Defect and Diffusion Forum
ISSN: 1662-9507, Vol. 434, pp 99-103
doi:10.4028/p-YKtpW3

Submitted: 2023-09-08
Revised: 2024-05-10
Accepted: 2024-05-10
Online: 2024-08-22

Differences between Polar-Face and Non-Polar Face 4H-SiC /SiO_2 Interfaces Revealed by Magnetic Resonance Spectroscopy

Ren Kondo[1,a*], Hongyu Zeng[1,b], Mitsuru Sometani[2,c], Hirohisa Hirai[2,d], Heiji Watanabe[3,e] and Takahide Umeda[1,f]

[1]Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki, 305-8573, Japan

[2]National Institute of Advanced Industrial Science and Technology, Tsukuba, 305-8569, Japan

[3]Graduate School of Engineering, Osaka University, Osaka, 565-0871, Japan

[a]s2220264@u.tsukuba.ac.jp, [b]s2220304@s.tsukuba.ac.jp, [c]m.sometani@aist.go.jp, [d]hirohisa-hirai@aist.go.jp, [e]watanebe@prec.eng.osaka-u.ac.jp, [f]umeda.takahide.fm@u.tsukuba.ac.jp

Keywords: MOS interface, non-polar face, ESR, EDMR

Abstract. We performed electron-spin-resonance (ESR) and electrically-detected-magnetic-resonance (EDMR) spectroscopy on 4H-SiC($11\bar{2}0$)/SiO_2 interface defects to study differences between polar-face and non-polar-face 4H-SiC MOS interfaces. We found that in the non-polar-face MOS system, interface defects prefer to form spin-less states of doubly-occupied states and/or empty states, probably due to charge transfer between Si and C atoms at the interfaces.

Introduction

4H-SiC metal-oxide-semiconductor field-effect-transistors (MOSFETs) are typically fabricated using a standard *polar face*, i.e., 4H-SiC(0001) Si-face. On the other hand, *non-polar faces* such as ($11\bar{2}0$) *a*-face and ($1\bar{1}00$) *m*-face may be also promising for MOSFETs, because of their high field-effect mobility (μ_{FE}) [1,2]. However, a simple dry oxidation on these non-polar faces suffers from a high density of interface states (D_{it}), resulting in much worse MOS characteristics as compared to the Si-face MOS interface with the same oxidation. There are no microscopic data on such high-density D_{it} of the non-polar faces. Therefore, we tried to observe electron-spin-resonance (ESR) signals of such interface defects using two techniques. One is ESR measurements on free-standing epitaxial 4H-SiC($11\bar{2}0$) substrates with dry oxidation. Another is electrically-detected-magnetic-resonance (EDMR) measurements on 4H-SiC($11\bar{2}0$) MOSFETs under MOS gate biases. Both the former and latter experiments successfully revealed MOS interface defects on Si-face MOS substrates [3,5] or MOSFETs [4,5], respectively. In this paper, we compare ESR and EDMR results between the polar and non-polar faces.

Experiments and Results

(1) ESR measurements

For ESR measurements, we fabricated free-standing substrates of a high-purity and high-quality undoped epitaxially-grown 4H-SiC($11\bar{2}0$), as illustrated in Fig. 1(a). Previously, such a special substrate enabled us to observe ESR signals of the P_{bC} center (interface carbon dangling-bond center) in Si-face MOS interfaces, by taking advantage of minimizing bulk ESR signals [3]. We prepared such substrates for Si-face ("Si sub") and *a*-face ("a sub"). In addition, "Si dry" and "a dry" substrates were prepared by the standard dry oxidation. The oxide thicknesses are 50 nm for "Si dry" and approximately 60 nm for "a dry". Table I summarizes the four ESR samples.

ESR measurements were carried out by Bruker E500 X-band spectrometer with/without UV light illumination (3.40±0.15 eV, ~1 mW) in a wide temperature range (4 to 295 K). The UV illumination may help to excite interface defects to their different charge states (either paramagnetic or spin-less states).

Table I. ESR samples of 4H-SiC(0001) and 4H-SiC(11$\bar{2}$0) epitaxial layers.

