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Nanotechnology for Smart Polymer Optical Devices

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Summary: Within the last decade the use of nano-structured polymers for biochips, biosensors and novel nano-optical devices gained world-wide attention due to a number of key-developments. The most fascinating example is microelectronics, where smaller means more cost efficiency, more circuits per chip, faster, and less heat to dissipate. Many intriguing new phenomena occur at nanometer dimensions including quantum size effects, Coulomb blockade, plasmon wave guides and electron tunnelling.

Defined multilayer nano-assemblies enable to construct three-dimensional devices based on Plasmon and nano-optic resonance. Decisive for these types of devices and sensors is the ultra-precise nanometric assembly. Manufacturing of opto-nano-devices thus requires the development of a completely new set of ultra-precise techniques to deposit, arrange, and couple nano-polymer layers. These nano-layers are the most essential key elements of novel nano-optical-devices. Smart-responsive nano-polymer gels as transducer and building blocks for nano-devices open novel routes to photonic nano-optical sensors and chips. Optical effects based on 'resonance enhanced absorption (REA)' in combination with nano-layers of smart-stimulus-response polymers allow the construction of a new type of sensor device.

The article will focus on up-to-date lithographic techniques of nanolayers, continue to smart-nanolayer polymers, describe the REA effect and lead to a functional REA-polymer-sensor.

Keywords: nanolayer; nanotechnology; resonance enhanced absorption (REA); sensor; smart polymer

1. From photoresists to nanolayers

Photolithography is the basis of modern microfabrication technology since its invention in the late fifties. Essentially all computer and telecommunication chips are made by this technology. Up-to-date photolithographic technology is based on a projection-printing system (a stepper). The image of the mask is reduced and projected onto a thin film of polymer resist deposited via spin-coating. The resolution is limited by Rayleigh diffraction [1,2,3].

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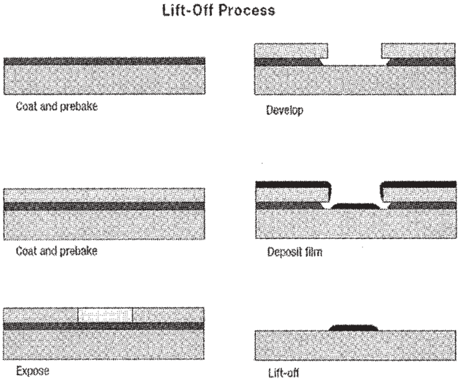


Figure 1: Resolution-optimized lift-off process

Any polymer, to be useful in device fabrication, must be capable of spin coating from a viscous solution. Vitally a thin and uniform film with good adhesion should be deposited on the substrate. A device is fabricated by lithography using radiation-sensitive spin-coated polymeric materials (resists) (Figure 1,2).

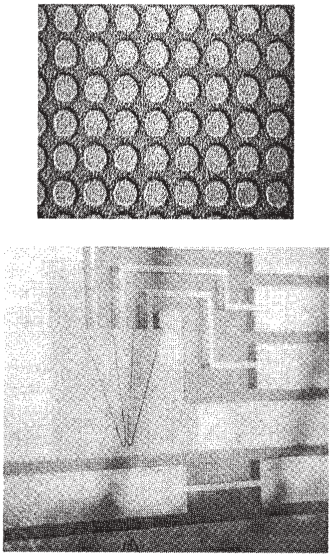
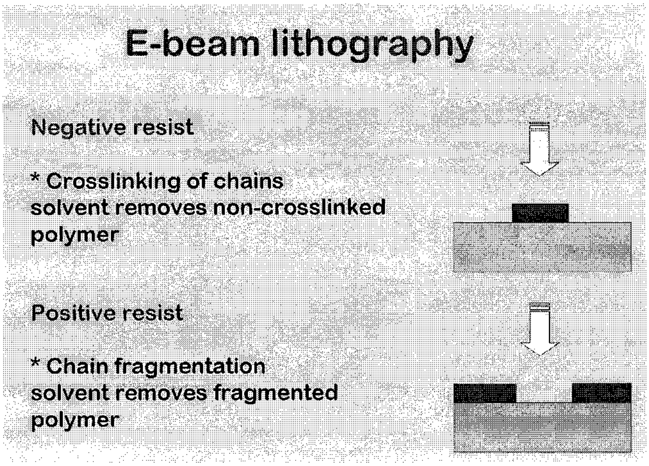


Figure 2: Simple nano-structures produced via photolithography and a complex electrochemical sensor produced via photolithography using a photo-resist, an isolation resist, a photo-crosslinked hydrogel and a self-assembled bilayer

The resist material is applied and then heated to remove the casting solvent (bake). The resist is subsequently exposed to light, X-rays or written with an focused electron beam. The exposed polymer is developed with a suitable solvent to generate the image. Either the exposure renders the resist film more soluble in the developer (positive), or the polymer becomes less soluble upon exposure (negative) (Figure 3). The resist film that remains is either used as a stencil for the deposition of a variety of materials or "per se". The polymer stencil either protects part of the wafer from the etching agent or allows lift-off lithography. The process is repeated to fabricate complex chips and sensors.



