LASER APPLICATIONS IN THE FIELD OF MEMS

Gabriel Moagar-Poladian(1), Zsolt Illyefalvi-Vitez(2), Balint Balogh(2),
Dumitru Ulieru(3), Antonie Coraci(1)
(1)IMT-Bucharest, Str. Erou Iancu Nicolae 126A, Bucharest, Romania, www.imt.ro
(2)Budapest University of Technology and Economics, Goldman t. 3, H-1111 Budapest, Hungary
(3) S.C. ROMES S.A., Str. Erou Iancu Nicolae 126A, Bucharest, Romania
(*) Coresponding author: E-mail: gabim@imt.ro

ABSTRACT

The paper overviews some of the most important applications of lasers in the field of microsystems (MEMS). We present applications from both technology and MEMS testing. Since these applications cover a wide range, the presentation does not aim to offer a thorough, detailed presentation of each of these, but only to underline some of the most important directions and features. We present the respective applications, their working principles, their advantages and their drawbacks. In some cases we present examples of microstructures realized by using laser techniques.

1. INTRODUCTION

Since their discovery at the beginning of 60's, lasers have found a lot of applications in industrial processing. This is due to some of their characteristics, such as power, directionality, coherence, focusing possibilities and to the fact that a laser beam is an energy flow from the source to the target.

On the other hand, the field of microsystems and nanosystems has experienced a great spread as regards the nature of the materials used, starting from the initial Silicon, SiO_2 and Si_3N_4 to polymers, ceramics and many other materials. This vast variety of materials has imposed the use of technologies that be able to process such materials, be environment friendly and, if possible, be applicable to a variety of materials as large as possible. By surpassing by far other competing technologies (such as plasma based), the lasers have proven a valuable tool for this kind of applications.

The use of lasers in the field of MEMS is multiple. Starting from characterization, testing and going to technology and working principle of the microsystems and nanosystems, the lasers find applications in any of these areas.

The accent will be put throughout the paper on the technological applications. As regards the testing of MEMS, the applications in this field is enormous, starting with Atomic Force Microscopy (AFM) and continuing with Near Field Optical Microscopy (NFOM) that allows tens of nm resolution, continuing with spectroscopy of micro- and nanostructures, photoluminescence studies, displacement measurement of microsystems, etc. . A special field emerging now is that of using light pressure for testing the mechanical and optical properties of microsystems.

2. TECHNOLOGICAL APPLICATIONS

2.1 Laser deposition

This technique refers to deposition of thin films by using laser evaporation. The principle of operation is as follows: the laser beam is incident on the target material, material that must be deposited on a certain substrate. The material evaporates and the vapours are deposited on the substrate. The schematic structure of a laser evaporation system is shown in figure 1.

INDLAS 2007: Industrial Laser Applications, edited by Mircea Udrea
Proc. of SPIE Vol. 7007, 70070K, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.801970

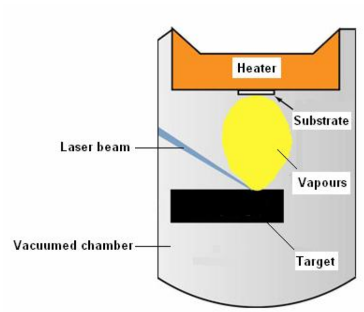

Figure 1 – The schematic structure of a laser evaporation system.

The laser is pulsed, the duration of pulse being from fsec to microseconds. Their repetition rate may vary from several Hz to hundreds of kHz. Depending on their wavelength, the mechanism of evaportaion is different. Thus, in the case of infrared beams, the process of evaporation is driven mainly by the non-equilibrum thermal evaporation. In the ultraviolet range, the bond breaking plays the essential role. Intuitively, in this case we may regard the atoms of the material as having the bonds break and being able to exit from the surface of the material, due to their thermal motion.

The repetition frequency is important since, in some cases, the vapour plume formed at the surface of the material absorbs the incident laser and reduces its impact on the material surface for further evaporation. Because of that, a preliminary study should be made for each material, so as to determine the best repetition frequency.

