LASER FABRICATION OF THREE-DIMENSIONAL MICROSTRUCTURES, CAVITIES AND COLUMNS

Bing SHEN , Ricardo IZQUIERDO, and Michel MEUNIER

Groupe des Couches Minces and Départment de Génie Physique
École Polytechnique de Montréal, P.O. Box 6079, Station "A", Montréal
Québec, Canada, H3C 3A7

ABSTRACT

A laser processing system is developed for laser microfabrication and micromachining of three-dimensional (3D) microstructures. We show the feasibility of laser induced chlorine etching of silicon under SiO_2 and Si_3N_4 membranes for the formation of underlying cavities and tunnels. Deposition of tungsten and silicon columns on SiO_xN_y/Si substrates is also demonstrated.

1. INTRODUCTION

Laser microfabrication offers the possibility of making unique structures which are difficult or sometimes impossible to be made by conventional technology[1,2,3]. The emerging field of microelectromechanical systems (MEMS) encourages the development of laser micromachining which is becoming an attractive option in the fabrication of 3D micromechanical structures[4]. Laser assisted chemical vapor deposition (LCVD)[5,6] of 3D objects and laser induced chemical gas etching of 3D microstructures[7-11] intend to avoid the conventional lithography and sacrificial layers in the fabrication of micromechanical structures. The mechanism of laser induced chlorine etching of silicon has been studied by many groups[12-18]. LCVD of tungsten and Si lines on different materials has also been investigated[19-25]. In this paper, we present a 3D microstructure etched in silicon by Ar^+ laser, as well as cavities and tunnels under SiO_2 and Si_3N_4 membranes. Furthermore, we show that stationary Ar^+ laser irradiation instead of writing can realize the deposition of tungsten and silicon columns on SiO_xN_y/Si substrates.

2. LASER PROCESSING SYSTEM

The system shown schematically in Fig.1 is composed of a continuous-wave (cw) Ar^+ laser operated at 488 nm, an optical system, x-y translation stages, and two gas distribution systems. The optical system which consists of mirrors and a microscope with a long-working-distance objective, delivers the laser beam into a stainless steel reaction cell where the samples are loaded. Two objectives with numerical apertures (NA) of 0.15 or 0.31 are used depending on the applications. The cell is mounted on computer-controlled x-y stages which have a spatial resolution of 0.1 μm and a maximum velocity of 100 μm/s. The z-direction movement is adjusted manually. Two isolated gas distribution systems and reaction cells have been set up, one for chlorine etching and the other for tungsten and silicon deposition. High-purity Cl_2 (99.99%) and Ar gas are used for the etching, while for the deposition, the gases are WF_6, H_2, SiH_4 and Ar.

3. LASER INDUCED CHLORINE ETCHING OF 3D MICROSTRUCTURES

Silicon can be etched by chlorine in a microreaction controlled by the laser. The localized Ar^+ laser beam (488 nm) heats the silicon surface and raises the temperature to the melting point to induce the formation of volatile products of silicon chlorides through the chemical reaction between the liquified silicon and chlorine. When high laser powers are used, the pyrolytic regime is predominant over photolysis[13]. The etching process can be controlled by the laser power, the scanning speed, the beam spot size, and the Cl_2 pressure. Since laser focus position is adjustable in z-direction, 3D objects can be processed[7,8,9].

To be published in "Laser-Assisted Fabrication of Thin Films and Microstructures", Editor: Ian W. Boyd, SPIE Proc. Vol. 2045.

