Sub-Wavelength Resolution Laser Lithography in the Field of Mems

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ABSTRACT

In this paper I present some techniques by which MEMS structures with sub-wavelength resolution can be obtained when using laser lithography. I concentrate on two major techniques: single photon and multi-photon absorption processes.

1. INTRODUCTION

Today we assist at an increased interest in different photolithographic techniques, the aim of these studies being the establishment of a technology able to scale down the size of the different parts of the circuits and micro-electro-mechanical structures (MEMS) while maintaining performance, ease of use and price at an appropriate level. This is due because scaling down to nanometer size may bring important benefits as regards size, energy consumption and performance of the respective devices.

There are several techniques that, according to the type of particles used, can be classified in four major groups: a) photolithography, which uses photons of appropriate wavelength that modify some properties of the photosensitive (photoresist) material; b) electronolithography, which uses electron beams instead of photons, the resolution being much higher (for example, at IMT-Bucharest, such an electron beam can create features of 10 nm); c) atom lithography, which uses atomic or ionic beams that are deflected and deposited onto the desired place on the substrate, in this case existing two procedures, one that uses atomic beams and the other that uses Bose – Einstein condensates; d) molecular lithography, which uses molecules or ionized molecules instead of atoms.

Because the field of lithography is very vast, I shall restrict the paper discussion only to photolithography. The reason is simple, since obtaining and manipulating light beams is much easier than using other particles and creation of materials with appropriate optical properties that be used as photoresists has matured enough. Moreover, optical techniques have evolved so as to allow the circumventing of the diffraction limit, patterning of features with less than 100 nm size being now possible, at least in laboratory.

I shall also take into account only the most important techniques, the consideration of all the others implying an unacceptable length of the paper

First, I present some techniques for reducing the size of the features, techniques that are diffraction limited. Further, novel techniques are presented for which it is possible to go down the diffraction limit and even down the radiation wavelength. The last part is devoted to a technique that is under development and practical demonstration at IMT – Bucharest and that, to our knowledge, is new and uses a modified version of the conventional photolithography.

2. BASICS OF PHOTOLITHOGRAPHY

A photolithographic process consists in illumination of a mask with a radiation of the appropriate wavelength and projection of the respective image onto the photosensitive material, material that is named photoresist. The radiation may have several effects on the photoresist, depending on the material: bond breaking, photopolymerization, photocrystallization (for example in the case of chalcogenide glasses). After illumination, the material is baked and

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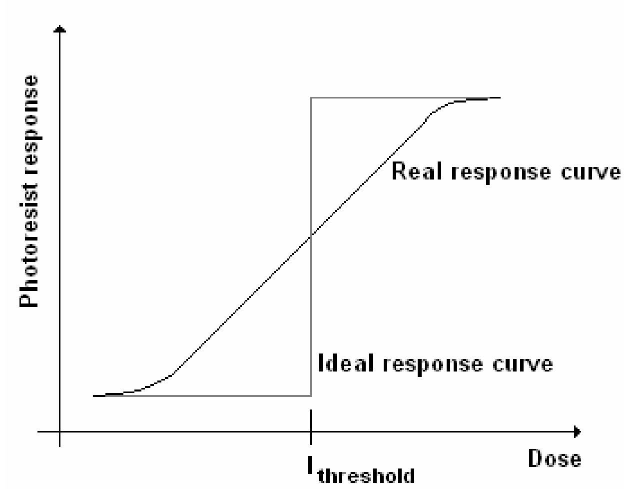
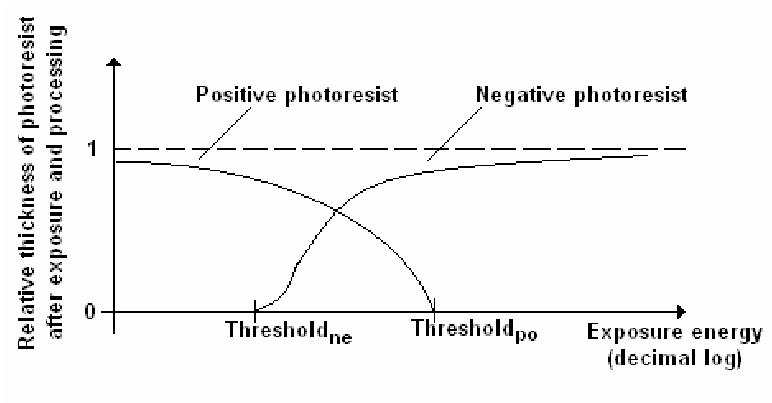
subjected to solvents that dissolve or etch selectively the illuminated (positive photoresist) or un-illuminated (negative photoresist) regions. The response of the photoresist depends on the illumination dose, which is on the product between light intensity and exposure time. On certain dose intervals, the dependence is linear. As happens with usual photographic emulsions, the photoresist also has a response curve that is gradual, which means its optical response does not vary sharply with the incident light dose but according to some law that is linear on a certain interval, as seen in figure 1.



