High-Efficiency Direct Bonding of SiC to Si via Atmosphere Inductively Coupled Plasma

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The SiC/Si heterostructure is pivotal in various applications owing to its superior performance and potential for advanced electronic and optoelectronic devices. A direct bonding method utilizing plasma to activate surface in a vacuum environment has been developed for SiC/Si heterogeneous integration. The necessity of a vacuum environment reduces the efficiency of plasma activation bonding (PAB), thus limiting its application in heterogeneous integration. In this study, we investigated the high-efficiency and low-temperature direct bonding of SiC/Si via atmosphere inductively coupled plasma (ICP). Following less than 5 s of Ar ICP irradiation, surface activation was achieved, resulting in the formation of a superhydrophilic surface (contact angle < 3°). The surface maintained the roughness and flatness that met the requirements for direct bonding during ICP irradiation. Additionally, ICP irradiation effectively eliminated surface contaminants and enhanced the quality of direct bonding. After low-temperature annealing, the bonding strength reached 4.38 MPa. The results show that ICP irradiation can efficiently activate the surface and improve the bonding quality without a vacuum environment. The direct bonding of SiC/Si heterostructures through ICP irradiation holds significant potential for the fabrication of high-performance power electronics and micro/nanofluidic devices.

1. Introduction

SiC is a third-generation semiconductor with excellent properties such as a wide bandgap, high thermal conductivity, high breakdown voltage, and strong mechanical stability. SiC is widely used in high-temperature complementary metal oxide semiconductors (CMOS), high-radiation hard detectors, new optical devices, high-frequency microelectronics, microelectromechanical systems (MEMS), and biosensors [1]. The SiC/Si heterojunction, formed by introducing a Si layer on the SiC substrate, further improves the reliability of the gate oxide [2,3].SiC/Si heterojunctions hold promising potential in high-frequency and high-power devices.

Since the proposal of the SiC/Si heterojunction, various techniques such as chemical vapor deposition, molecular beam epitaxy (MBE), and electron beam evaporation under ultrahigh vacuum (EBE-UHV) have been explored [4]. However, the large lattice mismatch between Si and SiC has made it challenging to obtain Si layers of sufficient quality for MOS-gated devices [5]. As a monolithic integration approach, direct bonding not only overcomes lattice mismatch, but also avoids surface contamination [6,7]. Mu et al. achieved high-quality bonding using surface activated bonding (SAB) which bonding strength higher than the bulk strength of Si without high-temperature annealing [8]. Nevertheless, However, SAB has limitations such as high cost and complexity, restricting its further development. Not only that, but SAB is not suitable for direct bonding of oxides. Wang et al. proposed a direct bonding method using ultraviolet (VUV) surface irradiation [9]. VUV surface irradiation is easy to operate and can be bonded at low temperature. However, VUV irradiation takes a long time to process and requires vacuum equipment. The contaminants generated in the process also require additional post-treatment processes. Plasma-activated bonding (PAB) is a more widely used method for SiC/Si direct bonding than other methods. Wang et al. achieved a bonding efficiency more than 90% at low temperature by reactive ion etching (RIE) O_2 plasma for 30 s [10]. Until now, most PAB methods still require expensive vacuum equipment, and the vacuuming process reduces activation efficiency.

In this paper, we investigated high-efficiency and low-temperature direct bonding of SiC/Si via atmosphere ICP surface activation. Both SiC and Si surfaces exhibit superhydrophilicity (contact angle < 3°) after less than 5 s of ICP irradiation, showing the high-efficiency activation ability of atmospheric ICP. To illustrate the facilitating effect of ICP on direct SiC/Si bonding, various characterization methods were used to measure the surface conditions of SiC and Si. In addition, the bonding strength and bonding interface after annealing were also evaluated to demonstrate the activation effect of ICP irradiation. The advantages of ICP irradiation, high-efficiency, simple operation, and no need for vacuum equipment provide potential benefits for the development of SiC/Si heterogeneous integration.

2. Experimental

2.1 Bonding Materials

4H-SiC substrates (10 mm × 10 mm × 500 μm in size) and (100)-oriented Si substrates (10 mm × 10 mm × 700 μm in size) were used in the experiments. The Si face (0001) of SiC was used as the experimental bonding face. After ultra-precision polishing, the roughness and flatness of both SiC (Sa < 0.1 nm, PV < 200 nm) and Si (Sa < 0.4 nm, PV < 300 nm) met the requirements for direct bonding.

