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Evolution of InP surfaces under low fluence pulsed UV irradiation

O.R. Musaev *, O.S. Kwon, J.M. Wrobel, D.-M. Zhu, M.B. Kruger

Department of Physics, University of Missouri Kansas City, Rockhill Road 5100, Kansas City, MO 64110, United States

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ABSTRACT

An InP wafer was irradiated in air by a series of UV pulses from a nitrogen laser with fluences of 120 mJ/cm^2 and 80 mJ/cm^2. These fluences are below the single-pulse ablation threshold of InP. Over the studied region the distribution of the radiation intensity was uniform. The number of pulses varied from 50 to 6000. The evolution of the surface morphology and structure was characterized by atomic force microscopy, optical microscopy and Raman spectroscopy. The relationship between mound size and the number of pulses starts out following a power law, but saturates for a sufficiently high number of pulses. The crossover point is a function of fluence. A similar relation exists for the surface roughness. Raman spectroscopic investigations showed little change in local crystalline structure of the processed surface layer.

1. Introduction

Interest in the fundamental properties of light–matter interactions and their technological applications continues to stimulate studies of laser irradiation effects on semiconductor surfaces [1]. Irradiation of GaAs and InP crystal surfaces with femtosecond infrared (780 nm) laser pulses with Gaussian intensity distributions at various fluences provided information about changes in surface morphology, physical and chemical characteristics of the surface in the processed crater [2–4]. The single-pulse threshold for laser ablation of InP has been studied under various environmental and illumination conditions [5,6]. In the current study, we have observed that single-pulse ablation occurs at fluences above 140 mJ/cm^2 for 337 nm, 10 ns pulses. Applying the same criterion for determining the ablation threshold [7], the current result is in good agreement with previous work under similar conditions [6,8].

Irradiation of semiconductor surfaces with nanosecond pulses attracts interest in research related to semiconductor technology because thermalization of electronic excitations occurs on the order of picoseconds. Nanosecond pulses cause mostly thermal effects while pico- to femtosecond pulses form localized defect structures. Nanosecond laser pulses of different wavelengths can be used for applications such as: surface alloy formation [9], modification of photoelectric and electrical properties of the surface [10], surface annealing [11], dry etching [12–14] and surface cleaning [15].

Although there have been numerous studies of the effects of nanosecond laser pulses on compound semiconductors [12–14], no research has been reported on the surface evolution due to multiple UV laser pulses with uniform intensity distribution below the single-pulse ablation threshold. Hence, investigation of such evolution of InP surfaces caused by irradiation with a series of nanosecond pulses of UV laser radiation with fluences below the single-pulse ablation threshold presents interest as an approach for controlled surface modification of InP and other semiconductors. The development of the surface morphology and the physical characteristics of the modified InP surface layer under radiation are the focus of the present investigation.

2. Experiment

In the present work a (1 0 0) InP wafer surface was irradiated in air by light from a nitrogen pulsed laser with a wavelength of 337 nm and a pulse duration of 10 ns at a 10 Hz frequency. The penetration depth of 337 nm radiation in InP is about 100 nm, which is an important depth-scale in semiconductor technology [1]. The laser beam was homogenized by passing it through a 1 m long multimode step index optical fiber (ThorLabs, P/N: BFH22-550). It was bent to provide better homogenization. Based upon the work of Tam et al., who used a similar fiber set up and had a greater laser intensity in the fiber, we estimate that the fiber increased the pulse duration by no more than 0.4 ns (4%) [16]. The image of the output end of the fiber was projected on a wafer surface by a lens with a 70 mm focal length. In contrast to the usually used Gaussian beams [17–20], due to the

* Corresponding author. Tel.: +1 816 235 2513; fax: +1 816 235 5221.
E-mail address: musaevo@umkc.edu (O.R. Musaev).

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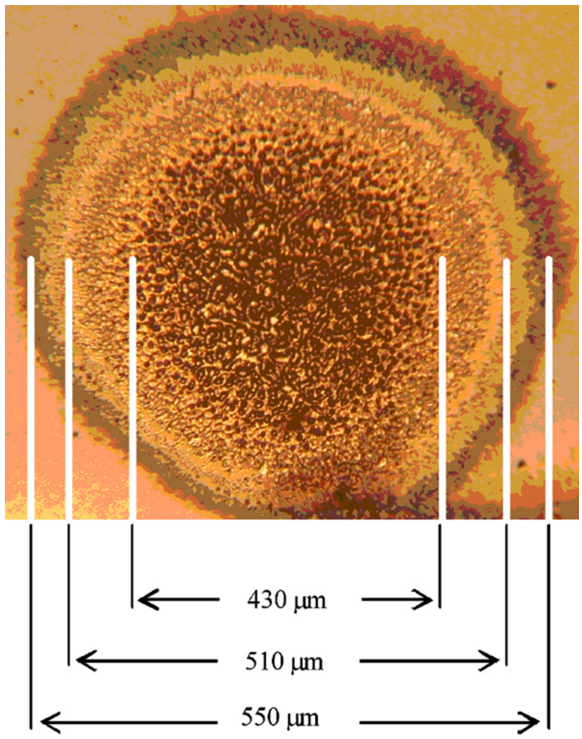

Fig. 1. Optical microphotograph of an InP wafer after processing by 3000 laser pulses with fluence of 100 mJ/cm^2.