a)



b)

Figure 1 - Schematic curve of a photoresist response. a) general form of photoresponse; b) relative thickness of photoresist after exposure and processing for positive and, respectively, negative photoresists.

As in the case of photographic films, the photoresist may be under-exposed (when subjected to a dose sligthly below the value for performing entirely the photo-chemical process) or over-exposed (when subjected to a dose much higher than the respective value). In the case of under-exposure, the photoresist is not well dissolved and removed, affecting the forthcoming technological processes. In the case of over-exposure, the margins of the feature become larger, since part of the light from the margins of the respective spot can also initiate a photoresponse.

Because smaller features, assuring a larger scale integration, are necessary, then UV radiation is used. The minimum feature size δ is limited by diffraction and is approximately given by the Rayleigh criterion:

$$\delta = k * \frac{\lambda}{n * NA} \quad (1)$$

where λ is the wavelength (in vacuum), k is a constant, n is the refractive index of the medium between mask and photoresists layer (n = 1 for air), and NA is the numerical aperture of the objective defined as [1], [2]:

$$NA = n*\sin\theta \quad (2)$$

where θ is half of the projection angle (I have considered projection method, formula (1) differs in the case of contact or proximity method).

Moreover, another important parameter is the depth-of-focus (DOF), which represents the region along the thickness of the sample corresponding to the focused spot:

$$DOF = \frac{\pi\lambda}{2 * (NA)^2} \quad (3)$$

The magnitude of DOF is important since in some cases the photoresist needs to be thick enough while δ and hence DOF have to be lowered.

More details about photolithography may be found in the book [1].

Up to now I have presented the 2D photolithography, which is the photolithography used for obtaining 2D images (the mask image). In the case of MEMS, this is useful when the MEMS device is made layer by layer, for each layer a different photolithographic process being necessary. This is time consuming and reduces production efficiency. Moreover, if someone wants to create a complex microstructure, as that of a microchain with several rings and with a total length of 100 microns, then the layer-by-layer techniques is unfeasible. Because of that there have appeared other techniques that offer good possibilities for creating complex MEMS.

In fact, there will be a trade-off between the complexity of the MEMS and the materials from which it can be obained. The layer-by-layer technique is applicable to almost every kind of materials, while the two-photon technique is applicable only to a class of polymers.

3. SOME TECHNIQUES FOR IMPROVING RESOLUTION

There are two aspects. The first one considers the reduction of the features size while maintaining their dimension above the light wavelength. The other one considers the possibilities by which the features size can be reduced under the wavelength of the radiation.

Let consider each case.

III.1 Size greater than the radiation wavelength

III.1a Wavelength reduction

In this case, one obvious way, as results from (1), is to reduce the wavelength while keeping constant or increasing the numerical aperture. This fact was considered when lasers of shorter and shorter wavelengths have been devised and used in photolithography, as excimer lasers in the 157 nm – 248 nm range. The advantage of this technique is that the basic set-up of the photolithographic equipment is not changed (excepting below 193 nm). As regards the minimum feature size, this is decreased by 1.28 when passing from 248 nm to 193 nm. The same happens with DOF, which is not a very big problem for microelectronics but can be an important one for MEMS, since in some cases the photoresist must be quite thick.

