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Nanosecond laser-induced periodic surface structures on wide band-gap semiconductors

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ABSTRACT

In this work we report on fabrication of laser-induced periodic surface structures (LIPSS) on different semiconductors with bandgap energies in the range of 1.3–3.3 eV and melting temperatures from 1100 to 2700 °C. In particular, InP, GaAs, GaP and SiC were irradiated in air with nanosecond pulses using a linearly polarized laser beam at 266 nm (6 ns pulse width). The nanostructures, inspected by atomic force microscopy, are produced upon multiple pulse irradiation at fluences near the ablation threshold. LIPSS are perpendicular to the laser polarization direction and their period is of the order of the irradiation wavelength. It was observed that the accumulative effect of both fluence and number of pulses needed for LIPSS formation increased with the material bandgap energy. These results, together with estimations of surface temperature increase, are discussed with reference to the semiconductor electrical, optical and thermal properties.

1. Introduction

Since the early observation of laser-induced periodic surface structures (LIPSS), also termed as ripples, on semiconductors [1] this kind of nanostructures have been imprinted on almost all kinds of materials and have been extensively investigated using low power cw and pulsed laser sources of nanosecond (ns) and femtosecond (fs) duration [2–8]. In general, the ripples have a period Λ dependent on laser wavelength λ, on the angle of incidence of the radiation Θ_i and on index of refraction n and can be described by the relation $\Lambda = \lambda/(n - \sin\Theta_i)$ [2]. After exposure of a smooth solid to a linearly polarized radiation at normal incidence, often the lateral period of the fabricated LIPSS is very close to the wavelength of the incident radiation. It has been proposed that this type of ripples arises from optical interference effects due to the superposition of the incident radiation with a surface electromagnetic wave which is created at the material-medium interface during irradiation together with a feedback mechanism [3–8].

Recently, LIPSS resulting from fs laser irradiation of solids have received considerable attention in attempts to determine their formation mechanism [9–19]. Irradiation of surfaces at normal incidence usually leads to the formation of low spatial frequency LIPSS (LSFL) with period comparable to the laser wavelength. This type of structures is explained in reference to the previously mentioned interference mechanism. In the case of metals, semiconductors and dielectrics, the formation of ripple structures with subwavelength periods has also been observed. These high spatial frequency LIPSS (HSFL) have been obtained using fs laser pulses of different duration, wavelength, fluence and number of pulses [20–25]. Several mechanisms have been proposed as the origin of HSFL, such as interference effects along with transient changes in the optical properties during laser irradiation [26], second harmonic generation [24,27], excitation of surface plasmon polaritons [28], resolidification [29], self organization [11–13] and Coulomb explosion [30].

Wide band gap (WBG) semiconductors have expanded the scope of applications beyond those of silicon. The developing list of such materials for use in device production is remarkable and continues to provide new design possibilities. The inherent properties of WBG make them ideal candidates for high-power, high-temperature electronic devices, power amplifiers, switches, and short wavelength light sources. Therefore, modification of structure and properties of WBGs at the nanometer scale attracts great interest [31].

In this work, LIPSS were imprinted on the surface of WBG semiconductors wafers of indium phosphide (InP), gallium arsenide (GaAs), gallium phosphide (GaP) and silicon carbide (SiC) by irradiating in air with linearly polarized, 266 nm, 6 ns laser pulses. The period and amplitude of the LIPSS were characterized by atomic force microscopy (AFM) as a function of the laser fluence and number of pulses. We have observed that as the bandgap of the semiconductor material increases, higher fluence or number of pulses are needed for LIPSS formation whereas the amplitude of the ripples is related with the optical and thermal penetration depth.

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Table 1
Initial roughness[a] (R_a), energy bandgap [33], melting temperature [33] (T_m), specific heat [33] (c), thermal conductivity [33] (k), density [33] (ρ) and linear absorption coefficient at 266 nm [32] (α) of semiconductor wafers.

Material	R_a (nm)	Bandgap (eV)	T_m (°C)	c (J/Kg K)	k (W/m K)	ρ (Kg/m^3)	α (cm^{-1})
InP	0.30	1.35	1060	310	68	4810	1.47×10^6
GaAs	0.28	1.42	1240	330	55	5316	1.72×10^6
GaP	0.62	2.30	1457	430	110	4138	1.21×10^6
SiC	0.65	3.37	2730	690	370	3210	2.44×10^6

[a] Estimated by AFM.

Table 2
Minimal fluence (F_m) required for LIPSS fabrication and experimental conditions (fluence and number of pulses) and ripple properties (period and amplitude) for optimum LIPSS of semiconductor wafers.

Material	F_m (mJ/cm^2)	Fluence (mJ/cm^2)	Number of pulses	Ripple period (nm)	Ripple amplitude (nm)
InP	100	125	200	248 ± 6	5 ± 1
GaAs	135	150	200	253 ± 7	9 ± 2
GaP	125	125	300	263 ± 10	15 ± 5
SiC	>300	–	–	No LIPSS observed	

Estimations of surface temperature increase are discussed with reference to the WBG semiconductor electrical, optical and thermal properties.