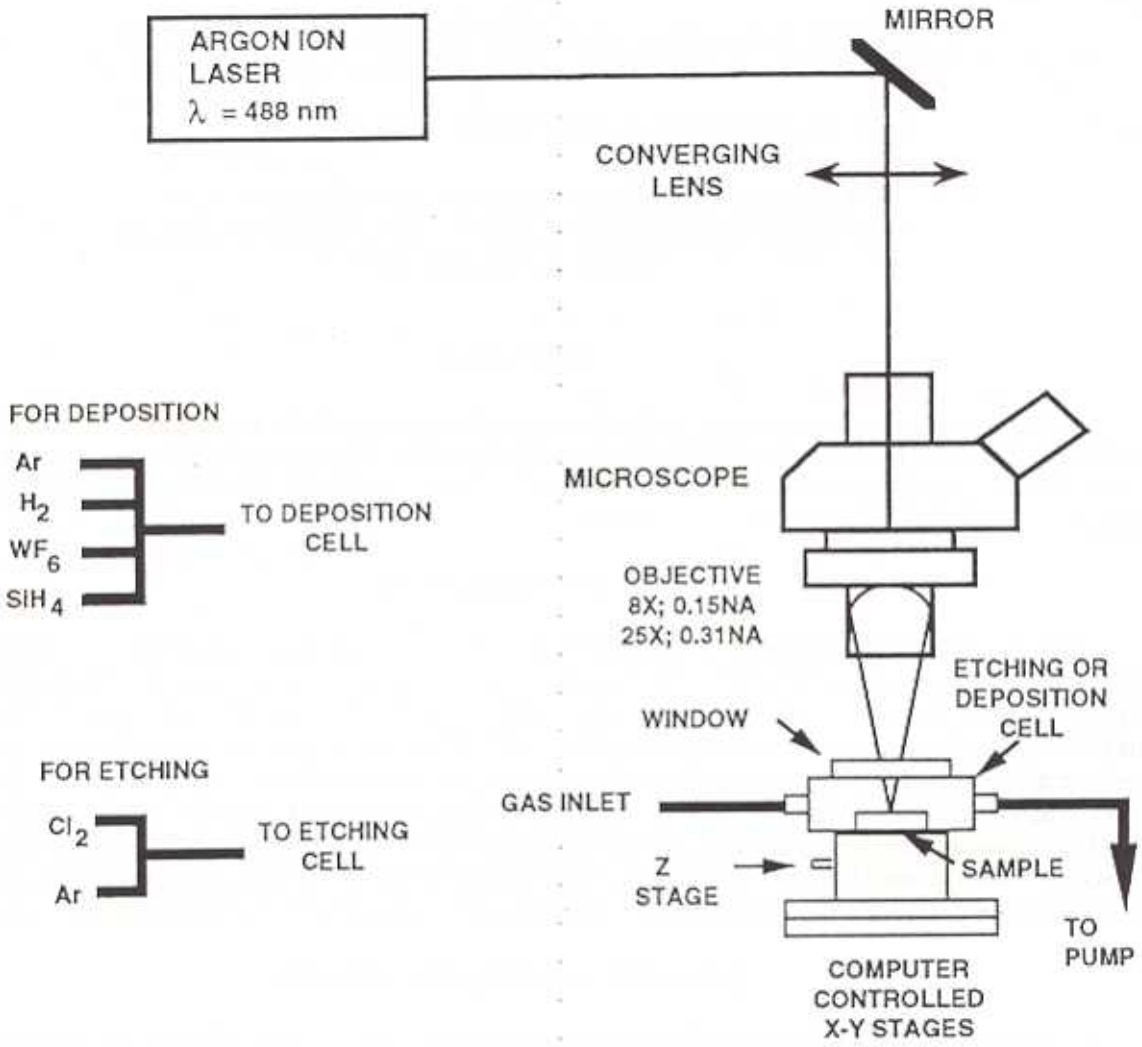


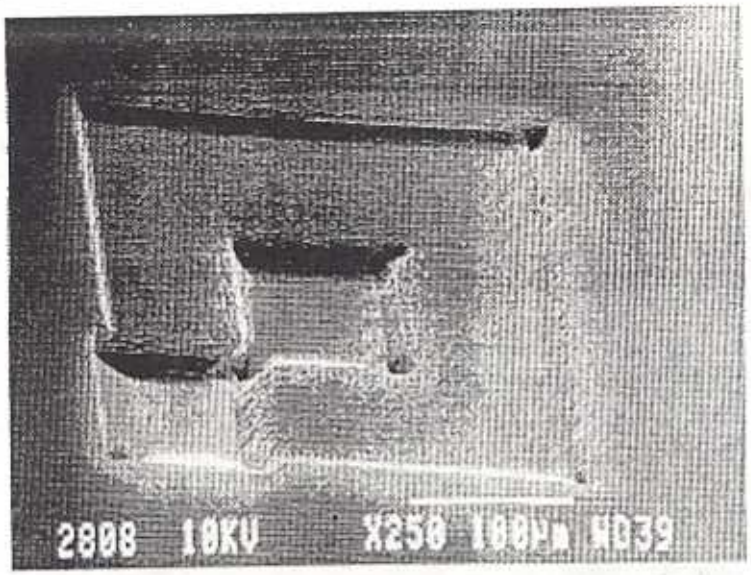
Fig.1 A schematic diagram of the laser processing system for laser 3D microfabrication and micromachining.

3.1 Fabrication of 3D microstructures with stepped patterns

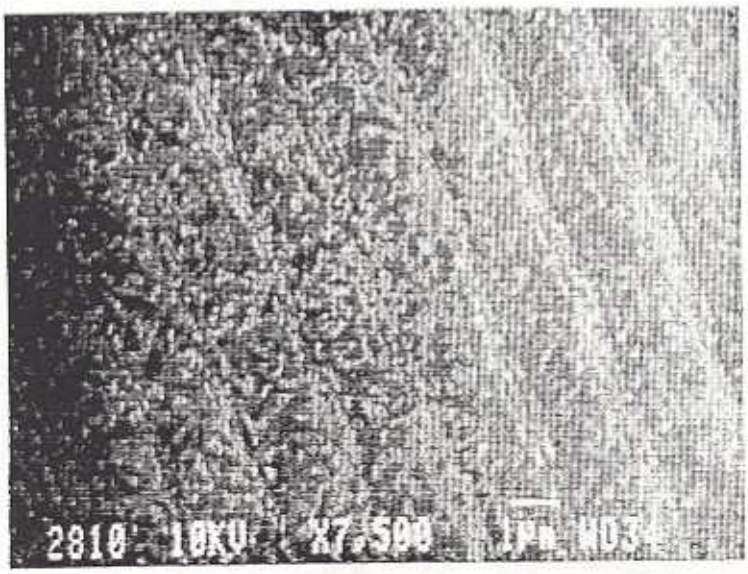
Prior to experiments, undoped Si (100) samples were degreased in hot trichloroethane (TCE), acetone, and propanol, rinsed in deionized (DI) water, then immersed in a (1:10) solution of HF-H_2O for 10 seconds to remove the native oxide. After being loaded with the cleaned samples, the reaction cell was evacuated by a mechanical pump to a base pressure of about 10^{-3} Torr and purged with an argon gas flow of 150 standard cm^3/min (sccm) for one hour. If needed, the cell can also be heated in order to reduce humidity. The laser induced etching of silicon experiments were carried out in a static chlorine ambient.

Figure 2(a) shows a 3D microstructure (300x300 μm^2) with stepped patterns (100x100 μm^2 for each one) etched at a total Cl_2 pressure of 300 Torr, with an incident laser power of 0.9 W and a beam spot size of 5 μm. The x-y translation stages were moved at 100 μm/s in the specific pattern controlled by the computer. The etched plane was written line by line, and the interval between each line was 2 μm. To adjust the focus position, the objective was lowered in 3 μm increments after completing each plane. The base square was scanned 4 times leading to a 12-μm-deep structure. Six scannings resulted in the 18-μm-deep stepped patterns (two inner squares). The measured removal rate was 600 μm^3/s which is much lower than 2.0×10^4 μm^3/s reported by other researchers[9], probably due to the much lower laser power density and lower chlorine pressure. The SEM micrograph also shows deep holes at all corners of the structure. Since the scanning decelerates when the laser beam is

approaching the corners, deep holes could be formed due to a longer laser dwell time. A computer-controlled shutter could be used to overcome this imperfection.