2.2 Experimental Details

The whole process flow is depicted in Fig. 1. SiC and Si substrates were sequentially cleaned by ultrasonic-assisted cleaning with alcohol and deionized water for 20 min. After drying, the samples were irradiated by Ar plasma in an atmospheric environment to activate the surfaces. The total flow rate of Ar was 19.5 sccm, with carrier Ar and cooling Ar set at 1.5 sccm and 18 sccm, respectively. After ICP irradiation, the samples were placed in deionized water for ultrasonic-assisted cleaning and post-processing of the activation. Subsequently, the SiC and Si substrates were pre-bonded under a pressure of 5 MPa. Finally, the pre-bonded sample was annealed at 200 °C for 18 h to enhance the bonding strength.

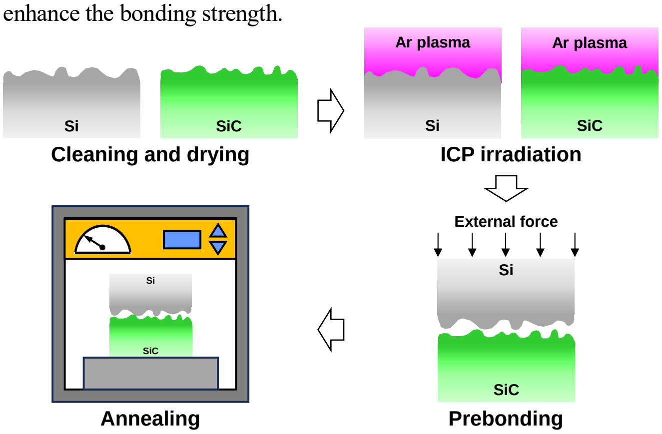

Fig. 1 Schematic diagram of the direct bonding process via ICP irradiation.

2.3 Characterizations

The contact angle of the surface was measured using a contact angle tester (DSA25, KRÜSS). Surface roughness and flatness were evaluated with an atomic force microscope (AFM, Bruker Dimension Edge) and a white light interferometer (WLI, NewView™ 9000, ZYGO), respectively. Optical microscopy (OM, ML15B, Lapsun) was used to capture images of the surfaces before and after ICP irradiation. The number of particles in the images was counted using ImageJ software. The interface after prebonding was observed with a laser scanning confocal microscope (LSCM, VK-X1000, KEYENE).

3. Results and Discussion

Direct bonding is extremely demanding on the surface conditions of the sample. Achieving direct bonding requires a superhydrophilic surface, typically characterized by a contact angle of less than 6° [11]. Flatness is another crucial factor, as poor flatness can lead to large cavities or even bonding failure [12]. Additionally, extremely low roughness (Sa < 0.5 nm) is essential for high-quality bonding [13].

3.1 Surface Hydrophilicity after ICP Irradiation

The RF power and irradiation time of the ICP are important parameters for surface activation. As shown in Fig. 2, the contact angle of SiC and Si substrates' surfaces was less than 3° after ICP irradiation at the RF power ranging from 500 to 1000 W for 5 s, indicating that the surfaces were superhydrophilic. This means that high-efficiency activation can be achieved at low temperatures using low-power ICP. The high activation efficiency is attributed to the ultra-high density of radical generated by high-energy atmospheric ICP [14]. What's more, when the irradiation time was extended to 25 s, and the surface of the samples remained superhydrophilic during the process. The result ensures that it is feasible to remove surface contaminants with prolonged irradiation to achieve higher quality bonding interfaces.

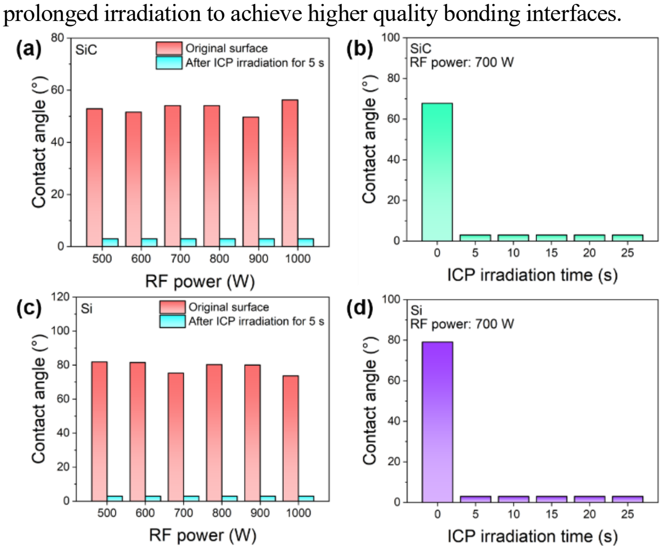

Fig. 2 Contact angle variation of SiC surface under different (a) RF power. (b) ICP irradiation time. Contact angle variation of Si surface under different (c) RF power. (d) ICP irradiation time.

