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Tailoring Femtosecond-Laser Processed Black Silicon for Reduced Carrier Recombination Combined with >95% Above-Bandgap Absorption

Xiaolong Liu,* Behrad Radfar, Kexun Chen, Toni P. Pasanen, Ville Vähänissi, and Hele Savin

The femtosecond-pulsed laser processed black silicon (fs-bSi) features high absorptance in a wide spectral range but suffers from high amount of laser induced damage as compared with bSi fabricated by other methods. Here, the aim is to minimize the charge carrier recombination in the fs-bSi caused by laser damage as indicated by the sub-bandgap absorption and as quantified by the carrier lifetime, while maintaining high absorption in the above bandgap. The effect of the laser parameters, including the focal position, the average power, and the scan speed are systematically studied by characterizing the surface morphology, the absorptance spectra, and the minority-carrier recombination lifetime. For the surface passivation of fs-bSi, the well-established atomic layer deposited (ALD) Al₂O₃ is used. The results show that with the tailored laser parameters, high average absorptance of about 96% in the visible range and minority carrier lifetime of 54 μ s at the injection level of $\Delta n = 1 \cdot 10^{15}$ cm⁻³ can be obtained simultaneously. This work paves the way toward high-performance broadband optoelectronic devices based on surface passivated fs-bSi.

1. Introduction

Black silicon (bSi) features surface textures from micro- to nanoscales, exhibiting reduced optical reflection and thus enhanced absorption.^[1–4] It is generally acknowledged that the antireflection effect due to the surface textures contributes to the high absorptance for wavelengths below 1.1 μ m,^[5] which applies especially to the visible range (400–750 nm) and as a result the bSi shows darkened color to naked eyes. High visible absorption can be obtained with different fabrication methods with optimized surface morphology, and those methods include, e.g., electrochemical etching,^[6] stain etching,^[7] metal-assisted

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chemical etching,^[8] reactive ion etching,^[9] and so on. Among these methods, the high-intensity femtosecond-pulsed laser is a promising alternative to process black silicon surface (fs-bSi).^[4] Despite the disadvantages of laser processing such as low throughput and induced structural defects to the material as compared to other methods, the most significant advantage of the fs-bSi is its possibility to attain changes in optical properties in the broadest wavelength range, even for wavelengths beyond the band gap of Si ($\lambda > 1.1 \,\mu$ m).^[10,11] Thus, the fs-bSi has a high promise in applications that benefit from broadband responsivity extending from UV to IR such as photodetectors and solar cells.^[12,13]

There are several mechanisms that explain the sub-bandgap absorption in fs-bSi especially at near IR. For instance, fs-laser processing has the capability to tex-

ture the surface and simultaneously introduce dopants in high concentration in controlled atmosphere, e.g., S in SF₆ atmosphere.^[14] The incorporation of supersaturated dopants in Si (so-called hyperdoping) is known to form intermediate bands within the bandgap, which generate electron-hole pairs by absorbing photons with energy below the band gap of Si.^[15] while the surface texture further reduces the reflection. These mechanisms allow to achieve near-unity absorption in broad wavelength region.^[10,11] Additionally, it is known that the laser processing also induces lattice damage which forms to the Urbach states in band tails, which also leads to some increase in IR absorption below the Si band edge.^[16,17] However, in most cases, the contribution of the laser-induced lattice damage to the spectral absorptance is hidden from the strong sub-band gap absorption induced by the supersaturated dopants. To better manifest the contribution of the laser-induced defects to the sub-bandgap absorption so that the level of the laser damage could be determined, the fs-bSi can be fabricated without deep-level dopant precursors.[16,17]

Although the laser damage can contribute to the sub-bandgap absorption, it is mostly considered harmful as it facilitates bulk carrier recombination reducing the charge collection in the final devices. In the past, the reduction of laser induced damage has relied mainly on post laser treatments aiming to repair crystal-linity.^[12,16,17] However, such treatments require additional

X. Liu, B. Radfar, K. Chen, T. P. Pasanen, V. Vähänissi, H. Savin Department of Electronics and Nanoengineering Aalto University Tietotie 3, FI-02150 Espoo, Finland E-mail: xiaolong.liu@aalto.fi

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adpr.202100234.