(a)



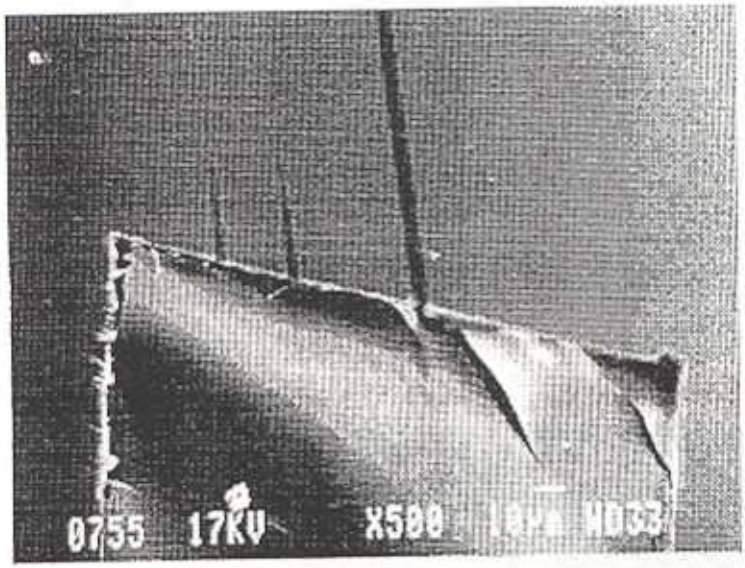
(b)

Fig. 2 Scanning electron micrographs (SEM) of a 3D microstructure with two stepped patterns etched in silicon at a Cl_2 pressure of 300 Torr. (a) and (b) show the whole structure and the texture of etched surface respectively.

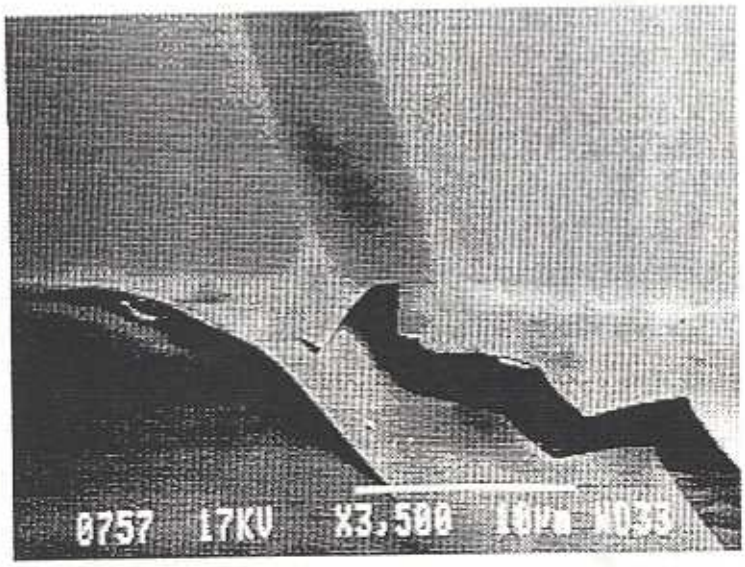
The texture of the etched surface is shown in Fig.2(b). The plane was scanned in the x direction and the y direction alternately in order to avoid possible deep grooves caused by unidirectional scanning. It can be observed that the surface is etched line by line, and a roughness of 1 μm is achieved. Even though high resolution requires a small beam spot size and a low Cl_2 pressure, high volume etching rate and smooth surface need relatively larger spot sizes and higher Cl_2 pressures[8,9]. In our experiments, the compromise was made to choose intermediate laser power (0.9 w), spot size (5 μm) and Cl_2 pressure (300 Torr) to obtain smooth surfaces. The optimum condition will be determined by performing more experiments.

