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Relationship between C-face defects and threshold-voltage instability in C-face 4H-SiC MOSFETs studied by electrically detected magnetic resonance

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Abstract. We present EDMR (electrically detected magnetic resonance) observations on "C-face defects" in C-face 4H-SiC MOSFETs. We found that negative threshold-voltage shifts of C-face MOSFETs are increased in association with EDMR signals of C-face defects as well as with gamma-ray irradiation.

Introduction

4H-SiC metal-oxide-semiconductor field-effect transistors (4H-SiC MOSFETs) are promising key devices for future power electronics. Their on-state performance can be significantly improved by using C-face [4H-SiC(000$\bar{1}$) face] MOS interfaces, because they exhibit several times higher field-effect mobility (μ_{FE}) (60–100 $cm^2/V{\cdot}s$) than the standard Si-face MOSFETs (20–40 $cm^2/V{\cdot}s$). However, C-face MOS interfaces sometimes increase the instability of the threshold voltages (V_{th}) of MOSFETs [1-3], which may be one of the hardest barriers for the commercialization of C-face MOSFETs. To understand the microscopic mechanism of the V_{th} instability in C-face MOSFETs, we are investigating their MOS interfaces by means of electrically-detected-magnetic-resonance (EDMR) spectroscopy, which enables an electrical detection of electron spin resonance (ESR) of defects in semiconductor devices. In earlier studies, we have reported that the C-face MOS interfaces have intrinsic defects, which we named "C-face defects" [3-5]. In this study, we examined the relationship between the C-face defects and the V_{th} instability in C-face MOSFETs.

V_{th} instability in C-face 4H-SiC MOSFETs

We prepared two types of lateral *n*-channel C-face 4H-SiC MOSFETs. Their gate length and width are 100 μm and 150 μm, respectively. A 50-nm-thick gate oxide was grown by wet oxidation at 1000 ºC, and was subjected to H_2 POA at 1100ºC for 30 min. The oxidation processes as well as epitaxial growth and ion-implantation processes were the same for the two types of MOSFETs [3], however, we found a significant difference in their V_{th} instability. Accordingly, hereafter we call them "bad type" MOSFET and "good-type" MOSFETs. Fig. 1 shows an example of drain-current (I_d) versus gate-voltage (V_g) curves of the two types of MOSFETs. In "bad-type" MOSFETs [Fig. 1(a)], I_d-V_g curves were horizontally shifted toward the negative

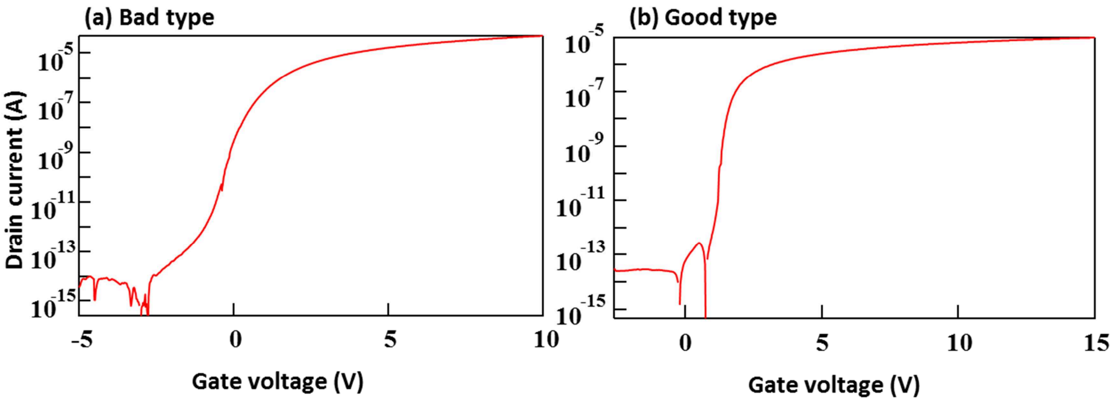

Fig. 1. I_d-V_g curves of "bad-type" and "good-type" C-face 4H-SiC MOSFETs. These curves were measured under a drain voltage of 0.1 V, source and well voltages of 0 V.

