C-face interface defects in 4H-SiC MOSFETs studied by electrically detected magnetic resonance

T. Umeda[1,a *], M. Okamoto[2,b], R. Arai[1], Y. Satoh[1], R. Kosugi[2,c], S. Harada[2,d], H. Okumura[2,e], T. Makino[3,f], and T. Ohshima[3,g]

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

[2] National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8568, Japan

[3] Japan Atomic Energy Agency (JAEA), Takasaki 370-1292, Japan

[a]umeda@bk.tsukuba.ac.jp, [b]mitsuo-okamoto@aist.go.jp, [c]r-kosugi@aist.go.jp, [d]s-harada@aist.go.jp, [e]h-okumura@aist.go.jp, [f]takafumi.makino@jaea.go.jp, [g]ohsima.takeshi28@jaea.go.jp

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Abstract. This paper reports an EDMR (electrically detected magnetic resonance) observation on 4H-SiC(000$\bar{1}$) "C face" MOSFETs. We found a new strong EDMR signal in wet-oxidized C-face 4H-SiC MOSFETs, which originates from intrinsic interface defects on C-face SiC-SiO_2 structures.

SiC-MOS interfaces: "C face" versus "Si face"

The capability of metal-oxide-semiconductor (MOS) structures is a great advantage of SiC as compared with other wide-gap semiconductors. Especially, 4H-SiC MOSFETs (MOS Field Effect Transistors) will have a wide range of impacts and applications in power electronics. The SiC-SiO_2 interface has structural similarities to the famous Si-SiO_2 interface; namely, they form abrupt interfaces consisting of Si-O bonds. However, electronic properties of the two MOS interfaces are quite different. The interface-state density (D_{it}) is typically much higher on 4H-SiC (10^{13} ~ 10^{11} $cm^{-2}eV^{-1}$) than on Si (10^{11} ~ 10^{10} $cm^{-2}eV^{-1}$). These high-density interface states are believed to link with a serious degradation of the channel mobility (field-effect mobility, μ_{FE}) and an instability of the threshold voltage (V_{th}) of MOSFETs. Therefore, the identification of their microscopic origins is a big issue for SiC MOSFETs.

Regarding with this issue, we should remember that μ_{FE} and V_{th} are strongly dependent on wafer orientations. Figure 1 shows current-voltage characteristics of 4H-SiC(000$\bar{1}$) "C face" MOSFETs and 4H-SiC(0001) "Si face" MOSFETs, revealing their quite different behaviors. The Si-face MOSFETs exhibit low μ_{FE} [1~20 cm^2/Vs, see Fig. 1(c)] in both as-oxidized (dry oxidation) and improved (nitrided oxide) samples. On the contrary, the two C-face MOSFETs show a more dramatic change. The dry-oxide MOSFET on C face could not activate any channel currents, while the wet-oxide MOSFET was drastically improved and achieved a very high μ_{FE} up to ~ 100 cm^2/Vs. In addition to the wet oxidation [1], H_2 annealing processes are also effective on C face, indicating that hydrogen is the key atom to change this interface [1].

Such a strong sensitivity to hydrogen is similar to the case of silicon. In Si-MOS structures, hydrogen atoms passivate the P_b centers (interfacial Si dangling bonds) [2], and their de-passivation at elevated temperatures and under a bias stress causes the V_{th} shift, e.g., known as the "NBTI" (negative-bias temperature instability) problem [2]. In SiC, the V_{th} shift after a negative bias stress is larger on C face than on Si face, as is shown in Fig. 1. By analogy to the case of silicon, hydrogen might be related to the larger V_{th} shift on C face.