E-beam lithography

Negative resist

*** Crosslinking of chains solvent removes non-crosslinked polymer**

Positive resist

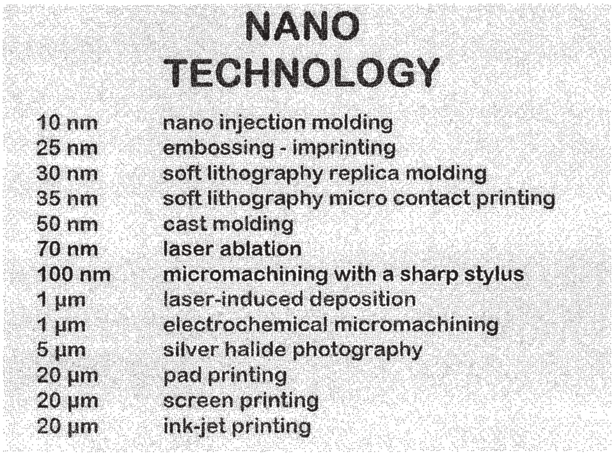
*** Chain fragmentation solvent removes fragmented polymer**

Figure 3: Writing of a nano-mask via direct e-beam lithography

Whereas the first generation of resists was based on phenol- formaldehyde polymers with a low quantum yield (< 1) modern polymer systems are much more sensitive. The first effective resist for microlithography was reported by Frechet and Willson combining Onium salts with the acid-deprotectable poly(4-[t-butyloxycarbonyl-oxy]styrene). For chemical amplification resists a mobile catalyst is produced by the primary photochemical event, inducing a cascade of polymer-transforming events. This amplification increases the overall quantum yield up to several hundred. Along with their higher sensitivity and contrast, these polymers are versatile in radiation source (light, X-ray, e-beam or particles) and compatible with dry etching. The most popular resists are based on two- component systems.

Resists for nanotechnology can be divided into four groups on the basis of the radiation source: UV, electron-beam, ion beam or X-ray. Lithography using near-UV (350-450 nm), mid-UV (300-350 nm), and deep-UV (< 300 nm) light, still the predominant technology in semiconductor production, is limited by the wavelength and numerical aperture induced limitation in resolution. Krypton fluoride (248 nm) and argon fluoride (193 nm) excimer laser technologies are emerging and allow lithography down to < 80 nm. The next generation at 157 nm (F_2) needs new developments in resist technology. Due to their high optical absorbance at 157 nm, standard photoresists are not a viable alternative. In the future X-ray and ion-beam projection lithography will be capable of producing high-resolution, high-aspect-ratio images. Meanwhile E-beam lithography is still the technique of choice for mask design at research level.

Although the introduction of shorter-wavelength light sources and resolution enhancement techniques will allow device miniaturization for several more years, a point will be reached where optical lithography can no longer attain the required feature sizes and new nano-techniques are unavoidable.



NANO TECHNOLOGY

10 nm	nano injection molding
25 nm	embossing - imprinting
30 nm	soft lithography replica molding
35 nm	soft lithography micro contact printing
50 nm	cast molding
70 nm	laser ablation
100 nm	micromachining with a sharp stylus
1 µm	laser-induced deposition
1 µm	electrochemical micromachining
5 µm	silver halide photography
20 µm	pad printing
20 µm	screen printing
20 µm	ink-jet printing

Figure 4: Novel nano-manufacturing techniques and reasonable resolution obtained

2. Structuring of nano-layers

The drive in nanotechnology is based on a need for simpler and more cost efficient non-photolithographic techniques. Within the last ten years research on nano-layers and nano resists has become a new and interdisciplinary field of science. The manufacturing of nanoscale patterns in polymeric thin films is driven by a competitive race to smaller devices in electronics, nano-sensors, and nano-actuators. Whereas coating is still possible by spin casting techniques, pattern formation needs novel approaches. Two options of patterning show up. In a top-down approach, nano-layers are directly patterned by novel lithographic techniques, whereas the bottom-up approach is based on a self-assembly, on grafting or in-situ synthesis.

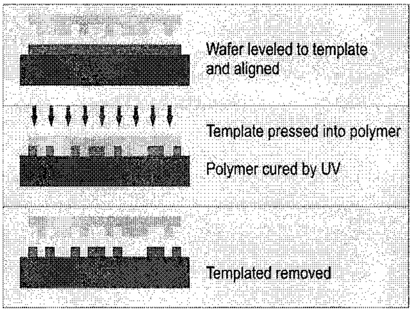


Figure 5: 3D-nano- molding via UV – polymer curing for soft polymers

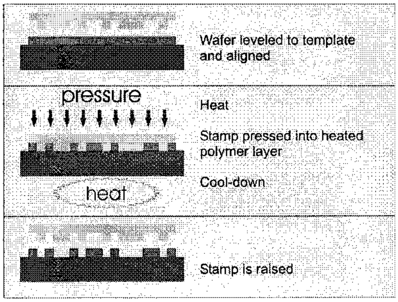


Figure 6: 3D-nano- molding via UV – polymer curing for thermoplastic polymers

Top-down techniques for fabrication of nano-devices span a wide range from X-ray and ion-beam lithographic methods to novel nano-printing and imprinting techniques. Nano-imprint lithography is a versatile set of techniques including micro-contact printing [4], mold-assisted lithography [5], nano-transfer molding [6] and hot embossing lithography (Figures 5 - 7).

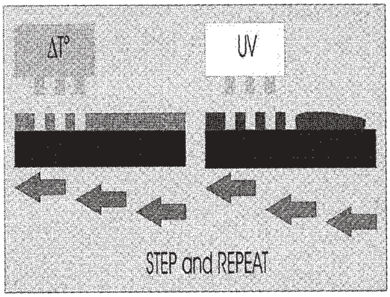


Figure 7: Nano-imprint lithography generates a relief pattern in a polymer layer by physically compressing the resist that has been thermally softened (left) or via UV-crosslinking of a polymer layer (right). In heat based imprinting a distortion of the imprinted structures or mold due to the thermal cycle of heating and cool-down is critical [13,14,15]. Room-temperature imprint lithography is based on plastic flow along with free-volume contraction. A polymer nano layer of 100 nm can be compressed by 10 - 30 nm through free volume compaction

Direct patterning, scratching and writing on a nano-meter scale with AFM and STM allows high precision but is limited to low number production (Figures 8, 9). Soft lithographic techniques are often combined with surface templating procedures to create ordered structures [7,8]. The formulation of the "ink" in such assembly strategies is complex and may use various surface active components [9,10,11,12] (Table 1).

