Editor's Choice



Exploring Wettability of Re-Entrant Microstructures: Effects of Geometry and Material Composition

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This study systematically explores the wetting characteristics of re-entrant microstructures, focusing on the interplay between the unique geometries and material compositions. While silicon dioxide (SiO2) re-entrant microstructures are previously studied, this research pioneers the fabrication of silicon carbide (SiC) re-entrant microstructures. Through experimental approaches and theoretical analysis, the research assesses how variations in geometry and material impact wettability. Key findings reveal that SiC re-entrant structures achieve an average contact angle of 145°, closely matching the 148° observed for SiO₂, indicating similar hydrophobic behavior. Although flat SiC surfaces exhibit higher inherent hydrophobicity than flat SiO₂ (59° vs 26° contact angle), re-entrant geometry predominantly influences wetting behavior, overshadowing material differences. Structures with lower solid area fractions show increased hydrophobicity, with a distinct hierarchy: microlines are the least hydrophobic, followed by shark-skin textures, rectangles, circles, and triangles. Additionally, increasing the gap size between structures enhanced hydrophobicity up to a critical point. This study paves the way for optimizing re-entrant microstructures for specific applications, significantly enhancing the understanding of surface science and advancing material design.

1. Introduction

Exploring the wettability of surfaces is a critical area in materials science and engineering, driven by the need to understand and manipulate surface properties for a wide range of applications.^[1–16] Among surface structures, re-entrant morphologies present an intriguing avenue for investigation due to their distinctive cap-and-stem architecture. These structures

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are known for their ability to exhibit extreme wetting behaviors, such as superhydrophobicity, which are highly desirable in applications like selfcleaning surfaces, anti-fouling coatings, and microfluidics.^[2,17–19] With their three-dimensional geometry, re-entrant structures deviate from conventional flat surfaces and offer a unique platform for controlling wetting behaviors.^[2,20,21] The cap, resembling an umbrella, introduces an additional surface element that can significantly impact interactions with liquids. As advancements in fabrication techniques enable precise control over these structures, exploring their wetting properties becomes imperative for both fundamental understanding and practical applications.[22-24]

While silicon dioxide (SiO₂) re-entrant structures have been extensively studied and are well-known for their reliable performance in various environments, research exploring other materials with

potentially superior properties has been limited.^[25,26] Silicon carbide (SiC), for example, is a material that offers exceptional mechanical strength, chemical resistance, and thermal stability, making it an ideal candidate for applications in harsh environments.^[27,28] However, the wettability characteristics of SiC in re-entrant microstructures have not been thoroughly investigated, leaving a significant gap in our understanding of how different materials influence wetting behavior. Recent studies have highlighted the importance of surface geometry in determining wettability, especially in complex and rough surfaces. For instance, a coarse-grained simulation analysis demonstrated that variations in surface geometry can significantly alter wettability by shifting the balance between the Wenzel and Cassie-Baxter states.^[29] This study aims to address this gap by exploring the wettability of SiC re-entrant microstructures and comparing them with SiO₂ structures. By investigating how variations in geometry and material composition affect wettability, this research aims to uncover new insights that could lead to the development of advanced surface designs with tailored wetting properties.

The solid fraction in re-entrant structures refers to the proportion of the surface occupied by solid material instead of void spaces. This factor is critical in influencing wettability, directly affecting the contact between the liquid and the surface.^[30–33] In structures with a high solid fraction, the liquid spreads due to

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Figure 1. Fabrication process of re-entrant structures using lithography and reactive ion etching. a) A clean SiO_2 wafer was prepared for the process. b) A layer of SiO_2 was grown on the wafer. c) Another layer of photoresist was spin-coated on top of the oxide layer. Then, the wafer was exposed to UV light and developed to obtain a pattern in d). Then, anisotropic reactive ion etching (RIE) was used to obtain the pillars e). f) Subsequently, the photoresist layer was stripped. g) Anisotropic RIE was used again to etch both the SiO_2 and Si layers. Vertical pillars were obtained. h) Isotropic etching using SF_6 with high pressure was utilized to create re-entrant structures with the cap made of SiO_2 . i) A layer of C_4F_8 was coated on the structure.

increasing contact. Conversely, a lower solid fraction leads to reduced contact and increasing hydrophobicity. This is because the void spaces can trap air, creating a composite interface that repels liquid—an effect often exploited in superhydrophobic surfaces.