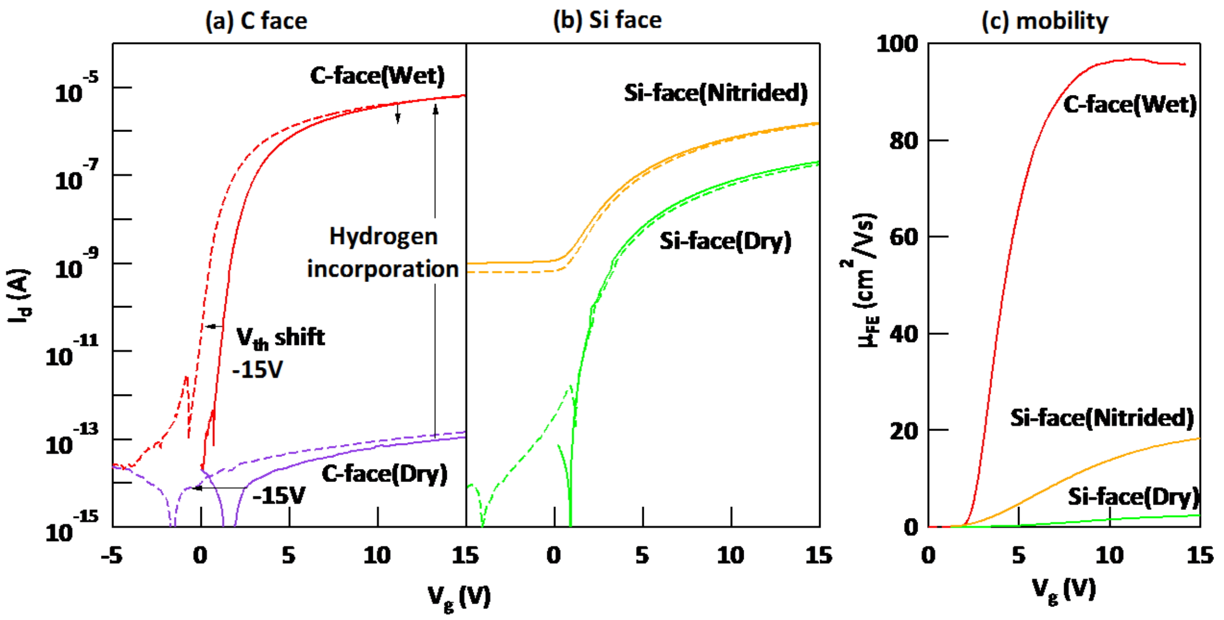

Fig. 1. Current-voltage characteristics of (a) our *n*-channel lateral C-face 4H-SiC MOSFETs and (b) Si-face 4H-SiC MOSFETs, where I_d is a drain current, V_g is a gate voltage. Drain voltage (V_d) was set to 0.1V, and source and well voltages were kept to 0V. Solid and dashed curves were measured before and after a negative V_g stress (-15V, duration = 400 s), respectively. (c) Field-effect mobility (μ_{FE}) for the three MOSFETs shown in (a) and (b). Oxide thicknesses are 50~60 nm for "Dry" (dry oxidation), "Wet" (wet oxidation), and "Nitrided" (dry oxidation + nitridation anneal at 1250 °C). Gate size (length/width) was 100/150 μm.

EDMR observation on "C-face" MOS interfaces

To reveal microscopic information about the interface states on C face and their interaction with hydrogen, and their correlation with the V_{th} shift, we examined C-face 4H-SiC MOSFETs by means of electrically detected magnetic resonance (EDMR) spectroscopy. Figure 2(a) shows our EDMR setup, which is based on an electron spin resonance (ESR) spectrometer and an ultra-high-sensitivity current meter. EDMR has already succeeded to reveal several types of interface defects in Si-face MOSFETs [3-7]. Actually, we have observed the P_{H0} center at Si-face MOS interfaces which corresponds to shallow interface states on Si face [3-5]. In those measurements, we monitored the channel current under a positive gate bias exceeding V_{th} [see Fig. 2(b)]. As is shown in the figure, this condition focuses on shallow interface states near the conduction band edge (E_C), because the Fermi level (E_F) at the MOS interface is moved to E_C, and singly-occupied states, which respond to ESR and EDMR, should be generated at shallow levels near E_F. On the other hand, EDMR measurements in this study were carried out under an opposite condition [Fig. 2(c)]. We examined deep interface states under a negative gate bias, in which they can transform from doubly-occupied states to singly-occupied states by lowering E_F at the interface. Since the V_{th} shift is generally associated with relatively deep electronic states, we tried to detect such states. It should be noted that the existence of high-density deep interface states on C face was strongly suggested by previous capacitance-voltage analyses [1].