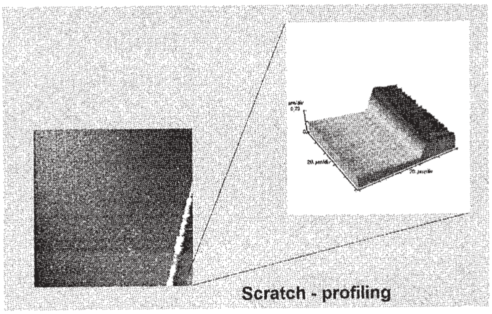


Figure 8: Direct AFM-(scratch)-writing

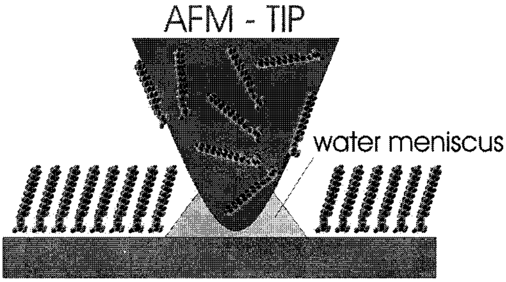


Figure 9: Dip-pen writing of nano-structures using a surface-reactive ink, e.g. thiol-modified molecules are used as an ink and written via an AFM onto a gold coated chip – resulting in a covalent thiol-nano-pattern. The water meniscus is necessary for continuous transfer of molecules from the tip to the chip surface

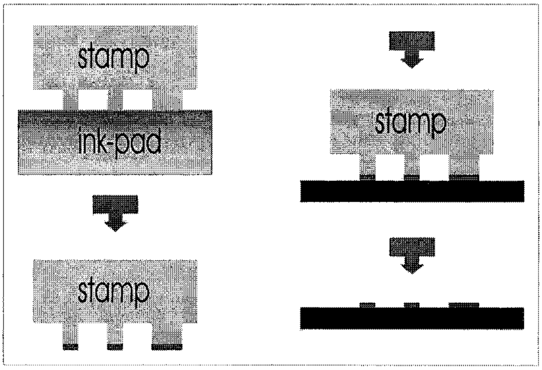


Figure 10: PDMS (flexible silicone polymer) - stamping of 2D-or 3D-nano-prints

Table 1: Surface functional groups employed in nano-pattern printing

Layer-Material	Functional groups in the surface-reactive ink
Au	R-SH, R-SS-R', R-S-R', R-SO_2H, R_3P
Ag	R-SH
Cu	R-SH
Pd	R-SH
Pt	R-NC
GaAs	R-SH
InP	R-SH
SiO_2	R-$SiCl_3$
Si-Cl	R-Li, R-MgX
Me-oxide	R-COOH, R-CONHOH
ZrO_2	-PO_4
ITO	-PO_4

Novel techniques allow the set up of solvent-free processes for in situ fabrication of polymeric nano-patterns. The methodology is e.g. based on a combination of polymerization and ion beam writing. Ions, generated by a source, are focused onto a monomer layer coated onto a cold substrate. As the ions are impinging the monomer layer, they initiate polymerization. Thus, a polymer pattern is grown on the surface.

The natural length scales of polymer chains and their morphologies, which are at the nanometer level, make polymers ideal building blocks for nano pattern formation. Nano-patterning via phase separation of block copolymers is a promising approach [16,17,18,19]. Flexible but chemically incompatible blocks can nano-phase separate into a variety of morphologies (Figure 11).

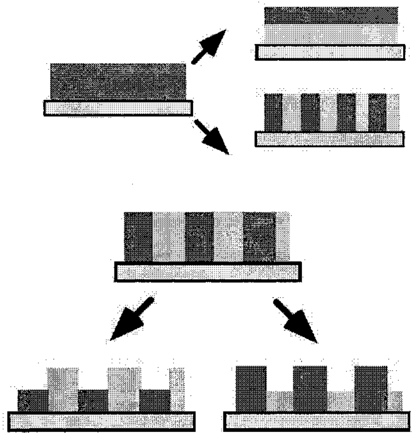


Figure 11: Nano-structures via polymer phase separation, e.g. a short heating step will induce the formation of local domains in a blend of phase-incompatible polymers

The randomly oriented nano-domains become macroscopic lamellae under the influence of the surface (Figure 12).

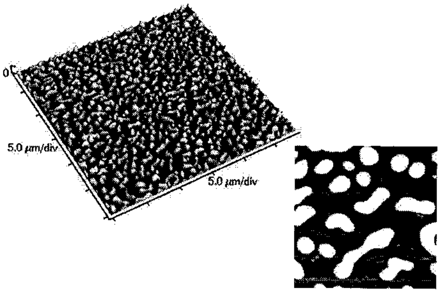


Figure 12: Nano-structure via surface dewetting, a polymer with low adhesion but high surface tension will form a layer of nano-droplets on the chip surface

This self-organization process is driven by an unfavorable mixing enthalpy and a small mixing entropy. The covalent bond within the polymer chain keeps the macroscopic structure homogeneous. The nano-phase separation can be controlled and turned into a useful nano-pattern. Block copolymers are powerful tools for fabricating nanostructures without any need for lithography. Self-assembled periodic nanostructures of block copolymers have e.g. been used for arranging nanoparticles with a considerable stability. The spatial arrangement of the nanoparticles is adjusted by the nano-domains of the block copolymers and the chemical moieties of each block. Layers of nano-vesicles filled with polymers are another approach for a well defined porous nano-structure consisting of an insoluble corona and a soluble core, spontaneously formed in a selective solvent (Figure 13) [internal data, ABT-TUDELFT].

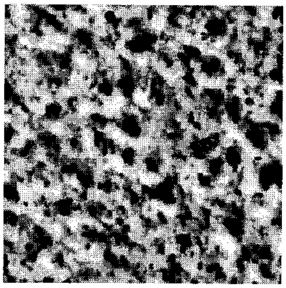


Figure 13: AFM-picture of a nano-porous membrane (produced via depositing a lipid vesicle emulsion embedded in a polymer matrix and a subsequent etch of the vesicle phase with an organic solvent.)