The main disadvantage is that special optics should be used. This is stringent in the case of 157 nm radiation, where CaF_2 is the material of choice. But CaF_2 monocrystals are difficult to be obtained at an appreciable size, the material is higroscopic and birefringent. These features add costs both as regards optics realization and modification to the equipment such that avoid the contact of the material with water vapours existing in the atmosphere (partially solved in the clean rooms of high quality). Moreover, radiation under 200 nm (and especially the 157 nm one) is strongly absorbed by the air, so that the beam must propagate through a buffer gas, such as N_2.

Other directions are the use of EUV radiation of 13.4 nm wavelength that should allow sub–50 nm resolution [3]. While photolithography with X-rays, involving wavelengths in the 0.8 nm – 1.5 nm, relies on the fact that the radiation is not absorbed by most of the materials, the EUV radiation is strongly absorbed such that great care must be taken so as to use every photon of the source. While “normal” UV radiation (down to 157 nm) is breaking the bonds of the molecules or it initiates photopolymerization, the EUV and X-ray photons are interacting with the inner electrons of the atoms. Because of that, designing photoresists for these spectral regions that have a good contrast, is an actual task.

3.1 Liquid immersion of the objective

In this case, the space between the objective lens and the photoresist layer is filled with a liquid, usually water. The schematic diagram of the set-up is given in figure 2.

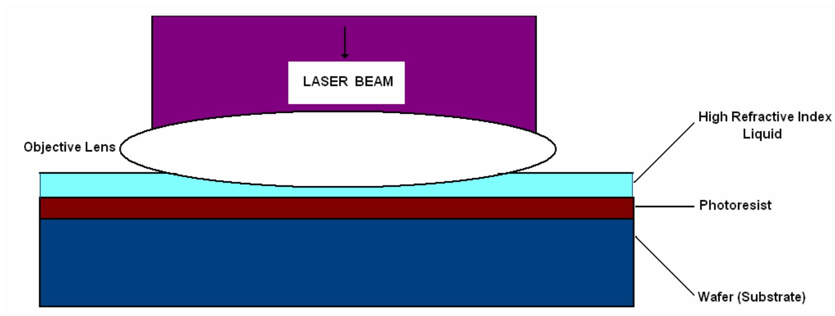


Figure 2 – The schematic set-up for the immersion objective technique.

The fluid layer is flowing from a fluid source to a fluid sink. The conditions for the fluid are that it must be very transparent to the radiation used. Water absorbs only 0.05 cm^{-1} at 193 nm, having a refractive index of 1.44. The fluid must be very clean (no solid particles), contains no air bubbles, wet the surface and not react with the substrate.

In the case of this technique, the wavelength is reduced by n times and the numerical aperture (at a constant angle θ) is increased by n times, so that δ reduces by n^2 times. In the case of water at 193 nm, the reduction is of 2 times. Increasing also the angle θ may scale down the minimum feature size further. But in this case, at extreme angles, polarization effects become important and care must be taken, because radiation polarized in the plane of incidence exhibits reduced image contrast. This is true for θ approaching 45^0.

The problem is that DOF is also decreased, so that the method is applicable only to thin photoresists. In the case of MEMS, it implies the use of layer-by-layer construction technique, so that complex MEMS are hardly fabricated with this type of photolithography.

The advantages of this technique are the fact that usual optics is used, that water is a fluid currently used in microfabrication, that features of several tens of nm can be obtained (around 70 nm at 193 nm wavelength), no special processes, excepting water flow, are involved.

The disadvantages for MEMS relies on that it does not allow fabrication of complex MEMS. Moreover, the temperature stability of the liquid (during exposure as well as from wafer-to-wafer) is crucial, since temperature variation implies variation of the refractive index of the liquid.

3.2 Size less than the wavelength

In this case, the techniques allow the obtaining of features with size less than the radiation wavelength, size that is not limited by diffraction. There are several techniques, as described in the following. If the above mentioned photolithographic techniques need an uniform light intensity distribution in the illuminated regions, requirement due to the necessity of equal response of the photoresist in these regions (that is obtain the same exposure in the regions of interest), the techniques that are described below make use of highly non-uniform intensity distribution in the illuminated regions.

