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Electric field-assisted laser ablation of silicon in air by using ultrashort laser pulses

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Abstract

Precise processing on silicon, as widely used material in electronic devices, has shown a rising interest in laser micromachining. To optimize this process, we apply an external electric field parallel to the laser beam axis during irradiation of samples with ultrashort laser pulses. When the electric field is turned on, the free electrons and holes are redistributed within silicon due to electron drift. The electrons can be localized near the surface area which is supposed to influence the laser excitation process. Thus, the external electric field influences the absorption process due to the reorganized spatial distribution of electrons. We investigated the effect of an applied static strong electric field during single- and multi-pulse treatment of silicon. An enhancement of the ablation depth is observed by applying the electric field in the direction of the laser radiation.

Keywords: silicon; ablation; external electric field; femtosecond laser fabrication

1. Introduction

In the area of laser micromachining, Gaussian beams are widely used. The typical beam profiles with the optical and thermal penetration depth result in spatially strongly inhomogeneous energy distribution. As a result, unwanted heat remains in the workpiece after removal, and parts of the removal plasma are heated up more than necessary. As a result, the processes must be designed in a way that the parasitic heat can be

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dissipated during processing. A further approach to optimize the ablation process is the use of processing gases with different pressures. However, the processing gas can only influence the heat accumulation of the workpiece on the macro-scale rather than achieve precise control of the laser beam energy distribution [Sun and Longtin, 2004]. To attain targeted control of the laser energy distribution on the workpiece, the approach to be pursued is the use of an electromagnetic field during the laser ablation process. In this way, the coupling, the energy distribution, or the ablation plasma can be influenced. This can be achieved by applying an electric field [Elhassan et al., 2010; Xiao et al., 2017; Maksimovic et al., 2020], a magnetic field [Ho et al., 2014; Maksimovic et al., 2019; Maksimovic et al., 2020; Zhang et al., 2021; Tang et al., 2019; Farrokhi et al., 2019] or both in combination [Lu et al., 2015]. Over the last decade, most of the investigations concentrated on the dynamics of laser-induced plasma under external field-assisted ablation by the excitation with long laser pulses. Especially to realize precise through-holes by minimized defects into the material [Lu et al., 2015; Ho et al., 2014]. Another method is the external field-assisted laser ablation in liquids to synthesize nanocrystals and to fabricate functional nanostructures [Xiao et al., 2017]. Recent studies show the potential for the control of the laser ablation process by using externally applied electric or magnetic fields during excitation with ultra-short sub-ps laser pulses and a strong focused laser beam (focal spot of ~2 µm in diameter) [Maksimovic et al., 2019; Maksimovic et al., 2020]. *Maksimovic et. al* shows that the distribution of debris can be controlled by an externally applied field and particularly to control the surface modifications by defined generated ripples structures.

Here, we introduce a fundamental study to investigate the influence of external applied electric fields on the energy dissipation at the initial stage of laser ablation when excited with ultra-short pulses in the time range from a few femtoseconds.

2. Experimental Setup

To study the effects of the externally applied electric field on laser treatment of the surface, a femtosecond fiber laser system (BlueCut, Menlo Systems GmbH) was used. The system delivers ultrashort pulses down to 400 fs with repetition rates from 10 kHz to 5 MHz by maximum pulse energy of 10 µJ. A galvanometric scanner system (hurrySCANR©II/14, SCANLAB AG) with a telecentric F-theta optic (f≈100 mm, Linos respectively Jenoptik AG) was used for deflecting and focusing the beam on the workpiece. To determine the laser spot size in the focal plane, the fit method from Liu [Liu, 1982] was applied and a spot radius of 9.5 µm ($1/e^2$ of the maximum) was obtained.