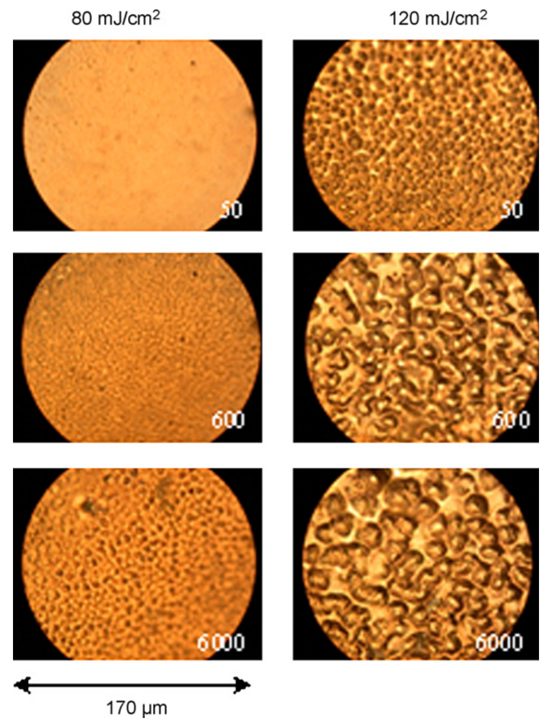

Fig. 2. Images of the central (diameter = 170 μm) regions of InP wafer processed by 50, 600 and 6000 pulses with fluence 80 mJ/cm^2 (left column) and 120 mJ/cm^2 (right column).

homogenization used in this experiment the spots on the surface were irradiated uniformly [16]. This has been verified by the morphology of the processed spots, as shown in Fig. 1. The central 430 μm spot of a 550 μm crater is uniform, and is surrounded by a 510 μm ring. In the case of Gaussian beams, the temperature across the spot is highest in the center and decreases to the edge of the processed surface. For a uniform intensity distribution, the temperature profile will depend upon the ratio of the lateral to normal heat flow. For the present case, in which the lateral to normal heat flow is small, the deviation of the temperature profile from a uniform distribution is insignificant. Different numbers of pulses, from 50 to 6000, all at fluences below the single-pulse ablation threshold, were used to form a set of processed spots on the surface of the wafer. Characterization of the surface was performed by atomic force microscopy, optical microscopy and Raman spectroscopy.

An Olympus microscope was used to make optical images of the spots processed on the InP surface. The images were used for the analysis of the lateral size of the mounds formed on the processed surface of the wafer.

Raman spectra were collected on an Acton Research Raman SPI-500i spectrometer in back scattering geometry. The 514.5 nm line of an Ar^+ ion laser was used for excitation [21]. At this wavelength, the expected penetration depth of light is about 100 nm. The beam was focused to a 40 μm diameter spot.

The atomic force microscopy (AFM) images were obtained with a Park Systems Inc. XE-100 scanning probe microscopy system. Silicon cantilever probes with an average force constant of 0.6 N/m and tip curvature radius less than 10 nm were used in imaging. The images were obtained using contact mode and 2 Hz scanning speed. The forces applied to the tips during imaging were less than 1 nN.

3. Results and discussion

Optical microscopic images of the processed, 170 μm diameter spots (central parts) of the InP wafer for fluences of 80 mJ/cm^2 and 120 mJ/cm^2 are shown in Fig. 2. From these images, the average lateral size of the mounds was evaluated. The dependence of the average size on the number of pulses for the two fluences is shown on a log–log plot in Fig. 3. The size increases monotonically with the number of pulses for both fluences. For a low number of pulses a power law can fit the data. These fits yield exponents of about 0.26 for the 80 mJ/cm^2 pulses and 0.37 for the 120 mJ/cm^2 pulses. For the 120 mJ/cm^2 fluence, the lateral size of the mounds approaches a saturation value. The crossover point between power law and saturation behavior occurs at ~1400 pulses.

The roughness of the processed surface was analyzed using atomic force microscopy. In Fig. 4, 10 μm × 10 μm AFM images for the central sections of the processed spots are presented for the two laser fluences. In addition to lateral mound dimensions obtained from optical microscopy, the AFM data provides information about the dimension perpendicular to the surface.

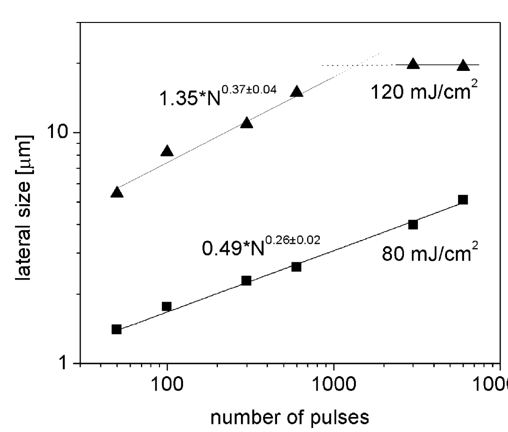

Fig. 3. The average lateral size of mounds for 80 mJ/cm^2 (■) and 120 mJ/cm^2 (▲) vs. the number of pulses in a double logarithmic scale for the two fluences.