Label	Process	Remarks
Si sub	RCA cleaning → sacrificial oxidation → remove oxide film	Only bulk and environmental signals are detectable.
Si dry	"Si sub" + dry oxidation (1200 °C, 28 minutes)	Interface states are detected with 3.8 × 10^{12} cm^{-2}.
a sub	RCA cleaning → sacrificial oxidation → remove oxide film	Only bulk and environmental signals are detectable.
a dry	"a sub" + dry oxidation (1200 °C, 28 minutes)	MOSFETs don't work due to a large number of interface states. No ESR signals.

Figures 1(b) and (c) show typical ESR spectra of the "Si dry" and "a dry" samples, in addition to their reference spectra of the "Si sub" and "a sub" samples, respectively. If interface signals appeared, we could find any differences between the two spectra. In fact, for Si-face, we found the P_{bC} signal with 3.8×10^{12} cm^{-2}, overlapping over a sample-rod signal (the *E*' signal in SiO_2) [6], at room temperature. In contrast, for *a*-face, we could not find any ESR signals at room temperature, suggesting that high-density interface states on *a*-face never retain singly-occupied states. To change electronic occupation (i.e., the charge state) of the interface states, we conducted low-temperature ESR experiments with a strong photo excitation. Nevertheless, we could not any differential ESR signals, despite a strong photo excitation generated photo-excited signals (broad signal and *E*'+H centers) in a quartz sample rod. This fact indicates that on *a*-face, all interface defects are stabilized into spin-less states. We suggest that non-polar faces such as *a*-face promote charge transfer between Si and C atoms at the interfaces, resulting in pairs of doubly-occupied and empty states (both are spin-less) and eliminating electron spins. This is strikingly contrast with the case of polar face such as Si-face which allow singly-occupied interface states (ESR-active states).

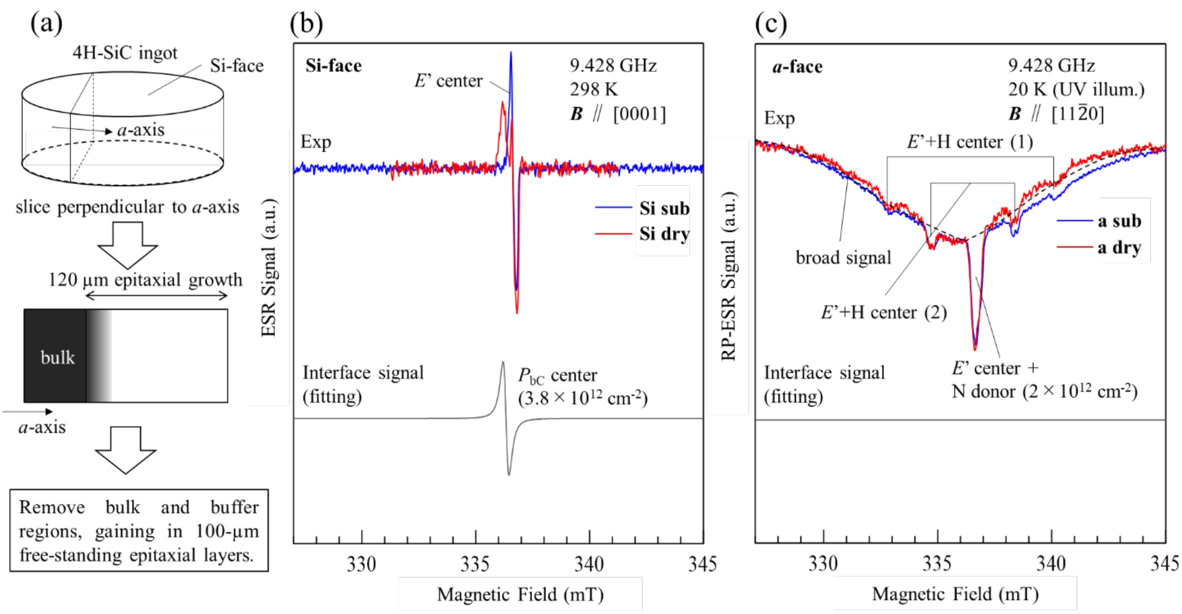

Fig. 1. (a) Preparation of free-standing epitaxial 4H-SiC substrates for ESR studies. ESR spectra of dry-oxidized 4H-SiC/SiO_2 interfaces on (b) Si-face ("Si dry") and (c) *a*-face ("a dry"). "Si sub" and "a sub" were measured for the same substrate before oxidation. Microwave excitation was 0.2 mW for (b) and 2 mW for (c). 100-kHz magnetic-field modulation was used for (b) and (c).

