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Electrically detected ESR study of interface defects in 4H-SiC metal-oxide-semiconductor field effect transistor

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Abstract. We present an electrically detected electron-spin-resonance (ESR) study on SiO_2-SiC interface regions of *n*-channel lateral 4*H*-SiC MOSFETs with hydrogen annealing. This characterization technique can reveal electrically active defects that interact with channel currents of the MOSFETs. The defects were observed at 20 K, and were labeled "P_{H0}" and "P_{H1}", one of which (P_{H1}) exhibited a ^{1}H hyperfine splitting of 5.3 mT.

Introduction

Interface states in SiO_2-SiC gate stacks are crucially important for the performance of SiC-based metal-oxide-semiconductor field effect transistors (MOSFETs). For controlling such states, incorporations of hydrogen and nitrogen atoms into the interfaces were found to be effective, similarly to the case of well-studied SiO_2-Si systems. Mechanism of such a control as well as a more efficient control has been surveyed both experimentally and theoretically. However, microscopic origins of the interface states are still not sufficiently clear. To identify their origins, electron-spin-resonance (ESR) studies have been performed [1-6] by analogy with the case of the P_b centers [Si dangling-bond (DB) centers] at SiO_2-Si interfaces [7]. Samples studied by ESR were oxidized 4*H*-SiC wafers [1], oxidized porous-SiC wafers [2,3], 4*H*/6*H*-SiC gate-controlled diodes [4,5], and 4*H*-SiC MOSFETs [6]. All these studies have been done at room temperature (R.T.).

Following to those works, we performed an ESR study on the SiO_2-SiC interfaces at low temperatures. We used an electrically detected ESR [electrically detected magnetic resonance (EDMR)] technique, which enables us to characterize interface regions inside fully-processed MOSFETs.

Experimental

We prepared *n*-channel lateral 4*H*-SiC MOSFETs with different processes. In this study, we would like to focus on the MOSFETs with post oxidation annealing with H_2 at a temperature of 800 ºC. They were fabricated on epitaxial layers of Cree 8°-off 4*H*-SiC(0001) Si-face wafers with *p*-type doping. The gate length and width are 100 and 150 μm, respectively. The initial gate oxide is a 50nm-thick dry oxide. Source and drain regions were formed by a high-dose phosphorous ion implantation. Poly-Si gate electrodes and nickel contacts were also made. After preparing the MOSFETs, some of them were subjected to a γ-ray irradiation (average energy = 1.3 MeV, dose = 2.7 Mrad). This irradiation is known to damage hydrogen bonds, e.g., Si-H or O-H bonds, creating DBs there [8]. Thus, we expected that the γ-irradiation can activate hydrogen-passivated defects in the samples.

EDMR measurements are similar to ESR ones, except that we monitor a change in the device current instead of a change in the microwave absorption of a sample. We used a magnetic-field-modulation (1.5 kHz, 0.5 to 1.0-mT width) technique for amplifying a small current change due to ESR. The key points for our measurements are that (1) we detect EDMR signals using lateral channel currents of MOSFETs in order to selectively observe defects interacting with the channel currents (on the contrary, previous EDMR works monitored diode currents flowing between source/drain and substrate [4-6]) and that (2) we measure EDMR signals at low temperatures. The latter condition will be necessary for detecting energetically shallow interface states that have a great influence on the channel currents.

