E., Tsoukalas, D., Microelectronic Engineering, 85 (5-6), pp. 1245-1247, (2008)

Lithography and Line Edge Roughness

10. “Stochastic simulation studies of molecular resists for the 32 nm technology node”, Drygiannakis, D., Patsis, G.P., Tsikrikas, N., Kokkoris, G., Boudouvis, A., Raptis, I., Gogolides, E., Argitis, P., Microelectronic Engineering, 85 (5-6), pp. 949-954, (2008)
11. “Processing effects on the dissolution properties of thin chemically amplified photoresist films”, Drygiannakis, D., Raptis, I., Patsis, G.P., Boudouvis, A., vanWerden, K., Microelectronic Engineering, 85 (5-6), pp. 955-958, (2008)

12. “Electron beam lithography simulation for the patterning of extreme ultraviolet masks”, Tsikrikas, N., Patsis, G.P., Raptis, I., Gerardino, A., Quesnel, E., Japanese Journal of Applied Physics, 47 (6 PART 2), pp. 4909-4912, (2008)
13. “Modelling MOSFET gate length variability for future technology nodes”, Patsis, G.P., Physica Status Solidi (A) Applications and Materials, 205 (11), pp. 2541-2543, (2008)

Other Collaborative Work

14. “Nonlinear classical model for the decay widths of isoscalar giant monopole resonances”, Papachristou, P.K., Mavrommatis, E., Constantoudis, V., Diakonos, F.K., Wambach, J., Physical Review C - Nuclear Physics, 77 (4), art. no. 044305, (2008)
15. “Rare events and their impact on velocity diffusion in a stochastic Fermi-Ulam model”, Karlis, A.K., Diakonos, F.K., Constantoudis, V., Schmelcher, P., Physical Review E - Statistical, Nonlinear, and Soft Matter Physics, 78 (4), art. no. 046213, (2008)
16. “Scattering off an oscillating target: Basic mechanisms and their impact on cross sections”, Brouzos, I., Karlis, A.K., Chrysanthakopoulos, C.A., Diakonos, F.K., Constantoudis, V., Schmelcher, P., Benet, L., Physical Review E - Statistical, Nonlinear, and Soft Matter Physics, 78 (5), art. no. 056207, (2008)

Publications in International Conference Proceedings

1. “Fractal dimension of line-width roughness and its effects on transistor performance” (oral), V. Constantoudis, E. Gogolides, Proceedings of SPIE - The International Society for Optical Engineering, San Jose, California, USA, 24 - 29 February 2008, 6922, art. no. 6922156, (2008)
2. “Electron-Beam-Patterning Simulation and Metrology of Complex Layouts on Si/Mo Multilayer Substrates” (poster), G. P. Patsis, D. Drygiannakis, N. Tsikrikas, I. Raptis, E. Gogolides, Proceedings of SPIE - The International Society for Optical Engineering, San Jose, California, USA, 24 - 29 February 2008, 6922, art. No. 692287, (2008)
3. “High resolution patterning and simulation on Mo/Si multilayer for EUV masks”, Tsikrikas, N., Patsis, G.P., Raptis, I., Gerardino, A., Proceedings of SPIE - The International Society for Optical Engineering, EMLC, Dresden, February 2008, 6792, art. no. 679216, (2008)
4. “An integrated microfluidics-on-SAW ("μF-on-SAW") setup for multi-sample sensing”, Mitsakakis, K., Tserepi, A., Gizeli, E., 2008 IEEE International Frequency Control Symposium, FCS, art. no. 4623015, pp. 337-340

