Effect of High Temperature Annealing on Characteristics of 4H Silicon Carbide MESFET

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Abstract: For very high temperature annealing (1620°C) after ion implantation for 4H silicon carbide (4H-SiC), the residual components of Al and O in the alundum furnace impact seriously on the surface of material, which yields the derivation of SiOC. This causes a significant degradation of the 4H-SiC surface characteristics according to the results of surface composition analysis. As validity, Ni/SiC ohmic contact measurement illustrates a higher specific contact resistance than the normal value by a factor of 2~3. Consequently the MESFET fabricated with this kind of 4H-SiC material results in a degraded I-V output performance compared with that of normal 4H-SiC MESFET.

Key words: silicon carbide; annealing; surface composition analysis; ohmic contact; I-V characteristics

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1 Introduction

Silicon carbide (SiC) is a promising material of wide band gap and it has been found wide applications in recent years, wherein 4H-SiC is a potential option for high temperature, high voltage, high frequency, and anti-radiation applications. However, a very high annealing temperature (> 1600°C) for the activation of implanted ions makes the SiC device fabrications difficult and incompatible with the technology of Si or GaAs devices[1-3]. In this paper, we investigated n-type 4H-SiC wafer which was nitrogen implanted and in turn annealed in an alundum furnace at argon ambient. After annealing for 30min at 1620°C, a damaged surface occured and the inherent defects were clearly shown in uncovered SiC specimen. The phenomenon was analyzed with scanning electron microscopy (SEM) and energy dispersive analysis X-ray (EDAX). The Auger spectrum was also used for deep layer analysis of annealed 4H-SiC. The fabricated MESFET was measured and compared with the normal 4H-SiC MESFET.

2 Experiments and surface analysis

After high dose nitrogen multiple implantation (total dose of 3 X 1015 cm-2 and approximately 0.2µm depth), the 4H-SiC multi-epitaxial wafer (detailed parameters given in Table 1) was divided into several specimens. Part of these specimens with the surface exposed and another with the surface covered by others SiC were all put on a SiC-covered graphite boat in the alundum furnace. After annealing for 30min at 1620°C in argon ambience...
ent, the exposed SiC specimen showed the polluted surface, but the covered one was normal. The possible sources of pollution were either the free aluminum or the residual oxygen, which separated out from the wall of alundum tube at very high temperature. Theoretically, at this range of temperature, the residual oxygen, even in air atmosphere, can only produce a very thin film of oxidation on SiC surface quickly and stop further oxidation consequently. Furthermore, this annealing temperature is not sufficient to significantly change the surface stability of 4H-SiC. Therefore, we proposed that the free aluminum from the alundum tube plays an important role in surface changes during annealing. It decreases the fusion point of SiC and makes the surface unstable. The residual oxygen can easily react with SiC, yielding SiO₂, and derivatives of SiOC. The possible reaction is

\[ \text{SiC} + \text{O}_2 \rightarrow \text{SiOC} + \text{SiO}_2 \]  

(1)

In fact, the SiO₂ has been fused at 1620°C, but still maintained its original structure when the temperature decreases. After chemically cleaned with HF, H₂SO₄ and HCl/HNO₃, SiO₂ is removed and SiOC remained, consequently causing the rough surface morphologies. We do not clearly understand the structure and the mechanism of SiOC. But it indeed has different properties from the SiO₂ and SiC because it is hardly etched in experiments. What is described above is illustrated with EDAX spectra and SEM images. Figure 1 (a) shows the special surface morphologies of annealed 4H-SiC after chemically cleaning. The phenomenon of homogeneous crystalline comes by means from arbitrary pollution. The reasonable explanation is that the surface structure of SiC is not stable as usual and the reaction is easier at high temperature. Figure 1 (b) gives a higher magnification of the same region. It is clear that the SiO₂ component formed by oxidation has been removed by HF. The SiC and

Fig. 1 SEM images for surface morphologies of annealed 4H-SiC after chemical cleaning

SiOC, however, hardly reacted with the chemical reagent mentioned above. There exists the hollowness and yields the rough surface accordingly. As validity, the SiC is further dry etched by reactive ion etching (RIE) with etching gas NF₃ under high power (> 250W). The black colour caused by free carbons is shown clearly and the etching rate is extremely low. However, the etching rate for 4H-SiC is not so low under the condition of NF₃ gas and high RF power (> 200W), and the rich carbons from fracture bond of SiC during RIE can be removed by

\[ \text{C} + x\text{F} \rightarrow \text{CF}_x(\text{or CF}_2) \]  

(2)

or by high power ion bombardment[4]. As comparison, we have got the normal surface morphologies and etching rate (approximate 30~ 50nm/min under 200W RF power) from the clean surface 4H-SiC specimen which is protected during annealing. It indicates that the combination of oxygen with
SiC has changed the characteristics of SiC, producing abnormal derivatives at very high temperature under the influence of aluminum. Figures 2(a) and (b) illustrate the surface compositions of two annealed 4H-SiC specimens by EDAX, respectively. Shown in Fig. 2(a) is the spectrum in which the Al has been eliminated but O remained after further cleaning, especially with strong and hot (80°C) HF. It is apparent that the O component is not from the SiO₂, but from the derivatives of SiC. However, this phenomenon does not occur in the clean specimen shown in Fig. 2(b). For further investigation of the SiC deep layer after annealing, the vertical components of the specimens were measured utilizing Auger energy spectrum. The profile in Fig. 3 shows that the O disappears under the surface and the N is the dopant of n type SiC. That means the surface degradation does not diffuse into the deep layer.

