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Multi-scale micro-nano structures prepared by laser cleaning assisted laser ablation for broadband ultralow reflectivity silicon surfaces in ambient air

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ABSTRACT

To meet the ultra-broadband perfect absorption of visible-infrared light on silicon surfaces, a green, efficient and economical method for fabricating multi-scale micro-nano composite structures in ambient air is proposed. We experimentally demonstrate laser cleaning assisted femtosecond laser ablation for fabricating anti-reflection structures. Laser cleaning technology not only effectively eliminates oxide deposition on the laser textured surfaces, but also manufactures the small scale fine-microstructures and nanostructures. A focused ellipse laser spot is innovatively applied to realize large area and energy decays continuously multiple laser cleaning of laser-treated surfaces, and solve the problem that new oxide deposition is generated in the cleaning process. The processing efficiency is also increased by 4.8 times. The average reflectance of 2.06% is reached from 300 to 2500 nm. Great enhancement of infrared light absorption of silicon from 2.5 to 16 μm is realized experimentally. The average reflectance is reduced to 4.98% with a broadband reflectance below 6.6%. Especially, a reflectance below 5.0% from 2.5 to 10 μm and an average reflectance of 4.3% is achieved, which is the least reported to date by laser processing techniques as far as we know. This strategy for anti-reflection structures is excellent candidate for future optoelectronic devices.

1. Introduction

Si is one of the most important materials for applications in silicon based solar energy cells and optoelectronic detectors [1,2]. In these applications, the high reflection at the air-silicon interface can hinder efficient light collection and greatly impact performance [3,4]. Therefore, anti-reflection Si surfaces are of widespread interests. Nature routinely produces micro-nano structures surfaces with useful properties and serve as an inspiration to scientists attempting to design anti-reflection Si surfaces [5–7]. There are several techniques for fabricating anti-reflection micro-nano structures, such as chemical etching, electrochemical etching, reactive ion etching, and surface plasmon resonance supported by metallic nanoparticles [8–12]. In the last few years, femtosecond (fs) laser processing has been demonstrated as a prospective approach due to its flexibility, simplicity, and controllability in creating various types of micro-nano structures, and are suitable for a wide range of applications [13–15]. Black Si surfaces with conical shape structures fabricated by fs laser in the presence of SF_6 and H_2S gases were studied by Mazur et al [16], and nanostructure-textured microgrooves by fs laser were also demonstrated by Vorobyev [17]. Reflection losses have been suppressed in the visible region, and the blackened surface has a reflectance less than 5%. Nevertheless, the reflectance of surfaces over the near-infrared spectrum (0.78–2.5 μm) has maintained about around 10%. There have been few reports of anti-reflection structures that work at infrared wavelengths (above 2.5 μm). It has been difficult to lower the reflectance in silicon surface below 20% in infrared range. For infrared wavelengths application like infrared detectors, infrared thermal imaging, fiber-optic communication, ultralow reflectivity Si surfaces are desired [18]. Overall, anti-reflection properties on Si surfaces meeting both broadband effectiveness and ultralow reflectance requirements are still great challenges for now. Therefore, the fabrication of broadband ultralow reflectivity black Si surfaces by fs laser have been a frontier and hot issue.

A large amount of deposited particles are produced on the material surface around the ablation area under laser irradiation [19]. If the processing environment is in ambient air, a great deal of foreign oxygen species is incorporated into the deposited particles. The silicon oxide deposition may have influences on the material and structural characteristics of silicon [20]. Most of the current reports on the fs laser induced black silicon are conducted in ambient gases [21–24] or vacuum [25,26]. Special laser processing environment makes equipment more complicated and increases processing costs, which would limit the

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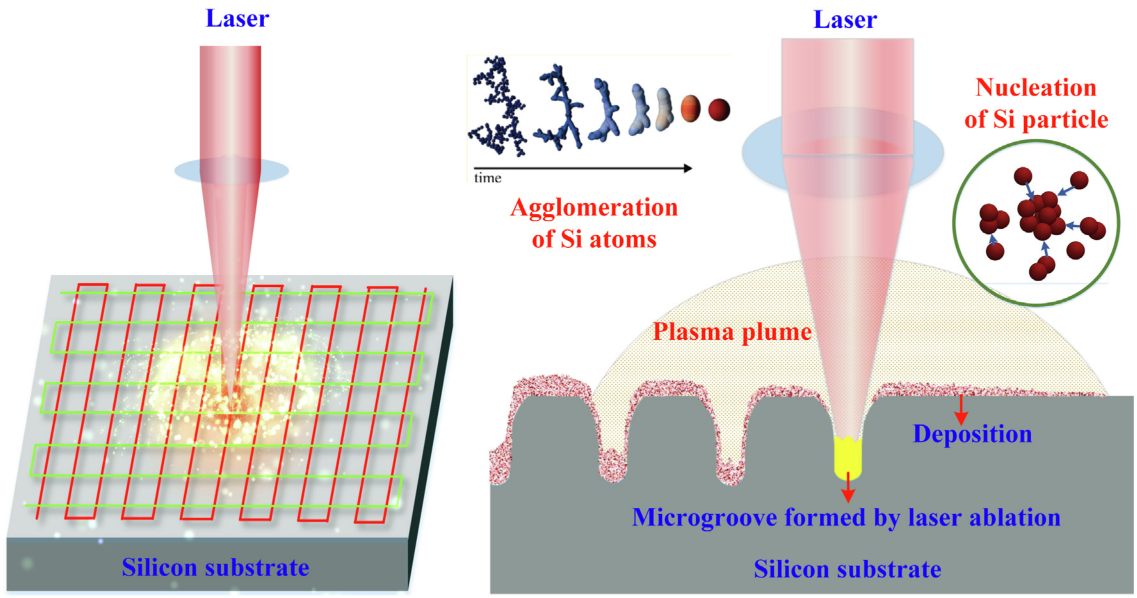

