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Direct modification of silicon surface by nanosecond laser interference lithography

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ABSTRACT

Periodic and quasi-periodic structures on silicon surface have numerous significant applications in photoelectronics and surface engineering. A number of technologies have been developed to fabricate the structures in various research fields. In this work, we take the strategy of direct nanosecond laser interference lithography technology, and focus on the silicon material to create different well-defined surface structures based on theoretical analysis of the formation of laser interference patterns. Two, three and four-beam laser interference systems were set up to fabricate the grating, regular triangle and square structures on silicon surfaces, respectively. From the AFM micrographs, the critical features of structures have a dependence on laser fluences. For a relative low laser fluence, grating and dot structures formed with bumps due to the Marangoni Effect. With the increase of laser fluences, melt and evaporation behaviors can be responsible for the laser modification. By properly selecting the process parameters, well-defined grating and dot structures can been achieved. It can be demonstrated that direct laser interference lithography is a facile and efficient technology with the advantage of a single process procedure over macroscale areas for the fabrication of micro and nano structures.

1. Introduction

Silicon has been the most commonly used material in semiconductor devices for many years. Periodic and quasi-periodic micro and nano structures fabricated on silicon surfaces do not merely play an important role in light-trapping for solar cells [1–3], but act as intelligent surfaces capable of multiple functionalities with applications in biomaterials [4] and photoelectric sensors [5,6]. In recent years, the applications of periodic structures have extended to other fields such as quantum dots [7] and OLEDs (Organic Light-Emitting Devices) [8–10]. Numerous approaches to the fabrication of periodic structures have been proposed, e.g. electron beam lithography (EBL), focused ion beam lithography (FIB) and scanning probe lithography (SPL). EBL and FIB are powerful technologies for prototyping with higher resolution [11]. They are probably the most widely used methods for the fabrication of sub 100 nm patterns. Another elegant method, SPL, uses the tip of a scanning probe microscope (SPM) to create patterns. The SPM tip can be used to produce marks by scratching, nanoindentation or by heating with the tip and the resolution can be as high as around 10 nm [12–14]. However, these conventional methods require a time consuming process [15]. Compared with the point by point writing strategy, nanosecond laser interference lithography is a parallel technology which can fabricate the various structures with two- or multi-beam laser interference simultaneously. The periodicity of structures corresponds to the interference distribution with maxima and minima intensities, which can be controlled from micrometers to nanometers continuously by adjusting the incident angles or wavelengths. The size of produced structures can be as much as the beam area (>cm^2). Besides the high throughput and low cost it does not need the mask. In summary, nanosecond laser interference lithography is a promising technology with the capability for the manufacturing of micro and nano structures.

Several research groups have reported that they used this technology for the fabrication of periodic structures in different materials. Castro et al. fabricated the periodic structures on multi-walled carbon nanotubes (MWNTs) which performed as transparent conductors by direct laser interference patterning [16]. Zhao et al. made a silver grating of periodicity of 220 nm by direct laser interference writing [17]. Guo et al. employed two-beam nanosecond laser interference technique to structure graphene oxide in order to fabricate a flexible humidity sensor [18]. However, there is the lack of theoretical analysis of the formation of laser

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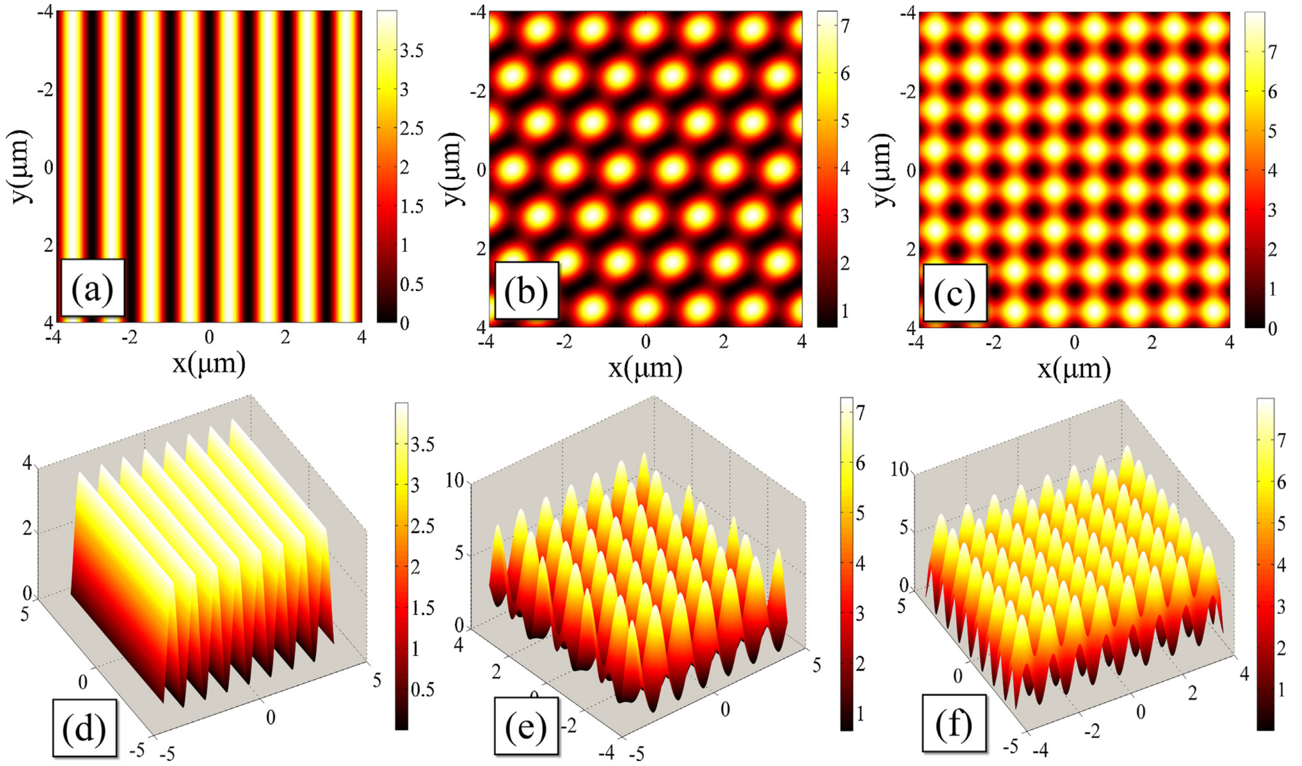