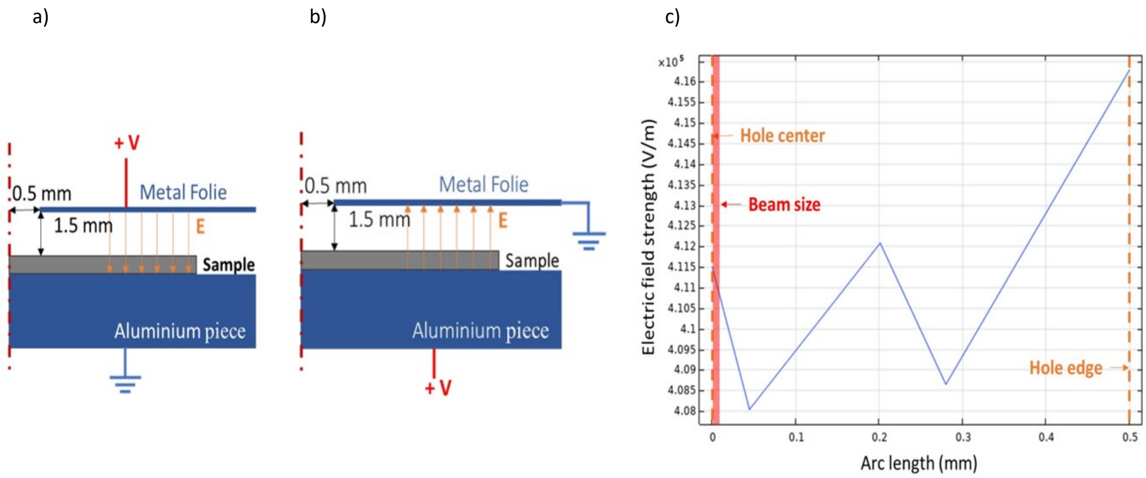

Fig. 1. An experimental scheme. (a) plus '+' direction of the applied electric field; (b) minus '-' direction of the applied electric field; (c) the electric field strength in the hole area.

To apply the electric field with the direction parallel to the beam direction, two conducting metal pieces attaching to a voltage generator were installed above and below the sample. To guarantee a relative homogenous steady field in the laser processing area without shadowing the laser beam, a tiny hole with a diameter of 1 mm was produced on the top electrode. In order to enhance the electric field strength in the middle of the laser processing area, a thin metal foil with a thickness of 100 µm was chosen as the top electrode for raising the edge effect of the electric field. Moreover, there is a space of 1.5 mm between the top electrode and silicon sample surface to avoid breaking through in silicon when a high electric field is applied. As the electric field was applied parallel to the laser beam in both directions (upwards and downwards), the direction of the applied field is defined in Fig. 1. When the electric field is pointing from top to bottom indicated by Fig. 1 (a), the electric field direction is regarded as plus ('+') direction, and vice versa. Fig. 1 (c) shows the strength of electric field distribution inside the center of the hole on the silicon surface with the generated potential of 500 V between the electrodes. The diagram in fig. 1 (c) also shows that the electric field is not uniform over the interesting area within the hole. For this reason, the top electrode is connected with the scan head and the silicon sample is moved referring to the laser beam that the relative position of the beam is always kept in the center of the hole. In the present work, the effect of external electric field on the ablation process is investigated by single-pulse and multi-pulse ablation. Thus, the microstructures are processed under the same strength as the electric field. The strength of the electric field inside the laser spot (spot radius: 9.5 µm) as marked in red in Fig. 1 (c) can be regarded as homogeneous with an electric field strength of 411.5 V/mm.

Our research focuses on the modification of the surface morphology and topography influenced by single-pulse and multi-pulse ablation of silicon. The textured surfaces were studied by using optical microscopy (Axio Imager, Carl Zeiss AG) and confocal microscopy (Zeiss smart proof 5, Carl Zeiss AG).

3. Results and discussion

To study the influence of external fields on the energy dissipation at the initial stage of laser ablation, we separate our investigations into two steps. In the first step, only single-pulse ablation was studied by changing the pulse energy depending on the direction of the applied electric field. Followed, by multi-pulse ablation to investigate the enhanced ablation process due to a defined heat and energy transport in the material by an applied electric field.

3.1 Single-pulse ablation

Following single-pulse irradiation, the craters are created with various laser pulse energies ranging from 1 µJ to 10 µJ. It is reported in the literature [Bonse et al., 2002] that the fs-laser ablated craters on silicon have always an annulus structure concerning the special material property of silicon by excitation with Gaussian-shaped laser beam. Since the annulus structure is not the main research object in our investigations, the structure is simplified as inner and outer areas regarding ablation and modification areas, as is illustrates in Fig. 2 (a). Whereas Fig. 2 (b) shows the ratio of the ablation size to modification size for the conditions without an electric field and with an applied electric field for each direction. This ratio makes it possible to observe the energy efficiency of the laser beam for the ablation process. The higher the ratio, the more laser energy is used for the material ablation process. In the investigated region we observed a minimum by the ratio between ablation and modification area by applied pulse energy of 3 µJ. For applied pulse energies smaller as well as higher pulse energies of 3 µJ the ratio increases, whereby for high pulse laser energies it is more systematic.