3.2 Flatness and Roughness after ICP Irradiation

The large thermal stress generated by the high temperature of high-energy ICP may cause warpage and thermal oxidation of the surface, resulting in deterioration of flatness and roughness. By using a numerical control (NC) platform to control the plasma torch for scanning, the accumulated temperature effect on the surface can be reduced, so as to achieve the purpose of reducing thermal stress.

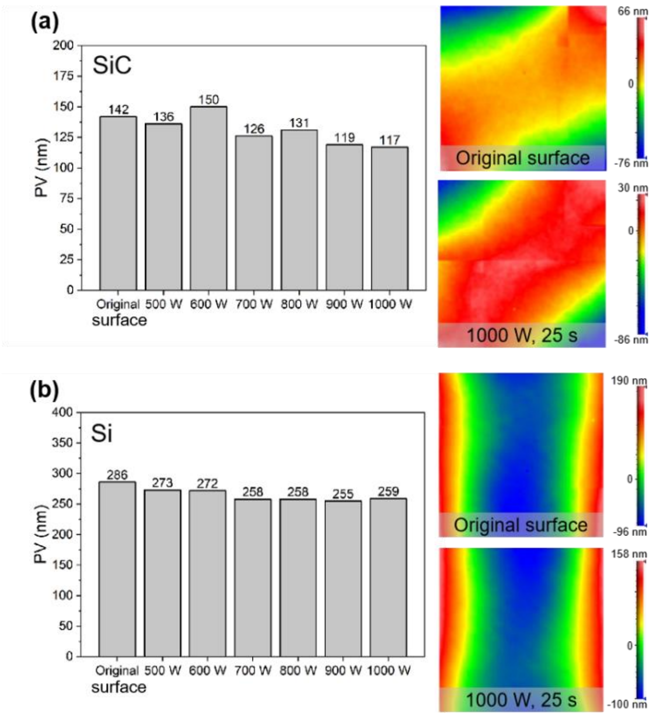

Fig. 3 Flatness of (a) SiC and (b) Si surfaces under different RF power.

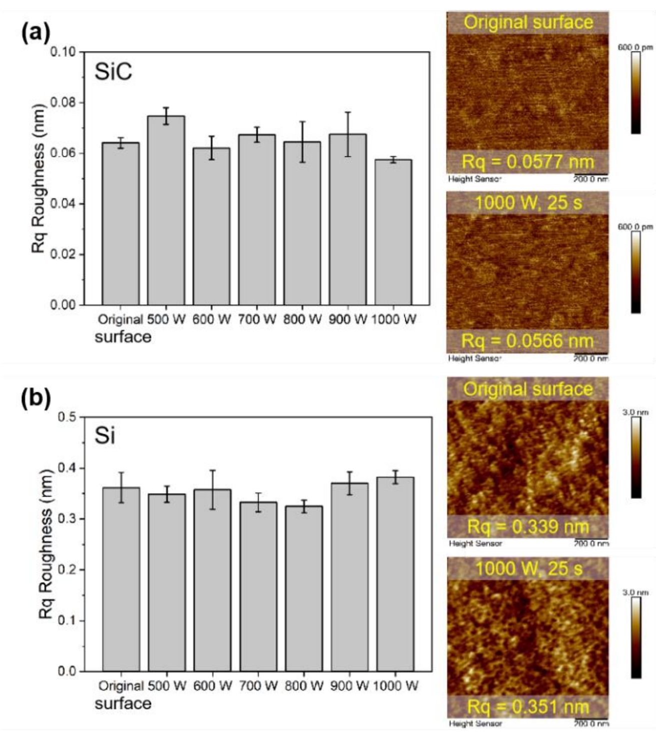

Fig. 4 Roughness of (a) SiC and (b) Si surfaces under different RF power.

The results of Fig.3 and Fig. 4 illustrated that the flatness and roughness of the sample surface were maintained at their original conditions during ICP irradiation. As shown in Fig. 5, the surface temperature of the sample is below 300 °C when the RF power used does not exceed 700 W. The method adopted above proved to be effective.

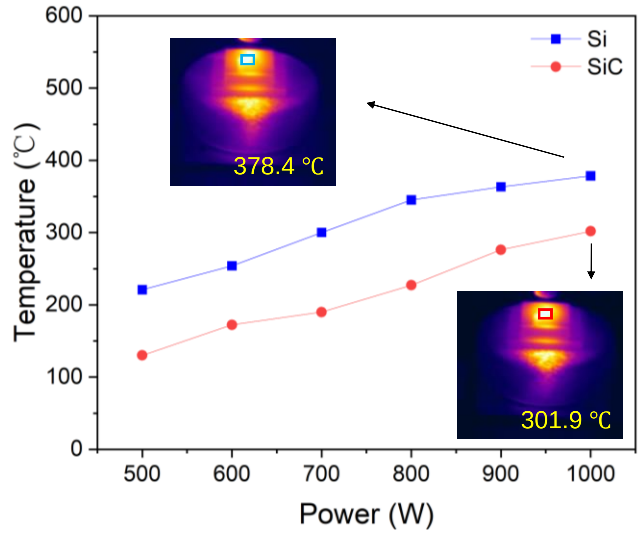

Fig. 5 Temperature of SiC and Si surfaces under different RF power.

