

SiC MOS Interface States: Difference Between Si Face and C Face

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This paper discusses the differences between Si-face and C-face MOS interfaces in 4H-SiC MOSFETs. The two interfaces exhibit unique electrical characteristics, which will be linked with the differences in interface defects. We carried out an electrically detected magnetic resonance (EDMR) study on Si-face and C-face 4H-SiC MOSFETs, and found that there are different types and different amounts of interface defects on each interface. We discussed the EDMR results in comparison with the electrical characteristics of Si-face and C-face MOSFETs.

SiC MOS Interfaces: Si face vs. C face

Silicon carbide is a promising wide-band-gap semiconductor for high-performance (high-voltage and high-temperature operational, low-energy-loss, and high-energy-density) power electronics. The main devices of SiC will be Schottky barrier diodes (SBD) and metal-oxide-semiconductor field effect transistors (MOSFETs) on 4H-SiC wafers. Both the devices expectedly have wide applications in power electronics. Currently, the SBD devices have been practically commercialized, but the MOSFETs still have some barriers for a mass commercialization. The major barriers are caused by the quality of SiC MOS interfaces. From a structural view point, SiC-SiO₂ interfaces are similar to the well-known Si-SiO₂ interface, as discussed in our earlier paper [1]. However, from an electrical view point, SiC MOS interfaces are much inferior to those of silicon. The important issues in 4H-SiC MOSFETs are (1) a serious degradation of the channel mobility (field-effect mobility, μ_{FE}), (2) a lower stability of the threshold voltage (V_{th}), and (3) a lower reliability of gate dielectric layers, as compared to the case of silicon. Such properties are strongly dependent not only on MOS processes [oxidation and post-oxidation anneal (POA), etc.] but also on the type of initial surfaces. In 4H-SiC wafers, typical surfaces are 4H-SiC(0001) (Si face) and 4H-SiC(000 $\bar{1}$) (C face), as shown in Fig. 1(a). The two ideal surfaces are dominated by either Si or C atoms. However, in practical cases, an intentional off-angle (4° to 7°) of wafers does not allow such ideal surface structures, and the growth of an oxide layer also destructs an initial surface [see Fig. 1(b)]. Accordingly, SiC MOS interfaces might form a mixed structure consisting of both Si and C atoms.

Nevertheless, the two MOS interfaces exhibit strikingly different behaviors, which are evidenced by the electrical measurements shown in Fig. 2. In this figure, four types of *n*-channel SiC MOSFETs fabricated on either Si face or C face are examined. Their specifications are summarized in Table I.