On the other hand, the pulse duration is important as regards the evaporation process. This evaporation could be of nearly-equilibrum (if the pulse duration is long enough) or can be of non-equilibrum (very short pulses). A longer pulse means energy diffusion throughout material, a shorter one limits the energy to the region of incidence. Because fsec pulses have a great intensity, they are preffered in evaporation applications. On the other hand, psec pulses have proven to be more suitable when high quality evaporation is necessary.

The vapours are deposited on the substrate or, in some cases, they condense in the gas and form nanograins that are falling on the target materials.

Because it is a non-equlibrum evaporation, the stoichiometry of the target is mostly preserved during deposition. Because of that laser evaporation is a technique widely used for depositing compound materials with complex compositions, such as lanthanides, titanides, ceramic oxides as those encountered in high temperature superconductivity.

The technique is easy to use and applicable practically to the whole classes of materials, such as silicon, germanium, glass, oxides, nitrides, salts, alloys, chalcogenides, binary and ternary compounds and alloys and metals (in this case ultraviolet radiation should be used, since metals reflect strongly in the infrared).

The interaction of the laser beam with the material and with the plasme or vapour plume formed is very complex and is studied extensively. As mentioned in [1], when the laser pulse is absorbed by the target, energy is first converted to electronic excitation and then into thermal, chemical and mechanical energy resulting in evaporation, ablation, plasma formation and even exfoliation. The plume contains many energetic species including atoms, molecules, electrons, ions, clusters, particulates and molten globules, before depositing on the typically hot substrate. Usually, inside the deposition equipment is made ultra-high vacuum. In some cases, the evaporation chamber may contain a gas, such as nictrogen or other inert gas. When oxidation is necessary, the chamber may contain oxigen that has the role to fully oxygenate the deposited films.

Another way of evaporating materials is the use of two laser beams, normally of different wavelengths. The pulses have a time delay between them. For example, the first pulse is in the infrared and have an energy just as to slightly heat the target. The second pulse, the more energetic, is in the ultraviolet and arrives at a time difference of few ns. Usually, the two pulses overlap, that is the end part of the first pulse overlaps with the front part of the second. This technique allow a better control of the evaporation and of the film quality by tuning the time and energy parameters of the two beams.

The reader is reccomended to read literature [2-4] for details.

2.2 Laser micro-welding, (re)crystallization and planarization

Laser micro-welding is another technology based on the thermal effect of the laser beam. It is used mainly for thin wire connections to contact pads. It is also useful when welding polymer and glass fibres to the substrate. It gives good bonding strength, applicable to almost all metals. IR lasers are used for microwelding.

Usual welding processes (gas-tungsten arc welding, plasma arc welding) have followed the scale down process in the MEMS industry to a point, they are finding difficulty in putting together very small components. Because the laser has the ability to deliver very precise amounts of energy, laser welding excels in joining the small parts that are common in MEMS manufacturing. Some of the laser microwelding advantages are: a) non-contact; b) low heat input; c) good strength; d) high welding speed; e) high precision; f) applicability to metals that usually are hard to weld, such as Aluminium, Nickel, Titanium; g) consistent weld integrity; h) high weld strength to weld size ratio; i) realiability; j) minimal heat affected zone.

Infrared lasers are used for micro-welding. In some cases, a fisrt step is done by abltaing the thin oxide layer existing on a metal. The oxide absorbs more in infrared than metals, so as can be removed before welding by laser evaporation. This is an important step since an oxide layer may disturb the wetability of the surface and may produce weldings of an unappropriate quality.

In laser micro-welding, the material in the heat affected zone of the workpiece experineces several processes, such as heating, melting, re-solidification [5].

The laser micro-welding process is very complex. It includes phenomena such as thermal conduction in a multi-phase system, fluid flow, gas dynamics, plasma effects. Because of that, describing the process taking into account all these effects is very complicated and usually some simplifications are made, for example considerations of only one of the phenmena mentioned [5], [6].

The welding energy depends strongly on the surface reflectivity of the metal and on the roughness of the surface.

An example of laser micro-welding is that of a copper layer with a thickness of 100 microns and a beryllium copper layer [5]. In this case, the laser used was an Nd:YAG laser at 1064 nm, with a spot diameter of 100 microns. The laser beam had an energy of 5 J and a pulse duration of 4 ms. Tensile tests indicated that the strength of the laser micro-welds is less than that of the base material, due to the increase in hardness at the heat affected zone of the micro-weld.