direction (i.e., a negative V_{th} shift occurred) after applying negative V_g stress or, at times, even without any stress. The field-effect mobility of "bad-type" MOSFETs was estimated to be 55–70 $cm^2/V \cdot s$. In contrast, "good-type" MOSFETs [Fig. 1(b)] did not show such large negative V_{th} shifts, and their V_{th} always remained positive values. Furthermore, their field-effect mobility was increased to 85–100 $cm^2/V \cdot s$. We suspected an influence of gate electrode, because the "bad-type" MOSFET shown in Fig. 1(a) had an Al gate electrode, while a poly-Si electrode was used for the MOSFET shown in Fig. 1(b). However, we obtained "good-type" MOSFETs with Al electrode. At present, there are no clear differences between the "good-type" and "bad-type" MOSFETs in terms of their fabrication processes. It is found that the "good-type" MOSFETs are the major type, and the "bad-type" MOSFETs are the rare type.

Using the "bad-type" MOSFETs, we studied the negative V_{th} shifts as a function of stress time, stress temperature, and an irradiation dose of gamma ray (γ ray), which are summarized in Fig. 2. In these experiments, we applied a negative V_g stress (V_{stress}) to the test devices. The negative V_{th}

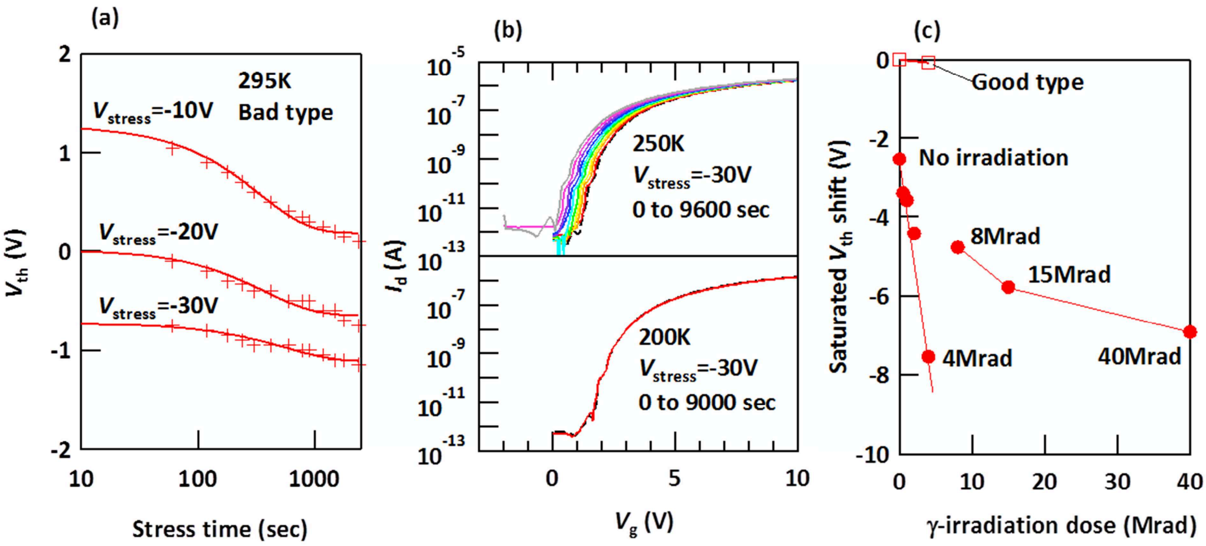

Fig. 2. Negative V_{th} shifts in "bad-type" C-face MOSFETs. (a) Stress-time dependence. Solid lines indicate single exponential relationships. (b) Temperature dependence. Dashed and solid lines are unstressed and stressed data, respectively. Negative V_{th} shifts were not activated at 200 K. (c) γ-irradiation-dose dependence. Saturated V_{th} shifts were measured after a long-time stress (V_{stress} = -35V, > 1800 sec). Two solid lines indicate the presence of two groups in the irradiation data. Square symbols represent data for "good-type" MOSFETs.

shifts showed a saturation behavior with a time constant of 10^2 sec (330, 370, and 560 sec for V_{stress} = -10, -20, and -30 V, respectively) at room temperature [Fig. 2(a)]. They were thermally activated, and they were no longer observed at 200 K and lower [Fig. 2(b)]. They could be enhanced by γ-ray irradiation [Fig. 2(c)]. In the "good-type" MOSFETs, no large V_{th} shifts were observed even after γ-ray irradiation [square symbols in Fig. 2(c)]. As seen in Fig. 2(b), I_d-V_g curves were simply horizontally shifted during the V_g stress, indicating that the channel mobility remained unchanged after the V_g stress. Actually, after γ-ray irradiations, we found almost the same μ_{FE} as observed before the irradiation (Fig. 3).