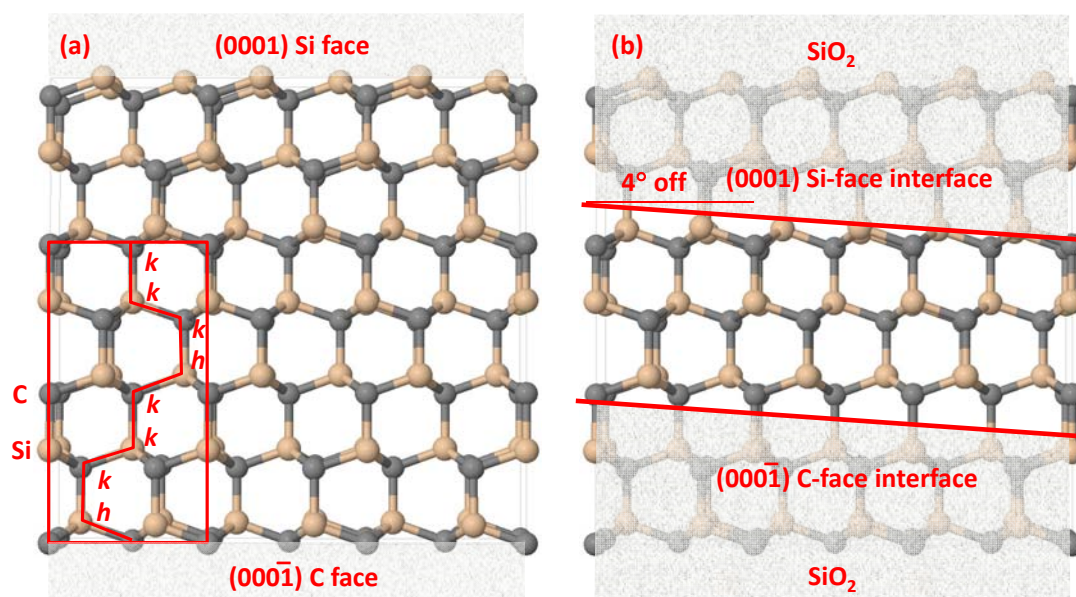


Figure 1. Schematic views of (a) 4H-SiC(0001) Si face and 4H-SiC(000 $\bar{1}$) C face and (b) their MOS interfaces. A unit cell and k and h sites are shown in (a). In (b), the standard 4° off-angle is drawn for a 4H-SiC(0001) wafer.

TABLE I. Lateral n -channel 4H-SiC MOSFETs examined in our experiments. Gate length is 100 μm and gate width is 150 μm .

Label	Substrate	Source/Drain	Gate	mobility
Si-face (Dry)	7°-off n -type 4H-SiC(0001) optimum n epi-layer [N] $\approx 5 \times 10^{15} \text{ cm}^{-3}$ Al-implantation [Al] $\approx 1 \times 10^{20} \text{ cm}^{-3}$	P-implantation [P] $\approx 1 \times 10^{20} \text{ cm}^{-3}$ Ni contact	dry SiO ₂ (50 nm) poly-Si	2 cm ² /Vs @20V
Si-face (Nitrided)	same as above	same as above	dry SiO ₂ (60 nm) poly-Si NO&N ₂ O POA 1250°C	19 cm ² /Vs @20V
C-face (Dry)	4°-off n -type 4H-SiC(000 $\bar{1}$) optimum p epi-layer $N_A - N_D \approx 5 \times 10^{15} \text{ cm}^{-3}$	P-implantation [P] $\approx 3 \times 10^{20} \text{ cm}^{-3}$ Al contact	dry SiO ₂ (50 nm) Al	0.0 cm ² /Vs (transistor did not work.)
C-face (Wet)	4°-off p -type 4H-SiC(000 $\bar{1}$) optimum p epi-layer $N_A - N_D \approx 5 \times 10^{15} \text{ cm}^{-3}$	same as above	wet SiO ₂ (52 nm) Al H ₂ POA 1100°C	97 cm ² /Vs

For C-face MOSFETs [Fig. 2(a)], dry oxidation was never successful and hence the C-face(Dry) MOSFETs did not work. Contrary to dry oxidation, wet oxidation dramatically improved C-face MOSFETs. The channel mobility increased up to $\sim 100 \text{ cm}^2/\text{Vs}$ [Fig. 2(c)], which is much higher than the standard value of Si-face MOSFETs. The H₂ POA at high temperatures ($\geq 800 \text{ }^\circ\text{C}$) was also useful for improving μ_{FE} [2]. Namely, C-face MOS interfaces are sensitive to the incorporation of hydrogen atoms [2], as similarly to the Si-SiO₂ interfaces. However, C-face(Wet) MOSFETs frequently revealed a large negative shift in V_{th} after a strong negative gate-bias stress, as is shown

in Fig. 2(a). The same trend may be also present in the C-face(Dry) MOSFETs [Fig. 2(a)]. This kind of instability seems to be a unique characteristic of C-face MOS interfaces, because Si-face MOSFETs (both “Dry” and “Nitrided”) did not exhibit such a large shift [Fig. 2(b)]. Furthermore, it should be mentioned that the V_{th} shift was accompanied with a reduction in the channel current [Fig. 2(a)], indicating that a degradation of μ_{FE} occurred simultaneously.