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processing which may also harm the material bulk properties, especially if not done in clean environment. Therefore, it is much more compelling to tackle the origin of the damage, i.e., the laser parameters during the texture fabrication. Since the laser parameters also affect the surface morphology determining the optical absorption,^[18] one needs to balance between the optical absorption and the recombination level induced by laser.

In addition to the damage induced by the laser, there is another recombination mechanism present that is associated with the dangling bonds at the silicon-air interface, which is further enhanced along with increased surface area resulting from the surface texture. For reducing such surface recombination, the so-called surface passivation is essential. The aluminum oxide (Al₂O₃) fabricated using atomic layer deposition (ALD) is preferred choice for the passivation film because it can provide excellent surface passivation due to the high fixed negative charge and low defect density at the interface between Si and Al₂O₃.^[19,20] It is well established that the ALD has excellent conformality and therefore it is especially well suited deposition method for passivating irregular surface micro/nanostructures. Consequently, it has been successfully applied to various bSi surfaces with low surface recombination velocity.^[20,21] Indeed, highperformance b-Si optoelectronic devices have been demonstrated using ALD Al₂O₃ passivation.^[22–28] When using such excellent surface passivation layer, in the fs-bSi samples the effective carrier lifetime (τ_{eff}) used to quantify the overall carrier recombination is more likely to be limited by the laser induced defects within the surface texture. It is rather surprising that the surface passivation has been often neglected in the fs-bSi and the carrier lifetime of the fs-bSi has been rarely reported. The best lifetime reported for fs-bSi in literature is only in the order of some µs and even that result required rather heavy tradeoffs in optical properties.^[29] This indicates that the properties of the fs-bSi are rather different from bSi structures fabricated by other methods, where several ms in lifetime have been demonstrated.^[19] Consequently, there is potential to reduce the carrier recombination and improve the carrier lifetime also in fs-bSi surfaces.

This work aims to minimize the laser-induced carrier recombination during laser processing without sacrificing the low reflectance of the fs-bSi in the visible range. The fs-bSi is fabricated in ambient air by high repetition rate fs-laser with high scan speed up to 2000 mm s⁻¹. The impact of different laser parameters is systematically investigated by characterizing the

surface morphology, the absorptance spectra and the effective carrier lifetime. The surface passivation scheme of ALD Al_2O_3 is applied for reduced surface recombination so that the overall recombination is limited by the laser-induced recombination active defects. The minority carrier lifetime that is a criteria of recombination activity is characterized by the well-established quasisteady-state photoconductance (QSSPC) method. In addition to the carrier lifetime, the contribution of laser induced damage is characterized qualitatively by measuring the sub-bandgap (NIR) absorption. Additionally, the surface saturation current density, J_0 , is extracted from the lifetime measurement to examine the recombination level in the vicinity of the laser-processed surfaces. Finally, the trade-off between the optical absorption and the carrier lifetime is discussed.

2. Results and Discussion

In our experiments, silicon surfaces are textured under varied laser parameters, or more specifically, the laser focal position (Δz) , the average laser power (P), and the laser scan speed (ν) are varied. As shown in Figure 1a, the laser focal position, Δz , is the distance between the Si surface and the laser focus point, determining the laser spot size and thus the laser energy density (laser energy divided by spot area), i.e., the fluence (F). To texture a larger area on Si surface than the size of the laser spot, the surface is raster-scanned by the laser pulse (Figure 1b) with a certain scan speed, ν . It is worth mentioning that the fabrication speed is proportional to the ν . Owing to the high repetition rate (417 kHz) of our laser system, a high ν up to 2000 mm s^{-1} can be used to texture the surface, which is especially suitable for patterning large areas. In contrast, fs-bSi is fabricated with only \approx 1 mm s⁻¹ with 1 kHz repetition rate fs-laser in most cases,^[12,30] which is 2000 times slower than our setup. Detailed experiment and process flow chart (Figure 1c) are described in the Method section.

2.1. Fs-bSi Samples Fabricated at Laser Focus

Figure 2a presents the absorptance spectra of fs-bSi areas (each $1 \times 2 \text{ cm}^2$ in size) fabricated with different focal positions using the same substrate. Regardless of focal position, enhanced optical absorptance is obtained compared with that of planar Si across the whole measured wavelength range. The fs-bSi area



Figure 1. Fs-laser processing diagrams and experimental process flow chart.