In Fig. 2(c), the irradiation data may be classified into two groups such as 0 to 4 Mrad and 8 to 40 Mrad. In the latter group, the V_{th} shifts seemed to be suppressed as opposed to those in the former group. We speculate that the reason for this may be a recovery process with a long time constant, cancelling the V_{th} shifts during a long-time irradiation (it took several weeks). Similar recovery phenomena were often observed in irradiation experiments on other semiconductor devices [6].

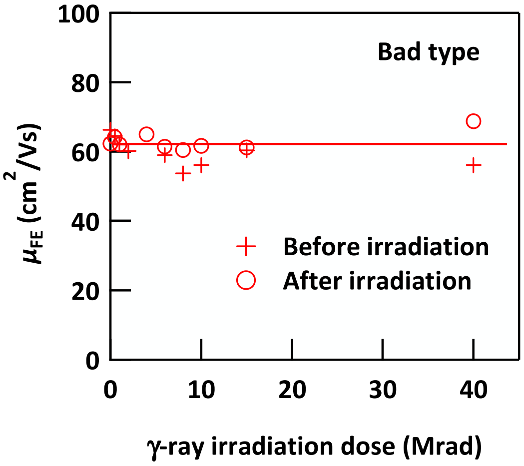

Fig. 3. Field-effect mobility (μ_{FE}) estimated in the γ-ray irradiation experiments. Values of μ_{FE} were estimated from I_d-V_g curves of "bad-type" C-face MOSFETs and a measured MOS capacitance. Solid line serves as a guide for the eyes.

EDMR studies on C-face MOSFETs

Fig. 4(a) compares EDMR spectra of "bad-type" and "good-type" MOSFETs before γ-irradiation. The observed EDMR signals coincide with those of "C-face defects" [3-5]. The C-face defects were observed only in C-face MOSFETs [3-5], and we here focus on the relationship between their EDMR signals and the V_{th} instability. Obviously, the much smaller EDMR signal in "good-type" MOSFETs corresponds to the much smaller V_{th} instability in this type of device [Fig. 2(c)]. Furthermore, the EDMR signal was drastically enhanced by the γ-irradiation in "bad-type" MOSFETs [1000 ppm → 2600 ppm after 4-Mrad irradiation, see Fig. 4(b)], as similarly to the case of the V_{th} shifts. The γ-irradiation is known to cause dissociation of hydrogen atoms from hydrogen-passivated defects [7]. Therefore, we concluded that the C-face defects were passivated by hydrogen atoms.

In Fig. 4(b), we plotted the negative V_{th} shifts as a function of the maximum EDMR intensities at the optimized bias conditions for three samples: an unirradiated and 4-Mrad-irradiated "bad-type" MOSFET and a 4-Mrad-irradiated "good-type" MOSFET. The 4-Mrad irradiation caused the largest change in the V_{th} shifts [Fig. 2(c)]. The linear line indicates a good correlation between the negative V_{th} shifts and the EDMR intensities of C-face defects.

The negative V_{th} shifts can be caused by the generation of positive fixed charges in the oxide layer. A typical candidate for the positive fixed charges is the famous E' center and their variants in SiO_2 [7], and some of them can be generated by the γ-irradiation [7]. Thus, such oxide defects are one of the possible candidates for the negative V_{th} shifts observed in Fig. 2. On the other hands, the C-face defects are interface defects, because they revealed anisotropic g factors in magnetic-field-rotation experiments with respect to the 4H-SiC crystalline substrate [5]. The result of Fig. 4(b) suggests that the interface defects also related with the formation of the fixed charges in the oxide layer.