![Fig. 3 Auger profile of the epitaxial deep layer](image)

### 3 Ohmic contact measurement

After high temperature annealing, the heavy doped n⁺ cap layer was formed. To fabricate ohmic contact layer on SiC device, a layer of NiCr alloy with the thickness of 500nm was deposited and rapidly annealed at 950°C for 5min at argon atmosphere. A thick layer of Au was then deposited on the NiCr metal to form the interconnection. A transmission length model (TLM) was fabricated to measure the ohmic contact resistance. The fabricated TLM pattern is shown in Fig. 4(a). The measurements from the normal and abnormal 4H-SiC specimens are shown in Figs. 4(b) and (c). The linear I-V characteristics indicate the formation of desired ohmic contact layers. However, the extracted specific contact resistances from these I-V characteristics are different between the two specimens. In Fig. 4(b), the specific contact resistance ρc approximately equals 4.9 × 10⁻⁵Ω·cm². But Fig. 4(c) shows approximately 1.6 × 10⁻⁵Ω·cm² for the abnormal specimen. This is higher than the normal value of this kind, which is between 10⁻⁷~10⁻⁶Ω·cm² in other papers [3]. It is of great influence for large ohmic contact resistance on the performance of devices in microwave power applications. Figure 4(d) gives the surface analysis of ohmic contact region after metallization of this kind. The existence
of O indicates that the derivatives of SiOx at the surface affect the regular silicide reaction between Ni and Si during metallization\(^6\), increasing the ohmic contact resistance.

Fig. 4 (a) SEM image of TLM pattern for ohmic contact measurement; (b) TLM ohmic contact measurement from normal annealed 4H-SiC specimen. The calculated specific contact resistance \( \rho = 4.9 \times 10^{-2} \Omega \cdot cm^2 \); (c) TLM ohmic contact measurement from abnormal annealed 4H-SiC specimen (there exists O component in the surface layer). The calculated specific contact resistance \( \rho = 1.6 \times 10^{-2} \Omega \cdot cm^2 \); (d) Surface EDAX spectrum of ohmic contact region after Ni/Cr metallization (950°C, 5min, Ar ambient)

4 \textbf{I–V characteristics of 4H-SiC MESFET fabricated by the specimens}

To investigate the effect of surface on device performance, the \( W/L_e = 120 \mu m / 1.2 \mu m \) single gate 4H-SiC MESFETs were fabricated with the abnormal and normal annealed 4H-SiC specimens. The NiCr/Ti/Au and Ti/Pt/Au were used for source/drain and gate contact metals. The recess-gate region (approximate 0.2 \( \mu m \) n\(^+\) cap layer was removed by RIE) was used for power MESFET structure. The SEM image of device is shown in Fig. 5(a). Both measurements of \( I–V \) characteristics are demonstrated in Fig. 5(b) and (c). For the specimen with O existence in the surface, the high ohmic contact resistance and the rough surface morphology (shown in Fig. 4(c) and Fig. 1) seriously impact the source/drain ohmic contacts and gate Schottky contact. As shown in Fig. 5(b), the output drain current and transconductance decrease, the leakage current increase, consequently degrading the performance of MESFET. As comparison, Figure 5(c) shows the better results because the 4H-SiC material maintains the normal surface structure after annealing. It is illustrated...
clearly that the low quality of surface in active region makes the device suffering poor output performance. This is actually one of the difficulties in SiC device fabrications. Although RIE and SacOx (sacrificial oxide) are used in S/D region and recess gate region, they hardly eliminate the surface defects absolutely. Thus a smooth surface is very important to elevate the performance of MESFET.

5 Conclusion

In this work, we investigated the properties of high temperature annealed 4H-SiC multi-epitaxial specimens after implantation. In poor surface morphological specimen, the presence and reaction of O with 4H-SiC surface produced abnormal SiOC derivatives during high temperature annealing. From the images and spectra of surface analysis, we proposed that the aluminum precipitated from the alundum tube makes the SiC surface unstable. The residual O can readily react with SiC, yielding SiO2 and SiOC. Compared with the previous experiments, the unique mechanism of SiOC is difficult to explain. It is clear that this kind of derivatives changes the surface properties of SiC and seriously degrades the electrical performance of MESFET through ohmic contact and I-V characteristics measurements. As comparison, the 4H-SiC MESFET fabricated by the normal annealed specimen demonstrates the better output performance.

References

离子注入高温退火对 4H-SiC MESFET 特性的影响

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摘要：采用人造金刚石高温炉管对 4H-SiC 进行 1620℃的离子注入后退火，实验测试发现，在金刚石管壁析出的微量铝的作用下，SiC 表面与残余的氧成分反应生成氧化物 SiOC，造成材料表面粗䊁和反应离子刻蚀速率很低。分别采用该种样片和正常样片制作了单栅 MESFET，对比测试的欧姆接触和 I-V 输出特性。评估了高温退火后材料表面对器件的影响。

关键词：碳化硅；退火；表面分析；欧姆接触；I-V 特性

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