(Re)crystallization is useful especially for transforming an amorphous material to its crystalline state. As regards the recrystallization, there are two effects on which this is based. The first one is a thermal effect, by which the material is locally heated and, after cooling, turns a crystalline or amorphous state depending on the heating, cooling and substrate conditions. This is usual, for example, for amorphous silicon, germanium, metals. The other mechanism, taking place in chalcogenide glasses, is bond breaking. The clusters achieve thus more freedom to reorient and may form microcrystalline regions [7]. This happens usually and blue and ultraviolet regions. Most applications are in the field of solid photoresists, data recording, microstructure realization. For (re)crystallization IR as well as UV lasers are used.

Another application is planarization of chalcogenide glasses. This effect was observed first in [8] and is presented in [7]. It takes place in chalcogenide glasses illuminated with ultraviolet radiation, the main mechanism being the modification of rheological properties such as viscosity and material flow. The freshly prepared amorphous material acquires a flat topography under UV illumination. This is important for applications where the roughness of the material is a problem and must be reduced. Such applications are photolitography, different types of thin film microsensors (especialy those read optically).

2.3 Laser assisted doping

This application refers to the control of the doping process of a given substrate. For example, silicon doped with B or P. It also refers to the diffusion of some metals, such as Ag, in some glasses from the group of chalcogenics [7].

Let consider the doping of silicon in more detail. Usually, the dopant (an oxide of it), is applied onto the wafer surface and the dopant enters by thermal diffusion into the substrate. The process is thermally activated, which means it occurs at high temperature. The dopant concentration is non-uniform, being higher immediatelly beneath the surface and decreasing toward the thickness of the wafer. This means that the movement of the dopants, which are in an ionized state, occurs both due to thermal diffusion (described by the Fick law) and due to the electric field existing in the respective region and trying to impinge them deeply into the wafer.

It was experimentally shown that illuminating Silicon with an infrared radiation (below the cutoff of the bandgap) has an enhanced diffusion while illuminated with ultraviolet radiation it shows a decreased diffusion. The explanation for this process is as follows: infrared radiation is not absorbed into the semiconductor and cannot generate free charge carriers. Its effect is thermal and this effect contributes to the local heating of the substrate and enhances diffusion. Moreover, existing free charge carriers are intra-band excited to higher energy levels, diffusing further in the wafer. For a n – type dopnat, this means that the dopant region is richer in electrons and the impurity has a positive charge. The enhanced diffusion of the elctrons deeper into the substrate means a higher depletion of the region containing the dopant, that menas there are less charges to screen the electric field of the dopant. This suplementary field accelerates the dopant ions into the bulk. Another efect at infarred wavelengths comes from the ions having a level somewhere at the middle of the substrate bandgap. In that case, a photon in the infrared can take an electron from the deep level of the impurity into the conduction band, thus ionizing the impurity (a +1 charge if it was initially neutral or a +2 charge if it was initiallt charged). Thus, the electric field is increased (the electron being very light compared to the impurity it diffuses almost immediatlely out of the region) and the diffusion enhanced. It this case, the spectrum of the infrared radiation is discrete, corresponding to the impurity states. On the other hand, ultraviolet radiation produces free charge carriers that are separated by the eletric field (photovoltaic effect), thus screening the electric field in the dopant region. As a consequence, diffusion is reduced mainly to its thermally activated component, which means it is decreased.

A schematic representation of the dopant distribution is shown in figure 2.

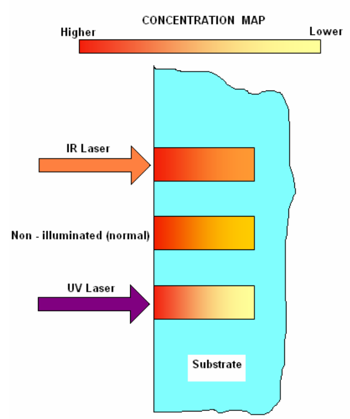

Figure 2 - Schematic of dopant concentration distribution in the three cases.

A darker orange means a higher dopant concentration, a lighter orange means a lower dopant concentration.

As regards chalcogenics doping with metals, there are several mechanisms that seem to produce the doping. Details can be found in [7].