To activate the current under a negative V_g, we used a forward current flowing between drain and well regions. A part of this current can interact with the interface states. We found that relatively small currents (~10 nA) were suitable for detecting the interface signals. For EDMR measurements, we prepared C-face 4H-SiC MOSFETs on an optimum 4°-off *p*-type epi-layer with wet oxidation (52-nm thick) and post H_2 anneal (800 ºC). They showed a high channel mobility as shown in Fig. 1(c), ensuring a good quality of our C-face MOS interfaces.

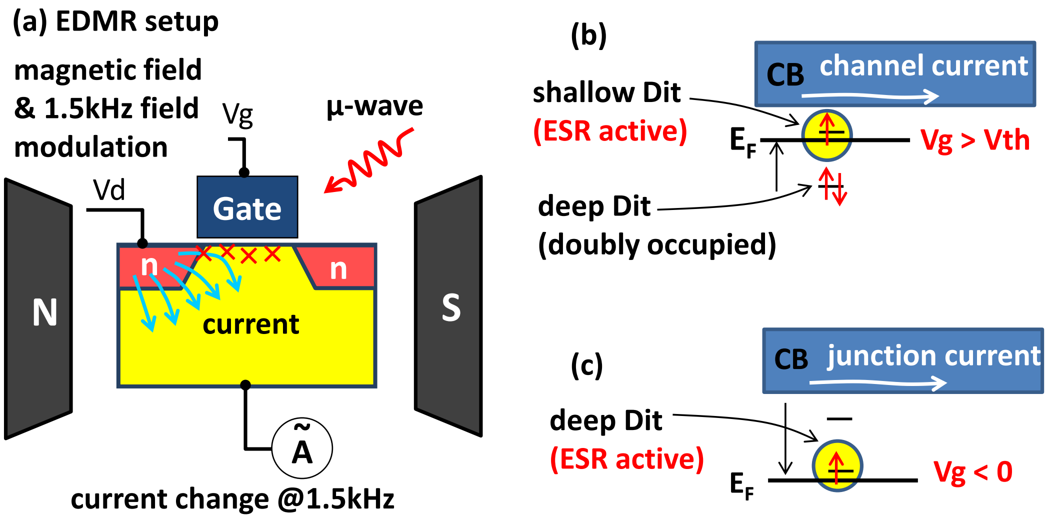

Fig. 2. (a) EDMR setup in this work. Microwave was 9.4 GHz at 200 mW. (b) Energy diagram at the MOS interface under flowing the channel current. This setup was used in previous low-temperature EDMR studies [3-5]. In this mode, shallow interface states will become ESR-active singly-occupied states. (c) Energy diagram at the MOS interface in this work. For activating deep interface states, a negative gate bias (V_g) was applied.

Figure 3 shows a series of EDMR spectra of our C-face 4H-SiC MOSFET measured at room temperature. As is seen in the figure, we have successfully detected EDMR signals on C face. These signals were not observed in Si-face 4H-SiC MOSFETs, indicating that they are intrinsic defects on C face. The EDMR signals were strongly observed under a large negative V_g, which is consistent with our expectation explained above. Thus, the observed EDMR signals should be related to relatively deep interface states. After applying a large negative V_g stress, a negative V_{th} shift as well as an increase in the EDMR signal intensity was simultaneously observed. It supports a correlation between the V_{th} shift and the observed EDMR signals. However, unfortunately, exact energy positions of the deep interface states are not determined at present.