3.2.1 Near field optical microscopy

I mention this technique only from an academic point of view, its practicability being very limited.

In this case, the light source is the tip of a near field optical microscope. The wavelength of the light is chosen is such a way that produces a response on the photoresist. Practically, the tip is moved along the desired path and evanescent field emerging from the tip reaches the photoresist, creating thus the needed pattern. The resolution can be at tens of nm. The technique has several disadvantages, among which I mention: a) is a very slow technique because it needs the movement of the tip along the desired path; b) it is a slow technique because it does not allow the parallel fabrication of all the chips on the wafer; c) it depends strongly on the surface roughness of the photoresist as well as on the substrate topography. Deviations of tens of nm of the surface may alter the pattern size. It is applicable to thin photoresists, since thicker layer may couple the radiation inside them by diffraction, increasing the spot size.

3.2.1 Two-photon absorption

This technique relies on the property of some nonlinear optical materials to absorb two photons of the same wavelength or, in some cases, of different wavelengths. This property arise from the intrinsic structure of the respective molecules that posses such an optical nonlinear polarizability. More details on two-photon absorption may be found in [4].

The intuitive description of the effect is as follows: suppose a system that has a wide energy gap equal to Δ. Imagine that a photon with an energy of half of Δ is incident on the system. According o the Heisenberg uncertainty law, the system absorbs the photon and stays in the virtual excited state for a period proportional to the inverse of $\frac{\Delta}{2}$. After that time the photon is re-emitted and the system returns to its ground state. If the intensity of the beam is very high, which means that a great number of photons arrive at almost the same time in the same place, then the system situated in the virtually excited state can absorb a second photon and thus passing the system to its true excited state. This transition of the system from its ground state to its true excited state by absorption of two-photons of lower energy is the two-photon absorption process. A schematic diagram of the process is depicted in figure 3.

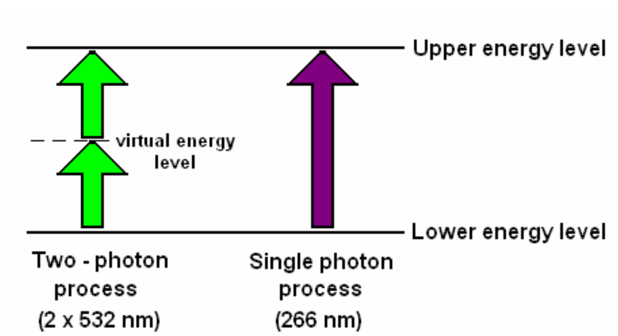


Figure 3 – Schematic diagram of the two-photon absorption process exemplified for green (532 nm) photons.

By two-photon absorption can be understood also multi-photon absorption. Multiphoton (more than two photons) absorption needs a higher beam intensity in order to take place than in the case of two-photon absorption. Because the lifetime in the virtually excited state, in the case of photons from the visible, is very small (of the order of 10^{-16} sec), it results that two-photon absorption takes place only at high intensities. Because of that femtosecond lasers are prefered for this purpose. This types of lasers posses some restrictions, as will be seen later.

The achieving of the high intensity is realized in two ways. The first one, consisting in the focusing of the laser beam by a high NA objective in the thick photoresin (the equivalent of the photoresist) creates a spot in the focus where photoreaction (usually photopolymerization, but other types of chemical reactions are also used) takes place. In order to make the structure, the spot is scanned both in plane (x-y) and along propagation direction (z), so as to create the desired structure. The throughput is small, since is a serial manner of work. If high yield of productivity is not a requirement, then is a useful way. The other way is by using computer generated diffractive masks (more precisely holographic type masks) that allows the realization of the desired intensity pattern over a large area. In this case, all the structures are made in parallel, in some cases being necessary z-scan. In this last case appears the problem of femtosecond lasers, since they have a broadband spectral range, each spectral component diffracting at a slightly different angle. This aspect imposes some caution, since the overlap between pulses coming from different direction may be affected [5].

In the case of two-photon absorption, the intensity distribution obeys the same diffraction limitation as in the usual photolithography but it is the nonlinear behaviour of the material that discriminates the intensity in the focused region and allows that the photoreaction takes place in regions smaller than the wavelength whose size is not limited by diffraction. A schematic representation of the principle of the technique is given in figure 4.