2.4 Laser micro-patterning

This is a useful techniques in the field of fabrication of Micro-Electro-Mechanical Systems (MEMS). Micro-patterning may consists in a simple draw of a line or creation of micro-holes or may be used for realizing complex microstructures. Practically, all the range of materials can be micro-patterned: silicon, germanium, silicon carbide, diamond, sapphire, ceramic, glass, polymers, metals, nitrides, chalcogenides, salts, alloys, binary and ternary compounds.

The technique is prefered when other means of microprocessing do not exist or are too expensive to be applied. For example, when working with hygroscopic materials or with materials that are hardly etched chemically or can not be put under plasma processing, then laser micropatterning is used. An example is given in figure 3, where several microstructures made in a KDP crystal (KH_2PO_4) are presented. The first one is a cantilever, the second one is an inertial mass containing four arms and the third one is a microbridge. We have used this kind of processing because KDP is a very higroscopic material and we needed good accurcay of the geometry, hardly obtainable by other means.

Figure 3 - Optical microscope images of different microstructures engraved in a KDP crystal

(left – cantilever, centre – suspended inertial mass, right – microbridge)

The basic process of micro-patterning is the ablation of the material, the remaining zones representing the microstructure to be obtained. The same lasers as in the case of laser ablation can be used. However, those working in the infrared are less suitable when geometry accuracy is crucial (as regards aspect of the margins, for example) because of the thermal spread in the material and the less rigorous quality of the resulting lines. UV lasers are preffered because of the better line quality (sharp lines due to the bond breaking) and of the possibility to obtain high power pulses when using fsec and psec lasers. Moreover, as in the case of laser ablation, there too few materials to resist at UV pulses while metals and some of the semiconductors are reflecting infraeed regions and thsu can not be patterned in that spectral domain.

The parameters of interest are the laser wavelength, the pulse energy, the pulse duration, the repetition frequency, the modal structure (or, generally, the intensity distribution within the beam area), the working atmosphere.

The micro-patterning may be achieved by translating the substrate or by dfelcting the beam according to the pattern to be obtained or may be achieved by masking of the beam. In the first case, the translation speed is crucial and must be synchronized with the pulse sequence of the laser so as to obtain good quality margins. In the second case, a mask is used of the on / off type (transparent / opaque). The mask may be put at a distance from the substrate, case in which image projection is used or may be put directly on the substrate (for example, by evaporation of a metal and etching of it). Morteover, the mask can be put a small distance from the substrate, in which case proximity method is used.

The advantages of the technique are many, the most important one being the ability to micro-pattern practically any kind of the materials. It is a dry technique and does not add impurities to the substrate. There are debris that fail on the substrate after evaporation of the material, but these debris are of the same nature as the base material and may be removed from the substrate by nitrogen blowing, for example, or by using a vacuumer during evaporation. It is a non-polutant and a cost effective technique. The only wastes are solid particles resulted from the condensation of the evaporated material.

There are not reported major disadvantages.

2.5 Laser assisted CVD and oxidation

The reactant species are in a vapour or gaseous state. The laser initiate the chemical reaction by which the desired compound is formed and deposited onto the substrate. The reaction can be in the whole deposition chamber or only at the substrate surface. In the first case the laser illuminates the entire chamber, in the second case illuminates only the surface. Ussualy, it results in removal (in this case it is a called a photo-etching process) or deposition of a material, a compositional change or a phase change on a sample surface. The reaction takes place as long as the laser beam is applied.

One of the most important features of LCVD is the freedom to make selective processing, i.e. the sample surface can be processed on selected areas but not on others without the need of lithographic mask steps. This freedom in manufacturing can also be extended to a three-dimensional deposition of freestanding structures. By adding complex movements, such as linear and rotational, more complex structures can be obtained, such as coils or other structures difficult to be realized by usual microprocessing techniques.

There are two ways in which the laser acts and influneces the chemical reaction. The first one is a thermal process (photo-thermal), in which the reaction is triggered by the local increase in temperature produced by the laser beam. The second one is a bond breaking or activation mechanism (depending on the substance used). It is called also a photolytic process. In this case, a non-thermal activation af a gas-phase takes place and this type of processing can be used to deposit a material at lower temperatures or to precipitate nano-particles heterogeneously from the gas phase.