Fig. 1. Laser ablation dynamics for micro/nano-structures' generation and their deposition on the silicon substrate.

application of the method of laser induced black silicon. Although the silicon oxide deposition can be eliminated by HF acid, HF acid is very harmful to human body and the waste acid solution has a strong pollution [27]. How to fabricate textured Si surface by laser in a green, efficient and low-cost way and improve the anti-reflection properties becomes a problem with vital importance.

Laser cleaning, as a kind of green and environment-friendly cleaning method, has become a new surface treatment technology, which has been applied on a large scale in many fields [28]. In this technology, the laser ablation threshold of contaminant is less than the bulk material, so that the contaminant can first reach the ablation threshold of the material and then be removed by gasification, fragmentation and peeling, so as to realize the process of removing contaminant without damaging the bulk material [29]. In this study, the ablation threshold of silicon oxide deposition is less than the silicon material. Therefore, the principle of laser cleaning technology is used to remove the oxide deposition covering the Si surfaces with textured structures. The problem of application performance degradation caused by surface oxidation in laser processing of textured Si surface can be solved in a green and economical way.

We report a facile and economical method to fabricate multi-scale micro-nano composite structures by laser cleaning assisted fs laser ablation on silicon surfaces in ambient air. Large scale microstructures were fabricated by the laser ablation at the high laser fluence. In order to remove the laser-redeposited particles, a focused ellipse laser spot was applied to realize large area and energy decays continuously multiple laser cleaning of laser-treated surfaces. Laser cleaning technology not only effectively eliminates oxide deposition on the material surface, but also manufactures the small scale fine-microstructures and nanostructures. Micro-nano composite structures can not only give a full play to the superiority of the microstructure and nanostructure to improve absorbing efficiency, but can effectively broaden the absorption spectrum [30]. Our laser processing method is able to provide a cost effective solution for fabricating broadband ultralow reflectivity Si surfaces in ambient air. In especial, great enhancement of mid-infrared light absorption of silicon over a broad wavelength band is realized. Which is favorable for silicon based solar energy cells and optoelectronic detectors practical applications.

2. Materials and methods

2.1. Micro–nano structure fabrication

Commercially available p-type silicon wafers (1 0 0) with a thickness of 625 μm were used here. Before laser processing, the silicon wafers were rinsed in an ultrasonic cleaner with acetone, ethanol, and deionized water for 15 min, respectively. A Pharos 20 W femtosecond laser system (Light Conversion) delivering pulses with a duration of 240 fs and a repetition rate of 200 k Hz, was used to fabricate broadband ultralow reflectivity silicon surfaces. The laser beam has a Gaussian energy density distribution with a beam diameter of 4 mm (@ 1/e2). A scanning galvanometer (CTI, EC1000) equipped with a field lens (the focal length of 170 mm) was used to focus and scan the laser beam on the silicon surfaces. A focused round spot with the diameter of 30 μm was obtained, which was used for the micro-nano fabrication and laser cleaning of oxidized deposition. An ellipse laser spot with a long axis size of 4 mm and a short axis size of 8.28 μm was obtained by using a cylindrical lens($f' = 75$ mm). A motorized xyz stage (OWIS, PS-30), was controlled by a computer and used to precisely position the samples in the process of laser cleaning by ellipse laser spot. In order to realize large area and efficient processing, the laser scanning direction was perpendicular to the long axis direction of the cylindrical lens.

2.2. Characterization and measurements

Surface morphology and elemental incorporation in the micro-nano structured surfaces are analyzed using a scanning electron microscope (SEM) (Hitachi, Japan) and energy dispersive X-ray spectroscopy system (EDS) (INCA x-Sight, model 7426). The wavelength dependence of the overall reflectance in the ultraviolet (UV), visible (VIS), and near-IR (NIR) regions (300–2500 nm) was characterized with ultraviolet spectrophotometer (Shimadzu, Japan). And a Bruker Tensor-Fourier transform infrared (FTIR) spectroscope with an A562 type integrating sphere was used for measuring the wave-length dependence of the overall reflectance in the mid-IR (MIR) region (2.5–16 μm).