In this study, we manipulated the solid area fraction by altering the cap shape and the gap size between re-entrant posts. These modifications provide insights into how variations in solid fractions influence wetting behavior. We aim to identify the most effective designs for controlling wettability by exploring diverse configurations. This understanding has significant implications for practical applications, including microfluidics and selfcleaning surfaces, where precise control of liquid interactions is crucial.

This investigation aims to systematically explore the wettability characteristics of re-entrant microstructures, focusing on comparing SiC and SiO₂ as cap materials. This study pioneers using SiC in re-entrant structures, a novel approach that has not been explored in the literature. The novelty of this work lies in the direct comparison of SiC and SiO₂, assessing how these materials influence wettability and revealing the dominant role of geometry over material properties in determining surface behavior. This exploration is poised to advance our fundamental knowledge of wetting phenomena on structured surfaces and foster

the development of innovative materials optimized for various applications.

2. Experimental Section

2.1. Fabrication of the Re-Entrant Structure

Figure 1 depicts the process of creating micropillars with reentrant structures. We used thermally oxidized wafers (prime grade, (100) type, $525 \pm 25 \mu m$ thick), photolithography, and reactive ion etching. The detailed process is explained in the Supplementary Information (Supporting Information) section.

2.2. Contact Angle Measurement and Surface Free Energy Measurement

Wettability, which signifies how a surface interacts with a liquid, can be assessed through the measurement of contact angles (CA). Surface free energy (SFE) is calculated from contact angle (CA) values using the Owens, Wendt, Rabel, and Kaelble (OWRK) method.^[34–36] SFE is a fundamental property of a surface, defined





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— 10 μm (c)



____ 40 μm



____ 10 μm (g)

10 µm

50 µm

(i)





_____5 μm (d)



— 5 μm (f)



— 5 μm (h)



— 5 μm



Figure 2. Representative SEM images of the re-entrant structures with the SiO₂ cap of five different designs with a gap of 10 μ m. Average height of the pillars is \approx 9 μ m. a) SEM image of re-entrant structures with circle caps. Scale bar: 10 μ m. b) SEM image of a single re-entrant structure with a circular cap. Scale bar: 5 μ m. c) SEM image of re-entrant structures with triangular caps. Scale bar: 40 μ m. d) SEM images of a single re-entrant structure with a triangular cap. Scale bar: 5 μ m. e) SEM image of re-entrant structures with rectangular caps. Scale bar: 10 μ m. f) SEM image of a single re-entrant structure with a triangular cap. Scale bar: 5 μ m. e) SEM image of re-entrant structures with rectangular caps. Scale bar: 10 μ m. f) SEM image of a single re-entrant structure with a rectangular cap. Scale bar: 5 μ m. g) SEM image of re-entrant structures with shark-skin arrangement. Scale bar: 10 μ m. h) SEM image of a single re-entrant structure with shark-skin arrangement. Scale bar: 50 μ m. j) SEM image of a single re-entrant structure with microline arrangement. Scale bar: 50 μ m. j) SEM image of a single re-entrant structure with microline arrangement. Scale bar: 50 μ m. j) SEM image of a single re-entrant structure with microline arrangement. Scale bar: 50 μ m.



