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Fabrication of Silicon Surface Grating Structures by Maskless Laser Beam Lithography

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Abstract: I report on the mask-less fabrication of grating structures on silicon surface with pulsed laser beam exposure. The mask-less fabrication of grating structures has been carried out with two-beam holographic exposure of fourth harmonic wavelength (266 nm) of Nd: YAG laser. I have investigated the grating surface by Fourier method to understand the effect of number of laser pulses on patterned surface. The root mean square (RMS) roughness, power spectral density (PSD) and cross-sectional analysis have been carried out to understand the effect of increasing number of shots. It has been observed that with increasing the number of shots, valley depth of grating pattern increases which leads to many spatial frequency components other than the fundamental frequency of the structure due to increase in extreme amount of interfacial roughness. The influence of number of laser shots on the periodicity of grating structures is reported.
Keywords: Pulsed Laser, Silicon, Grating structure, Periodicity, Power Spectral Density

I. INTRODUCTION

Surface and subsurface gratings are very important for many applications such as wavelength filtering, thin film displays and variety of other devices of commercial, scientific interest in storage and sensing [1]. Typical techniques to fabricate the grating structures are electron lithography and photolithography [2-4]. To fabricate the grating structures, electron lithography is slow and very expensive other than the difficulty in obtaining accurate pattern. On the other side, photolithography is a multi-step process, which requires preparation of mask is usually a tedious task. Additionally, deposition of radiation sensitive layer (photo resist) upon the substrate and etching, also expensive and time consuming. In recent years, development of high pulse-energy and high peak power lasers, particularly in the UV range, has led to resurgence of interest in direct writing of surface or subsurface gratings on variety of materials and development of very attractive alternative technology known as laser interference lithography or holography lithography. It is a preferred method to fabricate the periodic structures, as it is a relatively simple and mask-less method, utilizing the interference of two or more coherent beams, and ideal for low cost and large area exposure [5- 8]. It has advantage over other techniques, provides flexibility in grating period and depth by changing the incident angles and irradiation time. Thus the interference method using laser beam holography has great potential for fabricating gratings with fine periods. Fayou Yu and co-workers [1] and M Csete and co-workers have [6] reported the formation of grating structures by maskless two-laser beam interference patterns exposure on polymer. Daniel and coworkers [9] have fabricated grating structure on PVD gold coated silicon surface. Fabrication of grating structures on silicon surface has also been reported by Cheng-Yen Chen and coworkers [10]. They have studied the laser fluence dependence grating formation and found that at low fluence levels, grating formation was mainly caused by oxidation of silicon, however, at high laser fluence levels grating could be formed with thermal ablation. To the best of my knowledge there is no reported work on the effect of number of laser pulses on the grating periodicity in these experimental conditions. In the this paper, a study on the influence of number of laser pulses on the periodicity of grating fabricated by two-beam holographic exposure of fourth harmonic wavelength of Nd: YAG laser is presented.

II. EXPERIMENTAL

Boron doped p-type (100) oriented Si wafer has been used as the substrate. The substrate has resistivity ~ 1-10 Ω-cm, doping concentration ~ 2.5×10^{15} cm^{-3} and thickness ~ 400 μm. A Q-switched Nd: YAG laser, which works at different wavelengths (1060, 532 and 266 nm) with a pulse repetition rate (PRR) of 10 Hz and a pulse width of 5 ns, has been used for pattering the surface. The fourth harmonic wavelength of the laser beam having p-polarization in which electric vector lie in the plane of incidence, were split in two equal parts, which are then guided by the mirror to superimpose on the sample surface under an energy density of 123 mJ/cm^2 and angle ~ 6.8^0 to form an interference pattern in air. The surface morphologies of the patterned surface have been investigated using scanning electron microscope (SEM).

