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COMPARATIVE NANOSTRUCTURING OF SILICON VIA LASER–PLASMA SYNERGY: TOWARD ENHANCED LIGHT MANAGEMENT IN PHOTOVOLTAICS

Summary

This study systematically investigates laser-assisted surface texturing of n-type silicon to increase the light absorption for next-generation photovoltaic (PV) technologies. Using nanosecond lasers at fluences of 1.5–5 J/cm² in cold plasma environments and ambient air, we examined the controlled formation of low- and high-spatial-frequency gratings, ripple formation, and etched structures. Laser ablation coupled with cold plasma enabled precise control for regular surface patterning by mitigating excessive energy coupling; however, ambient air promoted hydrodynamic instabilities and fracture-induced texture. Flowing gas further influenced etching dynamics and ripple stability. Raman spectroscopy confirmed consistent alterations in the structural properties of the textured material which turned out to be effective in improving the light-trapping features of the surface. These insights affirm laser-structured silicon as a promising and transformative platform for the development of scalable, high-efficiency photovoltaic (PV) devices and integrated solar energy systems.

Keywords: PV Technology, Surface texturing, DBD plasma, Scanning electron microscopy

1. Introduction

The modification of silicon surfaces through laser-induced periodic surface structures (LIPSS) has developed as a transformative method for improving the electronic and optical properties of materials, necessarily for advancing photovoltaic (PV) cell technology and integrated PV systems (sun et al. 2018) (Niyibizi et al. 2012). LIPSS, created by laser irradiation, produces micro- and nanoscale patterns that considerably enhance light absorption decreasing surface reflection, and enhancing charge carrier collection (Florian et al. 2020). Research studies in this field have traditionally favored ultrashort femtosecond lasers due to low thermal diffusion and specific control over energy deposition (Ren et al. 2021). However, nanosecond (ns) laser sources remain highly desirable for large-scale processing (Verma et al. 2022). Unlike anisotropic surface texturing LIPSS can be formed on silicon with arbitrary crystal orientation as well as micro and nanocrystalline material.

The latest advancements have investigated the use of cold atmospheric plasmas, specifically dielectric-barrier-discharge (DBD) plasmas, to control the laser ablation phenomena (Zeng et al. 2018) [6]. Laser ablation of silicon in a cold plasma atmosphere can reduce excessive thermal effects, allow more uniform energy coupling, and increase the fabrication of highly ordered LIPSS, foremost to superior surface functionalization critical for photovoltaic cells (Khan et al. 2023) (Morphy et al. 2018). Despite promising early investigation, the essential mechanisms and optimization approach for cold plasma-assisted ns laser surface texturing of silicon for PV applications remain marginally addressed in literature (Amirfeiz et al. 2000) (Vaghasiya et al. 2023).

In this study, we investigated the formation mechanisms of surface structuring on n-type silicon material using single and multiple nanosecond laser pulses at focus and off-focus points under two distinct environmental conditions: ambient air and atmospheric pressure cold DBD plasma. By examining the morphologic transitions, ablation characteristics of the material, and consequential surface properties, we aim to develop a direct pathway for improving the light-harvesting capabilities and optoelectronic performance of silicon surfaces, thus contributing to the next generation of high-efficiency PV cells and integrated photovoltaic systems.

2. Methodology:

In this study, surface structuring of n-type silicon (260 μm thick, 8–12 Ω·m) was achieved using nanosecond laser pulses (1064 nm, 30 ns) under three different environmental conditions: directed ambient air, and dielectric barrier discharge (DBD) plasma. The laser beam, linearly polarized and focused by using a convex lens (f = 180 mm), ablates the material at and below the focal point using 1–7 pulse laser shots. In the cold plasma-assisted configuration, , DBD plasma was generated by applying a 3–5 kV, 30 kHz sinusoidal voltage to a central copper wire electrode integrated with airflow. The laser fluence, ranging from 1.2 to 1.4 J/cm², was determined based on crater diameters considered via scanning electron microscopy (SEM). Post-laser irradiation, surface morphology and topography were characterized using SEM and Gwydion software. At the same time, Raman spectroscopy (using 532 nm light) was used to study changes in sound waves in areas of the material that were not much affected by heat.

