Effects of Slag Treatment Conditions on Boron Removal from Metallurgical Silicon by United Gas-Slag Refining Technology

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Abstract
Impurities in industrial silicon strongly affect the performance and appliance of silicon products, so raw industrial silicon must be refined to reduce impurity content and improve its quality. In this work, the slag agent CaO-SiO₂-CaCl₂ and the mixed Ar-H₂O-O₂ gas were used to refine the industrial silicon in a high-temperature gas blowing furnace. The effects of the slagging refining conditions on impurity removal were studied. The chemical composition of slag agent, mass ratio of slag to silicon, refining time and refining temperature were experimentally explored and the optimal efficiency of boron removal was found to be 96.77%. The boron content in refined industrial silicon decreased from 22 ppmw to 0.6 ppmw. The significant decrease of boron content in silicon indicates that the united gas-slag refining is an effective method to remove impurities from industrial silicon.

Keywords Industrial silicon · Purification · Slag agent · Blowing · Mechanism

1 Introduction

With the continuous industrialization and economic development, the demand for industrial-grade silicon in metallurgy, chemical industry, electronics, energy development and other fields has grown rapidly. In particular, the ongoing energy crisis and environmental degradation have led to an increase in the demand for installed solar cell capacity. Solar cells currently account for more than 94% of the global photovoltaic market due to their low cost, high solar energy conversion efficiency and stability [1]. For many years, due to the weak technical strength of the organic chemical and polysilicon industries, the market demand is relatively small, and there has been little research on high-quality industrial silicon in China. Traditional production technology only addresses the reduction in the content of the Fe, Al, and Ca impurities in industrial silicon products. As clearly stated in the China Industrial Silicon Standard (GB/T2881-2014) for the contents of the boron and phosphorus impurities, the boron and phosphorus contents in high-quality industrial silicon are required to be less than 30 ppmw and 50 ppmw, respectively. This has motivated extensive interest in the purification of silicon and the identification of the optimal purification conditions [2], triggering in-depth research on the development of high-quality industrial silicon.

The refining technology used to produce high-quality industrial silicon involves air blowing refining [3], slag refining [4], solvent refining [5], bubble flotation [6], electromagnetic purification [7], vacuum melting [8], directional solidification [9] and many other techniques. Due to the large segregation coefficient of boron in silicon and its low saturation vapor pressure [10], it is difficult to effectively remove it through the processes such as vacuum refining and directional solidification. By contrast, air blowing refining and slagging refining convert impurity boron into other substances through the chemical reactions between boron and oxygen or slag agent, which cab effectively reduce the content of boron in silicon. Nishimoto et al. [11] used 55% SiO₂-CaO to conduct refining experiments under 1823 K high-purity argon protection conditions. Their experimental results showed that the boron content was reduced from 360 ppmw to 80 ppmw, and the removal rate reached 77.8%, verifying the feasibility of slagging
refining for boron removal. Wu et al. [12] used a compressed oxygen of 8 L/min to purify metallurgical silicon by bottom blowing at 1873 K. The boron content was reduced from 35 ppmw to 18 ppmw, and the removal rate of Al and Ca impurities exceeded 90%, but the experiments also revealed problems such as the severe oxidation of the silicon substrate and large silicon loss. Solvent refining [13] and plasma refining [14] are two highly effective methods for the removal of boron impurities in industrial silicon, but their complicated refining process and high energy consumption hinder their application. Blowing refining [15, 16] is a simple and inexpensive method for the removal of impurities such as Al, Ca, Ti and B. The main methods of refining molten silicon outside the ladle furnace are slag refining and air blowing refining [17]. Among these, the slag used to remove impurities has higher solubility for impurities than molten silicon. The solubility of silicon in the slag must be low to minimize losses. In addition, the slag must be inert to molten silicon, and must be able to separate based on density differences. Slagging is usually carried out by treating molten silicon by CaO–SiO2–Al2O3–MgO, CaO–SiO2, CaO–SiO2–MgO–Al2O3 at high temperature of approximately 1500 °C. Boron and phosphorus are the most difficult elements to remove from silicon, so that a slag with strong alkaline and oxidizing properties is preferred [18]. In air blowing refining, industrial oxygen or compressed air is blown into the metallurgical silicon melt through the nozzle system at the bottom of the ladle, the impurities in the metallurgical silicon are converted into corresponding oxides, and the oxide film floating on the surface of the silicon melt is formed and then removed, improving the purity of the metallurgical silicon [19]. In a study performed by Nordstrand et al. [16, 20], a hydrogen generator was used to blow the mixed H2O–H2 gas into a vacuum induction furnace to improve boron removal. They found that the chemical reaction between the gas phase and elemental boron is the rate-limiting step in the process of boron removal from the silicon melt by blowing wet hydrogen. The boron removal rate depends on the partial pressure of hydrogen and water vapor in the gas phase, and the maximum boron removal rate is obtained under the conditions of mixed blowing of hydrogen and water vapor. The increase in the temperature leads to a lower boron removal rate that may be due to the thermodynamics of the H-B-O (HBO) gas [21]. By adding H2–3.2%H2O, the boron content can be reduced from 90 ppmw to 1.0 ppmw.