Conference Presentations

Invited talks

1. “Microfluidics and microarrays on smart, plasma processed, polymeric substrates”, E.Gogolides, A. Tserepi, N. Vourdas, K. Tsougeni, M.E. Vlachopoulou, S. Kakabakos, P. Petrou, Nano2Life Annual Meeting, 25-27 June 2008, Heraklion, Crete, Greece
2. “Nano texturing / Patterning of Polymers with Plasmas: A Versatile Tool for Nanomanufacturing”, E.Gogolides, A. Tserepi, N. Vourdas, K. Tsougeni, M.E. Vlachopoulou, G. Boulousis, 1st International Conference from Nanoparticles & Nanomaterials to Nanodevices & Nanosystems, 16-18 June 2008, Halkidiki, Greece
3. “Micro- and Nano- Structuring of Polymers Using Plasma Processes and Potential Manufacturing Applications”, E. Gogolides, A. Tserepi, N. Vourdas, M. Vlachopoulou, K. Tsougeni, V. Constantoudis, G. Boulousis, D. Kontziampasis, 6th International Symposium on Nanomanufacturing, 12-14 November 2008, Vouliagmeni, Athens
4. “Polymer Nano-Texturing and Stochastic Nano-Patterning Using Plasma Processing”, E. Gogolides, A. Tserepi, N. Vourdas, M.-E. Vlachopoulou, K. Tsougeni, and D. Kontziampasis, The AIChE Annual Meeting, 16-21 November 2008, Philadelphia, PA

Other presentations

Microfluidics – Bioapplications

1. “Plasma etching as a method for fabrication of polymeric microfluidics and micro arrays, and control of their properties” (poster), N. Vourdas, M.E. Vlachopoulou, K. Tsougeni, D. Papageorgiou, P. Petrou, S. Kakabakos, A. Tserepi, E. Gogolides, Lab-on-a-Chip World Congress, 7-8 May 2008, Barcelona, Spain
2. “High density protein patterning through selective plasma-induced fluorocarbon deposition on Si substrates” (poster), P. Bayiati, E. Matrozos, A. Tserepi, P. S. Petrou, S. E. Kakabakos, A. Malainou, E. Gogolides, 10th World Congress on Biosensors, 14-16 May 2008, Shanghai, China
3. “High-Aspect-Ratio Plasma Induced Nanotexturing of Polymers (PDMS, PMMA, PEEK,…) for protein adsorption applications” (poster), M.E.Vlachopoulou, K.Tsougeni, P.Petrou, S.Kakabakos, A.Tserepi,

E.Gogolides, EIPBN (The Fifty Second International Conference on electron, ion and photon beam technology and nanofabrication): 27-29 May 2008, Portland