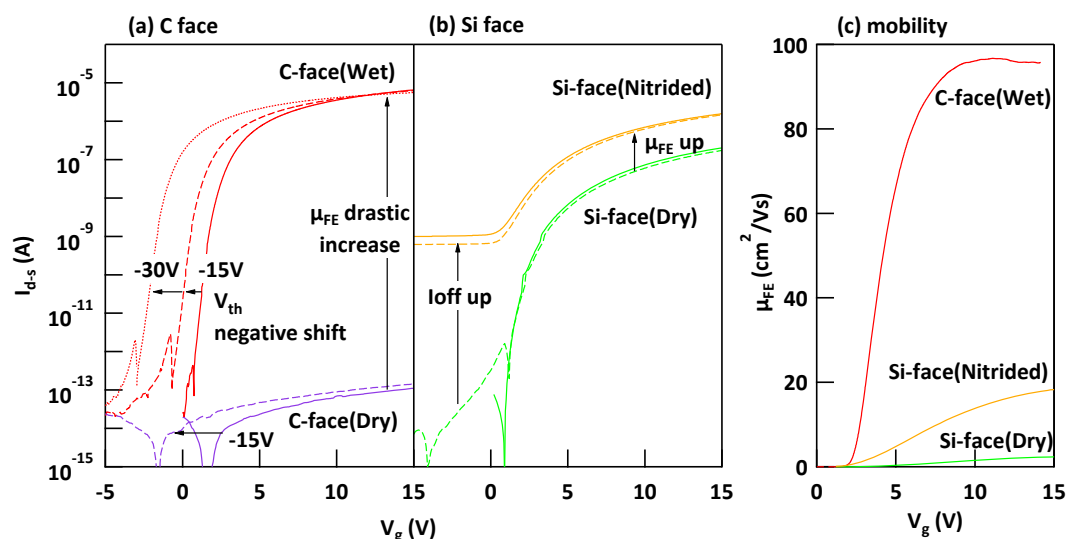


Figure 2. Different behaviors of Si-face and C-face 4H-SiC MOSFETs. I_{d-s} is a source-drain current, V_g is a gate bias, and μ_{FE} is the channel mobility. (a) I_{d-s} - V_g curves of two typical C-face MOSFETs (“Dry” and “Wet”). Solid and dashed curves were measured before and after a negative gate-bias stress (-15V or -30V, duration = 400 s), respectively, where a source-drain bias was set to be 0.1V and a well region was fixed at 0V. The C-face MOS interface is characterized by a drastic increase in μ_{FE} and a large negative shift in V_{th} . (b) I_{d-s} - V_g curves of two typical Si-face MOSFETs (“Dry” and “Nitrided”) measured with the same conditions as the case of C face. This face is characterized by a low μ_{FE} , a stable V_{th} , and an increase in off current (I_{off}). (c) Channel mobility of C-face and Si-face MOSFETs. These curves were derived from I_{d-s} - V_g characteristics and MOS capacitance values. All measurements were carried out at room temperature. Specifications of these MOSFETs are summarized in Table I.

Contrary to C-face MOSFETs, Si-face MOSFETs showed lower μ_{FE} of 1–20 cm^2/Vs [Figs. 2(b) and (c)]. The incorporation of hydrogen atoms is usually ineffective for this face, and nitrogen or phosphorus atoms provide the best way to improve Si-face interfaces [3]. In fact, after a nitridation POA, the channel mobility was improved by 10 times higher level [Fig. 2(c)]. However, the interfacial nitridation usually reduces a margin of normally-off threshold voltage [4]. The off current (I_{off}) is also increased by the nitridation, as is seen in Fig. 2(b). These are additional problems of the nitridation technique. On the other hand, V_{th} of Si-face MOSFETs was stable against a negative gate-bias stress, which is demonstrated in Fig. 2(b).

Such a striking contrast between Si-face and C-face MOSFETs are believed to originate from the differences in their MOS interface states. Up to date, there are only partial information on the microscopic origins of SiC-SiO₂ interface states; in Si-face

MOS interfaces, some carbon-related defects are present, such as the V_{Si}^- centers (generating carbon dangling bonds) [5,6] and the P_{H0}/P_{H1} centers [7,8]. However, it is doubtful whether these defects are responsible for the unique behaviors of the two interfaces, because Si-face MOSFETs still exhibited lower μ_{FE} even if these defects had been fully eliminated [5,6,8].