3. Results and Discussion:

This study investigated the comparative structural analysis of silicon (Si) surface texturing across different environments and multiples (n = 2–7) pulse laser shots. The main purpose is to design micro/nano-scale periodic patterns tailored for improved photovoltaic performance through increased light absorption phenomena and photonic manipulation. In ambient air, laser-induced periodic surface structures (LIPSS) appeared as concentric high-spatial-frequency ripples (HSFL) with periodicities ~530–550 nm—approximately λ/2 specified at the periphery of the crater. These patterns, aligned perpendicular to the laser polarization beam, emerge surface plasmon polariton (SPP) excitation and polarization-governed energy coupling. However, the central zone showed excessive thermal load revealing improper melting pools and re-solidified debris on the surface of the materials as shown in figure 1(b). The morphology in the air is thus governed by capillary recoil pressure, thermal gradients, and wild melt dynamics, which compromise structural uniformity and problems for photovoltaic light-trapping architectures where surface symmetry is necessary.

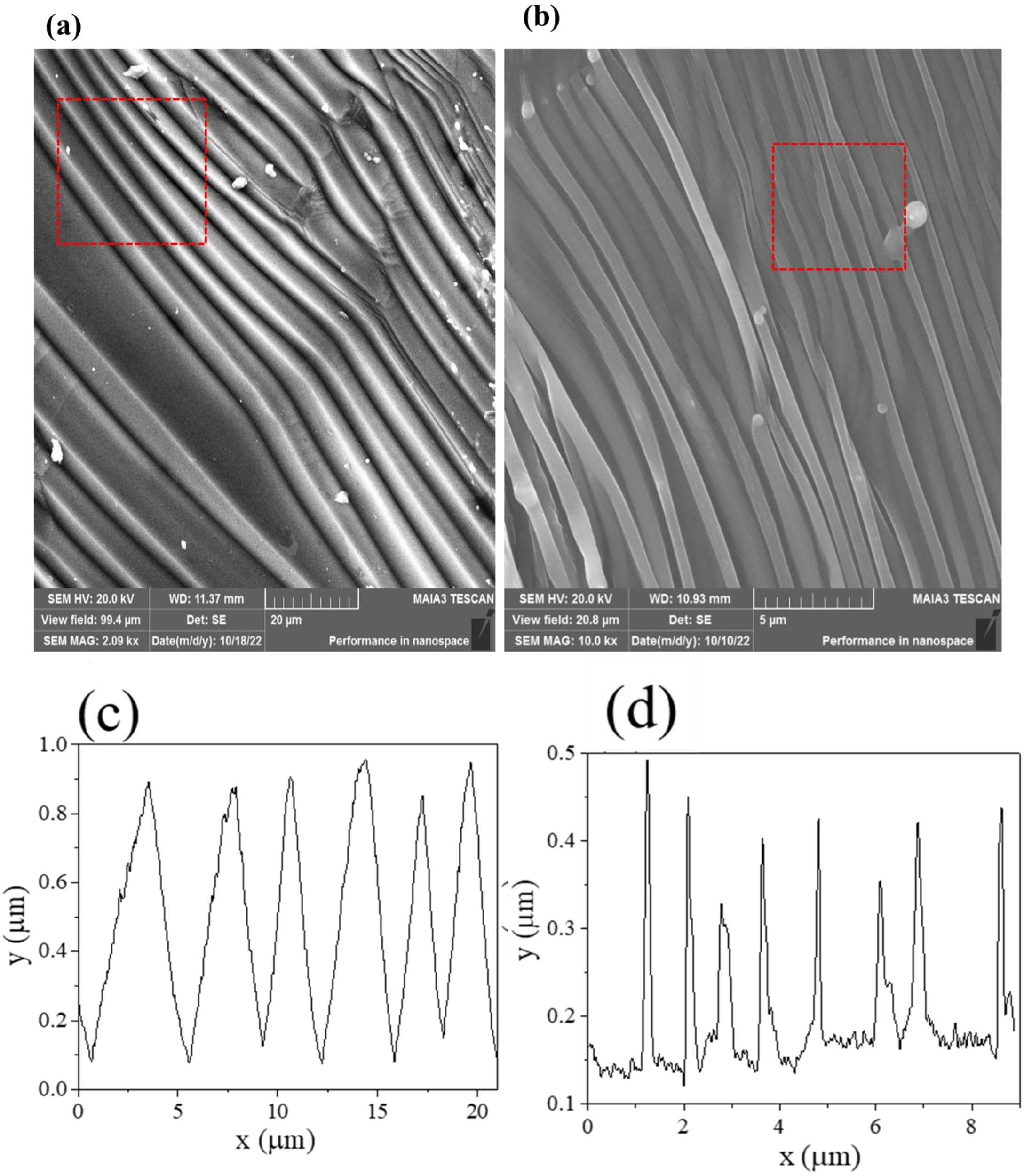

Fig. 1. SEM images of periodic surface structures made on Si using a laser power of 5 J cm⁻² (a) with DBD plasma and (b) in regular air. (c, d) Line scans show the surface profile in both conditions and point out the morphological differences.

Comparatively, in the DBD cold plasma atmosphere, a profound variation of the surface response is noticed. SEM and profilometry reveal the creation of both high and low-spatial frequency LIPSS, incorporating polycrystalline grating arrays with periodicities ranging from ~0.3 to 1 μm. Plasma-induced electron density gradients and refractive scattering improve optical interference properties at the ablation front, stabilizing ripple propagation phenomena. Significantly, Marangoni convection, underlying melt ejection, and spatially homogeneous thermal fields under cold plasma direct smoother ripple morphology, decreased central damage effects, and increased dimensional consistency are formed which shown in figure 1(a). The related line profiles, as depicted in Fig. 1(c–d), clearly