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Figure 2. Optical and electrical properties of fs-bSi samples processed near laser focus (P = 11 W and $\nu = 500$ mm s⁻¹). a) Absorptance spectra of fs-bSi samples with different focal positions (Δz). b) Injection-level (minority carrier density, Δn)-dependent effective carrier recombination lifetime (τ_{eff}) for ALD-passivated planar silicon and fs-bSi samples with different Δz .

fabricated at laser focus point ($\Delta z = 0$) exhibits the highest absorptance of $93.6 \pm 0.3\%$ averaged over the visible range (380-750 nm). The samples fabricated in other focal positions show clear reduction in absorptance in all measured wavelengths, as the absorptance generally decreases with increasing Δz and surface textures can be barely created when the $\Delta z > 2$ mm. The lowest absorptance measured from the fs-bSi samples is $78.7 \pm 0.8\%$ averaged over the visible range at $\Delta z = 2$ mm, which is still higher than that of the planar Si (63.1 \pm 3.9%). Regarding sub-band gap (NIR) absorptance $(\lambda > 1100 \text{ nm})$, additional conclusions can be made. Although the fs-bSi samples are fabricated in air and as a result the samples are inevitably doped with O2 and N2, these dopants are not significantly contributing to the NIR absorptance.^[16,17,17] Therefore, the measured absorptance in NIR indicates the presence of laserinduced lattice defects.

In practical devices, high absorptance does not always guarantee good device performance when it is limited by the minority carrier recombination (i.e., the carrier lifetime is poor). Here the effective carrier lifetime, $\tau_{\rm eff}$, is measured as a function of the injection level, or the minority carrier density, Δn (Figure 2b), with ALD Al₂O₃ surface passivation layer. We measure the $\tau_{\rm eff}$ from the passivated planar Si for reference, which shows a high $\tau_{\rm eff}$ of 8.5 ms at the $\Delta n = 1 \cdot 10^{15}$ cm⁻³ (the same injection level reported below for all samples unless otherwise stated). This suggests that our Si substrate has high bulk quality and the ALD Al₂O₃ provides excellent surface passivation. However, the fsbSi samples exhibit much lower lifetime with the lowest $\tau_{\rm eff}$ of 19 µs measured in sample with $\Delta z = 0$. Note that this sample features the highest absorptance while in other samples with lower absorptance, e.g., the sample with $\Delta z = 2$ mm (Figure 2b), τ_{eff} is much higher. This means that there is a trade-off between the optical absorptance and the minority carrier lifetime of fs-bSi, and the laser processing has clearly a negative impact on the lifetime. Thus, it is challenging to increase the τ_{eff} by changing the focal position without losing the optical properties. Please note that the anomalously high lifetime for the fs-bSi at lower injection ($\Delta n < 10^{15}$ cm⁻³) compared with that in the higher end most likely originates from a known phenomenon called trapping in the photoconductance-based lifetime measurement,^[31] whereas the curve is almost flat for planar Si at the $\Delta n < 10^{15}$ cm⁻³. This result confirms that there is a high density of laser-induced minority trap states present inside the fs-bSi.

As laser substantially changes the surface morphology, which is important for both enhanced absorptance and surface passivation, cross-sectional SEM is performed for the fs-bSi sample with $\Delta z = 0$ so that the reasons for poor lifetime could be possibly inferred. As seen in **Figure 3**a, after laser processing the surface contains deep grooves down to 60 µm with semienclosed entrance. As visible on a smaller scale in Figure 3b, the surface layer also contains pores that are in micro and nano sizes, which are hidden from the ambient and thus cannot be passivated conformally by the ALD Al₂O₃. In Figure 3c, the height of the laser textured area clearly overtops the original surface, suggesting that a µm-thick recast layer forms during the laser melting and recrystallization.^[32] The recast layer, as well as the surface debris near



Figure 3. Cross-sectional SEM images of the fs-bSi processed in laser focus position (corresponding to the $\Delta z = 0$ in Figure 2).