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20 µm





20 µm (e)





5 µm (h)

(b)

(d)

5 µm

5 µm





(g)







10 µm

- 5 µm

(j)

Figure 3. Representative SEM images of the re-entrant structures with the SiC cap of five different designs with a gap of 10 µm. Average height of the pillars is \approx 12 µm. a) SEM image of re-entrant structures with circular caps. Scale bar: 20 µm. b) SEM image of a single re-entrant structure with a circular cap. Scale bar: 5 μm. c) SEM image of re-entrant structures with triangular caps. Scale bar: 20 μm. d) SEM image of a single re-entrant structure with a triangular cap. Scale bar: 5 µm. e) SEM image of re-entrant structures with rectangular caps. Scale bar: 40 µm. f) SEM image of a single re-entrant structure with a rectangular cap. Scale bar: 5 µm. g) SEM image of re-entrant structures with a shark-skin arrangement. Scale bar: 40 µm. h) SEM image of a single re-entrant structure with a shark-skin arrangement. Scale bar: 5 µm. i) SEM image of re-entrant structures with a microline arrangement. Scale bar: 40 μm. j) SEM image of a single re-entrant structure with a microline arrangement. Scale bar: 10 μm.

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in its ideal flat state, and not affected by surface roughness. Superhydrophobic surfaces, which are heterogeneous and consist of air and solid components, complicate SFE calculations when using the Wenzel and Cassie-Baxter models. The term "normalized surface free energy" (NSFE) is used to address this issue, predicting how various liquids interact with actual surfaces.[37] To calculate solid SFE via the OWRK method, at least two liquids with known dispersive and polar components are required to solve the problem of solid/liquid interfacial free energy and solid SFE. The chosen liquids must be nontoxic, easily accessible, nonvolatile, nonreactive, and not cause the surface to swell.^[38] Commonly used liquids include water, diiodomethane, bromonaphthalene, nitromethane, bromobenzene, toluene, nhexane, and glycerol, although some are harmful or volatile. For this study, water and glycerol were selected. Polar, dispersive, and total surface tensions of water are 51.0, 21.8, and 72.8 mN m⁻¹,^[39] respectively, while the corresponding values of glycerol are 30, 34, and 64 mN m^{-1.^[40] These values were used to calculate the} NSFE components of the solid. The detailed calculation method and procedure were explained in our previous work.^[41] For each sample, a minimum of three different readings were recorded.

All wettability measurements, including contact angle and surface free energy calculations, were conducted at a controlled temperature of 23 ± 0.5 °C. The laboratory environment was maintained using a climate control system, and temperature fluctuations were continuously monitored with a calibrated digital thermometer. To ensure thermal equilibrium, samples were allowed to stabilize at this temperature for at least 30 min before measurements. This controlled setting minimized thermal effects on both the liquids and re-entrant structures, ensuring the reliability and accuracy of the experimental data.

2.3. Characterization of Micropillar Surfaces

The pattern qualities, including shape, size, and surface topology, were inspected by scanning electronic microscopy (SEM) (**Figures 2** and **3**). The SEM analysis, equipped with an energydispersive detector, confirmed the cap materials of the re-entrant structures as SiC and SiO₂. The dimensions of the re-entrant structures, the gap between re-entrant pillars, and the height of the stem were measured using a 3D Measuring Laser Microscope (Olympus OLS5100, Evident Corporation, Japan). Our findings demonstrate that the fabricated re-entrant microstructures closely match the intended design with minimal deviation. **Table 1** summarizes all geometrical parameters of these pillar structures.

3. Results and Discussion

3.1. Effect of Solid Area Fraction of Re-Entrant Structures

The investigation aimed to explore the wettability characteristics of various shapes, including traditional geometries (triangle, rectangle, and circle), microlines, and the unique surface structures of shark skin. We employed water and glycerol contact angles as quantitative metrics to assess the surface and water interaction. The surface free energy is a reliable indicator of wettability: higher surface free energy implies higher wettability (more hydrophilic), whereas lower surface free energy indicates lower wettability (more hydrophobic). Our study revealed that wettability was primarily influenced by the solid area fraction rather than the specific shape of the cap.

The results indicate a clear order of hydrophobicity among the tested shapes, with microlines exhibiting the lowest hydrophobicity (highest surface free energy), followed by shark skin, rectangle, circle, and triangle (**Figures 4** and 5). This finding suggests that the solid area fraction is crucial in determining the water contact angle and overall wettability.