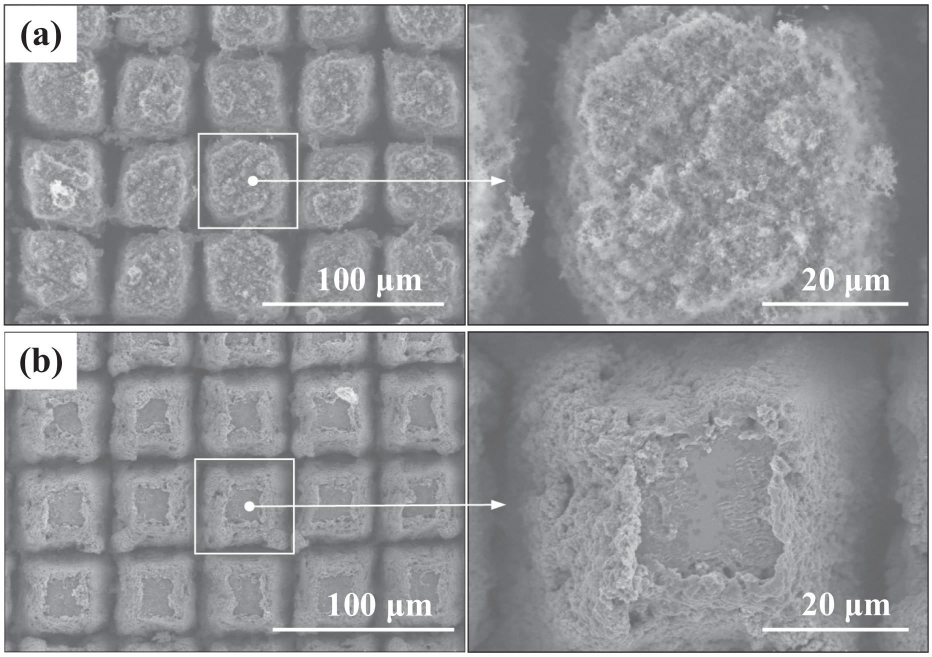

Fig. 2. (a) Morphology of microstructure formed by laser ablation. (b) Morphology of HF etched the laser textured Si surface.

3. Results and discussion

3.1. Formation of anti-reflection microstructures by laser ablation

Fig. 1 show the laser ablation for microstructures' generation. When the laser fluence is above the ablation threshold of the material, microgroove can be formed on the material surface via the laser scanning. Meanwhile, the irradiation of high-fluence laser pulses on material surfaces can form plasma plume, which consist of energetic species including atoms, clusters, and particulates. Some of them lose the initial kinetic energy before they can dissipate and deposit back onto the material surfaces due to the gravity force and the atmospheric pressure [13,31]. As we know, the larger the depth-width ratio of the groove, the more favorable the multiple reflections of the light in the groove and the lower the reflectivity. In order to improve the anti-reflection properties of material surface, multiple parallel-cross scanning way was applied to manufacture the microstructure.

Fig. 2a demonstrate that arrayed grid block microstructures by laser ablation on the silicon surface. It was found that a large amount of ablated particles were deposited onto the silicon surface under laser irradiation, and the surface of microstructures was covered with a layer of floccule. In order to measure the chemical composition of the silicon surface, EDS analysis was conducted. The analysis result showed that the chemical composition of the irradiated silicon surface were O and Si, the atomic percentage of silicon species was 70.28% and that of oxygen species was 29.72%, with the error limit of 7.09% and 4.21% respectively (see Fig. 3a, the etching time is 0 s). This result indicated that a great deal of foreign oxygen species was incorporated into silicon material during fs laser irradiation in ambient air. Specifically, the plasma plume is produced on the surface and discharged at high speed. It collides with oxygen molecules in the air and ionizes them, causing oxygen ions to enter the silica group and thus increase oxidation. The nucleation of the liquid silicon occurs at the gas-solid interface, and the surface of monocrystalline silicon is transformed into silicon oxide SiOx [32].

In order to study the effect of flocculated oxides on the reflectance of silicon materials surface, a simple approach, selective etching with HF, was employed. The etched sample was ultrasonically rinsed in deionized water for 15 min to remove the reactants. Fig. 2b show the morphologies of microstructures on the silicon surface after 40 min etching with HF. As can be seen, the flocculated oxides covering the silicon surface has been completely removed. Microstructures had regular four prism shapes, the top surface was relatively smooth with a small amount of nano-ripples, and the flank was covered with sub-micro-corrugations. Fig. 3 illustrates the change about the chemical compositions and the reflectance of the silicon surface microstructure in the waveband between 300 and 2500 nm under the different etching time. Results of the EDS analysis show that O is effectively eliminated with the increase of etching time (Fig. 3a). As demonstrated in Fig. 3b, the reflectance of the laser textured Si surface with oxide deposition was very high and the average reflectance was 23.98% (indicated by the red dash-dotted line). However, with the extension of etching time, the oxide deposition on the material surface was gradually removed, and the reflectance of the material surface was gradually reduced. After 2400 s etching with HF, the reflectance dropped to 9.2%. Therefore, it is an effective method to decrease the reflectance by removal of oxides on the silicon materials surface.