Fig. 1. Laser interference simulations. (a) 2D intensity distribution for two-beam interference; (b) 2D intensity distribution for three-beam interference; (c) 2D intensity distribution for four-beam interference; (d) 3D intensity distribution for two-beam interference; (e) 3D intensity distribution for three-beam interference; and (f) 3D intensity distribution for four-beam interference ($\lambda = 1064\,\mathrm{nm}$, $\theta = 30^\circ$).

interference patterns and their corresponding surface structures fabricated.

In this work, we focus on the silicon material and aim to create different well-defined surface structures based on theoretical analysis of the formation of laser interference patterns. Two-beam, three-beam and four-beam nanosecond laser interference systems were set up to modify the silicon surface, resulting in the grating, regular triangle and square structures. AFM was employed to observe the profiles of samples and analyze the structural dimensions. From the AFM micrographs shown, the critical features of structures have a dependence on laser fluences. By properly selecting the process parameters, well-defined grating and dot structures can be achieved.

2. Theoretical analysis and simulations

The theoretical equations of two, three and four-beam laser interference with proposed polarization modes describing the electric field vectors and interference intensity distributions are derived in this section [19–22]. When a beam irradiates on the sample, if the electric vector lies in the incidence plane, the polarized angle is 0° (TM polarization), and if the electric vector is perpendicular to the incident plane, the polarized angle is 90° (TE polarization). Besides the wavelength and incident angle, the polarization is an important parameter for the formation of interference patterns. In two-beam laser interference, the polarization mode will affect the pattern contrast obviously [11]. It is assumed that amplitudes of beams are identical and their initial phases are 0. If two beams follow a symmetrical configuration with the same incident angles, the intensity of two-beam laser interference with the TE–TE polarization mode can be written as

$$I_{\mathrm{TE-TE}} = A^2[2-2\cos(2k\cdot\sin\theta\cdot x)] \qquad (1)$$

In three-beam laser interference, if three beams follow a symmetrical configuration with the same incident angles, the intensity with the TE–TE–TM polarization mode can be written as

$$I_{\mathrm{TE-TE-TM}} = A^2\left\{\begin{array}{l} 3+\sqrt{3}\cos\theta\cdot\cos(k\cdot\sin\theta\cdot y) \\ -\sqrt{3}\cos\theta\cdot\cos\left[k\cdot\left(\frac{\sqrt{3}}{2}\sin\theta\cdot y+\frac{3}{2}\sin\theta\cdot x\right)\right] \\ -\cos\left[k\cdot\left(\frac{\sqrt{3}}{2}\sin\theta\cdot y-\frac{3}{2}\sin\theta\cdot x\right)\right] \end{array}\right\} \qquad (2)$$

In the same way, the intensity of four-beam laser interference with the TE–TE–TE–TE polarization mode can be written as

$$I_{\mathrm{TE-TE-TE-TE}} = A^2\left[4-2\cos(2k\cdot\sin\theta\cdot x)-2\cos(2k\cdot\sin\theta\cdot y)\right] \qquad (3)$$

In this work, Matlab was used to simulate 2D and 3D intensity profiles of the two, three and four-beam laser interference. The different interference patterns are shown in Fig. 1.

3. Experiment

In the experiment, a high power pulsed Nd:YAG laser (a Gaussian beam in TEM_{00} mode) with the wavelength of 1064 nm, pulse energy of 2 J and pulse duration of 7 ns was used for laser interference lithography. All the samples used in the experiment were polished single crystal silicon wafers and the experiments were carried out under ambient conditions. The beams were split by beamsplitters and high-reflective mirrors. Quarter wave plates and polarizers were placed before the exposed samples to control the power and polarization angles precisely. The power and energy of the laser were measured with the Laser Power and Energy Meter (Coherent LabMax-top, USA). The surface morphology of the samples was characterized with the atomic force microscope (AFM).