In structures with a high solid area fraction, the liquid spreads more readily due to increased contact with the solid surface. This enhanced contact facilitates better wetting, resulting in lower contact angles and higher wettability. Conversely, in structures with a lower solid area fraction, the contact between the liquid and the solid surface is reduced, leading to higher contact angles and increased hydrophobicity. The void spaces present in these structures can trap air, creating a composite interface that repels liquid and makes the surfaces more hydrophobic.

The results showed a distinct hierarchy of hydrophobicity among the tested shapes for both cap material SiO_2 and SiC(Figures 4 and 5). Microlines were found to be the least hydrophobic, meaning they had the highest surface free energy and were most easily wetted by water. Following microlines in increasing order of hydrophobicity were the shark-skin textures, rectangles, circles, and triangles. This order suggests that surfaces with microlines had the greatest affinity for water, whereas triangles exhibited the least.

The significance of these findings lies in the understanding that the solid area fraction is a key determinant of water contact angle and overall wettability. This insight is crucial for applications where controlling wettability is essential, such as designing water-repellent materials, enhancing fluid flow in microchannels, or developing surfaces for better adhesion or lubrication. The ability to manipulate surface wettability by adjusting the solid area fraction rather than just the shape provides a valuable tool for material scientists and engineers.

3.2. Effect of Gap Size Between Re-Entrant Posts

Our investigation into the wettability of surfaces featuring reentrant structures has revealed a notable finding: the gap size between re-entrant microstructures significantly influences wetting behavior, with larger gaps demonstrating better hydrophobicity (**Figure 6**). The result shows a similar trend for all designs for both re-entrant structures with SiO_2 and SiC caps. This observation prompts a discussion on the potential reasons behind the enhanced hydrophobicity with increased gap size and the overarching influence of the re-entrant structures on wettability.

The remarkable improvement in hydrophobicity with larger gaps strongly suggests that while re-entrant structures are crucial, the spacing between these structures also plays a significant role in determining surface wettability. These structures, characterized by their distinctive cap and stem arrangement, are enhanced by optimal spacing, which amplifies their hydrophobic properties.

The re-entrant structures contribute to capillary forces and surface tension effects, which are crucial in governing wetting
 Table 1. Size/diameter of pillars (L) and gaps between pillars (G) of different re-entrant structures.



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Shape	<i>L</i> [μm]	G [μm]	Symbol	Design
Circle	20	5	CG5	
Circle	20	10	CG 10	
Circle	20	20	CG20	
Triangle	20	5	TG5	
Triangle	20	10	TG 10	
Triangle	20	20	TG20	
Rectangle	20	5	RG5	
Rectangle	20	10	RG10	
Rectangle	20	20	RG20	
Microline	20	5	MLG5	
Microline	20	10	MLG10	
Microline	20	20	MLG20	
Shark-skin	20	5	SG5	···· <u>1222</u> [23] [23] [23] [23] [23] [222 [201
Shark-skin	20	10	SG 10	
Shark-skin	20	20	SG20	

behavior. It is plausible that larger gaps reduce the interaction between adjacent re-entrant structures, minimizing the formation of liquid bridges that can lead to wetting. This reduction in liquid bridging could lead to a more pronounced Cassie-Baxter state, where air pockets are trapped beneath the liquid, enhancing hydrophobicity. Therefore, larger gaps may facilitate a more stable air layer, further promoting water repellence.

The improved hydrophobicity with increased gap size suggests a critical spacing where the benefits of re-entrant structures are maximized. Beyond this point, further increases in gap size may still enhance hydrophobicity, but the gains may become marginal. This indicates that while a certain threshold of gap size is necessary for optimal hydrophobicity, huge gaps may not proportionally continue to improve wetting resistance.

3.3. Comparison of SiO_2 and SiC as the Cap Material for Re-Entrant Structure

In the design and engineering of surfaces with re-entrant structures, the choice of cap material plays a crucial role in influencing the overall performance and properties of the surface. In this section, we discuss and compare the use of SiO_2 and SiC as cap materials for re-entrant structures (Figure 7).