Oxygen blowing refining is a widely popularized refining method. Most factories use oxygen and air mixed bottom blowing to refine silicon outside the furnace. In this work, the slag blowing method combined with pickling technology was used to refine industrial silicon. The slag agent and industrial silicon powder were placed in an agate mortar according to different masses of CaO, SiO2 and CaCl2 to obtain different chemical compositions. The slag agent and industrial silicon powder were placed in an agate mortar according to the different slag-to-silicon mass ratios, and the mixture was evenly mixed. The raw materials were placed into a 100 mL corundum crucible. The corundum crucible with the raw materials was placed in the high-temperature gas blowing furnace (16Q-YC, Shang hai Feng Electric Furnace Co, Ltd), an intermediate frequency induction furnace (Jin zhou Hua xin Power Electronics Co, Ltd), a diamond wire cutting machine (Shen yang Ke jing Automation Equipment Co, Ltd, SAMICK SK-25) and a steam generator (Zhe jiang Jia xian Machinery Manufacturing Co, Ltd, LDR 3). Inductively coupled plasma atomic emission spectroscopy (ICP-AES, ELAN DRC), scanning electron microscopy (SEM, XL30E), and electron microprobe analyzer (EMPA, JXA-8230) instruments were used for the characterization of the samples.

The experimental process is illustrated in Fig. 1. The industrial silicon block was ground to the size of 100–200 μm by ball milling and an electronic balance was used to weigh different masses of CaO, SiO2 and CaCl2 to obtain different chemical compositions. The slag agent and industrial silicon powder were placed in an agate mortar according to the different slag-to-silicon mass ratios, and the mixture was evenly mixed. The raw materials were placed into a 100 mL corundum crucible. The corundum crucible with the raw materials was placed into a larger magnesia crucible (the magnesia crucible can prevent the leakage of the silicon melt and spray material in the blowing refining process) and the larger crucible was placed in the high-temperature gas blowing furnace. A corundum tube with a length and inner diameter of approximately 80 cm and 1 cm was inserted from the top of the converting furnace to a position 2–3 cm above the surface of the raw corundum crucible. Then, the resistance furnace heating program was started. During the heating process, argon gas was passed from the bottom of the conversion furnace. When the heating temperature reached the set refining temperature, the blowing pipe was inserted into the melt and the Ar-H2O-O2 gas was blown into the furnace for refining and pickling experiments. The composition of the slag agent, the mass ratio of slag agent to silicon, refining time, refining temperature and acid leaching conditions were explored to obtain the highest efficiency for boron removal from industrial silicon.

2 Experimental

2.1 Experimental Method

The experiment used industrial silicon with a purity of 99.5% produced by an industrial silicon manufacturer in Yunnan Province, China, with an impurity boron content of 22 ppmw. The reagents used in the fire refining experiment include high-purity boron powder, CaO, SiO2, CaCl2, argon, oxygen and absolute ethanol. The wet acid leaching experiment used HCl and HF, and the reagents used were all of analytical grade. The devices used in the experiments include a high-temperature gas blowing furnace (16Q-YC, Shang hai Feng Electric Furnace Co, Ltd), an intermediate frequency induction furnace (Jin zhou Hua xin Power Electronics Co, Ltd), a diamond wire cutting machine (Shen yang Ke jing Automation Equipment Co, Ltd, SAMICK SK-25) and a steam generator (Zhe jiang Jia xian Machinery Manufacturing Co, Ltd, LDR 3). Inductively coupled plasma atomic emission spectroscopy (ICP-AES, ELAN DRC), scanning electron microscopy (SEM, XL30E), and electron microprobe analyzer (EMPA, JXA-8230) instruments were used for the characterization of the samples.