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III. RESULTS AND DISCUSSION

Fourth harmonic wavelength of Nd: YAG laser beam is used to make the good quality grating structures on silicon surface. Figure 1 shows SEM images of grating structures fabricated with two beam interference pattern exposed on Si (100) in air at energy density 123 mJ/cm^2 for varying number of laser shots from 600 to 1500 at a fixed incident angle ~ 6.8^0. The insets show the 2D Fourier transform of the micrographs. The Fast Fourier Transform (FFT) reveals that grating structures fabricated with UV laser beam have fewer lower frequency components (magnitude of these spatial frequencies are very small compare to fundamental spatial frequency) other than the fundamental frequency of the structures. We can see bright dots on a dark background in the insets represent frequency component of the grating structures. The dot represents single frequency and bright backgrounds arise in between the dots shows the frequencies correspond to roughness frequencies in the structures. Line scan profiles of the grating structures fabricated with 600, 900 and 1500 laser shots are shown in Figure 2, which clearly shows that the grating structures fabricated with UV laser beam are of regular, uniform and of well controlled periodicity. With increasing number of shots from 600 to 1500, the valley depth in grating structure also increases from 30 nm to 70 nm, accompanied with increasing interfacial roughness.

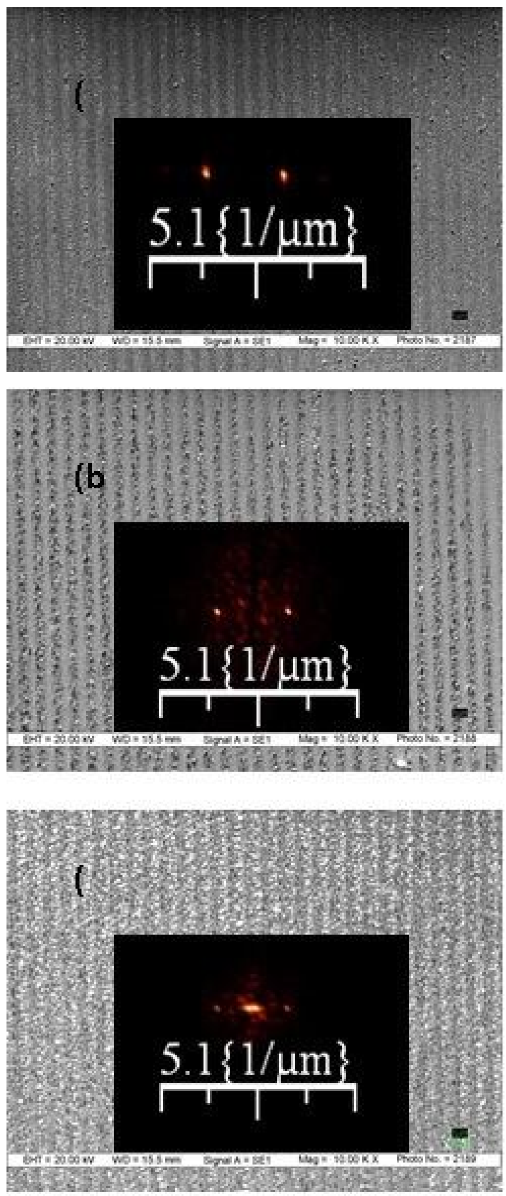

Fig. 1: SEM images (magnification 10.00 kX) of the surface gratings fabricated with two beam interference pattern exposed on Si (100) in air at energy density 123 mJ/cm^2 of 266 nm laser beam with number of laser pulses (a) 600, (b) 900 and (c) 1500. The insets show the 2D Fourier transform of the micrographs.