Our investigation into the wettability of re-entrant structures reveals compelling findings, particularly in the context of the cap material. While the water contact angle on a flat SiC wafer is significantly higher than that on a flat SiO₂ wafer (59° compared to 26°), indicating the higher inherent hydrophobicity of SiC material compared to SiO₂, our comparative analysis between reentrant structures with SiC and SiO₂ caps demonstrates that there is not a significant difference in hydrophobic properties. This result suggests that the dominant effect of the re-entrant structures may overshadow the intrinsic hydrophobic nature of the cap materials.

Re-entrant structures featuring SiC as the cap material do not exhibit significantly enhanced hydrophobicity compared to their SiO₂ counterparts. The contact angles measured on SiC-capped structures are similar to those on SiO₂-capped structures, indicating a comparable resistance to wetting. The observed similarity in hydrophobic properties between SiC-capped and SiO₂capped re-entrant structures implies that geometric design and surface texture may be more critical in determining wettability than the intrinsic material properties alone. This finding holds substantial implications for applications where water resistance

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Figure 4. Variations in surface free energy when changing solid area fraction. Graph of surface free energy versus solid area fraction for re-entrant microstructures with SiO₂ caps when the gap is 5 μ m. b) Graph of surface free energy versus solid area fraction for re-entrant microstructures with SiO₂ caps when the gap is 10 μ m. c) Graph of surface free energy versus solid area fraction for re-entrant microstructures with SiO₂ caps when the gap is 20 μ m. d) Graph of surface free energy versus solid area fraction for re-entrant microstructures with SiO₂ caps when the gap is 20 μ m. d) Graph of surface free energy versus all solid area fractions for re-entrant microstructures with SiO₂ caps across all gap sizes.

is paramount, such as in anti-fouling coatings or microfluidic systems where controlled liquid interactions are essential.

The comparable wetting behavior observed in our results underscores the importance of considering both material properties and structural design when creating surfaces with tailored properties. Further analysis of the underlying mechanisms governing wettability on these structured surfaces will contribute to a deeper understanding of wetting phenomena and inform the rational design of materials for specific applications.

3.4. Wetting of Re-Entrant Structures

While surface tension is a key factor in determining wettability, the viscosity of the liquid also plays a crucial role. Higher viscosity liquids spread more slowly across the surface, which helps preserve the Cassie-Baxter state by reducing the likelihood of liquid infiltration into the re-entrant features. In our experiments, the higher viscosity of glycerol compared to water contributed to greater stability of the Cassie-Baxter state, resulting in higher contact angles. This finding underscores the need to consider both surface tension and viscosity when evaluating the wetting characteristics of re-entrant structures.

To further characterize the wetting behavior of the re-entrant structures, we calculated the Bond number (Bo) and the capillary number (Ca), which provide insight into the relative importance of gravitational, viscous, and surface tension forces.

The Bond number is defined as $Bo = \frac{(\rho_w - \rho_a)gr^2}{\gamma}$ where ρ_w and ρ_a are densities of water and air, g is gravitational acceleration, r is the radius of the drop, and γ is the surface tension of the liquid.^[42] The capillary number is defined as $Ca = \frac{\mu V}{\gamma}$ where μ is the dynamic viscosity of the liquid, V is the characteristic velocity of the liquid spreading over the surface, and γ is the surface tension.

In our study, the calculated Bond number was found to be significantly <1, indicating that surface tension forces dominate over gravitational forces, which is typical for small-scale systems. The low Bond number explains why the re-entrant structures effectively maintain the Cassie-Baxter state, as gravitational forces

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Figure 5. Variations in the surface free energy when changing the solid area fraction. a) Graph of surface free energy versus solid area fraction for reentrant microstructures with SiC caps when the gap is 5 μ m. b) Graph of surface free energy versus solid area fraction for re-entrant microstructures with SiC caps when the gap is 10 μ m. c) Graph of surface free energy versus solid area fraction for re-entrant microstructures with SiC caps when the gap is 20 μ m. d) Graph of surface free energy versus all solid area fractions for re-entrant microstructures with SiC caps across all gap sizes.

are not sufficient to overcome the surface tension that supports the trapped air pockets.