For photo-thermal reactions IR lasers are used, while UV laser are used when the reaction is initiated by bond breaking. The last case is the most selective, for example isotopes of a selected type can be deposited according to the wish.

Usually, the resulting material structure in the case of UV lasers is a powder. For example, starting from ferrocene iron particles covered by a graphitic layer can be obtained, with a particle size can between few nm to tens of nm by depending on the experimental conditions.

The reaction can be a single photon process or a multi-photon one. In this case, the reaction takes place only in the regions with the highest intensity, since multi-photon process is dependent quadratically (in the case of two – photon absorption) on the intensity. If the multi – photon reaction is taking place at the surface of a material (for example when a gas is used to react under illumination with the substrate), then very small features can be obtained, in some cases under the diffraction limit.

A special case of optically activated chemical reaction is the photo-oxidation process. Oxidation is achieved by illuminating the surface of the substrate with a laser simultaneously with exposure to an oxygen atmosphere. The resulting oxide layer is very thin (few to tens of nm). The advantage is that the oxide layer is obtained at ambient temperature, so that the thermal stress is minimized accordingly.

As an example of oxidation in a humidity atmosphere, we present the case of chalcogenics [7].

The chalconenics is As_2Se_3. In an atmosphere containg humidity, there appears hydrolysis in wet medium undr UV illumination. The reaction are as follows:

$$As_2Se_3 \xrightarrow{h\nu} x * As + As_{2-x}Se_3$$

$$2 * As + \frac{3}{2} O_2 \rightarrow As_2O_3$$

$$As_2O_3 \xrightarrow{H_2O} H_3AsO_4 * \frac{1}{2} H_2O$$

In other words, the UV photon breaks the bond of As_2Se_3 and the resulting As react with oxygen forming As_2O_3. The oxide then hydrolise and forms orto-arseniate acid. The UV source had an intensity of 1.616 mW/cm^2 and the humidity was of 95 %.

Other examples are the formation of porous silicon by laser assisted porosification and, respectivelly, silicon photo-etching in acid solution.

The advantages of the technique are several, especially for the ultraviolet case, the main ones being: a) selectivity; b) ability to deposit isotopically pure substances; c) in the case of ultraviolet radiation, there is no thermal effect on the substrate, this giving rise to a lower mechanical stress in the layer. In the case when nanopowders are of interest, then the technique is also advantageous.

The disadvantages are due first to the fact that the reaction is limited only to the surface of the substrate. Secondly, the changing composition of the reaction chamber may give rise to parasitic laser absorption or scattering that can influence the reaction process.

2.6 Multi-photon absorption processes

This is a technique of rapid prototyping that uses two – photon absorption to polymerize a special resin. It is a technique useful in obtaining features with under – diffraction limit size. Special, highly non-linear, photoresins are used. 2D as well as 3D micro- and nano-structures are obtained. Th property of two – photon absorption arises 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 [9]. A schematic diagram of the process is depicted in figure 4.

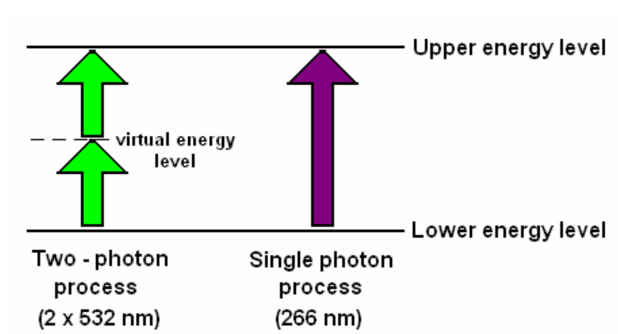

Figure 4 – Schematic diagram of the two-photon absorption process exemplified for green (532 nm) photons.

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 [10].

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 5.

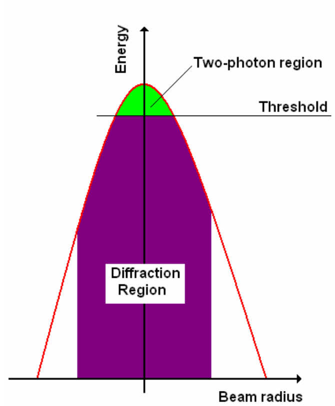

Figure 5 – The schematic representation of the way in which two-photon absorption circumvents diffraction limit.