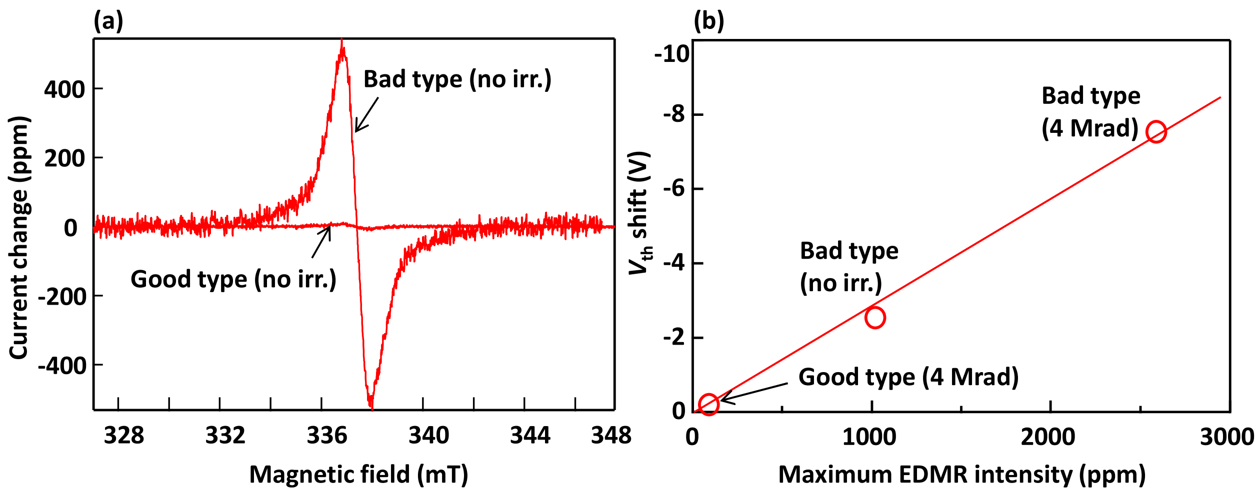

Fig. 4. (a) A comparison of EDMR spectra of "bad-type" and "good-type" C-face 4H-SiC MOSFETs. Vertical axis represents a current change due to ESR. To excite an ESR transition, magnetic field was applied parallel to the [0001] axis, and a microwave of 9.4 GHz and 200 mW was radiated to MOSFETs. The current change was detected by a lock-in amplifier synchronized to 1.5-kHz magnetic-field modulation. The modulation width was 1.0 mT. The currents monitoring for EDMR were about 15 nA and were activated by a negative drain bias (V_d) and a negative gate bias (V_g). For the "bad type" of MOSFET, V_d = - 2.2 V and V_g = -23 V. For the "good type" of MOSFET, V_d = - 2.0 V and V_g = -25 V. The accumulation times were set to be much longer for the "good type" sample, because of much smaller EDMR signal. (b) Relationship between the EDMR intensities and the negative V_{th} shifts.

Summary

We have studied relationships between the V_{th} instability and the EDMR signals of C-face defects in C-face 4H-SiC MOSFETs. The negative V_{th} shifts correlated with the increase in the EDMR signals of C-face defects as well as with the γ-ray irradiation.

References

[1] M. Okamoto, M. Iijima, K. Fukuda, and H. Okumura, Jpn, J. Appl. Phys. 51 (2012) 046504.

[2] M. Okamoto, Y. Makifuchi, M. Iijima, Y. Sakai, N. Iwamuro, H. Kimura, K. Fukuda, and H. Okumura, Appl. Phys. Express 5 (2012) 041302.

[3] T. Umeda, M. Okamoto, R. Kosugi, R. Arai, Y. Sato, S. Harada, T. Makino, and T. Ohshima, ECS Trans. 58 (2013) 55.

[4] T. Umeda, M. Okamoto, R. Arai, Y. Satoh, R. Kosugi, S. Harada, H. Okumura, T. Makino, and T. Ohshima, Mater. Sci. Forum, 778-780 (2014) 441.

[5] Y. Kagoyama, M. Okamoto, S. Harada, R. Arai, and T. Umeda, Mater. Sci. Forum. *in this series*.

[6] A. Holmes-Siedle and L. Adams, Handbook of radiation effects 2nd edition, Oxford University Press, 4.6, 1993, pp. 169-179.

[7] P. M. Lenahan and J. F. Conley, Jr., J. Vac. Sci. Technol. B 164 (1998) 2134.

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