3. Smart nano-polymer layers

Whereas most of the layers in micro- and nanolithography are just used to provide a shape or structure for other materials nanoscale polymer layers might serve as active elements in nanosensors and nano-motorized devices. Quite a number of stimulus-responsive smart gels have been described recently. These gel-nano-layers respond to stimuli, which induce abrupt changes in the physical and sometimes chemical nature of the matrix. External stimuli are temperature [20, 21], pH [22, 23], magnetic field [24, 25], a wide variety of ions and other effector molecules [26, 27], and, furthermore, biomolecules such as DNA and proteins in particular enzymes.

Similar to polymer micro-layers polymer nano-layers deposited at the chip surface will undergo a sol-gel transition or chain collapse induced by the stimulus. Whereas polymer micro-layers respond often with a strong hysteresis due to the slow kinetics of polymer chain conformation relaxation nanometric films are responding within milliseconds.

A wide variety of polymers is applicable for nano-reactive layers including homo-polymers, such as poly-*N*-Isopropylamide, binary block copolymers e.g. of polyethylene glycol and a reactive partner and even ternary systems. The vast majority of these materials are poly-electrolytes. Typical functional monomers are carboxylic acids (acrylic acid, methacrylic acid, vinylbenzoic acid), sulphonic acids (acrylamido-methylpropanesulphonic acid), and heteroaromatic (weak) bases (vinylpyridine, vinylimidazole). For metal chelating interactions, an iminodiacetic acid derivative is commonly used.

The properties of the polymers in solvents of high dielectric constant are governed by electrostatic interactions over distances larger than typical molecular dimensions. Quite a number of such functional materials are already used in other industrial applications as dispersants, flocculating agents, or conditioning additives. More recently, these polymers have become the basis of a rapidly growing family of smart polymers. Among them are electrically conducting polymers, conjugated polymers for light emitting devices and nanoparticle based layers. Multi-nanolayer coating involves the alternate adsorption of anionic and cationic polymer-electrolytes onto a suitable substrate. Typically, only one of these layers is the active layer. The oppositely charged electrolytes may serve e.g. as a barrier to protect the sensor material. Multilayer, reactive, thin films containing biological molecules (often enzymes) are the basis for novel sensors in biotechnology and biomaterials science.

For practical applicability smooth films with easily controllable thickness, a controlled level of penetration of the active component and high performance with respect to selectivity, sensitivity, response time and stability are required.

The gel requires a high affinity for the solvent and thus will become a nano-absorbing-sponge material. The degree of swelling may vary from 10% to several 100 %. Some hydrogels contain thousand times of their weight in water. Water based polymer gels may function as hydrogels or as absorbers. Hydrogels are made out of a hydrophilic chain backbone and tend to swell in an aqueous environment but will not dissolve. Due to the high surface to volume ratio, these polymeric networks are often extremely surface active.

Stimuli-responsive gels (often cited as smart-polymers) will react to various stimuli including temperature, pH, ionic strength, solvent, concentration, pressure, stress, light-intensity and electric or magnetic fields. Gel type polymer matrices are formed via physical or chemical crosslinking of hydrophilic polymers with semi-hydrophilic copolymers. Mixing of both polymers results in gel formation via molecular entanglement of polymeric chains or interactions due to ionic, pH-bonding, or hydrophobic interactions. Attractive interaction of polyelectrolyte chains of opposite charge, leads to the formation of ionotropic hydrogels. Gel-formation is reversible and the polymer network might be redissolved if the attractive interaction is weakened by the analyte.

Crosslinking of ionic polymers may either lead to rigid ion-exchange resins or, by choosing the appropriate ingredients, to stimuli-responsive hydrogels (Figure 14). The degree of crosslinking needs to be chosen as low as possible to make them insoluble but not to limit the smart-volume response of the gel.

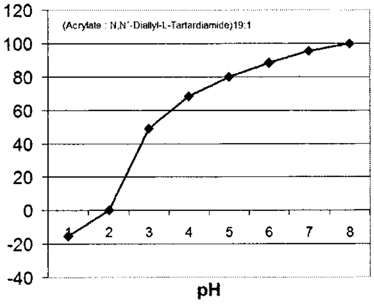


Figure 14: Volume response of acrylamide crosslinked with N,N'-diallyl-L-tartardiamide at a ratio of 19:1 (x-axis: relative volume change calibrated to maximal swelling at pH 8)

To construct e.g. a selective pH-sensitive gel, specific functional groups are introduced in a cross-linked polymer hydrogel. The spin-casted gel is designed to selectively swell and shrink as a response to the pH of the medium. Ionic polymers, with either a weak base or acid group, swell in response to pH. In a very straight-forward approach an ion-exchange polymer such as e.g. aminated polystyrene will exhibit protonation-induced swelling and shrinking.

Smart gel response is always based on two opposing forces: One force hydrating the gel and the other leading to a gel network collapse. A smart gel with a hydrated acid group will shrink on increasing the salt concentration or the pH level. Thus, all pH sensors based on polymer swelling are also responding to the ionic strength and chaotropic effect of the analyte. The mixed response due to salt and pH precludes successful application as a simple pH sensor. Combining a simple sensor with a reference sensor enables application in complex media. Thus, e.g. one sensor gel with sulfonic acid moieties will show a swelling/shrinking response dependent on the salt concentration but independent of pH (except at pH < 2) (Figure 15). A sensor with carboxylic groups (weak acid) will quantify pH and salt, thus a combination of both sensors will allow exact quantization of pH and ionic-strength.

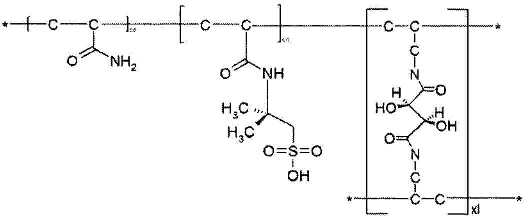


Figure 15: Structure of acrylamide-co- 2-acrylamido-2methylpropane-sulfonic acid crosslinked with N,N'-diallyl-L-tartardiamide. The $-SO_3H$ group becomes negatively charged by deprotonation. Typical material composition out of an inert matrix (acrylamide), a reactive monomer (sulfonated acrylate) and a crosslinker for gel formation

4. Optical resonance in nano-layers

Whereas standard resist layers with a thickness of 100 nm or more are studied via interference based techniques (Figure 16) optical resonance in polymer resists is not very effective in nanometric layers.