3.2 Etching of silicon under oxide and nitride layers

A unique property of chlorine etching is its high Si/SiO_2 material selectivity which can be as high as 1000:1[7,8]. This can lead to etching of Si without affecting an overlying SiO_2 layer. Initially, the focused laser beam opened a hole in the oxide film covering the silicon. Starting from the hole, the laser beam scanned the sample while optically penetrating the oxide layer without damaging it. In the meanwhile, the chemical reaction between chlorine, which was diffusing through the hole, and the Si atoms under the oxide layer was induced by the scanning laser. This mechanism enables us to make very interesting microstructures such as a single cavity connecting with tunnels under a SiO_2 membrane. This type of microstructures could eventually be applied to the fabrication of micromechanical devices such as pressure sensors and microfluidic structures.



(a)



(b)

Fig. 3. SEM micrographs of a cavity (partially shown) with tunnels etched in Si under a 0.3-μm-thick SiO_2 membrane. (a) Three tunnels connecting to the cavity. (b) Details of the joint of an underlying tunnel and the cavity. Cracks appear around the edges and the corners of the cavity.

Figure 3(a) and 3(b) show a cavity with tunnels in Si covered by a 0.3-μm-thick SiO_2 layer. The square pattern of 200x200 μm^2 was scanned at a laser power of 1 W and a chlorine pressure of 200 Torr. The scannings with 2 μm intervals were performed at 100 μm/s. The short tunnels were written at 100 μm/s while the longer one was made at 10 μm/s. Scanning speed plays an important role in the process. It can not be very high because the inlet can not supply sufficient etchant gas flow as fast as the laser scans to sustain the reaction. This explains why those short tunnels shown in Fig.3(a) are interrupted even if the laser scanned a longer distance. On the other hand, scanning speed can not be very low either, since the laser dwell time would be long enough to cause ablation of the oxide layer. Scanning speeds in the range of 10 μm/s to 100 μm/s have been found to be satisfactory depending on the geometry of the etched patterns. From Fig.3(a) and 3(b), we can also observe the cracks in the membrane around the edges and the corners of the cavity. They are probably due to the stress relaxation during or after the processing. Further investigation will be done to understand the cracking process more precisely and comprehensively in order to obtain a higher quality in the fabrication of microstructures.

Underlying cavities were also realized on Si_3N_4/Si samples. Figure 4 shows a square cavity of 50x50 μm^2 which was etched under a 0.7-μm-thick Si_3N_4 membrane with a laser power of 0.9 W and a chlorine pressure of 100 Torr. The scanning was performed at 100 μm/s with 1 μm interval between lines. In this case, no crack occurs in the membrane, and only two holes appear at an edge and at a corner of the cavity.

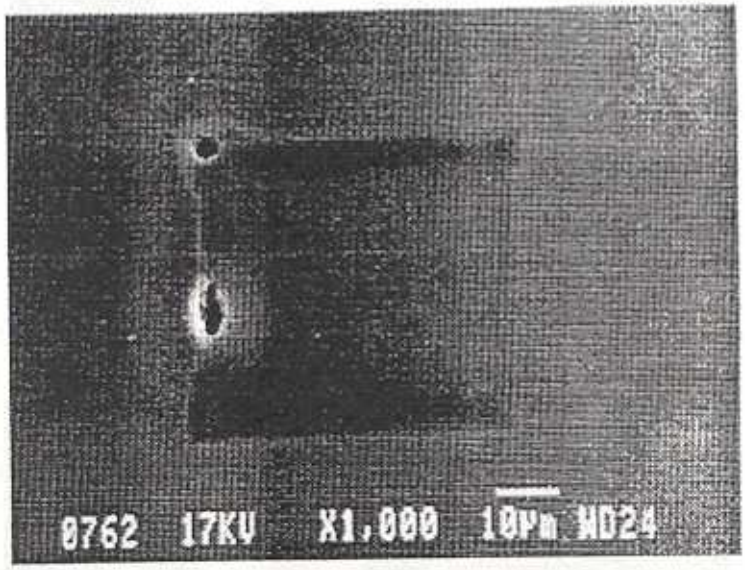


Fig.4. A SEM micrograph of a cavity etched in Si under a 0.7-μm-thick Si_3N_4 membrane.

