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Selected problems in IR and UV laser micromachining of Si and GaAs in submillimeter scale

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ABSTRACT

Results of laser micromachining of silicon and gallium arsenide in submillimeter scale were compared. Studies were performed using a laser beam with IR and UV wavelengths and pulses of femto- and nano-second duration. Investigation of effectiveness of micromachining with different parameters of laser beams was presented. Quality of surface and edges was estimated by means of an optical microscope and an electron microscope. Studies of surface profiles were performed using a confocal microscope. Results of micromachining were with good accordance with computer modeling.

1. Introduction

Using a pulsed nano-, pico-, and more recently a femto-second laser beam is currently the standard in laser micromachining. Using a multimode fiber laser [1] and a single mode fiber laser [2–4] was reported earlier in the aspect of effectiveness of the thermal ablation of silicon. Several researchers reported ablation of GaAs with nanosecond and femtosecond lasers [5,6]. In the present paper we have been discussing the problems connected with microfabrication of different semiconductor materials using various types of lasers. During micromachining by the femtosecond laser beam temperature of electrons T_e is higher than temperature of lattice T_l, but if the repetition frequency of pulses is lower than 100 MHz, a burst time between subsequent pulses is higher than several ps. That time is sufficient to allow cooling electrons and heating the lattice. During such process electrostatic ablation occurs and electron emission can be observed apart from electron–phonon exchange of energy. Drilling by such ultra-short pulses gives regularly shaped crater rims [7]. There is no Heat Affected Zone (HAZ) and any traces of damage caused by thermal stresses or shock waves in the surrounding material. Model of these phenomena assumes one-dimensional, two-temperature diffusion. Transfer energy from electron to lattice is of order ps, considering relaxation of hot electrons [7]. The intense evaporation occurs when C_iT_i is greater than ρC_{vap} where C_i — specific capacity of lattice, the grid temperature T_i, ρ — material density, C_{vap} — specific heat of vaporization, and electron cooling time $\tau_e > t_p$ is longer than the duration of the laser pulse. Quality and precision depend mainly on such parameter of lasers as a wavelength, fluence, duration of interaction, frequency of pulses and even scan speed. With higher frequency an effect of accumulation of heat in the zone of laser micromachining is observed. This effect can lead to improving aspect ratio of such treatment and to decreasing crack effect, because of reaching temperature of brittle to ductile transformation. High performance of such micromachining is possible to achieve by proper selection of scan speed and frequency of laser pulses. The effects are so difficult to predict that the calculations should be done by exact computer simulations of the whole phenomena [8]. HAZ and any traces of damage caused by thermal stresses or shock waves in the surrounding material can occur during laser ablation by nanosecond pulses. However, the costs of a nanosecond fiber laser are lower and under specific and carefully selected parameters of a laser beam: both HAZ and thermal stresses can be effectively reduced and quality of texturized surface of silicon or of GaAs can reach a sufficient level for many industrial applications and even MEMS and sensor systems. Nanosecond laser ablation involves diffusion of heat and formation of plasma plume. This plume can affect self-focusing of a laser beam as well as diminution of absorption of laser beam radiation by semiconductor material. If absorption of laser beam increases and duration of pulse decreases than degree and evolution of damages around laser spot diminishes.

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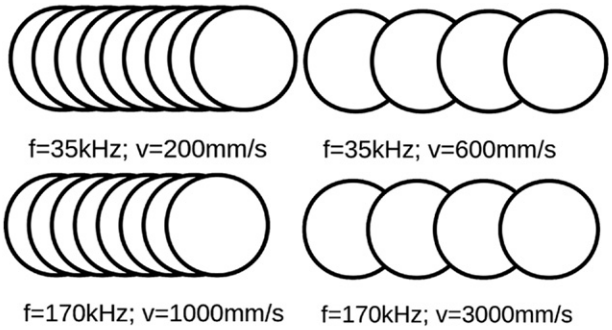

Fig. 1. Overlapping of successive pulses used in micromachining of silicon and GaAs; circles denote area of laser spots.

2. Experimental procedure

Experimental tests were carried out in order to determine the effectiveness and quality of laser ablation. Additionally the set of various microstructures was produced as practical verification of conclusions from these basic research. Silicon wafers with a crystal orientation (100), p-type, thickness 400 μm and with orientation (111), n-type, thickness 400 μm were used in our research, while GaAs wafers under investigation were undoped with orientation (100) and thickness 400 μm.