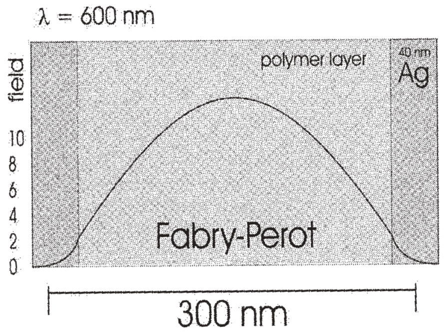


Figure 16: Optical resonance in polymer multi-layer sandwich in between two metal mirrors

To detect structural changes in nano-polymer layers with sub-nanometer resolution a novel nano-resonance phenomenon based on an abnormal optical absorption [28] is used transducing changes of thickness as well as conformation in real time.

The transducing mechanism is based on nano-resonance technology using the resonance of a metal nano cluster layer deposited at a polymer film and combined with a mirror in a precise well defined nano-distance [29]. These devices allow to detect and quantify structural changes of polymer nano-layers as well as the conformation of biopolymers such as nucleic acids and proteins. The optical property for the analytical application of metal cluster coated nano-films is the so-called anomalous absorption.

An absorbing film of clusters is positioned at a distance of 10-400 nm to an electromagnetic wave reflecting layer (Figures 17-19).

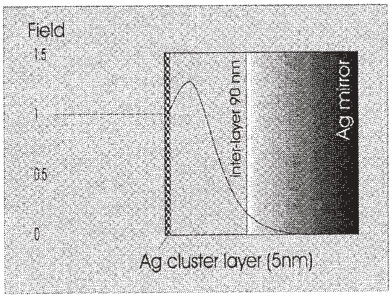


Figure 17: Optical resonance in a nano-cluster/polymer/mirror 3-layer sandwich

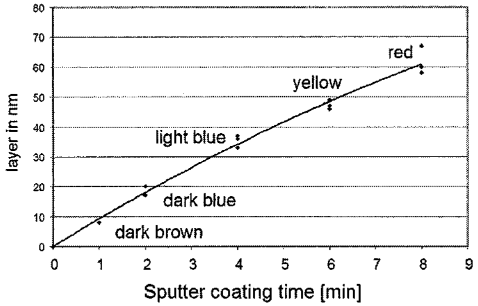


Figure 18: Optical appearance of a nano-cluster/polymer/mirror 3-layer sandwich. The thickness-versus-color calibration graph needs to be corrected for the refractive index of the polymer

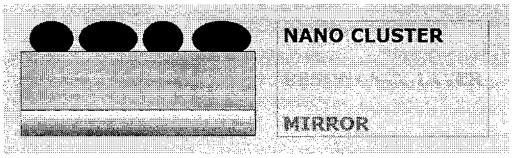


Figure 19: Setup of a polymer resonance enhanced cluster chip

At a certain distance of the cluster to the mirror the reflected electromagnetic field has the same phase at the position of the cluster as the incident fields. This feedback mechanism strongly enhances the effective cluster absorption coefficient. Such systems are characterized by a narrow reflection minimum whose spectral position shifts sensitively with the polymer layer, because of a given cluster-mirror distance and wavelength defines the optimum phase. Moreover, the spectrum will we modified in a characteristic way changing the angle of observation (Figure 20).

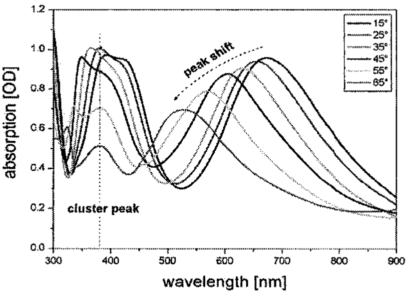


Figure 20: Spectra of angle dependent resonance color

Nano-clusters range from one to 500 nm in size. Large clusters are already visible via light scattering but can only be imaged in detail using AFM or electron microscopy. Metal clusters exhibit a unique physical behavior quite different from macroscopic bulk material [30]. This fact is caused by the semi-free electrons in such nanometer-sized clusters, which act like resonators (and not as relaxators) upon excitation due to their spatial confinement. The resonator properties of the cluster's electrons capture the incoming light. Gold nanoparticles from 5 - 50 nm in size being chemically most stable and corrosion-resistant, give a strong and reproducible optical resonance signal from 400 nm to 1300 nm. Thus, the cluster's resonance frequency is tuned via the spatial arrangement within the visible and the near IR range of the spectrum.

Interference based signal transducers will not provide the necessary signal intensity whereas AFM and nano-stepper based transducers will not provide the needed parallelism for a cost effective HT(high throughput)-device. The REA effect allows to create nano-scale devices for rapid HT-measurements in the field of polymer analysis as well as chemo- and bioanalytics, thus providing a cheap and simple means to transduce nanometric distance-changes in polymer layers into an optical signal in the visual range of the light-spectrum. This distance-dependent color change can be used to detect thickness-changes if a smart interlayer is applied between the cluster- and the mirror-layer. Thereby a signal is obtained as a peak shift of the resonance spectrum. Various polymers and biopolymers have been designed to serve as the transducer in a REA chemo-sensor chip.

REA-based detection was first introduced in 1998 to replace ELISAs and related capture assays and was applied in high throughput screening [31], allergen biochips [32], protein structure analysis [33], phage display library based Proteomics [34] and high quality security features [35].

Summing up, REA enables to transduce any nanometric distance change including changes of molecular structure (e.g. polymer conformation) quantitatively into an optical signal which can be observed directly as a color change of the sensor-chips surface and read out via a CCD camera.