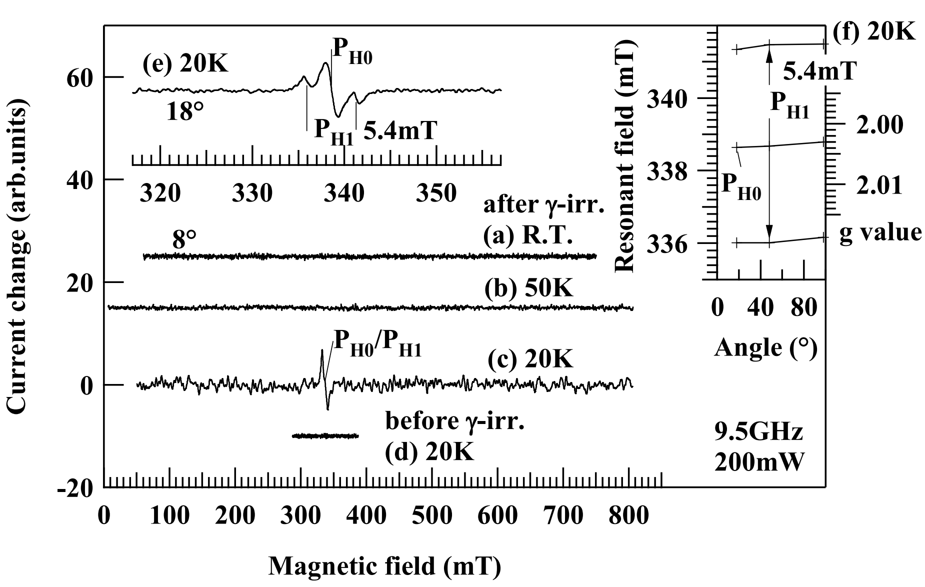

Fig. 1. EDMR spectra for channel currents of 4*H*-SiC MOSFETs with post hydrogen treatment at 800 °C. Channel currents and bias conditions are as follows: (a) 44 nA at V_{ds} = 0.3V, V_{gs} = 0.5V, (b) 58 nA at V_{ds} = 1V, V_{gs} = 6.5V, (c) 15 nA at V_{ds} = 1V, V_{gs} = 7V, (d) 370 nA at V_{ds} = 1V, V_{gs} = 17V, (e) 51 nA at V_{ds} = 2V, V_{gs} = 10V, where V_{ds} is a source-drain voltage and V_{gs} is a substrate-gate voltage. (f) shows angular dependences of P_{H0}/P_{H1} signals where magnetic field was rotated from [0001] (0°) to [1-100] (90°). To excite ESR transitions, microwave of 9.5 GHz and 200 mW was applied.

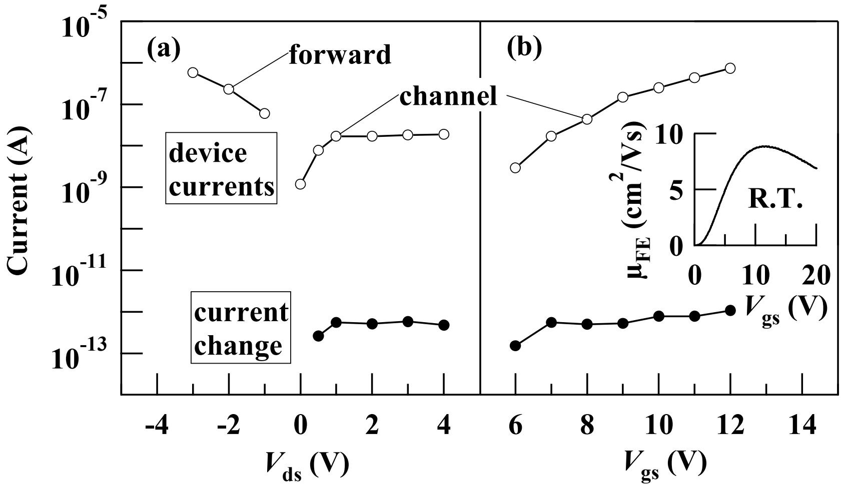

Fig. 2. Channel currents and EDMR signals (current changes due to ESR) as a function of V_{ds} and V_{gs} measured at 20 K. In (a), V_{gs} was set to be 7V. For forward currents ($V_{ds} < 0$), EDMR signals were not detected and one order weaker than the smallest signal in the channel currents. In (b), V_{ds} was set to be 1V.
Field-effect mobility (μ_{FE}) data at room temperature are also included in (b). The MOSFETs used in this study showed a maximum μ_{FE} of 9 cm^2/V·s.