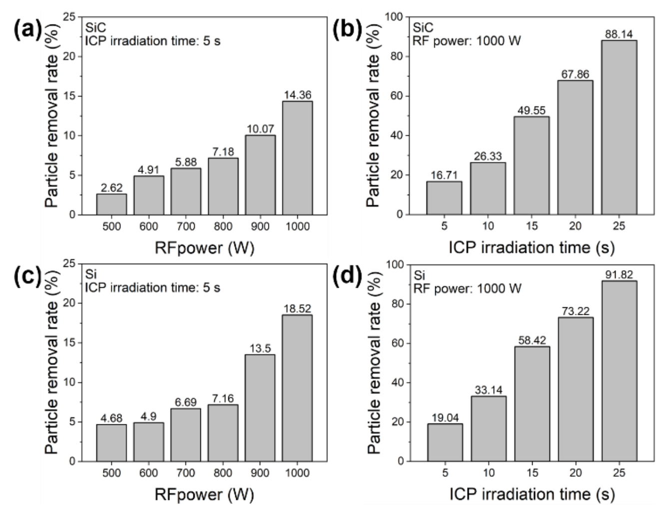

Fig. 6 Particle removal rate of SiC surface under different (a) RF power. (b) ICP irradiation time. Particle removal rate of Si surface under different (c) RF power. (d) ICP irradiation time.

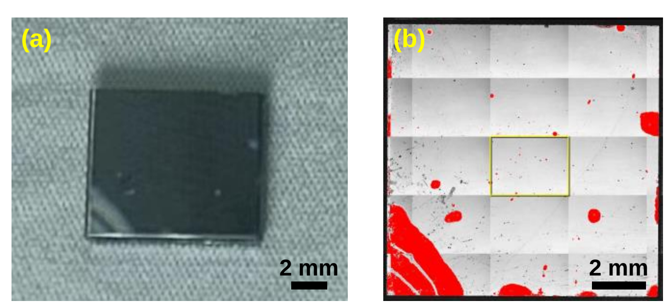

Fig. 7 (a) Image of the bonding interface. (b) Photograph of SiC/Si pre-bonded pairs.

3.3 Cleaning Effect of ICP Irradiation

The cleanliness of the surface has a direct impact on the bonding's quality. Fewer surface particles help reduce the area of the voids. Fig. 6 shows the effect of RF power and ICP irradiation time on the cleaning capacity of ICP. The particle removal rate increased with higher power and prolonged irradiation time. When irradiated with 1000 W of high-power ICP for 25 s, the particle removal rates of SiC and Si reached 88.14 % and 91.82 %, respectively, indicating that the surface can be further cleaned during the activation process.

3.4 Interface Characterizations and Bonding Strength

Based on the above results, to maximize surface cleanliness while maintaining activation effects, we used 1000 W power and a 25 s irradiation time for final sample processing. The entire pre-bonding process was conducted in an atmospheric environment at room temperature. Fig. 7 shows the bonding interface after pre-bonding. Most area of the surface is already bonded. The bonding efficiency was analyzed by the image processing software Image J, and as shown in Fig. 7 (b), the bonding efficiency was as high as 91.746 %. A high bonding area ratio means a better connection between the bonded samples, which is essential for improving bonding strength. The bonding strength of the SiC/Si sample reached 4.38 MPa after low temperature annealing.

4. Conclusions

In conclusion, we have achieved direct bonding of single crystal SiC to Si with a bonding efficiency of 91.746 % by atmospheric ICP, which led to a bonding strength of 4.38 MPa. The effects of RF power and irradiation time of atmospheric ICP on the surface conditions of SiC and Si substrates were systematically studied. The experimental results demonstrate that atmospheric ICP can effectively activate the surface hydrophilicity (contact angle $< 3°$) of both SiC and Si substrates at low power and in less than 5 s of irradiation time. Additionally, by utilizing a scanning mode, the original roughness and flatness of the substrate surfaces were preserved during ICP irradiation, ensuring an optimal bonding process. The cleaning effect observed during ICP irradiation also contributed to the production of a high-quality bonding interface. Atmospheric ICP irradiation emerges as a promising activation method for fabricating SiC/Si heterojunctions, offering an efficient approach to achieving direct bonding of SiC/Si substrates in atmospheric environments.

ACKNOWLEDGEMENT

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