5. A 'resonance enhanced absorption (REA)' smart-polymer chip

The setup of a smart nanolayer chip consists of three parts:

- A highly reflecting mirror-layer coated onto the chip

- A nanometric organo- or biopolymer interlayer with defined analyte sensing properties as transducer
- The metal-nanocluster layer coated onto the polymer for optical resonance.

5.1 The chips

Any solid surface with sufficient optical flatness can be used as a support, e.g. polyethylene terephthalate (PET) sheets metallized with titanium or aluminum, aluminum foils, glass or silicone wafers.

To create the required mirror either polished metal disks are used or a mirror is coated via high vacuum deposition techniques. Depending on process control and sputter rates, mirror formation is obtained within 60 s (Au) to 6 min (Al) using a commercial lab scale sputter coater. On research sputter coaters aluminum turned out to be quite unfavorable due to a low productivity of the process and the sensitivity to the oxygen partial pressure. Sandwiched aluminum-platinum mirrors exhibit a good mirror quality at satisfying costs, but the production is rather time consuming. Mirror qualities comparable to platinum but at lower production costs are obtained with chromium, even superior in substrate adhesion and stability, but a background color is obtained in the surface enhanced mode.

Optimal performance is obtained using a tungsten/palladium/silver mirror. Nevertheless, silver needs additional protection with a few nm of nitride, fluoride or oxide. At a wavelength larger than 400 nm Au mirrors exhibit best performance (note: Au will be corroded by chloride, bromide and iodide!). To test for adhesion under mechanical stress the standard peel off test is applied.

In order to achieve homogeneous coverage, the chip surfaces are cleaned by washing with ethanol or isopropanol. A controlled sputter cleaning of the chip surface is often required to remove organic contaminants from the wafer surface. This cleaning might either be done using an AC-sputter cleaner or in a standards DC-sputter coater using an aluminum target. Still, the sputter voltage and chamber pressure have to be carefully adjusted, not to deposit aluminum oxide.

If a polymer pattern needs to be applied micro structuring is done e.g. via PDMS-(Poly(dimethyl siloxane)-stamping using a metal photo mask to create the silicone master. A reactive surface (often gold) is patterned with the adhesion-promotor 16-mercaptohexadecanoic acid and the repelling agent 1-hexadecane thiol via micro contact printing.

Whereas noble metals are often primed with thiol based adhesion promotors metals forming a surface oxide are activated via silanes. The oxide layer on e.g. chromium or aluminum is reacted with silanes to achieve a monolayer of free amino-groups using e.g. (3-aminopropyl)-methyl-diethoxysilane. Gas phase silanization proved to be superior, using a saturated amino-silane solution in a vacuum chamber over night, then baking the chips for 30 min at 100°C to crosslink the amino-silane, removing unbound silane by rinsing with isopropanol, followed by drying. Free amino-groups of the linker are used as an anchor for coupling to the polymer.

Next, a polymer nano-layer is applied onto the mirror by spin-casting, microspotting, surface assembly or any other suitable technique (see chapter 1 and 2).

For deposition of gold or silver clusters either sputter coating or chemical coupling of the colloidal metal is used. The DC-sputter process is carried out using an argon plasma. The deposition of the metal is controlled by the time of the plasma reaction. Typically, within 10 s, at an argon pressure of 0.1 mbar and a sputter current of 40 mA about 5 nm (mass-thickness) of gold are deposited (Figure 21).

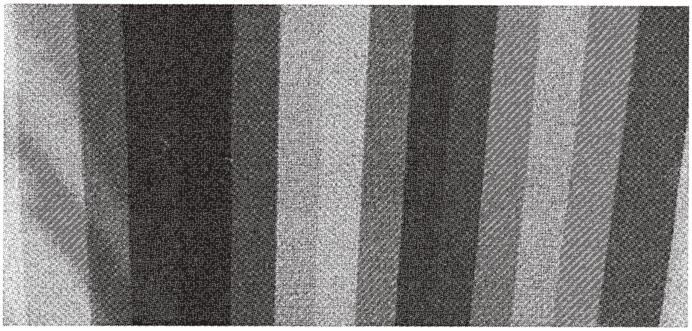


Figure 21: Color ladder produced via surface enhanced absorption resonance of an aluminum mirror - interlayer - gold cluster sandwich (the thickness of the interlayer increases from left to right starting at 0 nm)

5.2 The polymer

Smart polymer layers are deposited either by in-situ synthesis or via spin-coating or printing of the polymer. In-situ-radical-polymerization of a smart-layer on-chip often results in less reproducible results due to local inhomogeneities of the radical transfer, thus, the synthesis of a pre-polymer solution is recommended. Radical polymerization in solution turned out to be a good way to create linear pre-polymers. The reaction is well defined and therefore controllable via the applied starter concentration as well as temperature and monomer composition. To avoid insoluble hydrogels via intra-chain radical transfer the radical starter has to be separated from the polymer solution by simple precipitation of the polymer. Hydrophilic polymers are precipitated by ethanol or other alcohols, hydrophobic polymers by water. The precipitate either settles or is separated by centrifugation.

To obtain a viscous solution of the polymer, the precipitate is re-dissolved in a suitable solvent (most hydrophilic acrylates in water) and stirred for at least a few hours to reach the equilibrium. For smart-polymer coating the polymer-stock solution is diluted further to obtain the desired viscosity. This pre-polymer solution is stable for a prolonged time.

To crosslink the polymer nano-layer on the chip and to create the smart gel either new radical starter (ammonium peroxodisulfate, organic peroxides) is added or a photocrosslinker (e.g. 4,4′-diazidostilbene-2,2′disulfonic acid disodiumsalt tetrahydrate (DIAS) solution in distilled water) is applied. To allow efficient crosslinking of the pre-polymer e.g. bisacrylates (as crosslinker) and monomers are added to the pre-polymer solution to bridge the polymer chains. This mix should be kept in the dark. It is not stable and should be coated to the chips within a day.