Results and discussions

Figure 1 summarizes EDMR results for the channel currents of our samples. From R.T. to 50 K, we could not detect any EDMR signals [Figs. 1(a) and (b)]. On the other hand, at 20 K, EDMR signals were found after γ-irradiation, as shown in Figs. 1(c) and (d). The signals appeared only in the channel currents, as shown in Fig. 2.

Figures 1(e) and (f) shows a higher-resolution spectrum of the EDMR signals and their angular dependences, respectively. The EDMR signals consisted of two signals, labeled "P_{H0}" and "P_{H1}", and one of them (P_{H1}) exhibited a doublet splitting of 5.4 mT. This splitting is most probably due to a hyperfine interaction of a ^{1}H atom (nuclear spin = 1/2, natural abundance = 99.9%), because the splitting was isotropic [see Fig. 1(f)]. The g values of the two signals were tentatively estimated to be $g_{\|} = 2.004$ and $g_{\perp} = 2.003$, as is seen in Fig. 1(f). Their common g values suggest that they originate from the same defect but are distinguishable by the presence or absence of a ^{1}H hyperfine splitting (hfs).

In Table 1, ESR parameters of P_{H0}/P_{H1} are examined by comparison with various reported centers. First, we compare their g values. Most of the centers can be classified into either carbon DB centers [(2), (3), and (8)] or silicon DB centers [(1), (5), (6), and (7)]. It is well known that silicon DB centers exhibit a large g anisotropy ($|g_{\|} - g_{\perp}| = 0.004\text{-}0.010$), while carbon DB centers are characterized by a very small g anisotropy (≤ 0.001) and g values of ~ 2.003. Judging from such trends, we propose that the P_{H0}/P_{H1} centers are a type of carbon DB centers.

For P_{H1}, we observed an isotropic ^{1}H hfs as large as 5.4 mT. This splitting is similar to the case of (6) (^{1}H hfs = 7.5 mT) where a hydrogen atom is located at a back-bond site of a DB. Only for such a case, a strong isotropic ^{1}H hfs can be observed. Therefore, we propose that the origin of P_{H1} is a carbon DB with a hydrogen atom at a back-bond site.

For P_{H0}, we cannot conclude whether this center coupled with any hydrogen atoms. One probable model is that P_{H0} is a carbon DB after missing a passivated hydrogen atom (probably, such a hydrogen atom diffused far away). On the other hand, we can also consider a "vacancy + hydrogen" model like the cases of (7) and (8). If a DB and a hydrogen atom are separated inside a monovacancy space, ^{1}H hfs should be smaller than 0.3 mT, and no hfs signatures could be resolved. Such a case is applicable to the P_{H0} signal. Therefore, both "carbon-DB alone" model and "vacancy + hydrogen" model are