The EDMR spectra shown in Fig. 3 seem to include at least three signal peaks: i.e., one central signal and two satellite signals with an equal intensity. The splitting width of the satellite signals was estimated to be 1.1 mT. The room-temperature EDMR signals in SiC MOSFETs have been reported by Prof. Lenahan's group so far [6,7]. Their major signal was the Si-vacancy signal which was basically identical to the ESR signal of V_{Si}^- (negatively-charged Si vacancy at k site) in bulk 4H-/6H-SiC [8]. The V_{Si}^- signal has a doublet hyperfine structure of ^{29}Si (nuclear spin = 1/2, natural abundance = 4.7%). Likewise, the present spectrum also included the doublet structure, however, its splitting width (1.1 mT) is clearly different from 0.3 mT of the V_{Si}^- center. Alternatively, we suggest that the doublet structure originates from a hyperfine splitting of ^{1}H (nuclear spin = 1/2, natural abundance = 99.9%). The reasons why we judged so are that (1) the central signal and the satellite signals were independent from each other, judging from their dependences on V_g, microwave power, and temperature, and (2) the presence of hydrogen atoms is quite reasonable on C face. Further identification of the observed EDMR signals is running at present.

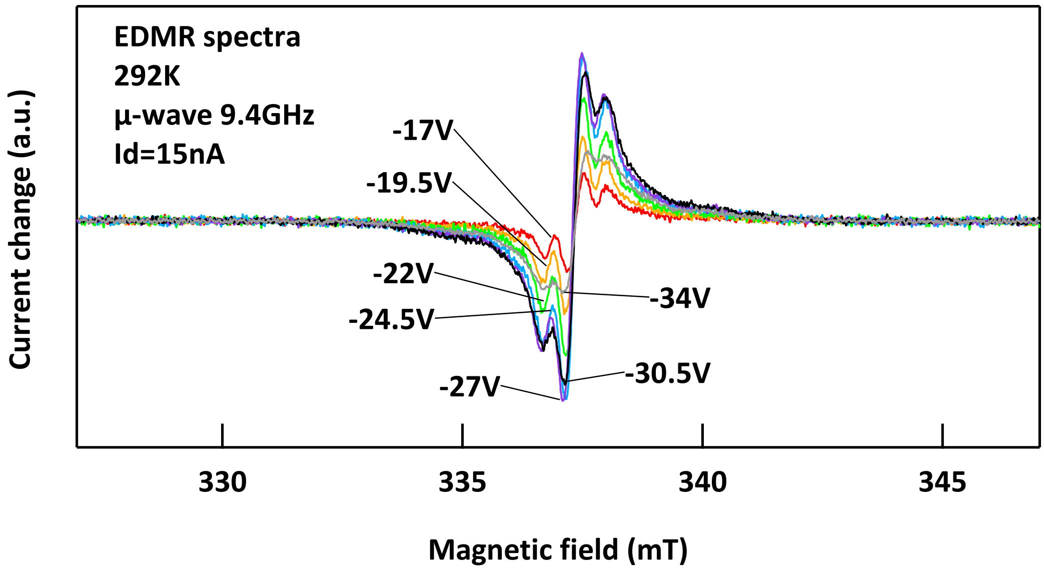

Fig. 3. EDMR observation on C-face interface defects in "Wet" C-face 4H-SiC MOSFET measured under different gate biases. Magnetic-field-modulation width was 0.25 mT.

Summary

The 4H-SiC(000$\bar{1}$) "C face" MOSFETs exhibit quite different behaviors as compared to the 4H-SiC(0001) "Si face" MOSFETs, indicating a crucial difference in their MOS interfaces. We suggested that the deep interface states on C face play the key role on the notable features of this face, such as a strong sensitivity to the hydrogen incorporation, a high channel mobility after the hydrogen incorporation, and a larger V_{th} shift after negative gate-bias stress. We performed a spectroscopic observation on such deep states using EDMR. Consequently, new EDMR signals of the deep states were detected at room temperature under specific bias conditions.

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