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Figure 4. Cross-sectional (first row, same scale bar) and 30° tilted view (second row, same scale bar) SEM images of fs-bSi samples fabricated by 1-line laser scan at different scan speeds, ν ($\Delta z = 0$, P = 11 W).

the laser textured area, contain both multicrystalline and amorphous Si structures, hence increasing the recombination due to lattice disorders.^[33] Above all, the poor lifetime of the fs-bSi sample is attributed to the failed conformal deposition of passivation film and the heavy recombination present in the fs-laser-processed structures, both of which can be inferred from the surface morphology which seems highly damaged by laser processing.

2.2. Tailoring Surface Morphology for Reduced Recombination

The surface morphology presented above is clearly not favorable for efficient ALD Al₂O₃ surface passivation. For reducing the carrier recombination of the fs-bSi, it is vital to obtain a surface morphology with ALD-accessible grooves and avoid the recast layer by the laser processing with reasonable parameters. We start by varying the scan speed, ν (10–2000 mm s⁻¹), while keeping the other parameters including Δz the same, and then characterize the surface morphology. It is expected that the higher ν would lead to less damaged surface as it means smaller number of pulses delivered onto the surface, especially considering how much more pulses per unit time are generated with such high repetition rate. As shown in **Figure 4**, at a low ν , the grooves are replaced by excess amount of porous structure due to high thermal accumulation. With the increasing ν , the grooves become shallower and eventually reach open structures that should be possible to coat conformally by the ALD. It can be inferred that the surface morphology depends heavily on the ν . However, at the highest speed limit of the tool, $\nu = 2000 \text{ mm s}^{-1}$, the laser textured area is still fully covered by the recast Si as determined from the tilted view, which indicates that the sample suffers still from heavy recombination.

Since increasing the scan speed still leads to destructive surface features, the reason might be too high laser fluence so that even a single laser spot can contain very high energy. Next, we reduce the laser power directly while keeping the scan speed

constant. Figure 5a shows the surface morphology of a fs-bSi sample fabricated by using only 10% of the maximum laser power (~1.1 W). Quite surprisingly, the excess Si layer can still be observed even with such a low laser power. However, further reduction in laser power resulted in unevenly textured area unless the spacing between scanned lines was much narrower than the line width ($\approx 10 \,\mu$ m), which increased substantially the fabrication time. Nevertheless, as seen from the trend in Figure 5b, the reduction in laser power could reduce the recombination in the laser processed area. The figure depicts the saturation current density, Jo, instead of carrier lifetime as it represents better the recombination at the vicinity of the surface.^[34] The J_0 values are fitted from the higher injection range than 10^{15} cm^{-3} in the lifetime curves as described in Experimental Section. As seen in Figure 5b, the lowest I_0 obtained at the lowest power used here, is still several orders of magnitude higher than the I_0 obtained from planar Si without laser processing. This means the J_0 undergoes drastic changes at even low laser power. However, further reduction of the laser power is not an option because of the inaccuracy of the tool at small laser power. On the other hand, with the spot size estimated from Figure 5a, the laser fluence is estimated to be as high as $24 \text{ kJ} \text{ m}^{-2}$ at the small laser power of 1.1 W. This value is significantly higher than the ablation threshold of $\approx 2.8 \text{ kJ m}^{-2}$.^[35] which means there is still room for the optimization of the laser parameters with lower fluence that could be the key for achieving even lower recombination.

Based on the above results, the next logical step is to further reduce the fluence. In order to preserve rapid fabrication and for better adjustment accuracy of the fluence with a wide range of laser power, we change the focal position Δz away from the laser focus, which results in larger laser spot on the Si surface. In **Figure 6**, the corresponding spot diameter is $\approx 80 \,\mu\text{m}$ and the fluence is estimated to be 5.4 kJ m⁻² with the maximum laser power. As can be seen from the figure, with such a low fluence,



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Figure 5. a) 30° tilted view SEM image of the fs-bSi area fabricated with the reduced laser power (P = 1.1 W). Only two vertically intersected laser-scanned lines are shown to estimate the line width. b) Saturation current density of the fs-bSi samples varied with the average laser power ($\Delta z = 0$, $\nu = 500$ mm s⁻¹). Error bar denotes maximum 20% uncertainty during fitting of J_0 . Data point indicated by the star (\approx 46 fA cm⁻²) is measured from planar Si.