4. LASER DEPOSITION OF TUNGSTEN AND SILICON COLUMNS

Tungsten and silicon were deposited using the same laser processing system as for Si etching but in a different reaction cell which was equipped with gas lines for Ar, H_2, WF_6 and SiH_4. Deposition can be made either in an isolated reaction cell or by flowing the gases into the cell at determined flow ratios. WF_6 and H_2 were filled to the operation pressures for W deposition, while SiH_4 was used for Si deposition. Substrates were 0.6-μm-thick plasma CVD grown silicon oxynitride (SiO_xN_y) deposited on c-Si with a composition, measured by X-ray photoelectron spectroscopy (XPS), of 30 at.% Si, 65 at.% O and 5 at.% N. Before the deposition, the samples were cleaned in hot TCE, acetone, and propanol and rinsed in deionized water. They were then heated to 140°C for at least 30 minutes to remove water from the surfaces. After being introduced into the reaction cell, the samples were heated again to 80°C with a 150 sccm flow of Ar for 30 minutes.

When moving the sample under laser irradiation with the appropriate gas mixture, W and Si lines were deposited[21-25]. However, when the laser spot was kept stationary for a period of time, columns were grown. The shape of those columns depends on various parameters: irradiation conditions (laser power and spot size), gas conditions (pressure, gas composition),

and the deposition time. Figure 5 shows a tungsten column deposited in 10 seconds in a flowing gas mixture of 2 sccm WF_6, 10 sccm H_2, and 20 sccm Ar, at a total pressure of 30 Torr. The laser power was 0.4 W, and the beam was focused with the 0.15 NA objective. The W column with a sharp tip has a height of 45 μm and a diameter of 25 μm approximately. Silicon columns can also be deposited. Figure 6 shows such a column deposited in a static gas mixture with a SiH_4 pressure of 400 Torr, a laser power of 0.5 W, a deposition time of 5 s and a 0.15 NA objective. Various 3-D structures with different shapes can be obtained by moving the sample in x, y and z directions during the deposition[5,6,26].

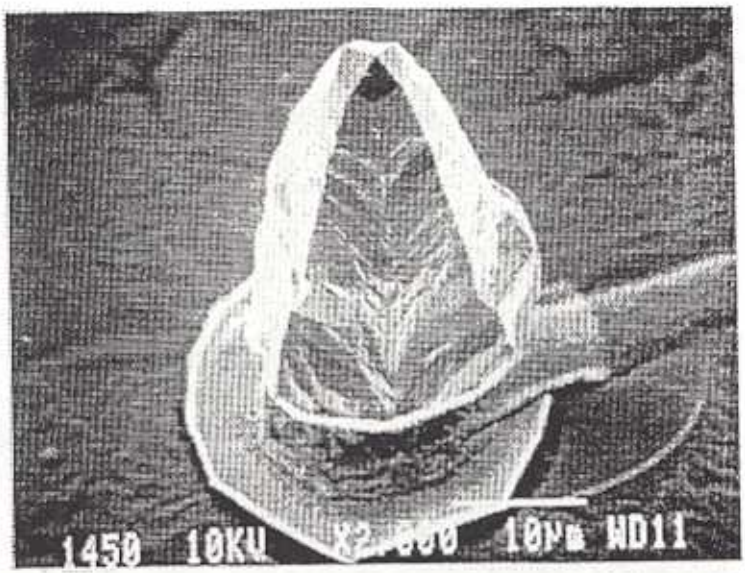


Fig. 5. A tungsten column deposited with a flowing gas mixture of 2 sccm WF_6, 10 sccm H_2, and 20 sccm Ar, at a total pressure of 30 Torr, a laser power of 0.4 W, a 0.15 NA objective, and a deposition time of 10 s.