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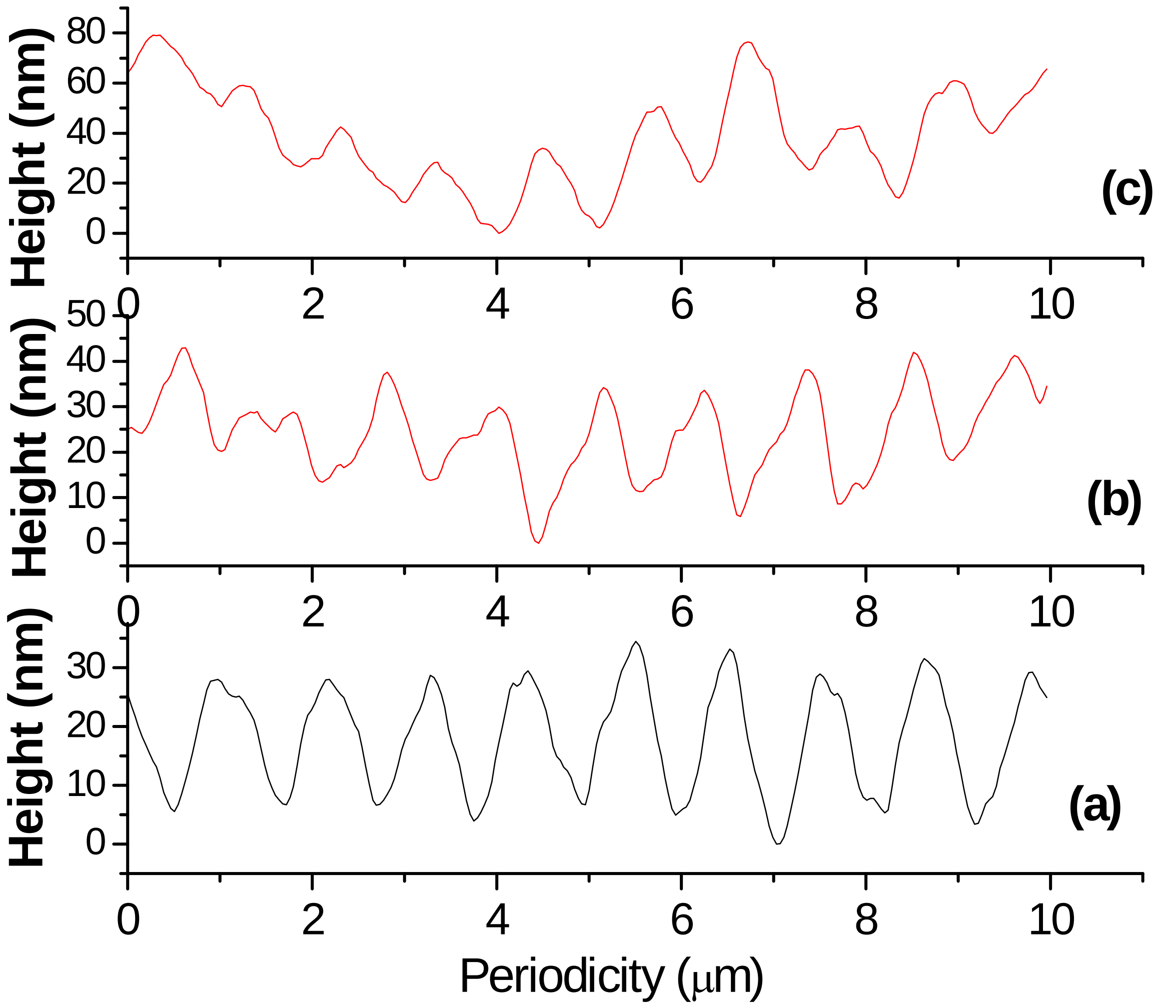

Fig. 2: Line scan profile of the grating structures fabricated with number of pulses (a) 600, (b) 900 and (c) 1500.

The PSD plots in Figure 3 of grating structures show that the frequency components other than the fundamental frequency have very low magnitudes. Table 1 lists the estimated root mean square roughness, fundamental periodicity and magnitude of other lower frequencies from the PSD analysis. For the structure fabricated with 600, 900 and 1500 laser pulses, the low-frequency component are 19.1 dB, 8.5 dB and 2.3 dB weaker than the fundamental frequency component, respectively. The PSD data clearly indicate the presence of other periodicities alongside the fundamental periodicity. The micro-roughness in the structures and their magnitudes rapidly increase with increasing the number of laser pulses, causing surface degradation and thus explain the appearance of other frequency components. The fundamental spatial frequency 0.92 μm^{-1} is estimated from the PSD plot of grating structures fabricated with number of laser pulses of 600 and 900 which corresponds to the periodicity of 1106 nm, and the fundamental spatial frequency 0.90 μm^{-1} is estimated for 1500 laser pulses which correspond to the periodicity 1086 nm. The decrease in periodicity with increasing number of laser pulses is not clear but it is similar to the observed reduced periodicity in laser induced periodic structures in glass and InP with increasing the number of laser pulses [11-13]. Lowering of periodicity from 1106 nm to 1086 nm with number of laser pulses points toward possible increase in refractive index due to nonlinear processes which may reduce the plasma generation or free electron density upon further laser pulses irradiation.