Figure 6. Cross-sectional and 30° tilted view SEM images of the fs-bSi samples fabricated with the fluence of F = 5.4 kJ m⁻² and different scan speeds, ν . The scale bar (4 µm) applies for all images except for the two on the top right as the structures are too small to be observed with the same magnification.

densely packed quasi-periodic microstructures are created. Similarly, than before, the scan speed, ν , plays an important role on the resulting surface morphology. At the lowest ν , the surface forms large microstructures that bush out on top into dense nm-scale structures, which is a sign of thermal accumulation. The size of the microstructures decreases with the increasing ν . According to the cross-sectional images, the surface morphology of the nanostructures fabricated at >100 mm s⁻¹ seems appropriate for conformal growth of ALD passivation film. Meanwhile, there is no sign of excess or porous Si layer in µm-scale, suggesting the laser ablation instead of the resolidification dominates the laser–solid interaction mechanism. Since the reduced recombination is inferred from the surface morphology, it is reasonable to try to characterize the recombination properties as well as the optical absorptance in these samples.

2.3. Carrier Lifetime and Optical Properties under Optimized Parameters

Figure 7a shows the absorptance spectra for the fs-bSi samples corresponding to Figure 6 with the fluence of F = 5.4 kJ m⁻² with various scan speeds. The sample fabricated with $\nu = 10$ mm s⁻¹ exhibits an untypical absorptance spectrum compared to the others, which complies to the formation of broccoli-like surface structure as observed in SEM. The surface morphology, together with the highest sub-band gap absorptance, indicates large recombination in this sample. The rest of the samples show enhanced absorptance compared to planar silicon throughout the measurement range (250–2500 nm). To present the absorptance for each spectrum is calculated separately for the visible (380–750 nm)



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Figure 7. a) Absorptance spectra of planar Si and fs-bSi samples fabricated with the fluence of F = 5.4 kJ m⁻² and different scan speeds. b) Average absorptance at visible (380–750 nm) and sub-band gap (1250–2500 nm) range as a function of the scan speed. c) Measured effective lifetime (τ_{eff}) at the specific minority carrier density of 10¹⁵ cm⁻³ as a function of the scan speed.

and the IR (1250–2500 nm). As shown in Figure 7b, the highest visible absorptance of 96.8% is obtained for the fs-bSi with the F = 5.4 kJ m⁻² and the $\nu = 50$ mm s⁻¹, indicating effective enhancement from the corresponding surface morphology (Figure 6). The reduced sub-band gap absorption, compared with that of the sample fabricated in the laser focus (Figure 2a), indicates a significant reduction in laser-induced damage and thus the reduced recombination. Further increase in ν leads to decreased absorptance both in the visible and in the IR. The former is likely due to the smaller dimension of surface microstructures, whereas the latter might be because of reduced laser damage. Nevertheless, the high visible absorptance >95% can be maintained by applying different laser parameters than in Figure 2.

With the implication of the reduced recombination from both the surface morphology and the absorptance spectra, the lifetime values are measured as shown in Figure 7c (the corresponding J_0 values are discussed later). Among these samples, the one with $\nu = 50 \text{ mm s}^{-1}$ has the lowest lifetime most likely due to the hidden pores (Figure 6) that cannot be passivated by ALD film. The others exhibit relatively high lifetime at around the same level. It is worth noting that, with the laser parameters of $F = 5.4 \text{ kJ m}^{-2}$ and $\nu = 100 \text{ mm s}^{-1}$, we obtain high average absorptance of 95.9% in the visible range and simultaneously optimized lifetime of 54 μ s. This means we have successfully fulfilled our goal—the laser-induced recombination is reduced with increased lifetime from 19 to 54 μ s, while the average visible absorptance is kept as high as 95.9%.

To study if we can increase the lifetime even further, another set of fs-bSi samples is fabricated with even lower fluence of $F = 3.2 \text{ kJ m}^{-2}$. As shown in Figure 8a, the variation of the absorptance by scan speed shows similar trend as the above, but the highest visible absorptance, 95.2%, is not as high as the above results (Figure 7b). Note that since the laser fluence is now closer to the ablation threshold, the effect of the scan speed on the lifetime becomes more prominent. As shown in Figure 8b, the lifetime increases clearly with the increased ν after 100 mm s^{-1} . The highest lifetime of 77 µs is obtained from the fs-bSi sample with $F = 3.2 \text{ kJ m}^{-2}$ and $\nu = 2000 \text{ mm s}^{-1}$. However, such high lifetime comes with the cost of low absorptance of <80% in the visible range. This means there is a trade-off between the optical absorptance and the minority carrier lifetime even under such low laser fluence. One needs to consider if it is worthwhile to sacrifice the optical properties with only little improvement in the lifetime.