4. “High-Aspect-Ratio Plasma Induced Nanotexturing of Polymers (PDMS, PMMA, PEEK,…) for protein adsorption applications” (poster), M.E.Vlachopoulou, K.Tsougeni, P.Petrou, S.Kakabakos, A.Tserepi, E.Gogolides, Nanobio : 9-13 June 2008, Barcelona, Spain
5. “Microfluidics and microarrays on smart, plasma processed, polymeric substrates” (oral invited), E.Gogolides, A. Tserepi, N. Vourdas, K. Tsougeni, M.E. Vlachopoulou, S. Kakabakos, P. Petrou, Nano2Life Annual Meeting, 25-27 June 2008, Heraklion, Crete, Greece
6. “Plasma-Induced Nanotexturing of Polymers and application in protein adsorption” (oral), M.E.Vlachopoulou, K.Tsougeni, P.S.Petrou, S.E.Kakabakos, A.Tserepi, E.Gogolides, ISPPBA (1st International Symposium on Plasma Processing and Biomedical Applications), 27-29 August 2008, Milos Island, Greece
7. “Selective plasma modification of patterned Si and glass substrates for the fabrication of high-density biomolecular micro-arrays” (oral), P. Bayiati, A. Malainou, E. Matrozos, A. Tserepi, P. S. Petrou, S. E. Kakabakos, E. Gogolides, ISPPBA (1st International Symposium on Plasma Processing and Biomedical Applications), 27-29 August 2008, Milos Island, Greece
8. “A novel microfluidic integration technology for PCB-based devices: Application to microflow sensing” (poster), K. Kontakis, A. Petropoulos, G. Kaltsas, T. Speliotis, E. Gogolides, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
9. “Effect of surface nanostructuring of PDMS on wetting properties, hydrophobic recovery and protein adsorption” (poster), M.-E.Vlachopoulou, P.S.Petrou, S.E.Kakabakos, A.Tserepi, K.Beltsios, E.Gogolides, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
10. “Nanotexturing of polymeric surfaces using plasma processes and applications in wetting control and in protein adsorption” (oral), K. Tsougeni, P. S. Petrou, A. Tserepi, S. E. Kakabakos, E. Gogolides, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
11. “SAW device integrated with microfluidics for array-type biosensing” (poster), K. Mitsakakis, A. Tserepi, E. Gizeli, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
12. “Fabrication of Polymeric Microfluidic Devices and Control of their Surface Properties by Plasma Processing” (oral), K. Tsougeni, N. Vourdas, K. Kontakis, A. Tserepi and E. Gogolides, 6th International Symposium on Nanomanufacturing, 12-14 November 2008, Vouliagmeni, Athens
13. “Plasma-based fabrication of PDMS microfluidic devices of controlled surface roughness” (oral), M.E. Vlachopoulou, A. Tserepi, G. Boulousis, E. Gogolides, Microflu’08 (1st European Conference on Microfluidics) : December 10-12, 2008, Bologna, Italy
14. “Fabrication, Surface Modification and Characterization of Polymeric Microfluidic Devices UsingPlasma Etching and Plasma Processing Technology” (oral), K.Tsougeni, D. Papageorgiou, K. Kontakis, N. Vourdas, A. Tserepi, E. Gogolides, Microflu’08 (1st European Conference on Microfluidics) : December 10-12, 2008, Bologna, Italy
15. “Plasma-deposited fluorocarbon films as hydrophobic layers for electrowetting on dielectric based droplet transport” (oral), P. Bayiati, A. Tserepi, D. Goustouridis, K. Misiakos, E. Gogolides, Microflu’08 (1st European Conference on Microfluidics) : December 10-12, 2008, Bologna, Italy

Plasma Nanostructuring, Plasma Processing, Plasma Simulation

16. “Nano texturing / Patterning of Polymers with Plasmas: A Versatile Tool for Nanomanufacturing” (oral invited), E.Gogolides, A. Tserepi, N. Vourdas, K. Tsougeni, M.E. Vlachopoulou, G. Boulousis, 1st International Conference from Nanoparticles & Nanomaterials to Nanodevices & Nanosystems, 16-18 June 2008, Halkidiki, Greece
17. “Modeling of roughness evolution during the etching of inhomogeneous films : Material-induced anomalous scaling” (oral), V.Constantoudis, H. Christogianni, H. Zakka and E. Gogolides, International Conference in Statistical Physics SigmaPhi 2008, 14-18 July 2008, Kolympari - Chania, Greece
18. “Integrated plasma processing simulation framework, linking tool scale plasma models with 2D feature scale etch simulator”, M. Hauguth, B.E. Volland, V. Ishchuk, D. Dreíler, T. Danz, I.W. Rangelow, G. Kokkoris, P. Geka, A. Panagiotopoulos, E. Gogolides, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
19. “Modeling of line edge roughness transfer during plasma etching”, V. Constantoudis, G. Kokkoris, P. Xydi, G. P. Patsis, E. Gogolides, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
20. “Periodic nano-structuring of polymers using plasma processes: Towards plasma-directed polymer self-assembly?” (poster), N. Vourdas, D. Kontziampasis, G. Boulousis, V. Constantoudis, A. Tserepi, E. Gogolides, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
21. “Coupling Reaction Kinetics of Gas Phase, Reactor Wall, and Wafer Surface in C4F8 and SF6 Plasmas with Global Models” (oral), G. Kokkoris, E. Gogolides, A. Goodyear, M. Cooke, 2008 AVS 55th INTERNATIONAL SYMPOSIUM AND EXHIBITION, Boston, MA, 19-24 October, 2008