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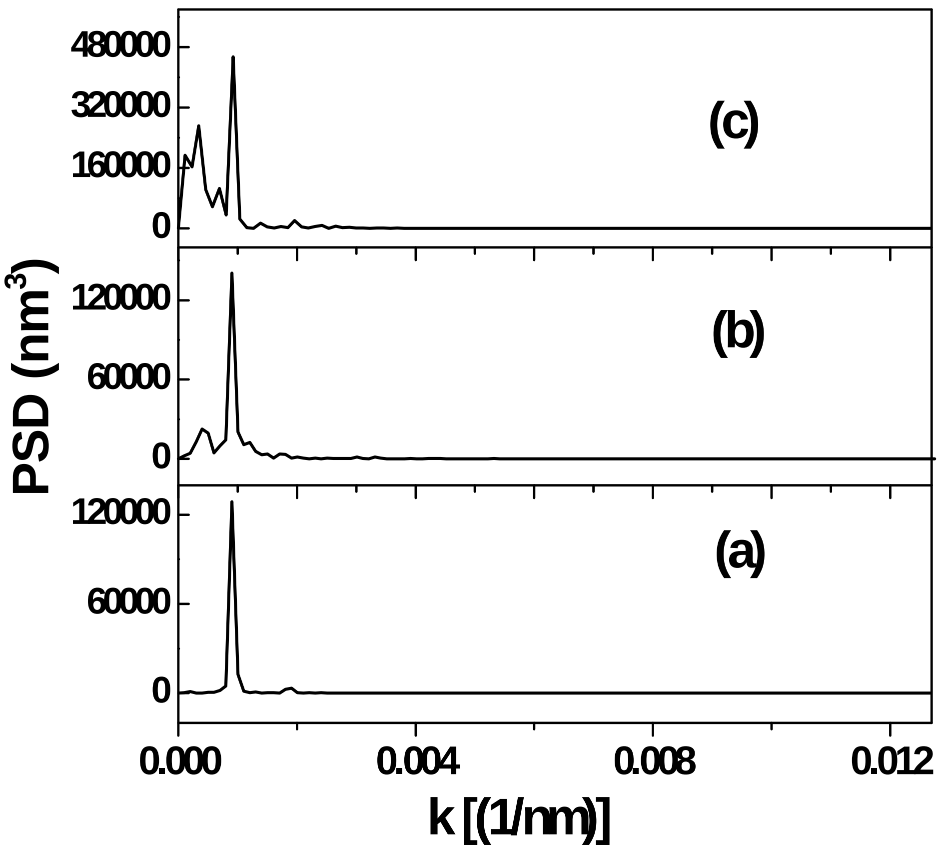

Fig. 3: 1-D Power Spectral Density (PSD) plots of the grating structure fabricated with UV laser beam with (a) 600, (b) 900 and (c) 1500 laser pulses.

Table 1 Calculated Parameters Of Grating Structures For Different Number Of Pulses

No. of pulses	RMS roughness (nm)	Fundamental Periodicity (nm)	Relative PSD of lower frequency with fundamental frequency (dB)
600	21.82	1106	-19.1
900	28.93	1106	-8.5
1500	39.40	1086	-2.3

It is evident from the power spectral density and roughness data given in Table 1 that the grating structures substantially deviate from ideal analog structure due to increasing contribution of micro-roughness. Therefore, grating structures fabricated with increasing number of pulses, above a certain number of pulses, the presence of micro structural surface roughness leads to increasing amplitudes of lower spatial frequency components and eventually to surface deterioration.

IV. CONCLUSION

Grating structures have been fabricated by mask-less laser beam holographic exposure on silicon surface with fourth harmonic wavelength of Nd:YAG laser beam. The effect of increasing number of shots on the pattern surface has been studied. It has been found that grating structures generated with fourth harmonic beam have regular, uniform and well-controlled periodicity. Power Spectral Density (PSD) and cross-sectional analysis reveal that with increasing the number of shots, valley depth of grating pattern increases which leads to many spatial frequency components as well other than the fundamental frequency of the structure due to increase in extreme amount of interfacial roughness.