3.2. Improved anti-reflection performance by laser cleaning oxidized deposition with round spot

HF acid has a strong corrosive and intense irritating odor, which is very harmful to human body. The operational method of using HF acid is troublesome, and waste acid solution has great pollution to the environment. Therefore, it is not good to use HF acid to corrode the oxide deposition to improve the reflectance of laser textured Si surface.

Laser cleaning is a novel non-contact cleaning method, which is characterized by powerful removing force, high flexibility and environment-friendly method. Therefore, laser cleaning has been demonstrated as a potentially promising means to meet highly demanding cleaning needs. As the schematic illustration of laser cleaning of oxidized deposition by round spot shows in Fig. 4, the laser textured Si surface was covered with a layer of flocculent oxide deposition. The ablation threshold of the monocrystalline silicon and the silicon oxide deposition on the laser textured silicon surface can be compared by laser scanning ablation experiment. Two materials were ablated at the same laser fluence and different scanning velocities. Fig. S1 and Fig. S2 (Supporting Information) illustrates the evolution of the surface

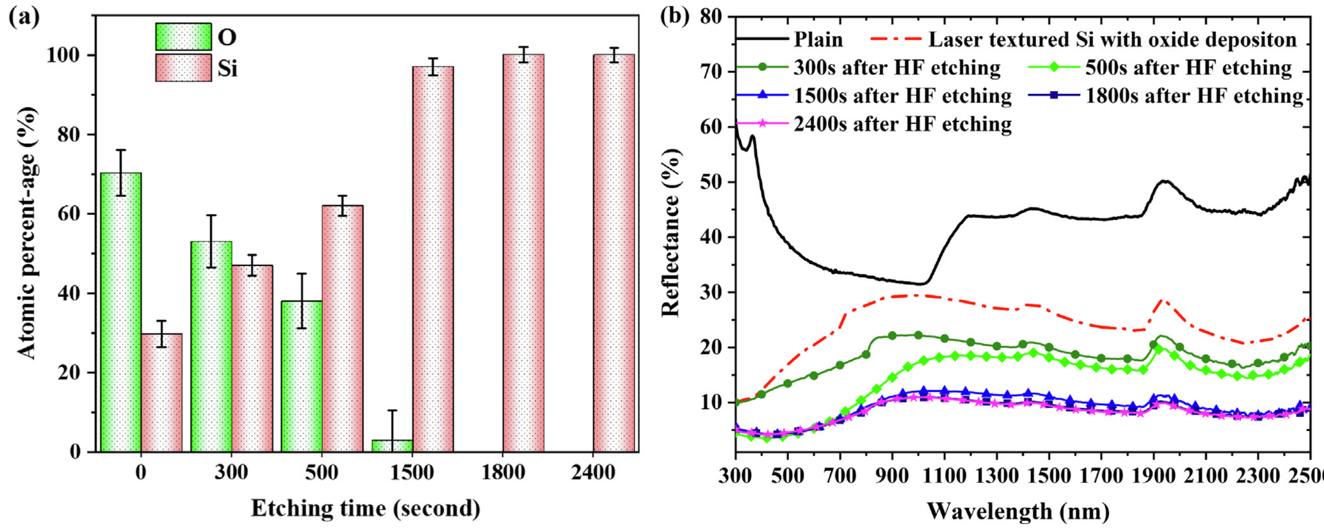

Fig. 3. (a) Chemical composition analysis of the silicon surface under the different etching time. (b) Evolution of surface reflectance of the silicon surface.

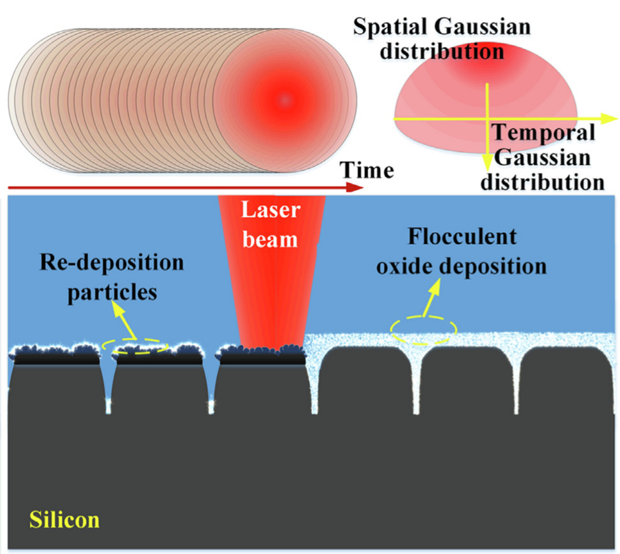

Fig. 4. Schematic illustration of laser cleaning of oxidized deposition by round spot.