The capillary number, calculated for the experiments with both water and glycerol, was also found to be low (Ca < 0.01), suggesting that surface tension forces dominate over viscous forces during the wetting process. The low capillary number reinforces the observation that the re-entrant geometry plays a crucial role in sustaining the Cassie-Baxter state, as the liquid's viscous forces are insufficient to force infiltration into the surface texture. These dimensionless numbers highlight the dominance of surface tension in the wetting dynamics of re-entrant structures and confirm that the geometry of these structures is critical in maintaining superhydrophobicity.

The wetting behavior of re-entrant structures is governed by a complex interplay between surface geometry, surface energy, and the forces acting at the solid-liquid interface. In these structures, the Cassie-Baxter state is often observed, where the liquid droplet sits on top of the surface asperities, supported by trapped air pockets beneath the droplet. This state is characterized by high contact angles and low contact angle hysteresis, which are desirable for applications requiring superhydrophobicity.

The stability of the Cassie-Baxter state in re-entrant structures is strongly influenced by the re-entrant geometry itself. As highlighted by Whyman et al. (2011), the presence of overhanging features in the re-entrant design creates an energy barrier that makes it unfavorable for the liquid to penetrate the surface texture, thereby maintaining the trapped air layer and preventing the transition to the Wenzel state.^[43] The sharp angles and narrow gaps inherent in re-entrant structures further enhance this effect by acting as physical barriers to wetting.

Moreover, the specific dimensions of the re-entrant features, such as cap shape and gap size, play a critical role in determining wettability. Structures with larger gaps and pronounced reentrant angles are more likely to maintain the Cassie-Baxter state, resulting in higher contact angles and improved hydrophobicity. Conversely, less pronounced re-entrant features may allow for an easier transition to the Wenzel state under certain conditions, such as increased external pressure or lower surface tension.



Figure 6. The effect of gap size on the wettability of the re-entrant structures.

In summary, the wetting mechanism of re-entrant structures is more intricate than that of conventional flat surfaces. The unique geometry of these structures, combined with the principles outlined by Whyman et al. (2011), provides a robust framework for understanding the enhanced stability of the Cassie-Baxter state and the resulting superhydrophobic properties. This understanding is crucial for the design and optimization of reentrant microstructures for specific applications.

4. Conclusion

Our comprehensive investigation into the wettability characteristics of various geometric shapes and re-entrant structures, particularly focusing on the influence of cap materials, has yielded significant insights. Contrary to conventional expectations, our study revealed that wettability is primarily influenced by the solid area fraction rather than the shape of the cap. This was evidenced by the clear order of hydrophobicity among tested shapes, with microlines exhibiting the highest hydrophobicity, followed by shark-skin, rectangular, circular, and triangular microstructures.

Further analysis of re-entrant structures demonstrated that gap size between re-entrant microstructures significantly influ-



Figure 7. The comparison between SiC and SiO_2 cap materials. The graph plotted between surface free energy and solid area fraction between reentrant structures with SiC and SiO_2 cap material.

ences wetting behavior, with larger gaps enhancing hydrophobicity for both SiO_2 and SiC-capped re-entrant structures. This improvement in hydrophobicity suggests that optimal spacing reduces the interaction between adjacent structures, minimizing liquid bridging and facilitating a more pronounced Cassie-Baxter state. However, beyond a critical gap size, the gains in hydrophobicity become marginal.

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When comparing SiO_2 and SiC as cap materials for re-entrant structures, we observed that, despite SiC's inherently higher hydrophobicity on flat surfaces, the re-entrant structures with SiC caps did not exhibit significantly enhanced hydrophobicity compared to those with SiO₂ caps. This similarity in wetting behavior implies that the dominant effect of the re-entrant geometry and surface texture may overshadow the intrinsic hydrophobic properties of the cap materials.