In order to visualize the *hidden* interface defects, we examined UV excitation at low temperatures (4 to 20 K) for *a*-face. Because of a long spin relaxation time at low temperatures, we used a rapid-passage (RP) ESR detection which can focus on long-relaxation-time spins. The results are shown in Fig. 1(c). A strong UV illumination damaged a sample rod and a cryostat tube (SiO_2), creating the *E*' and *E*'+H centers as well as a growing broad signal [6]. In spite of UV irradiation, no interface signals were found.

(2) EDMR measurements

EDMR measurements on a MOSFETF enable us to tune spin states of interface defects via a MOS gate bias (V_g). Therefore, we performed EDMR measurements on *a*-face MOSFETs. Unfortunately, the "a dry" condition (see Table I) cannot allow its MOSFET to activate the channel current. Alternatively, we prepared lightly-nitrided *a*-face MOSFETs ("a NO10") for EDMR studies. Table II shows specifications of EDMR samples. The "a NO10" sample can activate the channel current, but its maximum μ_{FE} is much lower than the "Si dry" sample, suggesting a much higher D_{it}.

Our EDMR spectrometer was used commonly in previous studies [4,5,7-9]. We applied bipolar-amplification-effect (BAE) EDMR measurement [10] to the MOSFETs, which is effective for detecting MOS interface defects.

Figure 2 compares room-temperature EDMR spectra of *n*-channel 4H-SiC MOSFETs of "Si-dry" and "a NO10". For the "Si-dry" MOSFET, we detected an EDMR signal of the P_{bC} center under negative V_g (e.g., -10 V). For "a NO10", we found a weak isotropic EDMR signal under negative V_g. This means that the observed center generates a singly-occupied state in the valence-band side. Although "NO10" should have a much higher D_{it} as compared to "Si dry", its EDMR signal was 1/25 or less of the P_{bC} signal in "Si dry". No other signals were observed. The weak signal of "a NO10" shows $g = 2.0019$, suggesting that it arises from a carbon-related interface defect.

We therefore speculate that, on non-polar *a*-faces 4H-SiC MOS interfaces, a high-density interface states may be mainly located in the conduction-band side. When a singly-occupied state is close to the conduction band, such a shallow level becomes invisible to ESR (likewise shallow donors and acceptors), due to the lifetime broadening effect at room temperature. Such shallow interface states may interact more effectively with carries, resulting in larger mobility degradation. Thus, we performed EDMR measurements at 20 K in order to visualize the interface states close to the conduction band. This temperature makes it possible to observe ESR signals of shallow donors in 4H-SiC [5].

Figure 3(a) shows low-temperature EDMR spectra of "a NO10" under positive gate biases, focusing on the conduction-band-side interface states. We found an abnormal large hysteresis in I_d-V_g curve of "a NO10", as shown in Fig. 3(b). This hysteresis was only visible at low temperatures (< 100 K) and is most probably related to a high-density shallow interface states close to the conduction band. Its origin will be studied elsewhere. Although we varied V_g over a wide range in order to cover both sides of the abnormal hysteresis as well as tried additional UV illumination, we did not find any EDMR signals of the shallow states, even we were able to reduce the EDMR noise level sufficiently.

Table II. EDMR samples of 4H-SiC MOSFETs. NO post-oxidation anneal (POA) was carried out at 1250 °C. When NO POA time was elongated to 60 min., the "a NO60" MOSFET showed a maximum μ_{FE} of 65 $cm^2V^{-1}s^{-1}$.