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certain period of time, the mixed gas from the blowing pipe was stopped while Ar flow from the bottom of the blowing furnace was maintained until the temperature in the furnace decreased to room temperature.

We have investigated the effect of the mixed Ar-H₂O-O₂ composition on boron removal in our previous studies [22, 23]. The optimal ratio of H₂O to O₂ was confirmed to be equal to 2, so that this chemical composition was adopted for all of the experiments in this work. The experimental conditions of slag composition, mass ratio of slag to silicon, refining time and refining temperature were shown in Table 1.

The refined sample was cut with a diamond wire cutter. The silicon obtained after high-temperature refining was crushed by ball-milling down to the size of 100 μm and then was leached with HCl-HF mixed acid at 343 K for 5 h. The leaching conditions are shown in Table 2. Finally, ICP-AES, SEM-EDS and EPMA measurements were carried out to analyze high-temperature refined silicon and acid-leached silicon.

Due to the extremely low concentration of the boron impurity in industrial silicon (only 22 ppmw), it is difficult to detect the occurrence of boron in silicon using physical analysis methods such as SEM and EPMA. To reveal the transformation process of the microscopic morphology of the boron impurity in the refining process, in this study, high-purity boron powder with a mass fraction of 3% was mixed into industrial silicon raw materials. According to the melting conditions shown in Table 3, industrial silicon powder and high-purity boron powder were pre-melted in an intermediate-frequency induction furnace to obtain Si-3%B alloy raw materials, and then the slag agent with a mass ratio of CaO/SiO₂/CaCl₂ of 2/1.33/1 was used to refine the Si-3%B alloy raw materials. The mass ratio of slag to silicon, the refining time and the refining temperature were 1/1, 3 h and 1823 K, respectively. Then, the refined silicon sample was pickled according to the conditions in Table 2.

2.2 Refining Mechanism

Slag refining is the addition of a slag-making agent that has a strong affinity to the impurities in silicon and reacts with the impurities to form stable compounds in the silicon melt. In iron and steel smelting, the CaO-SiO₂-CaX₂ (where X is a halogen element) slag system is widely used. Industrial silicon smelting and steel smelting have many similarities. CaO-SiO₂-CaCl₂ can not only oxidize non-metallic impurities to form calcium borate CaO·B₂O₃ in the slag phase. By the Gibbs free energy of reaction, the independent reaction between boron and SiO₂ or CaCl₂ is almost impossible. However, calcium borate can be generated with the existence of CaO in calcium silicate slag flux. Similarly, because of the negative Gibbs free energy, the gaseous boride clusters are more likely to be generated.

\[
B + \frac{3}{4}O_2(g) + \frac{1}{2}CaCl_2 = BOCl(g) + \frac{1}{2}CaO
\]  

As shown in Fig. 2, the Ar-H₂O-O₂ mixed gas is blown into the industrial silicon melt for refining, and Ar gas stirs the melt. This increases the collision probability of the inclusion particles in the silicon liquid, promotes their polymerization and growth, increases the floating speed of the inclusions in the silicon liquid, and makes the inclusions adhere to the surface of the argon bubble. When the bubbles rise, the inclusions are removed from the liquid silicon to achieve the removal of the inclusions. The H₂O and O₂ in the mixed gas oxidize the impurity boron forming boron oxide B₂O₃ and boron hydroxide H₂BxOy respectively [22]. The results of thermodynamic calculations show that HBO and SiO are the main volatile substances of boron and silicon, respectively. Secondary volatile species include HBO₂, BₓHₓ (x is from 1 to 3) and SiHₓ (y is from 1 to 3) [24]. Under alkaline conditions, H₂O can decompose into H and OH which is conducive to the formation of gaseous boride HBO through the reaction of boron and OH and the removal of boron. A previous study showed that the best boron removal effect of 96.77%, and the lowest impurity boron content of 0.71 ppmw are obtained for the H₂O/O₂ volume ratio of 2 [23].