22. “Nano-Column Formation on Polymers Using Plasma Processes and Application in Wetting and Optical Properties Control” (oral), K. Tsougeni, M. E. Vlachopoulou, N. Vourdas, A. Tserepi, E. Gogolides, 6th International Symposium on Nanomanufacturing, 12-14 November 2008, Vouliagmeni, Athens
23. “Micro- and Nano- Structuring of Polymers Using Plasma Processes and Potential Manufacturing Applications” (oral invited), E. Gogolides, A. Tserepi, N. Vourdas, M. Vlachopoulou, K. Tsougeni, V. Constantoudis, G. Boulousis, D. Kontziampasis, 6th International Symposium on Nanomanufacturing, 12-14 November 2008, Vouliagmeni, Athens
24. “Polymer Nano-Texturing and Stochastic Nano-Patterning Using Plasma Processing” (oral invited), E. Gogolides, A. Tserepi, N. Vourdas, M.-E. Vlachopoulou, K. Tsougeni, and D. Kontziampasis, The AIChE Annual Meeting, 16-21 November 2008, Philadelphia, PA
25. “Coupling Gas Phase and Surface Reaction Kinetics In C4F8 and SF6 Plasmas Used for Si and SiO2 Etching” (oral), G. Kokkoris, E. Gogolides, A. Goodyear, and M. Cooke, The AIChE Annual Meeting, 16-21 November 2008, Philadelphia, PA

Lithography and Line Edge Roughness

26. “Fractal dimension of Line Width Roughness and its effects on transistor performance” (oral), V.Constantoudis and E. Gogolides, SPIE conference: Advanced Lithography 2008, 24-29 February 2008, San Jose, California, USA
27. “Advanced lithography models for strict process control in the 32nm technology node” (oral), G. P. Patsis, D. Drygiannakis, I. Raptis, E. Gogolides, A. Erdmann, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece
28. “A new imaging approach based on a thermally developable, etch resistant molecular material” (poster), Th. Manouras, A. M. Douvas, N. Vourdas, E. Gogolides, P. Argitis, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece

Other Collaborative Work

29. “Partially fluorinated methacrylate polymers as active and cladding components in optical waveguides”, M. Vasilopoulou, A. M. Douvas, L. C. Palilis, P. Bayiati, D. Alexandropoulos, N. A. Stathopoulos, P. Argitis, 34th International Conference on Micro and Nano Engineering 2008, 15-18 September 2008 Athens, Greece

Publications in Greek Conference Proceedings

1. “Monte Carlo modeling of micro and nano-roughness evolution during the etching of inhomogeneous films : Material origins of anomalous scaling behavior” (oral), V.Constantoudis, H. Christogianni, H. Zakka and E. Gogolides, XXIV Panhellenic Conference: Solid State Physics and Materials Science, 21-24 September 2008, Herakleion, Greece
2. “Wetting, Optical Property and Protein adsorption Control of Polymer Surfaces by Plasma Nanotexturing” (poster), K.Tsougeni, M.-E.Vlachopoulou, K.Kontakis, D.Papageorgiou, P.S.Petrou, S.E.Kakabakos, A.Tserepi, E.Gogolides, 7th Hellenic Polymer Conference : September 28 – October 1 2008, Ioannina, Greece
3. “Periodic nanodot formation on polymers with plasmas: Towards plasma-directed polymer self-assembly?” (poster), D. Kontziampasis, N. Vourdas, G. Boulousis, V. Constantoudis, A. Tserepi, E. Gogolides, 7th Hellenic Polymer Conference : September 28 – October 1 2008, Ioannina, Greece

Ph. D. thesis
Treatment and modification of polymeric materials for the fabrication and electrowetting actuation of microfluidic devices

Pinelopi Bayiati, Chemist, MSc, PhD
Thesis advisor-supervisor**:** Angeliki Tserepi
Co-advisors: Prof. Nikos Hadjichristidis, Ass.Prof. Hermis Iatrou
National and Kapodistrian University of Athens, Chemistry Dept.