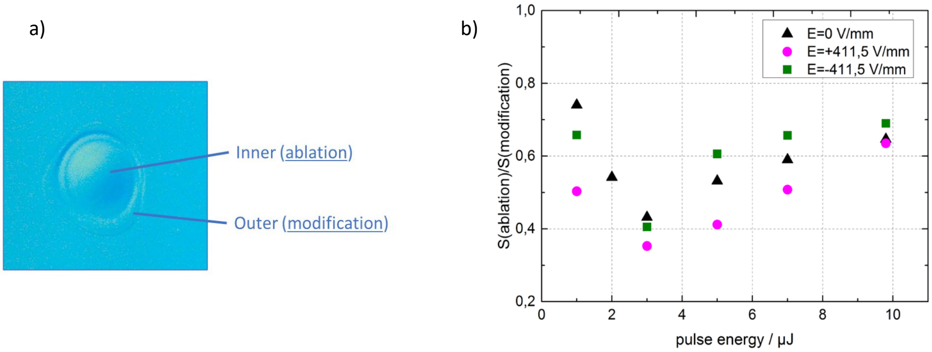

Fig. 2. (a) Light microscopy image of the crater with their corresponding definitions for the analyzing structure; (b) The ratio of the ablation area to the modification area in dependence of the applied pulse energy E_p

By an applied negative electric field a better efficiency compared to without electric field is reached. In the case of an applied positive electric field, even a reduced efficiency occurs. When the pulse energy is smaller than 3 µJ, the most efficient ablation happens without an applied electric field.

Furthermore, the depths *h* of the ablated craters were measured. For comparison of the results, the relative change of removal depth is calculated by using equation (1).

$$\text{relative change in removal depth}=\frac{\text{h(with electric field)-h(without electric field)}}{\text{h(without electric field)}}*100\ \% \qquad (1)$$

Fig. 3 illustrates the change in the removal depth depending on the applied pulse energy. In general, with a negative applied electric field, the ablated craters are much deeper compared to the produced ablated craters without an electric field. An increase in the ablation depth of up to 30 % could be reached. Equally the change in the removal depth increases by increasing the applied pulse energy up to 6 µJ by a positive applied electric field. However, the maximum enhancement amounts to approximately 15 %. In contrast, for applied pulse energies higher than 6 µJ, the change in removal depth remains almost constant. Whereby an enhanced removal of approximately 10 % occurs by an applied negative electric field. In comparison, a slightly reduced ablation process occurs by an applied positive electric field compared to the ablation process without an electric field.

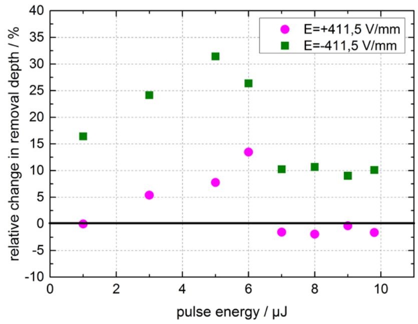

Fig. 3.The change in the removal depth for a single-pulse ablation in dependence on the applied pulse energy E_p by changing the electric field direction.

Those results show, that under an applied electric field the movement of the electrons could be controlled for a defined influenced laser ablation process. By applying a current in the direction of the sample surface the concentration of charge carriers will be much higher, by what the electron and thus also the lattice temperature will be higher compared by an applied current in the opposite direction. In this case, the arising heat will be more transferred into the material and away from the surface. Thus, by changing the direction of the applied field a defined control of heat penetration depth could be obtained and can be used to enhance the efficiency of the ablation process.

3.2 Multi-pulse ablation

In multi-pulse ablation experiments, 10-pulse and 20-pulse ablation were done by varying pulse energy between 1 µJ and 10 µJ. Hereafter, the results of the 20-pulse ablation process will be presented. The results of the 10-pulse ablation process show the same behavior. As it was already described for a single-pulse ablation, the crater diameter and the removal depth are taken as the factors for evaluating the external electric field effects during laser processing. For comparison, the relative change of the depth or rather the ablation diameter as introduced in Eq. (1) was used. For the case of relative change in the diameter, the depth *h* in Eq. (1) will be replaced by the diameter *d*. Fig. 4 illustrates the relative change in the removal diameter and the removal depth depending on the applied pulse energy by changing the direction of the applied electric field.