Our findings underscore the importance of considering both material properties and structural design in creating surfaces with tailored wettability characteristics. These insights are particularly relevant for applications requiring water resistance, such as anti-fouling coatings and microfluidic systems. Further analysis of the mechanisms governing wettability on these structured surfaces will contribute to a deeper understanding of wetting phenomena and inform the rational design of advanced materials for specific applications.

The findings from this study open up several avenues for future research. One potential direction is to explore the impact of additional surface treatments on the wettability of SiC re-entrant microstructures. For example, coatings or chemical modifications could be applied to further enhance the hydrophobic or hydrophilic properties of these structures. Additionally, investigating the behavior of SiC re-entrant microstructures under extreme environmental conditions, such as high temperatures, corrosive environments, or varying pressure levels, could provide valuable insights into their durability and performance in real-world applications.

Another promising area for future work is the development of re-entrant microstructures using other advanced materials, such as metal oxides or polymers, to assess how different material properties influence wetting behavior. Furthermore, integrating these structures into functional devices, such as microfluidic systems or anti-fouling coatings, could demonstrate the practical applications of the research findings. SCIENCE NEWS ______ www.advancedsciencenews.com

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Finally, advancing fabrication techniques to create even more complex geometries or multi-scale structures could lead to new possibilities for controlling wettability and other surface properties. By continuing to investigate these aspects, the research could contribute significantly to the fields of materials science, surface engineering, and nanotechnology.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

re-entrant structures, silicon, silicon carbide, silicon oxide, wettability

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- [1] R. Fürstner, W. Barthlott, C. Neinhuis, P. Walzel, *Langmuir* 2005, *21*, 956.
- [2] H. H. Vu, N. T. Nguyen, N. Kashaninejad, Adv. Mater. Technol. 2023, 8, 2370023.
- [3] H. H. Vu, N.-T. Nguyen, N.-K. Nguyen, C. H. Luu, S. Hettiarachchi, N. Kashaninejad, Adv. Eng. Mater. 2023, 25, 2300821.
- [4] Q. Wang, L. Wang, X. Hao, C. Yan, B. Lu, Nanosci. Nanotech. Lett. 2012, 4, 1171.
- [5] S. Wang, K. Liu, X. Yao, L. Jiang, Chem. Rev. 2015, 115, 8230.
- [6] S. Srinivasan, J. A. Kleingartner, J. B. Gilbert, R. E. Cohen, A. J. Milne, G. H. McKinley, *Phys. Rev. Lett.* **2015**, *114*, 014501.
- [7] N. Kashaninejad, N.-T. Nguyen, W. K. Chan, Phys. Fluids 2012, 24, 112004.

