Applied Surface Science 305 (2014) 670–673

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Cross-sectional study of high spatial frequency ripples performed on silicon using nanojoule femtosecond laser pulses at high repetition rate

R. Le Harzic[a,*], M. Menzel[b], S. Henning[b], A. Heilmann[b], F. Stracke[a], H. Zimmermann[a,c]

[a] Fraunhofer Institute for Biomedical Engineering (IBMT), Ensheimer Str. 48, D-66386 St. Ingbert, Germany
[b] Fraunhofer Institute for Mechanics of Materials (IWM), Halle, Walter-Hülse-Straße 1, 06120 Halle, Germany
[c] Saarland University, Chair Molecular & Cellular Biotechnology/Nanotechnology, D-66123 Saarbrücken, Germany

ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 21 March 2014
Accepted 22 March 2014
Available online 31 March 2014

Keywords:
Nano-ripples
HSFL
Femtosecond laser
Patterning
Silicon
Nanograting

ABSTRACT

We report on investigations of fine cross-sectional cuts performed by focused ion beam on periodic high spatial frequency ripples generated on large areas of silicon in air under ultrashort low energy pulses irradiation at high repetition rate. The morphology, depth profile, and aspect ratio which was found to be of 1:1 are quite independent from the energy and number of pulses applied even if a slight decrease of the aspect ratio was found at high energies and high number of applied pulses. Furthermore, even if the orientation of the HSFL is perpendicular to the polarization the profile and aspect ratio of the cross sections are not influenced by the rotation of the polarization.

Introduction

High spatial frequency laser-induced periodic surface structures (HSF-LIPSS or HSFL) have been observed on a variety of sample surfaces following irradiation of ultrashort laser pulses [1–13]. HSFL have typical spatial periods in a range of $\lambda/4$–$\lambda/6$ and are solely generated for multiple pulse irradiation with low energy. The origin of these nano-ripples is still quite controversially discussed in the current literature. Proposed mechanisms for HSFL generation include surface instability and self-organization [2], second harmonic generation (SHG) [1,3,13,14], excitation of surface plasmon polaritons [10,15] or Coulomb explosion [16]. If several studies have been performed on the influence of parameters such as the energy per pulse, the number of applied pulses, the polarization, the wavelength, etc. on the morphology and the periodicity of the ripples on the surface of Silicon (Si), much less information is available about the cross-sectional structure of the nano-patterns. Some studies on cross-sectional cuts of ripples with periods closed to the wavelength, known as low spatial frequency LIPSS (LSFL), have been performed in Si [17–20]. Cross-sectional investigations on HSFL generated in Si under water confinement have been presented [21]. These cross-sectional studies give essentially information on the nature and structural phase of the ripples. In this work we focus on the influence of illumination parameters on the cross section profile. We study the influence of the pulse energy and the number of applied pulses as well as the polarization on the morphology, depth profile, and aspect ratio of the HSFL generated on Si in air. For this purpose, cross-sectional cuts of structured fields entirely filled with HSFL were performed by Focused Ion Beam (FIB) under low fluence pulses (nJ) at high repetition rate (MHz). Scanning electron microscopy (SEM) observations on cross-sectional cuts reveal a quite homogeneous sinusoidal-like depth profile of the HSFL with a relative constant aspect ratio until a certain level of energy and pulse number. The orientation of the HSFL is dependent on the direction of the polarization and perpendicular to this latter but no influence of the direction of the polarization has been observed on the profile and aspect ratio of the cross sections of HSFL.

Material and methods

HSFL have been generated in air on standard one-side-polished, boron-doped p-type Si wafers with a thickness of 525 μm and a crystallographic orientation 100 using a compact ultrafast

* Corresponding author. Tel.: +49 6894 980 167.
E-mail address: ronan.leharzic@ibmt.fraunhofer.de (R. Le Harzic).