Nordstrand et al. [16, 20] concluded that the increase of water vapor amount would lead to the more loss of silicon. In addition to the oxidation of silicon by oxygen, silicon will also be oxidized by the H₂O vapor to form SiO. The newly formed SiO will be further oxidized to form a passivation
layer of SiO₂ that hinders the boron removal. This process is described by Eqs. (2)–(4).

\[
\text{[Si]} + \text{H₂O} = \text{SiO} + \text{H₂} \quad (2)
\]

\[
\text{H₂O} + \text{SiO} = \text{SiO₂(l)} + \text{H₂} \quad (3)
\]

\[
\text{SiO₂(l)} = \text{SiO₂(s)} \quad (4)
\]

3 Results and Discussion

3.1 Impurity Morphology in Silicon after Refining

3.1.1 MG-Si after Slag Treatment and Acid Leaching without Doped Boron

First, the industrial silicon raw material was mixed with the CaO-SiO₂-CaCl₂ slag agent at a mass ratio of 2/1.33/1 according to the slag to silicon ratio of 1/1. The mixture was refined at 1823 K for 3 h, and then the refined silicon sample was pickled at the process conditions specified in Table 2. Finally, the obtained silicon ingot was sliced, polished, and subjected to SEM-EDS microscopic morphology analysis. The microstructures of the samples are shown in Fig. 3.

Figure 3a shows the microstructure of the original silicon sample and Fig. 3b shows the microstructure of the sample after slagging and refining. It is observed that the sample shown in Fig. 3b has less impurities than the original silicon sample presented in Fig. 3a, but many bright white impurity phases enriched in the main Si phase are still observed. Figure 3c shows the microstructure of the sample after pickling. Comparison of Fig. 3c to Fig. 3a, b shows that essentially all of the bright white impurities have been removed, and the main body shows the Si phase, demonstrating that the pickling affects industrial silicon to effectively remove the metal impurities.

3.1.2 Silicon Doped with 3% B after Slag Treatment and Acid Leaching

The Si-3%B alloy doped with boron was processed by the slag treatment and then by pickling. In the slag treatment process, the mass ratio of the CaO/SiO₂/CaCl₂ slag agent, the refining time, the slag-to-silicon mass ratio and the refining temperature were 2/1.33/1, 3 h, 1, and 1823 K, respectively, and the pickling process was carried out according to the conditions specified in Table 2. Figure 4 shows the microstructure of the polished and refined silicon samples.

Comparison of the samples with and with 3% B doping presented in Fig. 4a, b, respectively, shows that a large number of black boron particles appear in the industrial silicon doped with boron. Moreover, the sizes of the boron particles of the two samples are also different. The distribution of boron particles is irregular, and most of boron is enriched in the main silicon matrix, while some boron is enriched with metal impurities. Figure 4c shows the sample after slag refining, and the comparison of this figure to Fig. 4b shows that the boron impurity removal effect was quite good, with only a few boron particles remaining in the Si matrix and the inclusion phase, and the refined silicon is still enriched with a large amount of the metal impurity phase. Figure 4d shows the sample after the subsequent pickling of the refined silicon from the slag. It is observed that the boron impurities are essentially completely removed, and the amount of the impurity phase is also greatly reduced, with the sample consisting mostly of the main silicon phase.

To more clearly observe the occurrence form of the impurity boron in silicon, the boron-doped silicon, directly pickled boron-doped silicon, boron-doped silicon after slagging refining, and borosilicate after slagging and pickling were analyzed by EPMA morphology analysis, by EDS scanning analysis of the impurity area in the images, with the results shown in Fig. 5.
It is observed from Fig. 5a that the black area is mainly the Si-B phase, in which a small amount of the Ca metal impurity is dissolved. The dark white inclusions are mainly the Si-Fe-Al phase, which is the enrichment area of the metal impurities in industrial silicon. Figure 5b shows that a large amount of Ca appears in the impurity phase after slagging and refining. This is due to the use of the CaO-SiO₂-CaCl₂ slag agent that increases the impurity calcium content in silicon after refining. The calcium acid slag agent has no effect on the removal of the Fe impurities, and an examination of the distribution diagram shows that the amount of boron impurity in silicon after refining is greatly reduced, and boron is mainly enriched with metal impurities in the Si-B-Ca and Si-B-Ti-Fe phases. Comparison of the sample obtained after slagging, refining and pickling presented in Fig. 5d to the sample obtained after slagging and refining presented in Fig. 5b shows that the boron-containing compounds have completely disappeared. This indicates that the removal of boron is quite thorough, and the amount of metal impurities is further reduced. A small amount of the Si-Al-Cu phase is observed because the impurity Cu in silicon is difficult to remove by pickling with the HCl-HF solution.