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. The second type of two-photon absorption makes use of entangled photons, as described in [11]. 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 6.

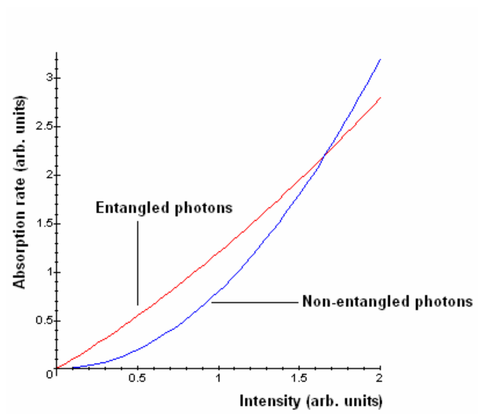

Figure 6 – The absorption rate dependence on intensity for the two-photon absorption process, for the case of entangled and, respectively, un-entangled photons.

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.

Among the advantages of the two-photon techniques we mention: a) usual lasers and optics are used; b) the minimum size is not diffraction – limited; c) can be used for 2D – photolitography as well as for 3D – photolitography (in MEMS technology).

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.

2.7 Other technological applications

There are several other applications of lasers in the technology of MEMS. Sometimes, these are developed for particular materials or structures. However, there is an important application, that of laser lithography. This process allows the patterning of the photoresist according to a specified mask, so as to obtain the desired features on the substrate. More on lithography can be found in [12] and [13]. We will not insist here on the subject, since it is treated in more detail in another paper in this Proceedings [14].

Some other applications are using the gradient forces exerted by the light on different types of nanoparticles from particle-in-solvent suspension, so as to obtain laser-guidance deposition of nanoparticles [15]. The laser beam confines axially the partciles and propels them into a hollow optical fiber towards the substrate. A laser beam axially confines and propels the particles inside a hollow optical fiber towards a substrate. Confining is provided by the gradient forces arising from light refraction or electrical forces on polarizable particles.

3. NON – TECHNOLOGICAL APPLICATIONS

In this case, lasers are used not at the processing of the substrate for making different types of MEMS, but at the excitation and characterization of these structures.

As regards characterization, there are several techniques: beam deflection, laser interferometry, laser optical heterodyne, laser Doppler vibrometry.

Beam deflection is used when the MEMS has a movement of rotation when a certain stimulus is applied on it. By measuring the angular deflection it can be determined the angle of rotation and hence the MEMS response to the stimulus can be estimated. One important application of this technique is the Atomic Force microscopy, where the cantilever that senses the surface topography is deflected or torsioned according to what it encounters on the surface. The deflection is measured by a laser beam incident on top of it that is reflected to a photodetector array.

Laser interferometry is used mainly for determining translation movement with sub-nm resolution. This is useful in the case of micro-bridges or micro-membranes, when the main type of movement is the translation of the MEMS. Again, in this way is estimated the way in which the MEMS responds to a stimulus. It can be used for studying steady state response as well as dynamic response of the MEMS.

Laser optical heterodyne, as well as laser Doppler vibrometry are used for measuring the dynamic response of the MEMS, in order to determine the amplitude of motion, the oscillating frequency, the phase lag between stimulus and MEMS response, the instantaneous speed. Again, translation movement is considered for these applications.

As regards MEMS excitation, the moment based light pressure is the factor used for exciting the structure. For example, in the paper of [16], light pressure of an ultra-short light pulse is used to excite the mechanical vibration of a circular micro-membrane. The light pulse is short enough in comparison with the response time (and eigenfrequencies) of the micro-membrane, so that it can be considered an ideal Dirac pulse. Such a pulse is applied and the vibration of the micro-membrane is read optically or electrically, depending on the experimenter wish. In this way almost all of the eigenmodes of the micro-membrane are excited.

Other methods of exciting mechanically the MEMS is to use gradient force light pressure due to non-uniform light intensity distribution in a beam [17].

The advantages of using light beams for exciting mechanically the MEMS are: a) is a non – contact technique; b) it is simple and does not require electrodes or other elements that may complicate technology; c) short pulses can be assimilated to ideal Dirac pulses; d) a great number of excitation modes are available; e) the light intensity can be controlled precisellly, so as to obtain the required effect.