http://dx.doi.org/10.1016/j.apsusc.2014.03.159
0169-4332/

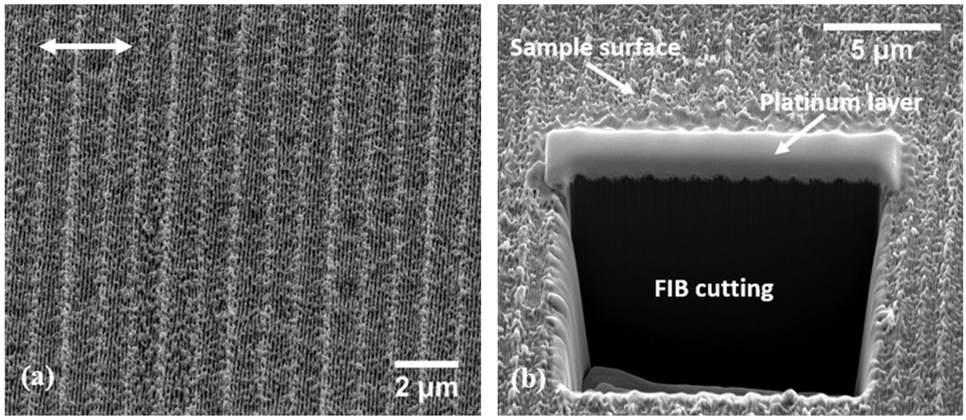

Fig. 1. (a) SEM image of HSFL generated in Si at 800 nm, 2.5 nJ/pulse and 160 000 applied pulses after etching. The double arrow represents the polarization of the laser irradiation. (b) SEM image of the corresponding FIB section.

Ti:Sapphire tuneable laser system (80 MHz, $E_{max} \sim 40$ nJ/pulse, $\tau = 140$ fs (FWHM), $\lambda = 800$ nm) coupled to a laser workstation specially designed and developed for accurate micro- and nano-processing. Details on the experimental setup can be found in a previous work [22]. Large areas were processed by scanning the sample in order to yield representative numbers of ripples per profile. The low energy femtosecond laser pulses were focused by the use of a 20× focusing objective with a relatively high numerical aperture (NA) of 0.75 to reach the fluence threshold of HSFL generation. The focus diameter is about 1.3 μm at the surface of the sample.

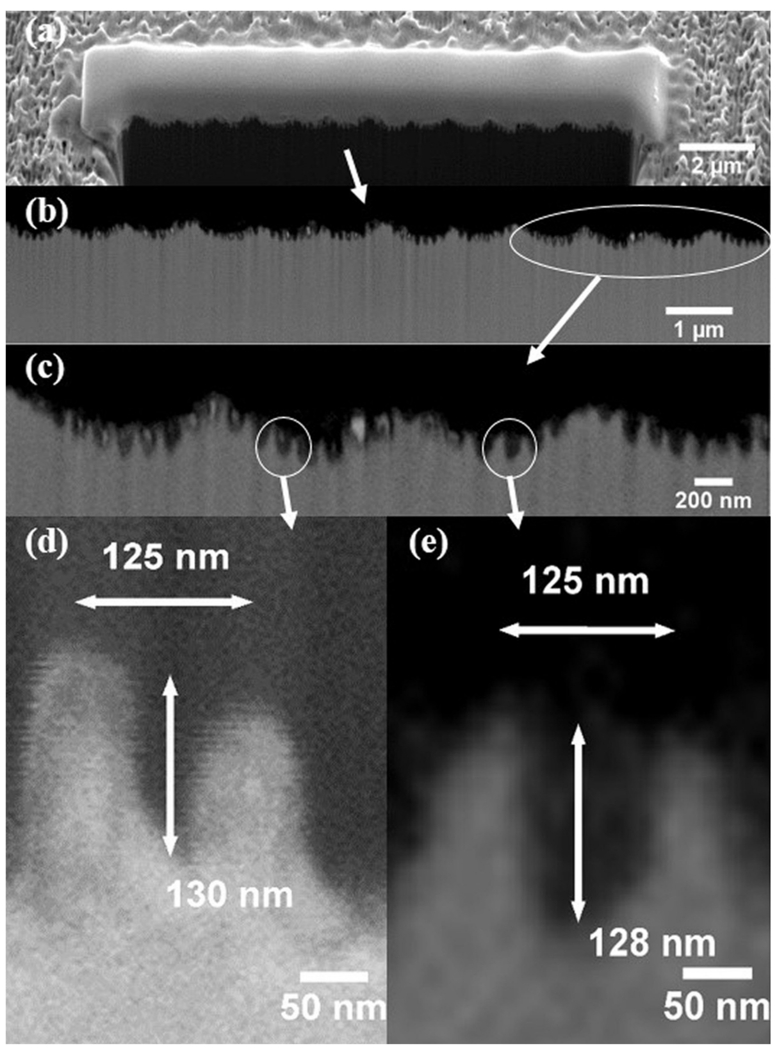

Fig. 2. SEM images of cross sectional profile of HSFL in Si. (a) FIB section overview (refer to Fig. 1(b)). (b) Cross sectional profile overview of the HSFL. (c) Details of the cross sectional morphology and profile of the HSFL. (d) and (e) High magnification of HSFL profiles.