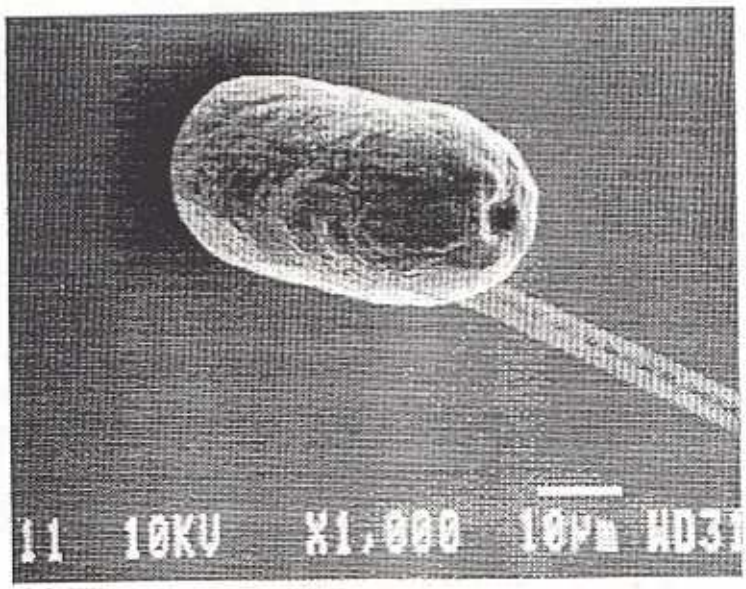


Fig.6. A silicon column deposited in a static gas mixture with a SiH_4 pressure of 400 Torr, a laser power of 0.5 W, a deposition time of 5 s and a 0.15 NA objective.

5. CONCLUSIONS

Laser processing has been used to fabricate 3D microstructures, and to deposit tungsten and silicon columns. Based on the mechanism of laser induced Cl_2 etching of silicon, a 3D microstructure of 300x300 μm^2 was etched in a silicon substrate under a Cl_2 pressure of 300 Torr using an Ar^+ laser of 0.9 W at 100 μm/s scanning speed. The cavities and tunnels covered by SiO_2 or Si_3N_4 membranes were also made by laser etching due to the high material selectivity of Si/SiO_2 and Si/Si_3N_4. It is found that laser scanning speed and Cl_2 pressure must be chosen carefully to obtain good quality in the fabrication. Column depositions on SiO_xN_y substrates were performed using stationary laser irradiation. A sharply tipped tungsten column with a height of 45 μm and a diameter of 25 μm was achieved. Silicon columns were also deposited. More experiments are underway to improve the quality of the microstructures. Investigation on the integration of LCVD with laser induced chemical etching is being pursued to explore potential applications in the field of MEMS.

6. ACKNOWLEDGMENTS

We thank Ms. Marie-Hélène Bernier for SEM analysis, and technical assistance from Mr. Jean-Paul Lévesque is also acknowledged. This project is funded by National Sciences and Engineering Research Council of Canada (NSERC).