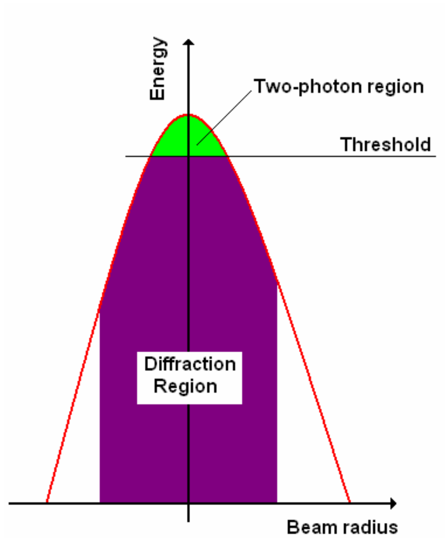


Figure 4 – The schematic representation of the way in which two-photon absorption circumvents diffraction limit.

The two-photon process may be of two types.

The first one involves the absorption of normal, non-entangled photons and behaves as described above. The probability of two-photon absorption increases with the square of the incident intensity. In this case, as described for example in [5], the necessary intensity for a SU8 photoresist is of approximately 0.7 TW/cm^2. This high intensity poses some questions on the resistance of both photoresist and underlying material as regards resistance to such energetic radiation. This is a problem with this sort of microprocessing. The resolution obtainable in this case, when using a 800 nm laser, is of approximately 200 nm in lateral and approximatelly 800 nm in DOF. This difference in lateral and DOF resolution is easily explained by taking into account that DOF is given by the radiation wavelength, which is quite large. Longer wavelength diffracts at larger angles, so that for a given mask there are less diffracted beams than for smaller wavelength beams.

The second type of two-photon absorption makes use of entangled photons, as described in [6]. In this case, the initial laser beam is split, by parametric down conversion, into pairs of entangled photons, each photon from the pair propagating in a different direction than its partner. With the use of optics, these photons are recombined onto the photoresist, where two-photon absorption takes place. In this case, the absorption rate depends mainly linearly (with a small quadratic term) on the incident intensity and, because of the properties of the entangled photons, the overlap can be achieved on smaller regions than for usual two-photon absorption. The dependence of the absorption rate on incident intensity for the entangled and un-entangled cases respectively is shown in figure 5.

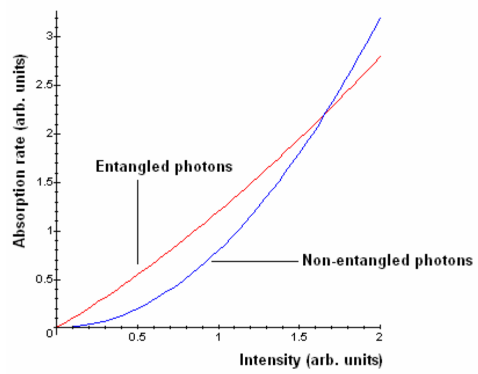


Figure 5 – The absorption rate dependence on intensity for the two-photon absorption process, for the case of entangled and, respectively, un-entangled photons.

As is seen from the above figure, entangled case is more efficient at low intensities, which means that the material are not exposed too much to damage.

As a general remark, all two-photon absorption techniques allow the direct, simultaneous fabrication of the whole 3D MEMS. From this point of view, multi-photon absorption techniques prove useful in rapid prototyping of such structures [7]. However, there is a problem when wishing to make the whole structure at once: the photoresin may change its optical properties during two-photon absorption. This implies that parts situated below the surface layer of the photoresin will be exposed to a beam with altered properties during time, since the refractive index of the above layers is changed. This fact alter the aspect of the MEMS. The problem may be overcome by using photoresins with optical properties unaltered by multi-photon absorption, but this aspect limits the available materials that can be used for 3D micro and nanostructuring.

Among the advantages of the two-photon techniques I mention: a) "normal" lasers and "normal" optics is used; b) the minimum size is not diffraction – limited; c) does not require special conditions for the photolithographic assembly; d) can be used for 2D – photolitography as well as for 3D – photolitography (in MEMS technology).