The main parameters of laser systems applied in ablative micromachining were the following: a single mode fiber laser (SPI red Energy G 3.1 SM) (Institute of Electrical Engineering Systems, Lodz University of Technology): λ = 1060 nm, pulse duration t_p = 15–220 ns, pulse energy E_p = 68–570 μJ (by max power), repetition frequency f = 35–170 kHz, average power P = 0–20 W, and scanning velocity v = 100–6000 mm/s. Scanning of the beam was carried out using a scanner Xtreme (Nutfield Techn. Inc.) equipped with a telecentric lens with a focal length of 164 mm. Research into effectiveness of laser ablation were usually carried out under atmospheric conditions. In some variants protective atmosphere (argon) with a flow of 15 l/min was applied. Micromachining with ultrashort laser pulses was performed using a femtosecond Yb:KYW fiber laser (IFFM Polish Academy of Science, Gdańsk), λ = 343 nm, t_p = 500 fs, pulse energy E_p = 27.5 μJ (by max power), f = 200 kHz, average power P = 5.5 W and v = 20–1000 mm/s.

Varying process parameters of treatment were selected in order to preserve the same degree of overlapping between successive pulses for different scan speeds (Fig. 1). Overlapping of consecutive spots made by successive laser pulses depends on scanning velocity v and repetition frequency f_{rep} of laser pulses. Increasing both values and maintaining the same ratio of v/f_{rep} we have obtained the same distance between centers of subsequent spots. Micromachining was performed on 3″ Si wafers with crystallographic orientations (100) and (111) and 2″ GaAs wafers. Examples of wafers after micromachining were

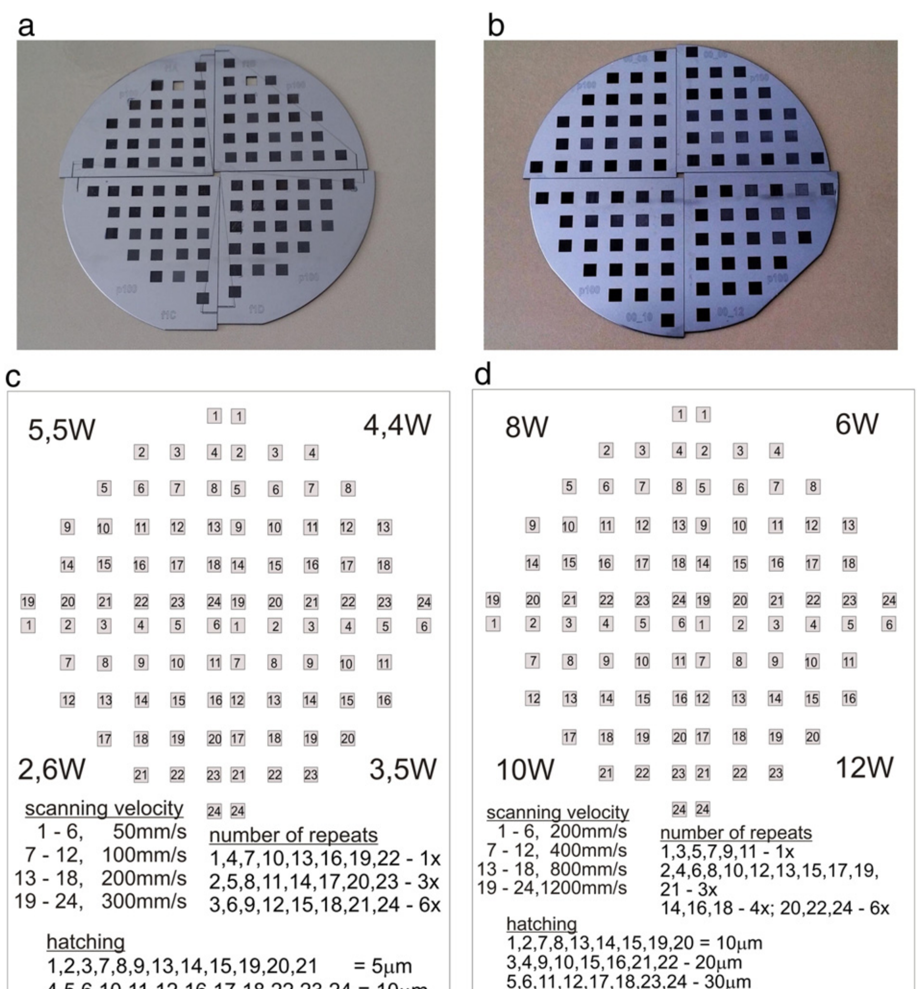

Fig. 2. Examples of laser micromachining of silicon with femtosecond (a) and nanosecond lasers (c), and the related scenario of laser treatment with different process parameters (b,d).