Aliquots of 20-100 µl are first spin-casted onto small (1 cm) hydrophilized disks to check the quality of the master-polymer. The small disks are either photocrosslinked via UV-light or incubated for 24 hours for radical polymerization with peroxides. Photocrosslinking with DIAS is done by irradiation of the chips with UV-light for 30 seconds (350 nm, 60 W). It is not recommended to use a shorter wavelength because irradiation below 320 nm causes DIAS decomposition.

Chips are coated with metal nano-clusters as described above. A gold cluster film might as well be deposited by covalent coupling or adsorptive binding of colloids synthesized in solution via e.g. the citric acid method according to Frens. Chemically synthesized clusters of 9 – 40 nm are concentrated (20 fold) via centrifugation and resuspension in H_2O and deposited by adsorption to a positively charged polymer surface (1-3 min). Sensors are rinsed extensively with H_2O and buffer to confirm cluster adhesion.

The small disks are used for smart polymer-quality control. Only after a successful batch of the polymer is coated to the mini- discs the polymer is used for chip production.

The first criterion for charged smart matrices is to prove that the nano effect is in full coherence with structural effects observed at the macroscopic level. The polymer should increase the distance between the wave-reflecting surface of the chip and the nano-cluster-layer, when charged sites are created inside the three dimensional network. Electrostatic repulsion takes place between groups of the same charge and water is bound within the network. Thus the polymer layer begins to swell. On the other hand, when the polymers turns into an uncharged state, the hydrophobic interactions dominate and the layer will shrink.

Quite a wide variety of matrix polymers might be used to construct smart polymer sensors. E.g. polymers blends based on acrylic monomers [36] are designed from 2-acrylamido-2-methylpropane-sulfonic acid (AMPS), N-[3-(dimethylamino)propyl]-acrylamide (DAPA) (Fig. 23 and 24) and acrylic acid (AS).

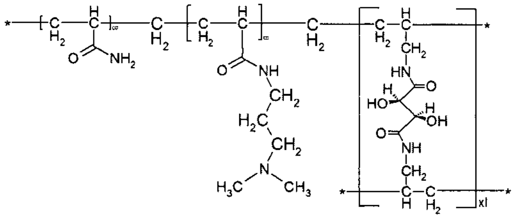


Figure 22: Structure of acrylamide-co- N-[3-[dimethylamino)propyl]-acrylamide crosslinked with N,N'-diallyl-L-tartardiamide. The $-N(CH_3)_2$ group becomes positively charged by protonation

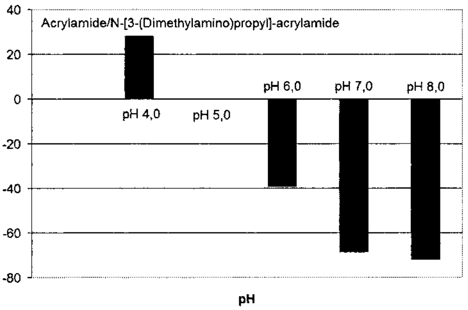


Figure 23: Volume response of acrylamide-co- N-[3-[dimethylamino)propyl]-acrylamide crosslinked with bisacrylamide (acrylate:bisacrylamide 19:1)

Effective crosslinkers to polymerize the linear master polymer are 1,4-Bisacryloylpiperazine (BAP), N,N'-Bisarcylamido-acetic acid (BAES), N,N'-diallyl-tartardiamide (DATD), N,N'-methylene-bisacrylamide (BA), Di(ethyleneglycol)-bisallylcarbonate (DEGA) or poly(ethyleneglycol) (n) diacrylat n=400 (PEG)

During variation of the pH value the polymers exhibit significant differences in relative thickness influenced by length, hydrophobicity and functional groups of the crosslinkers. All polymers swell in the range of increasing the internal charge. Acrylamide crosslinked with PEG-diacrylate in a molar ratio of 150:1 exhibits the highest change of thickness due to the extreme length of the crosslinker. Most polymers show an immense variety in their swelling and shrinking behavior. While AA/DAPA/DATD shrinks over a range from pH 4 to pH 8, AA/AMPS/DATD and AA/AMPS/AEM/DAPA swell because of conformational changes of the polymer matrix. Thus, the anionic polymers shrink at low pH (negative value at pH 4) and cationic polymers swell. At alkaline conditions the behavior is contrary.

A smart polymer with high performance can be obtained with a copolymerisate of AA/AS 4:1 crosslinked with DATD (copolymerisate/DATD 40:1).

Additionally to the charge effect many substances are known to cause structural changes via chaotropic or kosmotropic behaviour. Urea e.g. has denaturating properties by diminishing intramolecular forces that determine the tertiary structure of a polymer. This chaotropic effect actually influences the structure of any molecule. Polyvinylpyrrolidone, a linear polymer with well hydrated amide groups, is a good model substance for polypeptides and proteins(Figure 24) [37,38].

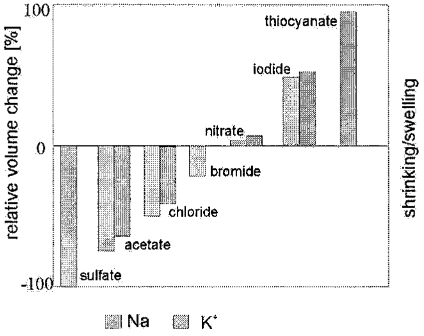


Figure 24: Polyvinyl-pyrrolidone a sensor material for chaotropes and kosmotropes. Sensor response is in good correlation with the Hofmeister series of caotropic/cosmotropic ions

A series of anions show stabilizing or destabilizing effects on polymer structures and can be set in correlation with the Hofmeister lyotropic series.

By incorporation of a redox sensitive crosslinker a volume response is obtained by interaction with reducing agents. Disulfide bridges can be reversibly opened by incubation with e.g. mercaptoethanol, DTT (dithiothreitol), glutathione or ascorbic acid (Figure 25).