As regards the requirements, these are: a) specially designed masks (holographic type); b) highly nonlinear photoresist; c) sharp response photoresist; d) high thickness uniformity of the photoresist; e) very smooth and plane surface of the photoresist.

The disadvantages are: a) high intensities are needed, that might affect the substrate (excepting for the case of entangled photons); b) the non-ideal behaviour of the photoresist (gradual response) that results in blurred contours; c) only special resins can be used today for making 3D microstructures.

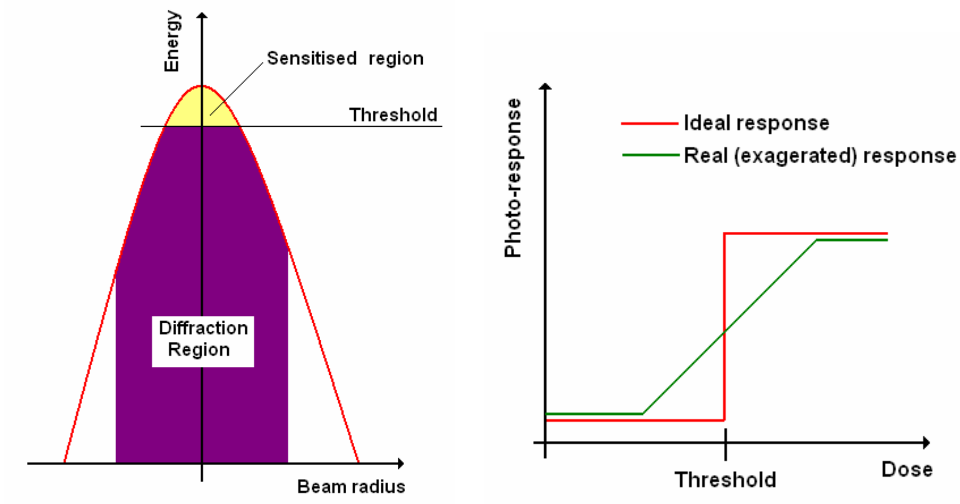
3.2.3 Use of metamaterials

This research direction, under intense study in our days, aims at creating optical elements from the so-called metamaterials, among which materials exhibiting a negative refractive index are the most interesting. Theoretically, such a material will allow the fabrication of a superlens that may focus light to very small spots, the possibility being given by the use of the evanescent fields emerging from such a structure. It is expected that resolutions of $\lambda/50$ be obtained with such optics.

3..2.4 Low dose / low intensity single photon lithography

This technique is under study at IMT-Bucharest. The aim is to use usual lithographic technique but with the aid of two new items: a) specially designed holographic masks; b) photoresists with a very sharp photoresponse.

The working principle is as follows: a non-uniform light intensity distribution is created onto the photoresists surface. Ideally, the sharp response of the photoresist will discriminate between the regions with an intensity lower than a threshold value and regions with intensity higher than the respective value. Is a technique similar to two photon absorption but by using single photons. For a positive photoresist, for example, the regions illuminated above the threshold value will be dissolved in the solvent. The schematic diagram of the operating principle, similar to that in figure 4, is depicted in figure 6.



a) b)

Figure 6 – Low intensity photolithography. a) schematic diagram of the operating principle, indicating the diffraction limited region and, respectively, the sensitised region; b) the schematic response of a photoresist (ideal case and real case);

As an example, let consider a gaussian beam of radius ‘a’ and peak intensity of value I_0. Let I_{th} be the threshold intensity at which photoresist response takes place. The radius of the photoresist response region, in the case of an ideal sharp photoresist, is depicted in figure 7.

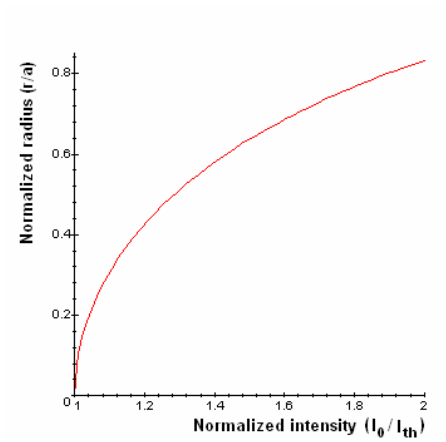


Figure 7 – Normalized radius of the sensitised region as function of the normalized intensity $\frac{I_0}{I_{th}}$ for a gaussian beam of radius ‘a’ and an ideal photoresist.