The laser fluence (5.4 kJ m^{-2}) resulting in simultaneously high visible absorptance and high lifetime is in the same range



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Figure 8. a) Average absorptance at visible (380–750 nm) and sub-band gap (1250–2500 nm) range as a function of the scan speed. b) Measured effective lifetime (r_{eff}) at the specific minority carrier density of 10¹⁵ cm⁻³ as a function of the scan speed. The fs-bSi samples fabricated with the fluence of F = 3.2 kJ m⁻².

than the fluence used previously in high-performance optoelectronic devices. For example, with the presence of SF₆ precursor, samples irradiated with fluences of $4-8 \text{ kJ m}^{-2}$ exhibited the highest sulfur doses,^[36] providing high sub-band gap absorption of photons. Similarly, for solar cell application, Sánchez et al. showed the highest absorptance in broadband wavelengths (400–2500 nm) with a laser fluence of 5 kJ m⁻², which resulted in increased photovoltaic efficiency due to extra gain from intermediate states in NIR.^[13] Although the tailored optical and electrical properties in our experiment are obtained in the absence of high sub-band gap absorption, the optimal laser fluence obtained in our work may also be applicable to fs-bSi after hyperdoping. In conclusion, the similar fluence used in different work suggests that the laser fluence is a key parameter to achieve high performance devices despite doping or post processing.

In photoconductors based on the fs-bSi, the recombination plays an important role in determining the device performance as the photoconductive gain depends on the carrier lifetime divided by the transit time.^[12] To increase the gain, most studies focus on reducing the transit time by increasing the bias voltage whereas the effect of carrier lifetime is rarely addressed.^[37] Huang et al. demonstrate that by reducing carrier recombination with post annealing and a-Si:H surface passivation, very high EQE up to 57 200% could be obtained for the fs-bSi photodetector with relatively small bias voltage of 20 V.^[12] They also pointed out that the laser-induced trap states resulted in a long fall time allowing such high gain on the device level. Our results also prove the presence of trap states and their effect on the lifetime, especially in smaller injection levels. Indeed, photodetectors often operate at low light condition with injection levels lower than reported here ($\Delta n = 10^{15} \text{ cm}^{-3}$). Therefore, the increasing trend in lifetime under low injection level (Figure 2b) is likely to result in high gain in photodetectors under low light conditions.

The corresponding J_0 values for the optimized samples mentioned in Figure 7 and 8 are in the range of 4000–9000 fA cm⁻², which are still significantly higher than that of the planar silicon (only several fA cm⁻²). While we were able to reduce the recombination significantly and by assuming that the ALD can conformally coat and passivate the surface, the carrier lifetime is still limited by the recombination from laser-induced lattice damage that cannot be completely avoided by tuning the laser parameters only. Although post annealing has been applied here to activate the ALD Al_2O_3 surface passivation, the annealing temperature (425 °C) is not enough to deactivate the laser-induced damage which requires higher temperatures.^[38] Further study on increasing the lifetime by other post processing steps, such as high temperature bulk annealing, is highly anticipated.

3. Conclusion

The ALD Al₂O₃ surface passivated fs-bSi was fabricated by high repetition rate fs-laser, which allows rapid surface texturization for large areas. The impact of various fs-laser parameters, such as focal position, average power, and the scan speed, on the electrical and optical properties were systematically studied by characterizing the surface morphology, optical absorptance, and effective carrier lifetime. When the samples were fabricated using the laser at focus position with high laser energy, a high absorptance of 94.0% in the visible range was obtained but the samples suffered from severe recombination caused by laser damage and improper surface passivation as the resulting surface morphology was noticed by SEM to be incompatible with conformal ALD deposition. After tailoring the laser parameters, we found out that the key for reduced recombination is a low laser fluence but also the scan speed had a significant impact on the material properties. With optimized laser parameters, we were able to reach simultaneously a high average absorptance of 95.9% in the visible range and a minority carrier lifetime of 54 µs. Consequently, this work paves the way for a better broadband optoelectronic performance using ALD Al₂O₃ coated fs-bSi.