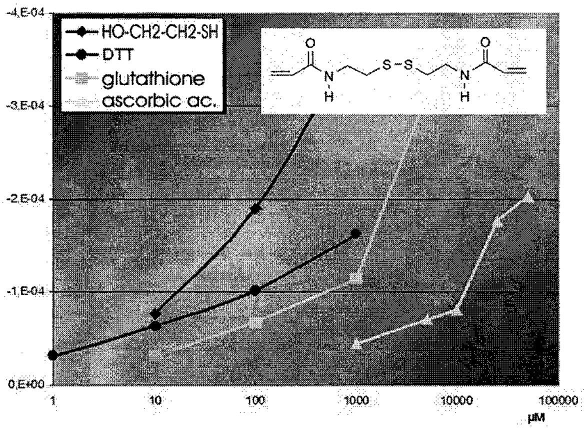


Figure 25: Redox volume-reactive gel using a redox-cleavable crosslinker

5.3 Data analysis

The nano-distance response of the smart polymer is transduced using either a fiber optic device, a spectrophotometer with reflection accessory (e.g. from Hitachi), an optical scanner in reflection mode or via a real time CCD-camera. The chips are e.g. put into a stainless steel flow-through cell and the analytes are injected into the FIA (flow injection analysis) system. A pumping speed of up to 5ml/min might be achieved using a ZEUSNT8-FIA system. Ions are assayed in a buffered solution to stabilize the pH.

Read out can be either done by measuring the shift of the peak maximum or by choosing a defined wavelength at the rising or falling side of the peak, quantifying the increase or the decrease of reflectance.

5.4 Application

Among a wide variety of applications a combination of smart polymer nanolayers with enzymes allows construction of biosensors. A urea-biosensor is obtained as followed: Urease is copolymerized within a polymer nearly insensitive to the pH, thus, without any charged groups in the polymer backbone. Polyvinylpyrrolidone, suited for this application, allows to detect chaotropic agents produced by degradation of the analyte. Urease degrades urea to CO_2 and NH_4^+.

These chaotropic products of the enzymatic reaction influence the structure of the polymer proportional to their concentration and thus to urea [39].

Even natural polymers such as complex carbohydrates may serve as reactive layers and vice-versa conformation changes in complex carbohydrates are directly accessible using REA based sandwich layers [40].

Sensors and sensor arrays for monitoring of organic solvents and organic chemical vapors are designed by using hydrophobic polymer networks. A hydrophobic polymer such as e.g. polypropylene, polybutadiene or related matrices enable to transduce the concentration of volatile organic solvents in gas phase into a reversible optical signal (Figure 26). A complex polymer array for identification of complex volatile odors is used for discrimination of petrol and diesel. Such chips are produced by spincoating of 2,5% polybutadiene in n-decane, micro structuring of the polymer is done via (photo)-crosslinking with 2,6-bis(-4 azidobenzyliden)-4-methylcyclohexanon.

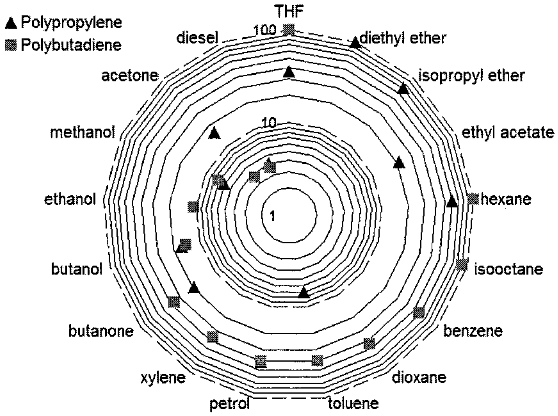


Figure 26: Polymer matrices sensitive to organic solvent vapour transduced via REA, logarithmic scale (100 = maximal polymer volume)

REA is moreover applicable to study the homogeneity of polymer films and nanoparticle contamination on chip-surfaces. Using highly polished aluminium chips as support and mirror layer (being invincibly cheap and easy in handling) REA allows to study micro-scratches, surface-adherent nano-particles, and a nano-structure induced by the production process using rollers (Figure 27).

Figure 27: Swell/shrinking response of an inhomogeneous polymer layer and comet tails induced by nano-dust particles transduced via 'REA'

6. Conclusions

Photolithography and photo-resists will of course be the dominant technologies in microfabrication of semiconductor devices for the next decades. However, many emerging applications require the characteristics of novel techniques. Soft printing and nano-layer techniques producing nanothin polymer films but involving large X/Y-features at µm-level can be conducted in an unprotected lab, and thus are especially useful to facilities of biotec-microfabrication. At the current state, nano-layers and soft lithographic techniques allow the construction of arrays, sensors, biosensors, and nano-analytical systems. Optical display devices and nano-optical devices based on reactive smart polymers now seem practical in a standard research lab. The success of novel lithographic techniques combined with new smart materials suggest a potential for application in emerging technologies combining lithographic with nano-patterning techniques. These devices exhibit a high flexibility, reproducibility, reliability, and still are easy to manufacture.

Due to the fact, that standard optical techniques based on interference phenomena are not applicable in those nano-material novel resonant optical techniques based on 'surface enhanced absorption (REA)' are required [41, 42]. For design of smart polymer chips and microarrays nano-optical transducers allow to monitor and quantify dimensions as well as structural changes of nanometric polymer elements and layers. Due to nano-dimensions, these novel nano-chips exhibit a fast response for analytes and provide simple and cost effective devices for many analytical applications.

Even biochips and polymer arrays make use of 'surface enhanced absorption' transducers. In the near future hundreds to thousands of polymer micropads will be applied via micro-arraying or printing to a single chip and serve as individual analyte-recognizing elements. Microarrays of smart polymers show good chemical and mechanical stability and are compatible with high throughput techniques. Pattern-recognition based approaches allow the identification of a broad variety of analytes.

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