M. Sc. thesis
Plasma etching of polymers for microfluidics fabrication and sealing

Konstantinos Kontakis, Electronics Engineer, MSc
Thesis Advisor-Supervisor: Evangelos Gogolides
Masters Programme in Microelectronics

Practical Training
Deep etching of polymers
Coralie Vissio
IUT Dept. of Chemistry, Grenoble
Research Supervisor: Angeliki Tserepi

Seminars and Courses

- “Microtechnology for the fabrication and liquid transport in microfluidic devices”, A. Tserepi, University of Crete, Department of Materials Science and Technology, Colloquia 2007-2008, March 14, 2008
- During the advanced summer school “Methods in Micro-Nano Technology and Nanobiotechnology”, June 30 - July 10, 2008 we tought the following labs:
  “Fabrication of microfluidic devices on plastic substrates by Soft lithography”
  (A. Tserepi, M.-E. Vlachopoulou)
  “Fabrication of plastic microfluidic devices by Lithography and deep polymer plasma etching techniques (E. Gogolides, K. Tsougeni, K. Kontakis)
  See video on Nano2Life Site: http://n2lvip.tau.ac.il/
- “A primer to top down micro and nano patterning of Materials for Lab on a Chip Applications”, E.Gogolides, A. Tserepi, Nano2Life meeting Crete June 25-27, 2008
- “Microelectronics and Microsystems fabrication processes”, (E. Gogolides, D. Davazoglou, A. Nassiopoulou), Postgraduate Programs on Microsystems and Nanodevices of the National Technical University of Athens and Micro and Nano Electronics of the National and Kapodistrian University of Athens
- “Plasma Processing for Micro and Nano Fabrication”, (E. Gogolides, G. Kokkoris, V. Constantoudis, A. Tserepi), Postgraduate Program on Microelectronics of the National and Kapodistrian University of Athens
- "Simulation of Micro and Nano-Patterning”, (E. Gogolides, G. Kokkoris, V. Constantoudis, A. Tserepi), Postgraduate Program on Mathematical Modelling in Modern Technologies and Financial Engineering of the National Technical University of Athens
- “Micro & Nano Fabrication”, (S. Logothetidis, A. Nassiopoulou, E. Gogolides), Postgraduate Program on Nanosciences & Nanotechnologies of the Aristotle University of Thessaloniki
- “Fabrication of integrated circuits: Laboratory courses”, (E. Tsoi, D. Kouvatsos, A. Tserepi), Postgraduate Program on Microelectronics of the National and Kapodistrian University of Athens
- “Microfluidic systems”, (D. Mathioulakis, I. Anagnostopoulos, A. Tserepi), Postgraduate Program on Microsystems and Nanodevices of the National Technical University of Athens
- “Computational methods”, (P. Trohidou, G. Kokkoris), Postgraduate Program on Microelectronics of the National and Kapodistrian University of Athens

New patent applications

- “Method for making a micro-array”, A. Tserepi, E. Gogolides, P. Petrou, S. Kakambakos, P. Bayiati, E. Matrozos, PCT Request Filing No: PCT/GR08/00048
- “Method for the fabrication of periodic structures on polymers using plasma processes”, E. Gogolides, A.Tserepi, V. Constantoudis, N. Vourdas, G. Boulousis, M.-E. Vlachopoulou, K. Tsougeni, D. Kontziampasis, Application No: 20080100404

Organization of Conferences, Workshops and Project meetings

- 3rd Nano2Life Summer School “Methods in Micro-Nano Technology and Nanobiotechnology”, June 30 - July 10 2008, http://imel.demokritos.gr/SummerSchool2008/index.htm
- 34th Micro and Nano Engineering Conference MNE08, September 15 - 18 2008, http://www.mne08.org/

Products for possible licensing or other development

- Software for LER measurement and characterization from SEM images. Demo available on our web site http://www.imel.demokritos.gr/software.html
- Software for nanolithography simulation and LER prediction based on Monte Carlo methods. Demo in Preparation
- Software for topography evolution simulation during plasma processing. Demo released and tested in graduate class for Micro and Nano Fabrication for Electronics and MEMS. (free from www.phietch.org)