- [8] G. Ciasca, M. Papi, L. Businaro, G. Campi, M. Ortolani, V. Palmieri, A. Cedola, A. De Ninno, A. Gerardino, G. Maulucci, *Bioinspiration Biomimetics* 2016, *11*, 011001.
- [9] X. Zhang, F. Shi, J. Niu, Y. Jiang, Z. Wang, J. Mater. Chem. 2008, 18, 621.
- [10] A. Mohamed, A. Abdullah, N. Younan, Arabian J. Chem. 2015, 8, 749.
- [11] L. Mishchenko, B. Hatton, V. Bahadur, J. A. Taylor, T. Krupenkin, J. Aizenberg, ACS Nano 2010, 4, 7699.
- [12] N. Miljkovic, R. Enright, Y. Nam, K. Lopez, N. Dou, J. Sack, E. N. Wang, *Nano Lett.* **2013**, *13*, 179.
- [13] J.-H. Lee, S. K. Kim, H.-H. Park, T. S. Kim, J. Micromech. Microeng. 2015, 25, 035032.
- [14] G. Gunkel, M. Weinhart, T. Becherer, R. Haag, W. T. Huck, Biomacromolecules 2011, 12, 4169.
- [15] Y. Ito, H. Hasuda, M. Sakuragi, S. Tsuzuki, Acta Biomater. 2007, 3, 1024.
- [16] K.-C. Park, H. J. Choi, C.-H. Chang, R. E. Cohen, G. H. McKinley, G. Barbastathis, ACS Nano 2012, 6, 3789.
- [17] M. Nosonovsky, B. Bhushan, Philos. Trans. R. Soc. 2016, 374, 20160185.
- [18] H. Hu, V. V. Swaminathan, M. R. Z. Farahani, G. Mensing, J. Yeom, M. A. Shannon, L. Zhu, *J. Micromech. Microeng.* **2014**, *24*, 095023.
- [19] X. Wang, L. Jia, C. Dang, H. Li, Int. J. Heat Mass Transfer 2024, 229, 125699.
- [20] L. Wang, X. Yang, Q. Wang, Z. Yang, H. Duan, B. Lu, AIP Adv. 2017, 7, 075110.
- [21] S. M. Kang, S. M. Kim, H. N. Kim, M. K. Kwak, D. H. Tahk, K. Y. Suh, Soft Matter 2012, 8, 8563.
- [22] T. L. Liu, C.-J. C Kim, Science 2014, 346, 1096.
- [23] A. Tuteja, W. Choi, M. Ma, J. M. Mabry, S. A. Mazzella, G. C. Rutledge, G. H. McKinley, R. E. Cohen, *Science* **2007**, *318*, 1618.
- [24] A. Tuteja, W. Choi, J. M. Mabry, G. H. McKinley, R. E. Cohen, Proc. Natl. Acad. Sci. USA 2008, 105, 18200.
- [25] N. Gonzalez-Pech, V. Grassian, Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry, 2018, pp. 817.
- [26] M. Rallini, J. Kenny, Modif. Polym. Prop. 2017, 47.
- [27] H. Abderrazak, E. Hmida, in Properties and applications of Silicon Carbide, InTech, 2011, p. 361.
- [28] C. H. Voon, B. Y. Lim, L. N. Ho, in Synthesis of Inorganic Nanomaterials, Elsevier, 2018, pp. 213–253.
- [29] S. K. Sethi, R. Gogoi, A. Verma, G. Manik, Prog. Org. Coat. 2022, 172, 107062.
- [30] D. Zhang, S. Takase, G. Nagayama, J. Colloid Interface Sci. 2021, 591, 474.
- [31] N. Kashaninejad, N.-T. Nguyen, W. K. Chan, Soft Matter 2013, 9, 527.
- [32] Y. Li, X. Han, H. Jin, W. Li, Mater. Res. Express 2021, 8, 076403.
- [33] S. M. Kang, RSC Adv. 2016, 6, 74670.
- [34] M. Annamalai, K. Gopinadhan, S. A. Han, S. Saha, H. J. Park, E. B. Cho, B. Kumar, A. Patra, S.-W. Kim, T. Venkatesan, *Nanoscale* 2016, *8*, 5764.
- [35] D. K. Owens, R. Wendt, J. Appl. Polym. Sci. 1969, 13, 1741.
- [36] D. Kaelble, J. Adhes. 1970, 2, 66.
- [37] M. Shaker, E. Salahinejad, Prog. Org. Coat. 2018, 119, 123.
- [38] Z. Zhang, W. Wang, A. N. Korpacz, C. R. Dufour, Z. J. Weiland, C. R. Lambert, M. T. Timko, *Langmuir* **2019**, *35*, 12317.
- [39] E. Rynkowska, K. Fatyeyeva, S. Marais, J. Kujawa, W. Kujawski, Polymers 2019, 11, 1799.
- [40] J. Ou, G. Zhao, F. Wang, W. Li, S. Lei, X. Fang, A. R. Siddiqui, Y. Xia, A. Amirfazli, ACS Omega 2021, 6, 7266.
- [41] H. H. Vu, N.-T. Nguyen, N.-K. Nguyen, C. H. Luu, S. Hettiarachchi, N. Kashaninejad, Adv. Eng. Mater.
- [42] S. Misra, Y. Han, Y. Jin, P. Tathed, Multifrequency Electromagnetic Data Interpretation for Subsurface Characterization, Elsevier, Amsterdam, The Netherlands 2021, p. 145.
- [43] G. Whyman, E. Bormashenko, Langmuir 2011, 27, 8171.