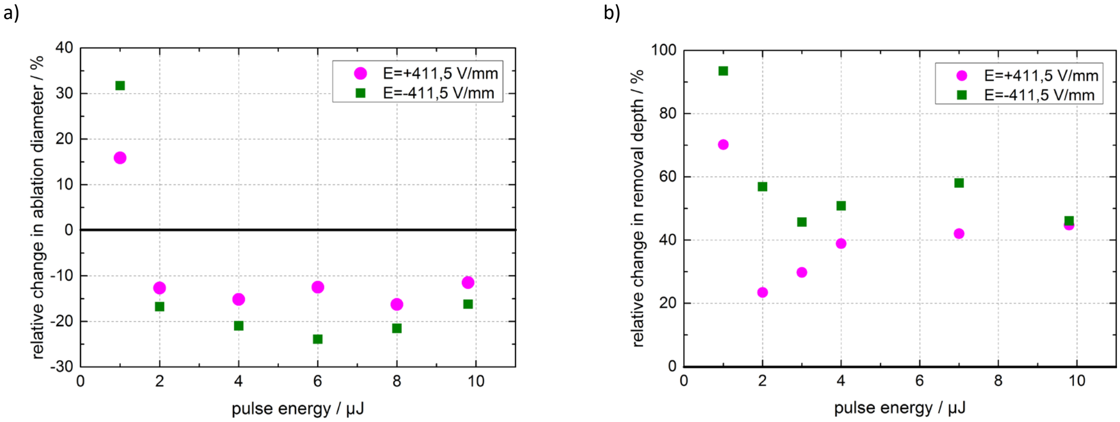

Fig. 4. (a) The change in the removal diameter for the 20-pulse ablation in dependence on the applied pulse energy. (b) The change in the removal depth in the 20-pulse ablation in dependence on the applied pulse energy.

By evaluating the experimental results of the change in both, the removal diameter and the removal depth, the results could be separated into two regions relating to the pulse energy. By applying pulse energies smaller than 2 µJ a significant enhancement in the ablation efficiency could be achieved due to an increased diameter and an increased depth of the ablated crater. For applied pulse energies greater than 2 µJ the ablated crater gets much smaller in the diameter relating to the ablated craters without an applied electric field. Whereby the effect for a negative applied electric field is more pronounced compared to a positive electric field. The crater created with the negative electric field-assisted ablation is roughly 5 % - 10 % smaller than with the positive electric field. Relating to the change in the removal depth, the electric field in both directions has more enhanced ablation in the depth. In general, the improvement by a negative electric field is much stronger.

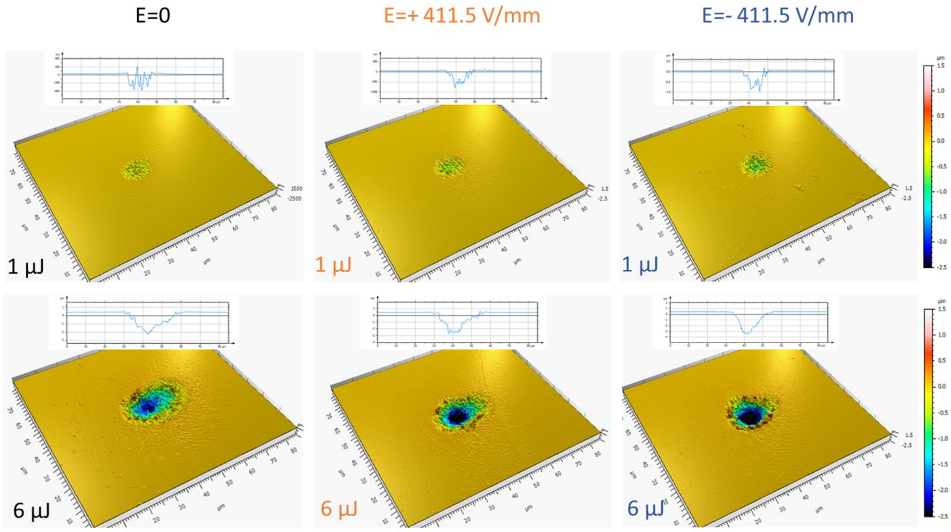

Fig.5. The confocal microscope picture of 20-pulse craters with low and high pulse energy in different processing conditions.

In addition, Fig. 5 shows three-dimensional images of selected ablated craters. For small applied pulse energies, the electric fields help to generate a more obvious ablation as the craters are deeper and wider in size. By using high pulse energies, it can be noticed that the crater with a negative electric field creates a deeper hole with a smaller size which indicates a better laser energy confinement with the help of an electric field. The crater with the positive electric field-assisted ablation is also slightly deeper and smaller compared to the traditional ablation process without an applied electric field.