7. REFERENCES

1. D.J. Ehrlich and J.Y. Tsao, *Chapter 3: Laser direct writing for VLSI,* VLSI Electronics: Microstructure Science, Vol.7, pp. 129-164, Academic Press, Boston, 1983.
2. See, for example, Laser Microfabrication: Thin Film Process and Lithography, edited by D.J. Ehrlich and J.Y. Tsao, Academic Press, Boston, 1989.
3. See, for example, Laser Chemical Processing for Microelectronics, edited by K.G. Ibbs and R.M. Osgood, Cambridge University Press, 1989.
4. E. Wiener-Avnear, "Laser cut microscopic paths with major potential," Laser focus world, Vol.29, No.7, pp. 75-80, 1993.
5. H. Westberg, M. Boman, S. Johansson, and J.A. Schweitz, "Truly tree dimensional structures microfabricated by laser chemical processing," Transducers 91: IEEE international conference on solid-state sensors and actuators, pp.516-519, 1991.
6. H. Westberg and M. Boman, "Free-standing silicon microstructures fabricated by laser chemical processing," J, Appl. Phys. 73(11), pp. 7864-7871, 1993.
7. T.M. Bloomstein and D.J. Ehrlich, "Laser deposition and etching of three-dimensional microstructures," Transducers 91: IEEE international conference on solid-state sensors and actuators, pp.507-511, 1991.
8. T.M. Bloomstein and D.J. Ehrlich, "Laser-chemical three-dimensional writing for microelectromechanics and application to standard-cell microfluidics," J. Vac. Sci. Technol. B 10(6), pp. 2671-2674, 1992.
9. T.M. Bloomstein and D.J. Ehrlich, "Stereo laser micromachining of silicon," Appl. Phys. lett. 61(6), pp. 708-710, 1992.
10. M. Alavi, S. Buttgenbach, A. Schumacher, and H.-J. Wagner, "Laser machining of silicon for fabrication of new microstructures," Transducers 91: IEEE international conference on solid-state sensors and actuators, pp. 512-515, 1991.
11. M. Alavi, S. Buttgenbach, A. Schumacher, and H.-J. Wagner, "Fabrication of microchannels by laser machining and anisotropic etching of silicon," Sensors and actuators A, 32, pp. 299-302, 1992.
12. D.J. Ehrlich, R.M. Osgood, Jr., and T.F. Deutsch, "Laser chemical technique for rapid direct writing of surface relief in silicon," Appl. Phys. Lett. 38(12), pp. 1018-1020, 1981.
13. D.J. Ehrlich and J.Y. Tsao, "A review of laser-microchemical processing," J. Vac. Sci. Technol. B1(4), pp. 969-984, 1983.
14. G.V. Treyz, R. Beach, and R.M. Osgood, Jr., "Rapid direct writing of high-aspect ratio trenches in silicon: Process physics," J. Vac. Sci. Technol. B6(1), pp.37-44, 1988.
15. G.V. Treyz, R. Scarmozzino, H.H. Burke, and R. M. Osgood, Jr., "Laser-induced atomic chlorine etching of silicon," Mat. Res. Soc. Symp. Proc. Vol.129, pp. 291-297, 1989.
16. T.J. Chuang, "Laser-enhanced chemical etching of solid surfaces," IBM J. Res. Develop. Vol.26, No. 2, pp. 145-150, 1982.
17. T. Baller, D.J. Oostra, A.E. de Vries and G.N.A. van Veen, "Laser-induced etching of silicon with chlorine," J. Appl. Phys. 60(7), pp. 2321-2326, 1986.

18. C. Arnone and G.B. Scelsi, "Anisotropic laser Etching of oxidized (100) silicon," Appl. Phys. Lett. 54(3), pp. 225-227, 1989.
19. A. Lecours, R. Izquierdo, M. Tabbal, M. Meunier, and A. Yelon, "Laser induced deposition of Tungsten on GaAs from WF_6," J. Vac. Sci. Technol. B11(1), pp. 51-54, 1993.
20. H.H. Gilgen, T.Cacouris, P.S. Shaw, R.R. Krchnavek, and R.M. Osgood, "Direct writing of metal conductors with near-uv light," Appl. Phys. B42, pp. 55-66,1987.
21. M. Meunier, R. Izquierdo, P. Desjardins, M. Tabbal, A. Lecours and A. Yelon, "Laser direct writing of tungsten from WF_6," Thin Solid Films, 218, pp. 137-143, 1992.
22. R. Izquierdo, A. Lecours and M. Meunier, "Laser CVD of tungsten on silicon oxynitride," Mat. Res. Soc. Symp. Proc. Vol.236, pp.111-116, 1992.
23. J.Y. Lin and S.D. Allen, "Laser chemical vapor deposition of W on Si and SiO_2/Si," Mat. Res. Soc. Symp. Proc. Vol.158, 1990.
24. D. Bauerle, P. Irsigler, G. Leyendecker, H. Noll and D. Wagner, "Ar^+ laser induced chemical vapor deposition of Si from SiH_4," Appl. Phys. Lett. 40(9), 1982.
25. D.J. Ehrlich, R.M. Osgood, Jr., and T.F. Deutsch, "Laser microreaction for deposition of doped silicon films," Appl. Phys. Lett. 39(12), 1981.
26. O. Lehmann and M. Stuke, " Generation of three-dimensional free-standing metal micro-objects by laser chemical processing," Appl. Phys. A53, pp. 343-345, 1991.