Understanding the characteristics of Si-face MOS interfaces

In the first place, we discuss how to understand the characteristics of Si-face MOS interfaces, because they are more intensively studied than C-face interfaces. In fact, we have studied shallow interface states in Si-face MOSFETs using low-temperature electrically detected magnetic resonance (EDMR) spectroscopy [8]. In addition to EDMR, interfacial nitrogen atoms have been characterized by X-ray photoelectron spectroscopy (XPS) [4]. Combining the EDMR and XPS data, we concluded that the nitrogen incorporation into the interface caused larger-scaled changes, as compared with a small change in the interface-state density (D_{it}). The primary change is the formation of a large number of “fixed nitrogen atoms” in the interface region [4]. They were chemically very stable and survived not only a strong hydrofluoric etching but also an exposure to air. Their amounts exceeded over $1 \times 10^{14} \text{ cm}^{-2}$, which is three orders of magnitude larger than the reduction in D_{it} ($10^{10} - 10^{11} \text{ cm}^{-2}$) [4]. The secondary change is the doping of shallow nitrogen donors into the channel region [8]. The amount of the doped nitrogen donors was estimated to be $\sim 10^{12} \text{ cm}^{-2}$ [9], which is comparable to the concentration of free carriers in the channel region [8]. Therefore, the nitrogen doping effect has a large impact on the electrical characteristics of MOSFETs. Basically, the nitrogen doping increases the number of carriers in the channel region. They will partially occupy interface states and inactivate them. The residual carriers will contribute to the channel current. With these factors, we expect an apparent increase in μ_{FE} by the nitridation. Since the increment of carriers ($\geq 10^{12} \text{ cm}^{-2}$) was one or more orders of magnitude larger than the reduction in D_{it} ($\leq 10^{11} \text{ cm}^{-2}$), the change in μ_{FE} will be dominated by the nitrogen doping effect. Our model can also explain the reduction in V_{th} and the increase in I_{off} associated with the nitridation, because the concentration of donors in the channel region is directly linked with V_{th} and I_{off} .

From a qualitatively view point, our model gives reasonable explanations on the behaviors of nitrided Si-face MOEFETs. In the next step, we will build a quantitative model accounting for the electrical characteristics of nitrided MOSFETs with respect to nitridation conditions. For example, the nitridation technique is known to be sensitive to nitridation temperatures and nitridation species. We deduce that such conditions will vary the amounts of both the doped nitrogen donors and the fixed nitrogen atoms. Actually, we found that the amount of the fixed nitrogen atoms increased as a function of the nitridation temperature, from $0.7 \times 10^{14} \text{ cm}^{-2}$ to $2.5 \times 10^{14} \text{ cm}^{-2}$ [4]. Likewise, we expect that the amounts of the nitrogen doping will depend strongly on the nitridation conditions.

Differences between Si-face and C-face MOS interfaces: A perspective from EDMR study

As is seen in Fig. 2, C-face MOS interfaces are entirely different from Si-face ones. To answer why the two interfaces are so different, we tried EDMR studies to find out the differences in their interface defects. The EDMR experiments on C-face MOSFETs are

just progressing, and we here present a preliminary result. This will give us a new aspect for understanding the differences between Si face and C face.

When we carried out EDMR measurements focusing on relatively deep interface states of MOSFETs, typical EDMR spectra are obtained as shown in Fig. 3. These spectra were measured at room temperature and using a negative gate bias that lowers the Fermi level of the MOS interface. In this experiment, the detectable signals should correspond to relatively deep interface states (located much lower than the conduction band edge of 4H-SiC), because EDMR spectroscopy detects singly-occupied energy levels near the Fermi level.