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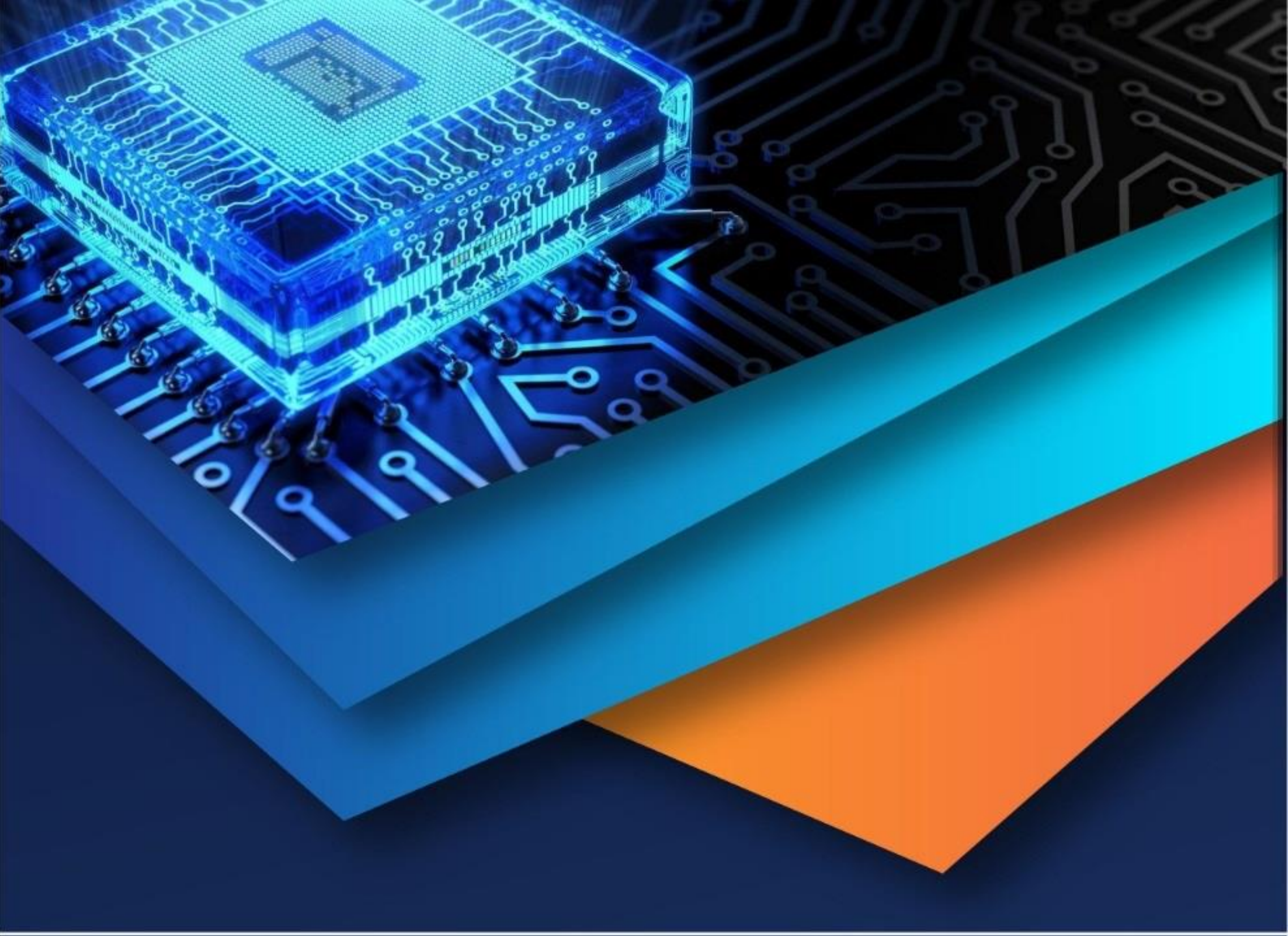

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