morphology on the silicon and silicon oxide deposition under different laser scanning velocities, respectively. It found that when the scanning velocity was 200 mm/s, silicon surface will no longer be ablated (see Fig. S1d). But when the scanning speed was 300 mm/s, the surface morphology and elemental mapping analysis demonstrated that silicon oxide deposition still be ablated (see Fig. S2d and 2i), and it will no longer be ablated at the scanning velocity of 500 mm/s (see Fig. S2e and 2j). Therefore, the experiment can prove that the ablation threshold of the silicon oxide deposition is less than the monocrystalline silicon. Therefore, the appropriate laser ablation parameter can be utilized to clean the silicon oxide deposition from the silicon surface. Laser-induced micro-nano structures on the silicon surface can be produced with laser fluence close to the ablation threshold of the material [33]. Then, the laser fluence close to the ablation threshold of the silicon was applied to clean the laser textured Si surface, and micro-nano structures were induced on the surface of grid block microstructures after the oxide deposition was fully removed by laser cleaning. As is well-known, microscale structures can produce a geometrical light-trapping effect and generate a multiple internal reflection process. Nanoscale structures can act as effective medium layers to alleviate the optical impedance mismatch between the solid substrates and air. It undoubtedly provides us with a new idea of broadband ultralow reflectivity Si surfaces by preparing multi-scale micro-nano composite structure in ambient air.

Fig. S3 illustrates the evolution of surface morphologies by laser cleaning under different laser scanning velocities. When the laser scanning velocity was 15 mm/s, the spot-overlap number was little and there was not enough laser energy to ablate. Therefore, as shown in Fig. S3a, part of the flocculent silicon dioxide deposition was melt and solidified on the material surface. There were a large amount of nano- and fine-micro structures formed on the material surface. The color of the material surface changed from adobe brown to gray to the naked eye in natural light (see Fig. 5a–b). Upon decrease the scanning velocity, increasing the incident energy per unit area caused remarkable changes in the material surface (see Fig. S3b). The flocculent silicon dioxide deposition was ablated and fine-microstructure was induced on the material surface. Meanwhile, it found that the silicon surface was cover with a layer of nanometer-scale flocculent structures. To the naked eye, the color of the material surface changed from gray to black (see Fig. 5b-c). As the scanning velocity continued to decrease, the phenomenon of ablation changed remarkably on the material. As shown in Fig. S3c, microstructures were produced and silicon surface was apparently rougher and covered by abundant particles of varied dimensions.

It was clear from Fig. S3b–c that laser cleaning technology not only eliminated oxide deposition on the material surface, but also fabricated multi-scale structures with substantial nanoparticles and fine-microstructures hierarchically attached on regularly arrayed four prism shapes microstructure surface. Fig. 5d shows the experimental reflection spectra of the laser textured Si surfaces by laser cleaning assisted at different laser scanning velocity. The reflectance of silicon surface was significantly reduced as the flocculent silicon dioxide was removed by laser cleaning. When the laser cleaning velocity was 5 and 10 mm/s, the average reflectance of silicon material dropped to 6.2% and 5.3%, respectively. Which were obviously better than the average reflectance after etching with HF (9.2%). The results further proved micro-nano structures induced on silicon surface by laser cleaning could optimize geometrical light trapping and enhance effective medium effect, which was more conducive to the reduction of the reflectance than HF acid etching. In our experiment, the lowest average reflectance of 5.3% was achieved by laser cleaning at 150 mW, with a 10 mm/s scanning velocity, 10 μm scanning pitch, after the optimization of laser cleaning parameter by round spot.

Meanwhile, we also found that the laser cleaning at the scanning velocity of 10 mm/s was superior to the scanning velocity of 5 mm/s in