If the peak intensity differs only by ε with respect to the threshold value, with ε << 1, then the normalized radius is equal to $\varepsilon^{1/2}$. If the initial radius is 100 microns and $\varepsilon = 10^{-6}$, then the radius of the sensitised region is approximately equal to 100 nm.

For the case of a focused spot, taking into account the relation that gives the intensity distribution at the focus [8] in the focal plane:

$$I(v) = \left(\frac{2 * J_1(v)}{v} \right)^2 I_0 \tag{4}$$

with:

$$v = \frac{2\pi}{\lambda} \frac{a}{f} r \tag{5}$$

and considering an ideal photoresist, a lateral resolution of several tens of nm is obtained if the peak intensity exceeds by 2 % the threshold value.

In the relation above the parameters are:

a – half aperture of the focusing lens

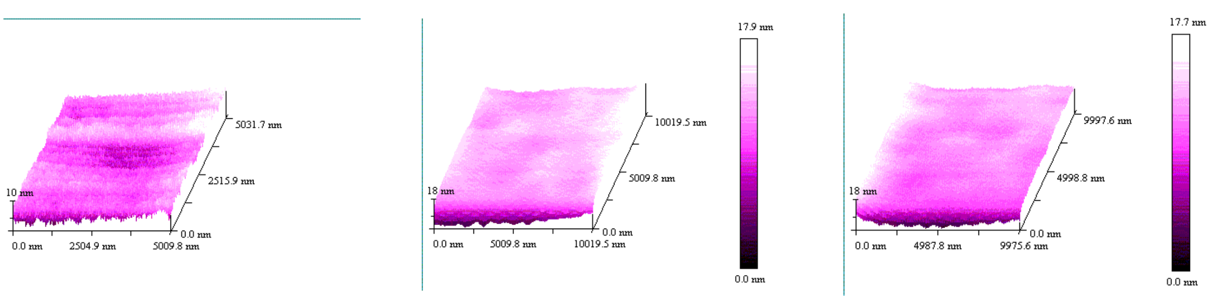
f – focal distance

r – distance in the focal plane

$J_1(x)$ – the Bessel function of index 1

The beam can be focused by a holographic mask, such that the desired intensity profile and pattern are obtained. Since the technique uses UV photons of a specific energy (within a narrow bandwidth), the errors introduced by the bandwidth of the beam are small. Moreover, since the photons are in UV, the diffraction limit is small, such that the regions above threshold can be made smaller than the wavelength.

There is no need of special optics. The crucial requirements are: a) an ultra-stabilized laser as regards its intensity (as possibility to control its value and during the time); b) an ultra-stable laser as regards its field profile within the beam; c) photoresist with a very sharp response, this being a challenge at the present time. Other requirements are: d) high thickness uniformity of the photoresist; e) smoothness and planeity of the photoresist. This last aspect is exemplified in figure 8, representing the Atomic Force Microscopy (AFM) image of a As_2S_3:Sn chalcogenide glass deposited on different kind of substrates.



a) b) c)

Figure 8 – AFM images of a As_2S_3:Sn chalcogenide glass photoresist deposited on different substrates. a) onto silicon; b) onto aluminium; c) the aluminium etalon.

As is seen from figure 8, the smallest roughness is in the case of chalcogenide deposited onto silicon, were the rms roughness is below 1 nm. The thickness of the chalcogenide layer is 160 nm. Even if a small waviness is observed (given by the silicon substrate), the photoresist material is of good quality for photolithographic processes.

The low intensity technique can be applied both for 2D as well as 3D photolithography. In the case of 3D photolithography we expect a better DOF than in the case of two-photon absorption, since the wavelength is shorter. However, the same caution should be taken as in the case of two-photon absorption for 3D microstructuring, since the variation of the optical properties of the photoresist during exposure may affect the layers situated in proximity of the substrate.