Label	Gate oxide thickness [nm]	Gate length (*L*)/width (*W*) [μm]	NO POA time [min]	μ_{FE} (maximum) [$cm^2V^{-1}s^{-1}$]
Si dry	30	5/2000	0	6.4
a NO10	60	5/200	10	0.1

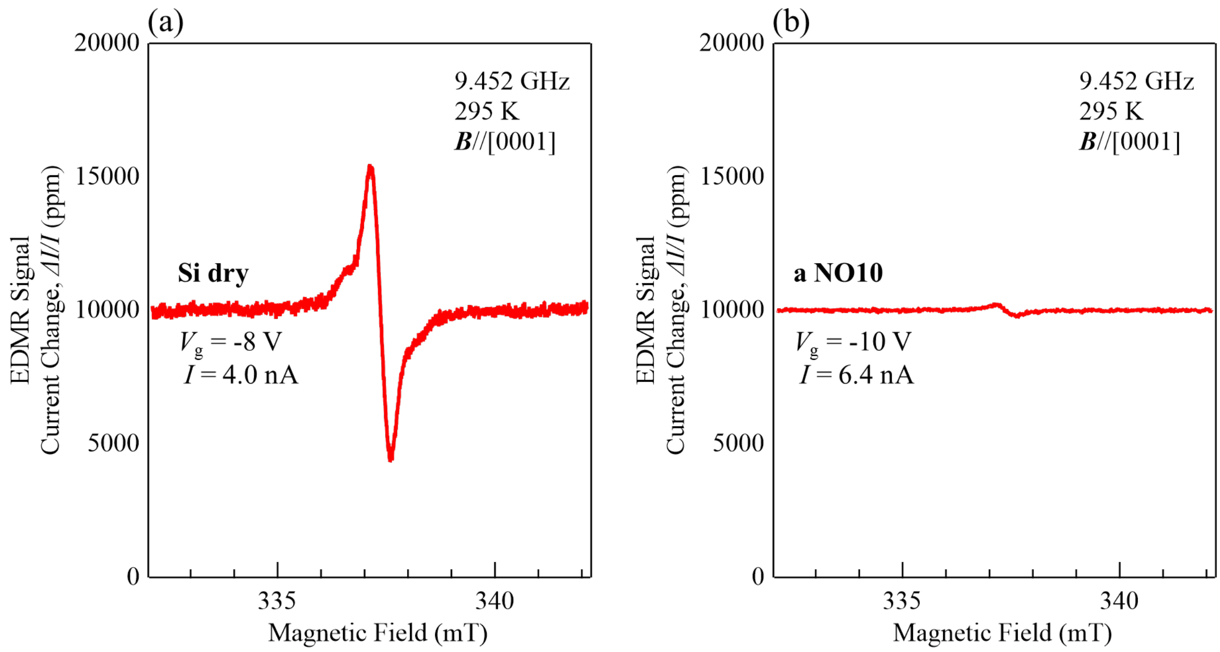

Fig. 2. Room-temperature EDMR spectra of *n*-channel 4H-SiC MOSFETs with dry oxidized Si-face ("Si dry") and lightly nitrided *a*-face ("a NO10") under negative V_g. Microwave excitation was 200 mW, and magnetic-field modulation frequency was set to 1.56 kHz.