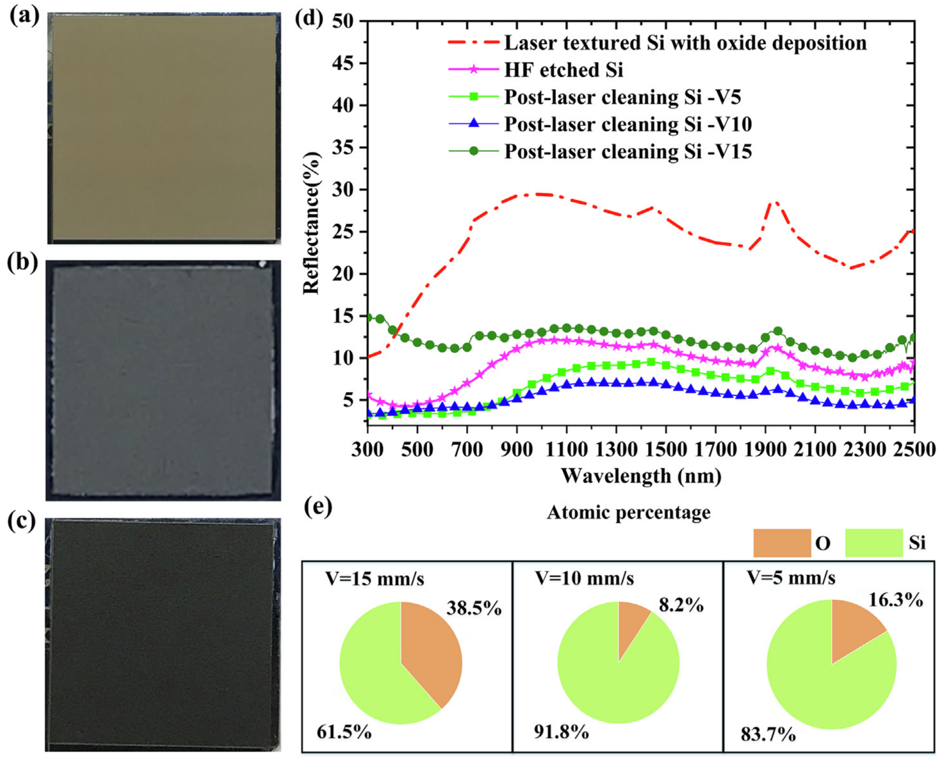

Fig. 5. (a) Photographs of the laser textured Si surface with oxide deposition. (b)–(c) Photographs of Si surface by laser cleaning with the laser scanning velocity of 15 and 10 mm/s, respectively. (d) Surface reflectance of the micro–nano structures. (e) Chemical composition analysis of the silicon surface.

removing the optical reflection from laser textured Si surfaces. This was because there was a significant amount of re-deposited particles on the Si surface after the laser cleaning (see Fig. S3b–c). As shown in the Fig. 5e, the results of EDX measurements indicated that foreign oxygen species were incorporated into silicon material during the process of laser cleaning. At the low scanning speed, more ablative particle deposition led to more obvious oxidation on silicon surface.

Although the laser energy can induce the micro-nano structure after cleaning the oxide deposition on Si surface, new oxide deposition particles were generated in the process of inducing the micro-nano structure in the air. How to solve the oxide deposition in the process of laser cleaning is a new problem to further improve the surface properties of silicon materials.

3.3. Improved anti-reflection performance by laser cleaning oxidized deposition with ellipse spot

The effective removal of oxide deposition on the materials surface can be achieved with round spot by reducing the laser cleaning energy for many times, but this treatment method is undoubtedly time-consuming and costly. An ellipse laser spot can be obtained by using a cylindrical lens when the laser beam was focused at normal incidence onto the surface of the sample. The schematic illustration of laser cleaning of oxidized deposition by elliptic spot is shown in Fig. 6. Due to the long axis of the ellipse laser spot was not focused by the lens, a wide range and small variation gradient of energy distributions conforming to the Gaussian function can be obtained (Fig. 6a). In pulsed laser line scanning, the chronological order of pulses is shown in Fig. 6b. This way, in a certain zone, such as the gray zone (Fig. 6b), the laser fluence as the scanning time goes is shown in Fig. 6a. Obviously, the laser fluence is also a Gaussian function of pulse serial number, which is the same as the energy density distribution across the laser beam. The low laser fluence (the right of blue arrow region) is suitable to remove the flocculent silicon dioxide deposition. The high laser fluence (red double arrow region) can be used to remove the flocculent silicon dioxide deposition and induce the micro-nano structure. The low laser fluence (the left of blue arrow region) can be used to remove the re-deposited oxide particles generated in the process of inducing the micro-nano structure by the high laser fluence in the air.

The laser fluence decays continuously with a small gradient along the long axis of the ellipse spot from the high energy region to the low energy region. Therefore, by virtue of this feature, a certain zone can be realize the multiple laser cleaning of oxide deposition particles with stepless decreasing laser energy (Fig. 6c). It can solve the problem that round spot requires multiple laser scanning through energy degradation and greatly improves the processing efficiency.

To optimize the antireflection properties of the laser textured Si surfaces by laser cleaning with ellipse spot, the different processing parameters, including the power, scanning velocity and scanning pitch, were tuned. Fig. S4 shows the experimental reflection spectra and chemical composition of the laser textured Si surfaces by laser cleaning at different laser powers, scanning velocities and scanning pitches. We can find that the reflectance of silicon surface and the atomic percentage of O species all appeared the evolution rule of falling first and then rising with the increase of laser processing parameters. As the power of laser cleaning increased from 400 mW to 600 mW, more intense ablation led to the removal of more material. The spot-overlap numbers decreased with the scanning velocity increasing from 4 to 12 mm/s, which resulted in the reduction of the ablation degree. Too weak laser ablation cannot completely remove the oxide deposition on the laser textured Si surface. If the laser ablation was too intense, the surface melting of the material would affect the hierarchy of the micro-nano structures, and more new oxide deposition would be generated. The ablation-overlap area would decrease with the scanning pitch increasing from 40 to 80 μm. Too small scanning pitch would cause excessive cleaning, which led to the melting of micro-nano structure and the increase of deposition particles. Too big scanning pitch would result in inadequate cleaning. Therefore, appropriate laser ablation parameters were selected to clean the oxide deposition on Si surface to improve the reflectance.