Center	ESR parameters	Remarks	Ref. and methods
P_{H0}/P_{H1} centers in *n*-channel 4*H*-SiC MOSFET with post hydrogen annealing	$g_{\|} = 2.004$, $g_{\perp} = 2.003$ (tentative) ^{1}H hfs = 5.4 mT (P_{H1})	measured for channel currents, created by γ-ray irradiation, observable at 20K. isotropic hfs (P_{H1}).	present EDMR
(1) Si DB-like center in oxidized 4*H*/6*H*-SiC wafers	$g_{\|} = 2.0028$, $g_{\perp} \leq 2.0062$	observed in *p*-type wafers observable at R.T.	[1] ESR
(2) Carbon DB (P_{bC}) in oxidized porous-SiC	$g_{\|} = 2.0023$, $g_{\perp} = 2.0032$	located at SiC-SiO$_2$ interface, observable at R.T.	[2][3] ESR
(3) Si-vacancy center (carbon DB center) in 4*H*/6*H*-SiC gate-control diodes	$g = 2.0027$	same as the V_{Si}^{-} center in bulk SiC, measured for diode currents, observable at R.T.	[4][5] EDMR
(4) DB center in *n*-channel 4*H*-SiC MOSFET with deposited ONO gate stack	$g_{\|} = 2.0026$, $g_{\perp} = 2.0010$	*c*-axial DB center, measured for diode currents, observable at R.T.	[6] EDMR
(5) Si DBs in Si-SiO$_2$ (P_b centers)	$g_{\|} = 2.0014\text{-}2.0015$, $g_{\perp} = 2.0080\text{-}2.0087$	the well-known Si DB centers, observable at R.T.	[7] ESR, EDMR
(6) E' center (Si DB in SiO$_2$) + hydrogen	^{1}H hfs = 7.5 mT (H in a back-bond site) ^{1}H hfs = 1.0 mT (H in a 2nd nearest neighbor site)	generated by hydrogen plasma treatments on SiO$_2$, observable at R.T.	[7] ESR
(7) Si DB + hydrogen in a monovacancy of silicon	$g = 2.001\text{-}2.011$ ^{1}H hfs < 0.3 mT	Si vacancy containing a hydrogen atom, showing a weak dioplar intreaction of ^{1}H (anisotropic).	[9] ESR
(8) Carbon DB + hydrogen in a monovacancy of diadmond	$g = 2.002\text{-}2.003$ ^{1}H hfs < 0.3 mT	Carbon vacancy containing a hydrogen atom, showing a similar weak dipolar interaction of ^{1}H.	[10] ESR

Table 1. Comparison between the P_{H0}/P_{H1} EDMR signals with other related ESR/EDMR signals. "g", "$g_{\|}$", and "$g_{\perp}$" represent the g value and two principal values of an axial g tensor, respectively.

possible for the origin of P_{H0}.

Finally, other important features of the P_{H0}/P_{H1} EDMR signals are mentioned. One is that both the P_{H0}/P_{H1} signals appeared after γ-irradiation (see Fig. 1). This result will be reasonable, because one can naturally expect that the DBs were passivated by hydrogen atoms after hydrogen annealing. The hydrogen passivation of the DBs is known to be much more stable for carbon (~850 ºC) rather than for silicon (~450 ºC) [3]. Thus, our hydrogen annealing at 800 ºC will be effective for passivating carbon DBs. As a result, carbon DB centers were observed after γ-irradiation. In this study, we have not observed Si DB centers. We speculate that the high-temperature hydrogen annealing may remove such DBs or that such DB centers may be unobservable owing to their deep energy levels (see the following discussion).

Second important feature is that the P_{H0}/P_{H1} signals were detected in the channel currents (see Fig. 2). This means that the P_{H0}/P_{H1} centers should be located at the SiC-SiO_2 interface and/or in the channel region of SiC. In the channel region, all energetically deep levels should be doubly occupied by electrons, and should be ESR inactive. Therefore, only energetically shallow defects are detectable in our measurements. Accordingly, the P_{H0}/P_{H1} centers should correspond to shallow energy levels near the conduction band. They interact with carriers (electrons) in the channel region, as evidenced by the appearance of their EDMR signals. These aspects are also consistent with the fact that the P_{H0}/P_{H1} signals were detectable at low temperatures such as 20 K.

Summary

We have performed a low-temperature EDMR (electrically detected ESR) study on the channel currents of fully-processed *n*-channel lateral 4*H*-SiC MOSFETs. Our EDMR measurements revealed the presence of hydrogen-passivated defects in the channel regions of the MOSFETs after post hydrogen annealing. Such defects were a type of carbon DB centers and could be converted into the P_{H0}/P_{H1} EDMR centers after γ-irradiation. They correspond to energetically shallow levels near the conduction band, and interact with the channel currents.

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