The photoresist must posses extremely reproducibility as regards its photoresponse, since the intensities that are used are only slightly above the threshold value. Moreover, the uniformity of the photoresist photoresponse across its surface is essential for obtaining good results.

As advantages, these are: a) usual photoresist equipments are used; b) ”normal” lasers and “normal” optics are used; c) applicable to a large number of techniques (see “alternatives”); d) the feature size is not limited by diffraction; e) can be applied for 2D – photolitography as well as for 3D – photolitography; f) does not make use of high power lasers that means the substrate is far from being damaged (as in the case of two-photon absorption); g) applicable to polymer photoresists and chalcogenide glasses.

The disadvantages considered up to now are: a) blurred margins of the features, especially at very small dimensions; b) fluctuations of the laser intensity or beam structure may alter the shape; c) photoresist inhomogeneities may alter dimensions; d) non – ideal response of the photoresist; e) in the case of some chalcogenide glasses (re)crystallization may occur that means the minimum feature size depends on the grain size.

Because the laser presents small fluctuations of intensity, it is desirable that the photoresist have a higher threshold value. In this way, a longer exposure time is necessary in order to achieve the threshold dose. If a negative feedback is used for correcting the laser intensity fluctuations and the feedback is very fast, then the long exposure time allows the reduction of the unwanted effects due to fluctuations.

Some versions of this technique may also be considered. One of these is the photoablation, in which case the photoresist material is ablated in the regions illuminated with an intensity greater than a specific value. In this case, more powerful lasers are needed, in the picosecond regime, so as to reduce thermal spread. Another version is the photodoping of a material, which means the doping of the photoresist with a metal under the exposure of light. Such a metal could be silver and the photoresist could be a chalcogenide from the As_xS_y group. GeSe are also an option for photodoping photoresists. The doped regions have a different etch rate with respect to undoped ones. The metal diffuses anisotropically along the illumination direction [1], which gives rise to good contrast images. Because the metal profile compensates for the diffraction effects at the margin, the photolitographical process using this kind of photoresist assures a high resolution. A sharp threshold of the process is necessary too, as in the previous cases. In the case of AsS group and Ag, the quality of the image is good for lithography, since the lateral diffusion of the metal is not significant [9]. The materials from the GeSe group, as well as AsS in combination with Cu, are not indicated for this kind of photolithography, since the lateral diffusion of the metal, acquired by thermal means, is quite large, thus resulting an image with blurred contours [9]. Another version is that based on photocrystallization, but special care must be taken so that the grain size of the resulted nanocrystals be suitable for sub – wavelength lithography. For this kind of photolithography, chalcogenics from the GeSe, TeGeAs TeGeSbS, SeS groups are useful materials [9].

The main problems of all these techniques are related to the photoresist homogeneity as regards properties as well as thickness. There is also a stringent need for low roughness and high thickness uniformity of the substrate, since the DOF is of the order of few hundreds of nm.

The photoresist being very thin (below 200 nm), the adhesion and surface coverage of the substrate must be very good.

Using these techniques may add several technological steps, such as vacuum deposition, plasma etching or reactive ion etching. These increase the processing time and costs.

In the case of chalcogenide photoresists used in silicon microprocessing, these could contaminate the substrate.

4. CONCLUSION

I have presented some of the photolithographic techniques that are used or will be use soon in microelectronics and especially in MEMS technology. Some of these techniques, based on the non-uniform light intensity distribution in the beam and on the nonlinear response of the photoresist, have a promise for direct 3D fabrication. Materials used for this purpose are photoresins of different type and, in some cases, chalcogenide glasses. These techniques comprise the already developed two-photon absorption technique as well as the technique under study now, that of low intensity single photon absorption. Moreover, these techniques seem to be good candidates for sub-wavelength resolution. For being able to obtain such small features special masks are needed, as well as photoresists with small molecules. From this last aspect, chalcogenide and polymer glasses seems to be advantaged. Another important aspect is that special designed masks, of the holographic type, are needed. The design of such a mask could be type consuming and require a large computing power. Moreover, the quality of the mask must be very good in order to avoid any unwanted distortion of the features that have to be obtained.

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