### Table 3 Pre-melting conditions of Si-3%B alloy

| MG-Si powder (g) | Boron powder (g) | Premelting atmosphere | Temperature (K) | time (h) |
|------------------|------------------|-----------------------|----------------|---------|
| 97               | 3                | Ar                    | 1823           | 3       |

### 3.2 Slag Treatment Conditions of Combined Refining

#### 3.2.1 Effect of Chemical Composition of CaO/SiO₂ on Boron Removal

In these experiments, the CaO/CaCl₂ mass ratio during the refining process of the slag agent was maintained at 2, the refining time was 3 h, the slag-silicon mass ratio was 1, and the refining temperature was 1823 K. The influence of the CaO/SiO₂ in the slag agent on the removal of impurity boron was examined and the experimental results are shown in Fig. 6.

Figure 6a shows that CaO/SiO₂ has a strong impact on the removal of the boron impurity in industrial silicon. With the increased addition of SiO₂, the boron removal effect is significantly improved, and the boron content in refined silicon reaches the lowest value of 1.37 ppmw for the CaO/SiO₂ mass ratio of 1.5, with the boron removal efficiency boron reaching 93.77%. The boron removal efficiency then decreases with the further increase in the proportion of SiO₂. This is mainly because the increase in the SiO₂ amount will reduce the amount of CaO in the calcium silicate slag agent. The impurity boron removal is affected by the basicity of the slag and the oxygen potential. When the amount of SiO₂ is too high, the O²⁻ and impurity boron are reduced, reducing the reaction rate and the boron removal effect. It is observed from Fig. 6b that the distribution coefficient of impurity boron first increases and then decreases. For the CaO/SiO₂ ratio of 1.5, the \( L_B \) distribution coefficient of boron reaches the

![Fig. 2 Schematic diagram of MG-Si by united refining technology](image)
maximum value of 6.7. The further increase in the CaO/SiO₂ value results in increasing SiO₂ and reduced activity. As the activity decreases, the boron removal effect also decreases, inevitably leading to a decrease in the \( L_B \) value. SAFARIAN et al. [25] added Na₂O to CaO-SiO₂ to carry out slag refining experiments. In addition to being transported into the slag, boron is partially gasified by the evaporation of sodium metaborate at the interface of slag and gas. The higher mass ratio of slag to silicon, the greater degree of boron gasification. The addition of CaCl₂ can effectively enhance the distribution coefficient of boron. The reason is that CaCl₂ is an active substance, which can reduce the melting point and viscosity of the slag agent and promote the volatilization of gaseous boride BOCl. It is experimentally concluded that the optimal boron removal is obtained with the CaO/SiO₂/CaCl₂ ratio of 2/1.33/1.

### 3.2.2 Effect of the Slag-to-Silicon Ratio on Boron Removal

In these experiments, the CaO/SiO₂ mass ratio in slag refining was maintained at 1.5, the refining time was 3 h, and the refining temperature was 1823 K, and the effect of the slag-to-silicon mass ratio on the removal of boron was studied. The results are shown in Fig. 7.

It is observed from Fig. 7 that as the slag-to-silicon mass ratio increases, the impurity boron concentration gradually decreases. The best boron removal effectiveness of 93.77% was obtained for the slag-to-silicon mass ratio of 1, while a further increase in the amount of slag agent and refine led to the increase in the boron content in silicon to 1.54 ppmw. This shows that when the mass ratio of slag to silicon exceeds a certain limit, the increase in the slag amount is no longer conducive to boron removal. When the slag-to-silicon ratio is too low, the reaction between the slag and silicon is insufficient, leading to decreased boron removal efficiency. According to Fang et al. [26], silicon loss can be explained by two possible mechanisms: silicon may volatilize into the atmosphere at high temperatures or it may react with SiO₂ during slag refining.

### 3.2.3 Effect of Refining Time on Boron Removal

In these experiments, we varied the refining time in the 0.5–3.5 h range and its effect on the removal of the boron impurity in industrial silicon. Here, the mass ratio of CaO/SiO₂, the slag-to-silicon mass ratio and the refining temperature were 1.5, 1, and 1823 K, respectively. The results are shown in Fig. 8.