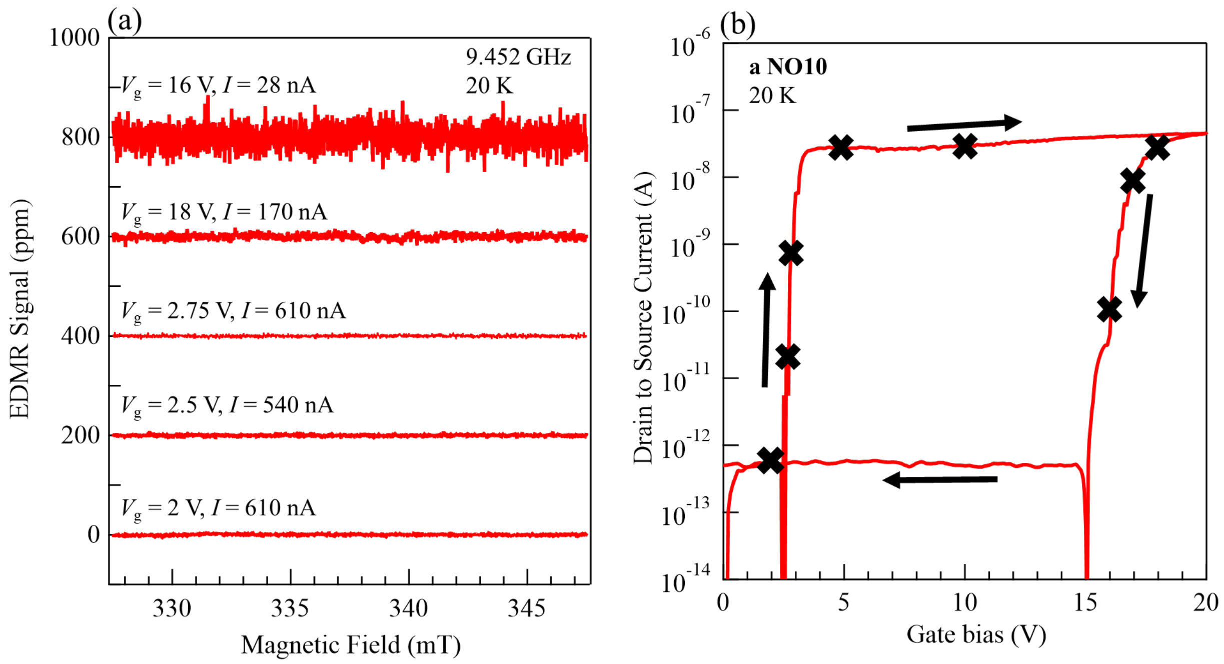

Fig. 3. (a) EDMR spectra of "a NO10" at 20 K under positive V_g. (b) Drain-to-source currents ($I_{d\text{-}s}$) versus V_g in EDMR measurements (plotted by "×" symbols). A solid line is an $I_{d\text{-}s}$-V_g curve at 20 K, showing an abnormal large hysteresis, possibly due to a high-density shallow interface states close to the conduction band. EDMR measurements were carried out with a pre-stress of either V_g = 0 V or V_g = +20 V for surveying the left- or right-hand-sides of the hysteresis, respectively.

Summary

We carried out ESR and EDMR spectroscopy on *a*-face MOS interfaces and compared their interface defects with those in the standard Si-face MOS interfaces. We could not detect ESR signals of very-high-density interfacial defects in the "a dry" sample (dry oxidized *a*-face), indicating that those defects are stabilized into spin-less states (doubly-occupied or empty states). We suggest that this phenomenon may be characteristic of non-polar faces because such faces may easily allow the charge transfer between coexisting Si and C atoms at the interfaces. In order to visualize the spin-less interface defects, we also performed EDMR measurements on lightly-nitrided *a*-face MOSFETs ("a NO10") with a help of MOS gate bias. However, we only detected a weak EDMR signal (carbon-related defect) in the valence-band side. The ESR/EDMR detection of *a*-face and other non-polar faces MOS interface defects with very high densities still remains an open issue.

Acknowledgements

This work was supported by MEXT project No. JPJ009777 and partly by JSPS KAKENHI No. JP20H0034.

References

[1] T. Kimoto and H. Watanabe, Appl. Phys. Express. **13** (2020) 120101.

[2] T. Hatakeyama, Y. Kiuchi, M. Sometani, S. Harada, D. Okamoto, H. Yano, Y. Yonezawa, and H. Okumura, Appl. Phys. Express. **10** (2017) 046601.

[3] T. Umeda, G. –W. Kim, T. Okuda, M. Sometani, T. Kimoto, and S. Harada, Appl. Phys. Lett. **113** (2018) 061605.

[4] T. Umeda, T. Kobayashi, M. Sometani, H. Yano, Y. Matsushita, and S. Harada, Appl. Phys. Lett. **116** (2020) 071604.

[5] T. Umeda, Y. Nakano, E. Higa, T. Okuda, T. Kimoto, T. Hosoi, H. Watanabe, M. Sometani, and S. Harada, J. Appl. Phys. **127** (2020) 145301.

[6] P. M. Lenahan and J. F. Conley, Jr., J. Vac. Sci. Technol. B **16** (1998) 2134.

[7] T. Umeda, Y. Kagoyama, K. Tomita, Y. Abe, M. Sometani, M. Okamoto, S. Harada, and T. Hatakeyama, Appl. Phys. Lett. **115** (2019) 151602.

[8] E. Higa, M. Sometani, H. Hirai, H. Yano, S. Harada, and T. Umeda Appl. Phys. Lett. **116** (2020) 171602.

[9] Y. Abe, A. Chaen, M. Sometani, S. Harada, Y. Yamazaki, T. Ohshima, and T. Umeda, Appl. Phys. Lett. **120** (2022) 064001.

[10] T. Aichinger and P. M. Lenahan, Appl. Phys. Lett. **101** (2012) 083504.