reveal that alterations in the surrounding environmental conditions employ a definite influence on the surface morphology of the irradiated silicon. These topographies directly relate to increased photon trapping ability and enhanced surface passivation potential for photovoltaic silicon interfaces. with increasing the laser pulse number (n = 2–7), shows a non-linear ripple growth. With increasing n, LIPSS domains increase laterally, accompanied by hierarchical structure formation, redeposition of nanoparticles, and specified structural disruptions exceptionally at the interfaces between low and high-energy deposition zones. The dynamic interaction between SPP fields, thermally induced stress waves, and surface self-organization develops the complication of texture formation. Raman spectroscopy confirm phonon redshift and peak expansion, representing lattice strain and disorder, both helpful for tuning the bandgap in photovoltaic devices and optoelectronic applications. Crater morphology assessment highlights that DBD plasma generates ring-shaped ablation profiles with increased adjacent energy reorganization, in stark contrast to the irregular and thermally stressed patterns. These results prove that plasma-assisted nanosecond laser ablation achieves superior control over the morphology, stress states, and structure periodicity of the materials, all of which are important in enhancing the efficiency and consistency of silicon-based photovoltaic and photonic systems.

4. Conclusion

In conclusion, this examination provides compelling insights into the laser-assisted surface texturing of n-type silicon (n-Si<100>) for photovoltaic technology, emphasizing the pivotal role of ablation conditions. Cold DBD plasma considerably improved periodicity, precision, and spatial confinement of surface structuring, advancing well-defined micro/nanostructures ideal for light trapping. These processed morphologies, specifically under plasma-assisted ablation, show promising potential for advanced solar technology and integrated photonic platforms. The improvements in surface condition and optical functionality are essential to foster the technique’s industrial scalability.

5. References

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