In Fig. 3, we found a striking contrast between Si-face and C-face MOSFETs; much stronger EDMR signals were observed in C-face MOSFETs, and a different type of a small signal was detected in Si-face samples. At present, their origins are not yet unraveled. We here suggest that the strong signals in C-face MOSFETs are closely related to the instability of V_{th} , because the deep interface states will capture carriers and behave like “fixed charges”. The presence of a large number of deep interface states was also suggested by the previous electrical measurements on C-face MOSFETs [3]. Furthermore, we speculate that the relevant defects may be also responsible for the drastic changes in μ_{FE} as well as the reaction between hydrogen atoms and C-face interfaces. Judging from the EDMR spectra, there are at least two types of defects at the C-face interfaces, as indicated by “signal 1” and “signal 2” in Fig. 3.

For Si-face MOS interfaces, we observed only a much smaller signal. This result will be consistent with the fact that the V_{th} shift was much smaller in Si-face MOSFETs than in C-face samples. In nitrided Si-face MOSFETs, the EDMR signal intensity was similar to that shown in Fig. 3, however, the type of signal seemed to change. Thus, we imagine that the interfacial nitrogen atoms reacted with the interface defects, creating another type of defects at the interface.

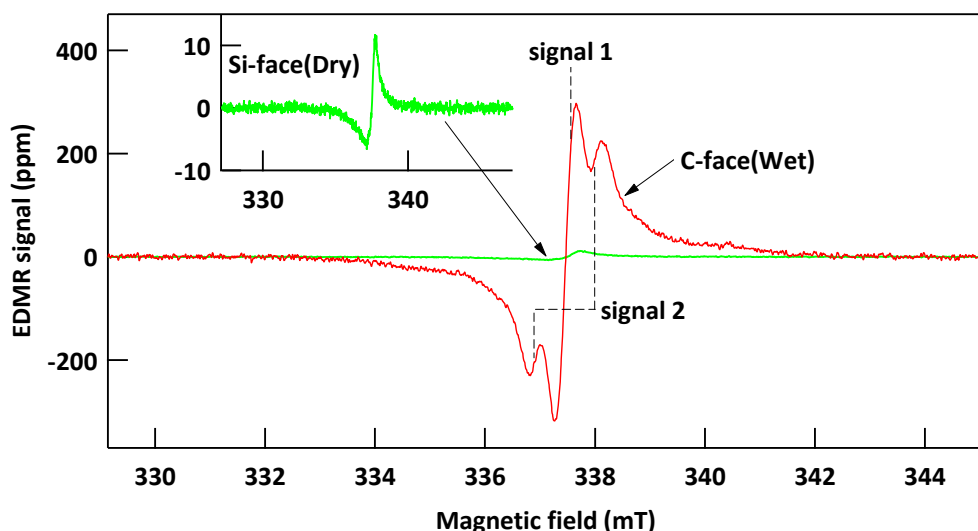


Figure 3. EDMR spectra of C-face(Wet) and Si-face(Dry) MOSFETs measured at room temperature and with 1.5-kHz magnetic-field modulation under microwave of 9.4 GHz and 200 mW. The currents for monitoring EDMR signals were 15 nA for C-face sample and 640 nA for Si-face sample, which were optimized to obtain the best signal-to-noise ratio. These signals correspond to relatively deep interface states in each interface.

Summary

In this paper, we focused on the striking contrast between Si-face and C-face MOS interfaces. Using EDMR spectroscopy, we revealed that the types of defects associated with deep interface states are clearly different between the two interfaces. Also the amounts of these defects presented a contrast; they were much larger in C face than in Si face. Such differences are believed to be linked with the differences in the electrical characteristics of Si-face and C-face MOSFETs. For nitrided Si-face MOSFETs, we highlighted the importance of larger-scaled changes ($\geq 10^{12} \text{ cm}^{-2}$) in the interface region, as compared with the smaller change in D_{it} (10^{10} – 10^{11} cm^{-2}). The interfacial nitridation caused the nitrogen doping into the channel region. Taking this effect into account, we could explain how the nitridation improves the electrical characteristics of Si-face MOSFETs.

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