ACKNOWLEDGEMENTS

The work was done partly under the CEEX contract no. 44 / 2005, CEEX contract no. 15 / 2005 and MATNANTECH no. 20 / 2001 financed by the Romanian Ministry for Education and Research.

REFERENCES

1. *Pulsed Laser Deposition of Thin Films*, edited by Douglas B. Chrisey and Graham K. Hubler, John Wiley & Sons, (1994).
2. Chin, R.K., Beuth, J.L. and Amon, C.H. (1995) "Control of Residual Stresses in Shape Deposition Manufacturing," Proceedings Solid Freeform Fabrication Symposium, The University of Texas at Austin, pp. 221–228.
3. Merz, R., Prinz, F.B., Ramaswami, K., Terk, M., and Weiss, L.E. (1994) "Shape Deposition
4. Manufacturing," Proceedings Solid Freeform Fabrication Symposium, The University of Texas at Austin, pp. 1–8.
5. Senthilnathan Mohanan - Laser assisted film deposition , Advanced Materials, 02-02-2004, http://www.uni-ulm.de/ilm/AdvancedMaterials/Presentation/MahananLaserassistedfilmdeposition.pdf
6. W. Han, R. J. Pryputniewicz - *Mechanical Characterizations of Laser Microwelds for MEMS Packaging,* Mat. Res. Soc. Symp. Proc. Vol. 782, p. A5.82.1 – A.5.82.6, (2004).
7. W.-S. CHANG, S.-J. NA - *A Study on Heat Source Equations for the Prediction of Weld Shape and Thermal Deformation in Laser Microwelding*, Metallurgical and Materials Transactions B, VOLUME 33B, p. 757 – 762, (2002).
8. M. Popescu, A. Andrieş, V. Ciumaş, M. Iovu, S. Şutov, D. Țiuleanu – The Physics of Chalcogenide Glasses, Editura Ştiințificã Bucureşti & I. E. P. Ştiința Chişinãu, (1996) (in Romanian).
9. S. J. Berkes, S. W. Ing, W. J. Hillegas – J. Appl. Phys. Vol. 42, p.4908, (1971).
10. G. Nemeş – *Introduction to Nonlinear Optics*, Editura Academiei R.S.R. (1972) (in Romanian).
11. S. Jeon, V. Malyarchuk, J. A. Rogers – "*Fabricating Three Dimensional Nanostructures Using Two Photon Lithography in a Single Exposure Step*", Optics Express vol. 14, no. 6, p. 2300 – 2308 (2006).
12. M. C. Teich, B. E. A. Saleh, A. V. Sergienko, J. Fourkas – "*Three Dimensional Fabrication Using Entangled-Photon Lithography*", US Patent US 2002/0093632 A1, (2002).
13. R. M. Bârsan – *Physics and Technology of Large Scale Integrated MOS Circuits*, Editura Academiei R.S.R. (1989) (in Romanian).
14. D. Bratton, D. Yang, J. Dai, C. K. Ober – "*Recent Progress in High Resolution Lithography"*, Polym. Adv. Technol. Vol. 17, p. 94 – 103, (2006).
15. G. Moagăr-Poladian – *Sub – Wavelength Resolution Laser Lithography in the Field of MEMS*, Proceedings of the First International Conference on Industrial Application of Lasers, p. xx – yy, (2007).
16. Juntao Xu, Changgong Zhou, Sheila Grant, Edward Nadgorny, Jaroslaw Drelich - *Laser Guidance Deposition Technique for Patterning Microstructures Made of Nanoparticles with Varying Surface Functionality*, Mat. Res. Soc. Symp. Proc. Vol. 728, p. S 7.6.1 – S 7.6.6, (2002).
17. F. Shen, J. Xu, A. Wang - *Measurement of the Frequency Response of a Diaphragm-Based Pressure Sensor by Use of a Pulsed Excimer Laser*, Optics Letters, vol. 30 no. 15, p. 1935 (2005).
18. G. Moagăr-Poladian - *On the Light Pressure Induced in a Medium by the Non-Uniform Light Intensity Distribution*, accepted for publication in Journal of Optics: Pure and Applied.