2. Experimental setup

For studying ripple formation, multiple pulse laser irradiation of undoped semiconductor wafers of InP, GaAs, GaP and SiC was carried out in ambient air at normal incidence. The electrical, optical and thermal properties of those materials [32,33] are summarized in Table 1. For irradiating the samples we used the linearly polarized fourth harmonic output of a Q-switched Nd:YAG laser (Quantel Brilliant B, 266 nm, τ = 6 ns FWHM, repetition rate 10 Hz, Gaussian beam profile). This irradiation wavelength corresponds to an energy of 4.67 eV, well above the bandgap energies of these semiconducting materials (Table 1). The central (4 mm diameter) most uniform part of the beam spot was selected for irradiation by using a diaphragm. The laser beam was focused on the substrate surface with a spherical lens of 15 cm focal length. The irradiation fluence was below the ablation threshold (F_{th}) for a single pulse of each material. The fluence was determined as the ratio of the laser pulse energy, measured in front of the sample with a joulemeter (Gentec-E, QE25SP-H-MB-D0), and the area of the irradiated spot, determined by the print left on an unplasticized polyvinyl chloride sheet. Ablation thresholds of samples were determined by measuring the minimum single pulse energy necessary to yield a surface change as detected by optical microscopy (Leica, S8APO) with a 160× microscope objective and equipped with a CCD camera. The obtained values are 190 ± 10, 380 ± 22, 470 ± 25 and 950 ± 40 mJ/cm^2, for InP, GaAs, GaP and SiC, respectively. The morphology of the laser treated semiconductor surfaces was characterized using AFM in tapping mode (Multimode 8, Bruker) and the images were analyzed with the software Nanoscope Analysis 1.40. The AFM measurements were performed in 5 different positions of each sample to check the uniformity of the fabricated nanostructures. The pristine substrates, of around 300 μm thick, present a flat surface, with mean roughness (R_a) values < 1 nm. R_a values are listed in Table 1 and indicate the arithmetic average of the deviations in height from the center plane of the sample. Each R_a value corresponds to the average of three independent measurements in different locations of the substrate surface.

3. Results

Irradiation of the semiconductor wafers was performed at different fluences and number of pulses in order to find the conditions for obtaining the most uniform ripples in terms of period and amplitude. The minimum fluence (F_m) needed for LIPPS fabrication is displayed in Table 2 together with the experimental conditions for the optimum LIPSS fabrication for each semiconductor wafer. Fig. 1 shows AFM height images and corresponding cross-section of the LIPSS obtained in InP, GaAs and GaP.

Fig. 1a displays the ripples fabricated in InP with 200 pulses of 125 mJ/cm^2. Ripples are perpendicular to the laser polarization

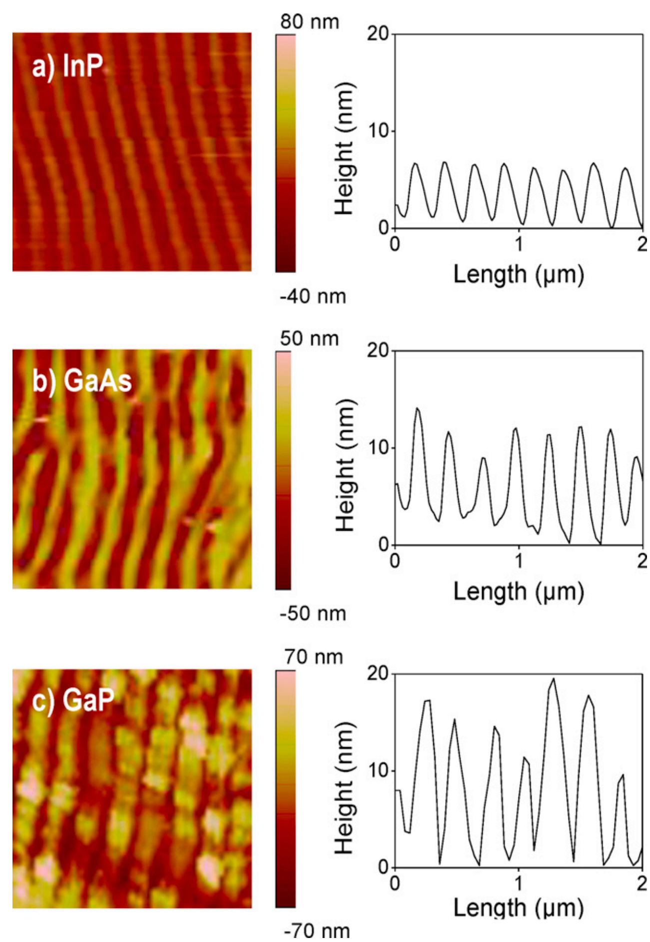

Fig. 1. AFM height images (2 × 2 μm^2 size) (left) and corresponding cross-sections (right) of LIPSS fabricated at 266 nm in (a) InP with 200 pulses at a fluence of 125 mJ/cm^2 (b) GaAs with 200 pulses at 150 mJ/cm^2, and (c) GaP with 300 pulses at 125 mJ/cm^2. The ripples are perpendicular to the laser polarization direction.