It is observed from Fig. 8 that with the extension of the refining time, the boron content in the silicon was significantly reduced, and the boron removal effect was significantly improved. When the refining time was increased from 0.5 h to 3 h, the boron content in metallurgical silicon was reduced from 22 ppmw in the original sample to 10.74 ppmw and 1.37 ppmw, respectively. When the refining time was extended to 3.5 h, the boron content in the refined silicon was essentially unchanged. The extension of the refining time ensures...
the full contact of the slagging agent with the impurity boron in silicon, so that the boron is oxidized and removed more thoroughly. When the refining time exceeds a certain range, the contents of boron in the silicon phase and the slag phase reach equilibrium. Considering the cost of refining, the optimal refining time was selected as 3 h.

Fig. 5 EPMA and EDS images of samples a Si-3%B alloy; b Si-3%B alloy after slag treatment; c Si-3%B alloy after slag treatment and acid leaching

Fig. 6 Effect of CaO/SiO$_2$ on boron removal a Concentration and removal efficiency of boron in refined silicon; b Relationship between $L_{\text{em}}$ and CaO/SiO$_2$ with different slag composition
3.2.4 Effect of Refining Temperature on Boron Removal

In these experiments, we varied the refining temperature in the range of 1773–1843 K, and studied the effect of the melt temperature on the removal of the boron impurity in industrial silicon. Here, the composition of CaO-SiO$_2$-CaCl$_2$ slag agent, the slag-to-silicon mass ratio, and refining time were 2/1.33/1, 1/1, and 3 h, respectively. The results are shown in Fig. 9.

It is observed from Fig. 9 that increasing the refining temperature will gradually reduce the content of the boron impurity in silicon. Between 1773 and 1803 K, the boron content in silicon after refining is relatively high. This is because the refining temperature is too low and the refining slag is not completely melted, resulting in the poor fluidity of the slag and limiting the reaction between the slag and silicon. When the temperature reaches 1823 K, the boron content in the refined silicon shows a significant decrease, and the boron content in silicon decreases from 1.4 ppmw to 0.71 ppmw. Between 1823 and 1843 K, the rate of decrease in the boron content in refined silicon with increasing temperature slowed down as the boron content decreased from 0.71 ppmw at 1823 K to 0.6 ppmw at 1843 K. These results show that a higher temperature leads to the greater fluidity of the slag and silicon that enables improved contact between the slag and silicon; then the increased rate of the reaction between the slag and silicon promotes the conversion of impurity boron. The optimal refining temperature was identified in this study as 1823 K.

4 Conclusions

Industrial silicon with a purity of 99.5% and an impurity boron content of 22 ppmw was used as the raw material and then underwent slag refining, air blowing refining and pickling to remove the impurity boron. It was found that the microscopic morphology of boron impurity in the refining process undergoes a significant transformation. The optimal conditions were identified as the CaO-SiO$_2$-CaCl$_2$ ternary slag ratio of 2/1.33/1, the slag-to-silicon mass ratio of 1/1, the refining time of 3 h, the refining temperature of 1823 K, the HF-HCl-H$_2$O ratio of 1/1/8 and the volume ratio of H$_2$O-O$_2$ of 2. For these conditions, the optimal boron removal of 96.77% is achieved, and the impurity boron content reaches the lowest value of 0.71 ppmw. With regard to temperature variation, it was found that when the temperature is increased from 1803 K to 1823 K, the boron content in silicon decreases from 1.4 ppmw to 0.71 ppmw. Between 1823 and 1843 K, the boron content decreased from 0.71 ppmw at 1823 K to 0.6 ppmw at 1843 K. These results show that the slagging refining gas blowing combined with the pickling process has a strong and positive removal effect on impurities in industrial silicon.
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Author Contributions Ji-jun Wu conceived the study, coordinated the conduct of the study; Qi-liang Wang participated in the design of the study, assisted in interpreting the data, and helped to draft the manuscript; Shuang-feng Qian participated in the design of the study, assisted in interpreting the data, and helped to draft the manuscript; Hua-zhen Gu participated in the design of the study, assisted in interpreting the data, and helped to draft the manuscript; Wen-hui Ma participated in the design of the study, assisted in interpreting the data, and helped to draft the manuscript;

Data Availability All data and software application support their published claims and comply with field standards.

Declarations

This study and all procedures performed involving human participants were in accordance with the ethical standards.

Consent to Participate All authors consent to participate in this publication.

Consent for Publication All authors consent to the publication of the manuscript in SILICON, should the article be accepted by the Editor-in-chief upon completion of the refereeing process.

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