The results of multi-pulse ablation show the same tendencies as after single-pulse ablation by applying an external electric field. Just the effect of an efficient ablation process is much more pronounced. For small pulse energies, an increase of up to 100 % in the ablation depth could be occurred compared to without an electric field. Moreover, by changing the direction of the applied electric field a defined control of the aspect ratio can be achieved. Those results regarded the same mechanism as introduced by single-pulse ablation, only the charge carrier excitation will be intensified due to enhanced energy coupling by using the incubation effect.

4. Conclusion

Fundamental and systematic investigations have been accomplished to study the ablation behavior for an enhanced ablation process by applying an external electric field parallel to the laser beam. By employing the electric field in both directions with a field strength of 411.5 V/mm, different effects are observed in different applied energy levels. In general, the effect is always stronger near the ablation threshold fluence and much more pronounced by an applied negative electric field. The ablated crater tends to be deeper instead of wider caused by the negative electric field, while multi-pulse ablation shows a significantly stronger effect compared to single-pulse ablation. A detailed theoretical study of this phenomena to understand the driving factors on the energy dissipation at the initial stage of laser ablation by an applied electric field is in progress.

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References

Bonse, J., Baudach, S., Krüger, J. et al., 2002. Femtosecond laser ablation of silicon–modification thresholds and morphology, Appl Phys A 74, pp. 19–25. https://doi.org/10.1007/s003390100893

Elhassan, A., Elmoniem, H. M. A., Kassem, A. K., Hairth, M. A., 2010. Effect of applying static electric field on the physical parameters and dynamics of laser-induced plasma, Journal of Advanced Research 1(2), pp. 129-136. https://doi.org/10.1016/j.jare.2010.03.004

Farrokhi, H., Gruzdev, V., Zheng, H., Zhou, W., 2019. Fundamental mechanisms of nanosecond-laser-ablation enhancement by an axial magnetic field, J. Opt. Soc. Am. B 36, pp. 1091-1100. https://doi.org/10.1364/JOSAB.36.001091

Ho, C.-C., Tseng, G.-R., Chang, Y.-J., Hsu, J.-C., Kuo, C.-L.,2014. Magnetic-field-assisted laser percussion drilling, Int J Adv Manuf Technol 73, pp. 329–340. https://doi.org/10.1007/s00170-014-5815-6

Liu, J. M., 1982. Simple technique for measurements of pulsed Gaussian-beam spot sizes, Opt. Lett. 7, pp. 196-198. https://doi.org/10.1364/OL.7.000196

Lu, Y., Sun, G.F., Wen, D.P., Zhang, Y.K., Feng, A.X., 2016. Effects of applying electric and magnetic fields on laser drilling, Int J Adv Manuf Technol 84, pp. 2293–2300. https://doi.org/10.1007/s00170-015-7842-3

Maksimovic, J., Ng, S.-H., Katkus, T., An Le, N.H., Chon, J.W.M., Cowie, B.C.C., Yang, T. Bellouard, Y., Juodkazis, S., 2020. Ablation in Externally Applied Electric and Magnetic Fields, Nanomaterials 10, p. 182. https://doi.org/10.3390/nano10020182

Maksimovic, J., Ng S.-H., Katkus T., Cowie B.C.C., Juodkazis S., 2019. External Field-Controlled Ablation: Magnetic Field. Nanomaterials 9(12), p.1662. https://doi.org/10.3390/nano9121662

Sun, J., Longtin, J.,2004. Effects of a gas medium on ultrafast laser beam delivery and materials processing, J. Opt. Soc. Am. B 21, pp. 1081-1088. https://doi.org/10.1364/JOSAB.21.001081

Tang, H., Qiu, P., Cao, R., Zhuang, J., Xu, S., 2019. Repulsive magnetic field–assisted laser-induced plasma micromachining for high-quality microfabrication, Int J Adv Manuf Technol 102, pp. 2223–2229. https://doi.org/10.1007/s00170-019-03370-5

Xiao, J., Liu , P., Wang, C.X., Yang, G.W., 2017. External field-assisted laser ablation in liquid: An efficient strategy for nanocrystal synthesis and nanostructure assembly, Progress in Materials Science 87, pp. 140-220. https://doi.org/10.1016/j.pmatsci.2017.02.004

Zhang, Y., Zhang, Z., Zhang, Y., Liu, D., Wu, J., Huang, Y., Zhang, G., 2021. Study on machining characteristics of magnetically controlled laser induced plasma micro-machining single-crystal silicon, Journal of Advanced Research 30, pp. 39-51. https://doi.org/10.1016/j.jare.2020.12.005