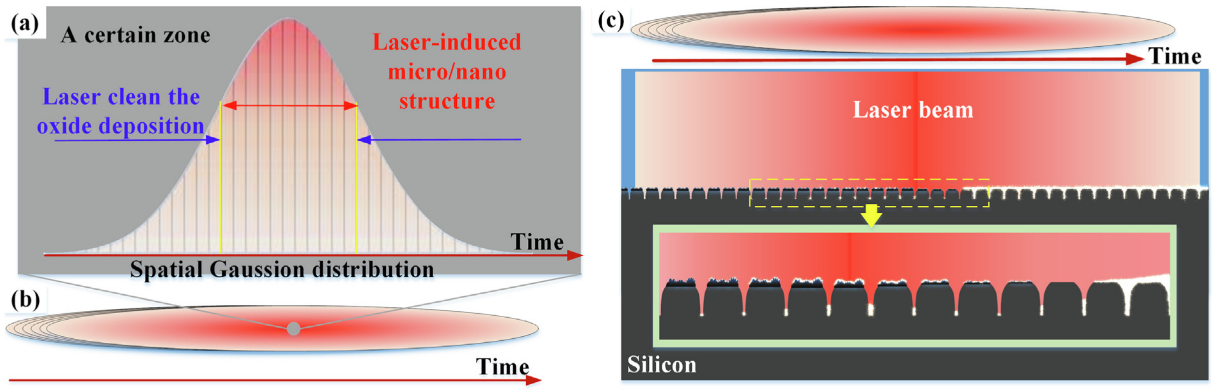

Fig. 6. Schematic illustration of laser cleaning oxidized deposition by ellipse spot. Inset "a" shows the irradiating laser fluence as the time goes (also mean the chronological order of pulses) for a certain zone. Inset "b" is the chronological order of pulses in laser line scanning. Inset "c" is the explanation of the cleaning mechanism of oxidized deposition by ellipse spot.

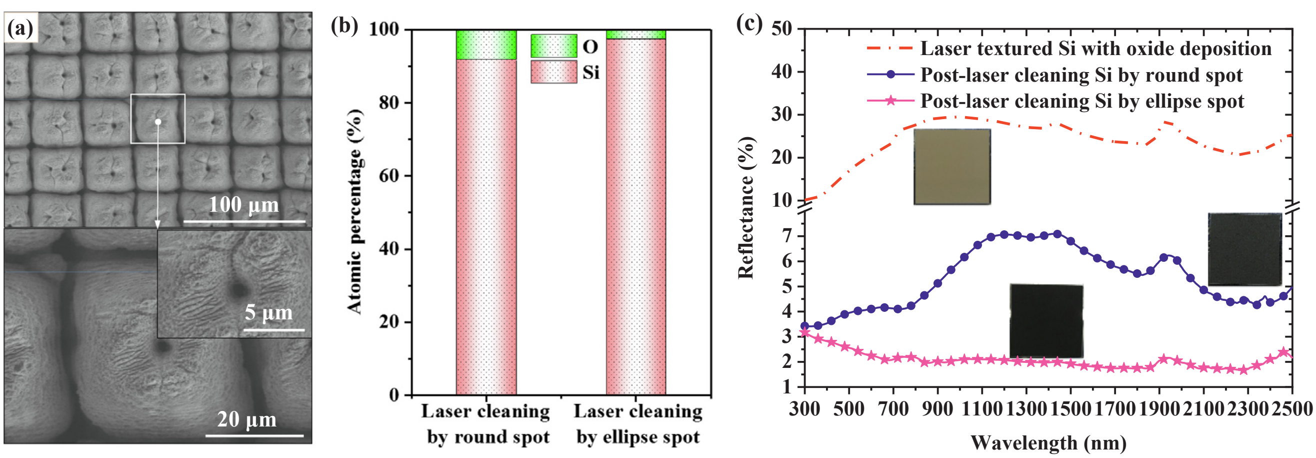

Fig. 7. (a) SEM images of surface structure morphologies by laser cleaning at 500 mW, with 8 mm/s scanning velocity, 60 μm scanning pitch. (b–c) chemical composition analysis and reflection spectra of the laser textured Si surfaces with and without laser cleaning by round spot or ellipse spot, respectively.

In our experiment, broadband ultralow reflectivity Si surface was achieved by laser cleaning at 500 mW, with 8 mm/s scanning velocity, 60 μm scanning pitch, which improves the processing efficiency for 4.8 times compared to the laser cleaning by round spot. We clearly observed that the nano and fine-micro structures were induced on the surface of grid block microstructures, and multi-scale micro-nano hierarchical structures prepared on silicon surface (SEM images of surface are shown in Fig. 7a). The varied dimensions of those features were beneficial for broadening the effective wavelength range of the light trapping and surface plasmon resonances, which could result in a more efficient effective medium. The result of EDX measurement indicated that O was effectively eliminated and was superior to the method of laser cleaning oxidized deposition by round spot (see Fig. 7b). As shown in Fig. 7c, the average reflectance was 2.06%, and reflectance minimum of 1.48% was reached in the wavelength ranges of 300–2500 nm, which was obviously better than the average reflectance by round spot (5.3%). This result also proved that the effective removal of oxidized deposition on the material surface was beneficial to reducing the reflectance of the material surface. A broadband reflection was reduced to below 2.86% over visible to near-infrared broadband spectrum regions. However, more importantly, we demonstrated an average reflectance of 1.94% throughout the NIR spectrum in the 780–2500 nm range, which was the least reported to date by laser processing techniques, to the best of our knowledge. The problem that it was difficult to realize the low reflectance on silicon surface due to the surface oxidation by laser processing in the air was solved.