4. Experimental Section

Fabrication of fs-bSi: The starting wafers were n-type FZ-Si wafers ((100) orientation, 3 Ω cm resistivity, 280 μ m thickness). Before the actual processing, the lifetime-limiting bulk defects in the FZ wafers were deactivated by a typical anneal at 1050 °C in an oxygen atmosphere for 30 min,^[39,40]



followed by a subsequent oxide removal in diluted HF solution. Fs-bSi was fabricated in ambient air by Spectra-Physics Spirit 1040-16-SHG laser (324 fs pulse duration, 417 kHz repetition rate) with adjustable average laser power, P (11 W maximum). The laser wavelength was 520 nm with second harmonic generation from the fundamental wavelength of 1040 nm. The laser beam was focused on the Si substrate with a laser spot size estimated from the width of a laser-ablated line of about $10 \,\mu m$ in diameter on the focal point. The spot size was changed by translating the samples in relative to the laser focus point and the translation distance was indicated by Δz (namely focal position) in Figure 1a. To create surface structure over large area, the laser was guided over a Galvo scanner system onto Si substrate in a progressive scanning mode with adjustable scan speed, ν , from 10 to 2000 mm s⁻¹. The scanning pattern is schematically shown in Figure 1b, and the line spacing was chosen according to the spot size to achieve uniform patterning. The fs-bSi area was fabricated to one side of the wafer to simulate the layout of most optoelectronic devices, such as photodetectors.

Lifetime Measurement: The as-fabricated fs-bSi samples were cleaned by acetone in ultrasonic bath, rinsed by isopropanol and deionized water, and dried by N2. The samples were subsequently RCA cleaned for further contamination removal. The Al₂O₃ deposition was performed on both sides of the wafers in a Beneq TFS-500 ALD reactor for 200 cycles at 200 °C with TMA and H₂O as precursors, and the deposited thickness was 22 nm as measured with Plasmos SD2300 ellipsometer from the planar Si reference. The samples were subsequently subjected to the thermal annealing in the forming gas at 425 °C for 30 min to activate the passivation. Finally, the injection dependent minority carrier recombination lifetime was measured by the contactless quasisteady-state photoconductance (QSSPC) method by using Sinton WCT-120.^[41,42] The diameter of fs-bSi samples used for lifetime measurements was 3 cm. Either transient or generalized analysis mode was chosen based on lifetime level. For accurate analysis with the generalized mode, the optical constant was estimated based on the PC1D simulation with the measured reflectance spectra as the input.^[42] The lifetime for planar Si was measured from the planar area without laser textures on the same wafer where the fs-bSi was fabricated. The saturation current density, J₀, was determined from the injection-dependent lifetime curve using the Kane and Swanson's method.^[43]

Characterization of Surface Morphology and Optical Properties: The surface morphology of the fs-bSi samples was observed with a Zeiss Supra 40 field-emission scanning electron microscope at a tilt angle of 30°. To observe the cross section of the sample, it was cleaved from the opposite side of the textured surface and the cross section was placed horizontally to the sample stage. The optical properties were measured from the Si samples with >1 cm \times 2 cm laser-textured area with Cary 5000 UV-vis-NIR spectrophotometer equipped with an integrating sphere at a wavelength step of 1 nm. The absorptance (A) spectra were calculated from the equation A = 1 - R - T, where R and T were the total hemispherical reflectance and transmittance, respectively. The instrument's built-in Zero \times Standard Reference (Stdref) correction was used to subtract the background noise as well as to normalize the R and T from 0 to 1. The correction was done by applying a standard reference (a white ceramic tile) to the reflectance port. Then, the corrected results were given by the equation $\frac{R_s - R_{005TBaseline}}{R_{1005TBaseline} - R_{095TBaseline}}$ (Baseline Stdref), where R denoted the ratio of the light intensity coming in the sample port to that coming in the reference port, and R_s , $R_{0\%TBaseline}$, and $R_{100\%TBaseline}$ were measured when there was a sample, the sample beam was blocked and when there was no sample at the sample port, respectively.

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This article was amended on January 20, 2022 to correct "versus" to the symbol of speed " ν ".

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

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