The anti-reflection performance of silicon in the long wavelength range is relatively poor. Up to the date, there have not been reports on direct fabrication of black silicon with enhanced mid-infrared (MIR) absorption in ambient air. In this context, we demonstrated an improved anti-reflection property as a function of wavelength in the region 2.5–16 μm. As shown in Fig. 8, great enhancement of MIR

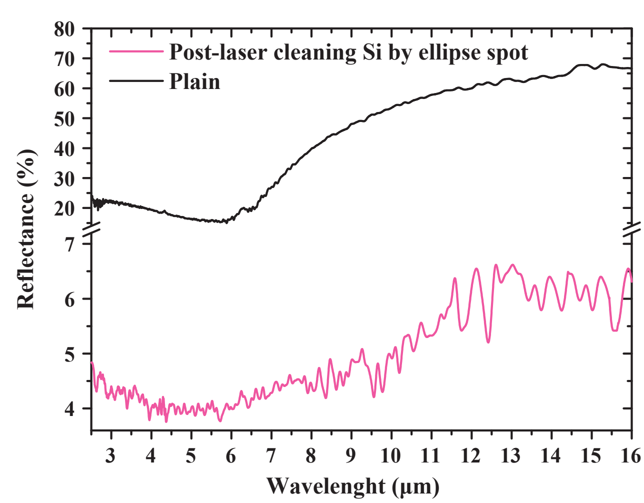

Fig. 8. Reflection spectra of micro-nano structures prepared by laser cleaning assisted laser ablation irradiation and untreated silicon in MIR region (the wavelength of 2.5–16 μm).

absorption of silicon over a broad wavelength band was realized experimentally. The result showed that the average reflection was reduced to 4.98% with a broadband reflection below 6.6%, which advances 8.7 times compared to the initial Si surface. Especially, a reflection below 5.0% from 2.5 to 10 μm and an average reflection of 4.3% was achieved, which was the lowest reflectance experimentally achieved on silicon surfaces by laser processing techniques as far as we know.

The antireflection structures are naturally and in situ formed via ultrafast laser interaction with silicon surface in ambient air, with no extra materials needing to be added. The advantages of this approach not only simplify the experimental devices and greatly reduce the processing cost, but also produce the broadband ultralow reflectivity silicon surfaces over large areas. All these advantages make the prepared method excellent candidates for practical solar energy cells and optoelectronic detectors.

4. Conclusions

We propose a facile and economical method to fabricate multi-scale micro-nano composite structures by laser cleaning assisted femtosecond laser ablation on silicon surfaces in ambient air, which has the potential to outperform the state-of-the-art methods for broadband ultralow reflectivity Si surfaces, and solve the problem that the preparation of black silicon by laser processing requires protective gas. Large scale microstructures covered with oxide deposition are fabricated by the laser ablation at the high laser fluence. A simple approach, selective etching with HF, was used to demonstrate that an effective method to decrease the reflectance by removal of oxides on the silicon materials surface. Laser cleaning is innovatively proposed to remove oxide deposition from laser-treated surfaces to improve the reflectance of the material surface. Laser cleaning not only effectively eliminates oxide deposition, but also induces the small scale fine-microstructures and nanostructures on silicon surface. The average reflectance of silicon material dropped from 23.98 to 5.3%. Which were obviously better than the average reflectance after etching with HF (9.2%). In order to solve the problem that new oxide deposition particles are generated in the process of inducing the micro-nano structure by round laser spot. A focused ellipse laser spot is applied to realize large area and energy decays continuously multiple laser cleaning of laser-treated surfaces and further improve antireflection performance. As a result, comprehensively improved antireflection performances can be realized. The average reflectance is 2.06% in the wavelength ranges of 300–2500 nm. A broadband reflectance is reduced to below 2.86% over visible to near-infrared broadband spectrum regions. Great enhancement of infrared light absorption of silicon over a broad wavelength band (2.5–16 μm) is realized experimentally. The average reflectance is reduced to 4.98% with a broadband reflectance below 6.6% (advance 8.7 times in infrared wavelengths compared to the initial Si surface). Especially, a reflection below 5.0% from 2.5 to 10 μm and an average reflection of 4.3% is achieved. In the same time, the efficiency of laser cleaning can be improved 4.8 times by using ellipse spot instead of round spot. Which is favorable for future applications in silicon based solar energy cells and optoelectronic detectors.

CRediT authorship contribution statement

Tong Chen: Conceptualization, Methodology, Data curation, Writing - original draft. **Wenjun Wang:** Resources, Methodology, Funding acquisition. **Tao Tao:** Software, Visualization, Investigation. **Aifei Pan:** Software, Validation, Writing - review & editing. **Xuesong Mei:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsusc.2019.145182.

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