SiC MOS Interface States: Difference between C face and Si face

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C-FACE AND Si-FACE SiC MOS INTERFACES

Silicon carbide (SiC) has superior electrical and thermal properties, which are especially suitable for high-performance power electronics. This material enables us to use MOS (Metal-Oxide-Semiconductor) gate structures with a thermal oxide or a deposited oxide. Among a variety of SiC devices, normally-off SiC MOSFETs (MOS Field Effect Transistors) are one of the most desirable devices, because of their wide range of impacts and applications. In the current stage, over-1kV normally-off 4H-SiC MOSFETs are ready for commercial productions. However, even in these MOSFETs, there are still unresolved issues such as a serious degradation of their channel mobility (μFE) as well as an instability of their threshold voltage (Vth). These issues are strongly dependent on the wafer orientation, typically either “Si face” [4H-SiC(0001) face] or “C face” [4H-SiC(000-1) face].

The two typical faces of 4H-SiC are chemically quite different. For example, the speed of thermal oxidation is much faster on the C face than on the Si face. The MOS interface-state density (Dit) near the conduction band is normally lower on the C face than on the Si face. As a result, the C face shows much larger μFE (~100 cm²/V-s), but wet oxidation or hydrogen incorporation is necessary on this face. On the other hand, wet oxidation is not effective on the Si face, and dry oxidation + post nitridation anneal or oxy-nitridation is conventionally used on this face. The typical μFE is only ~ 20 cm²/V-s on the standard Si face. Alternatively, this surface often achieves a higher stability in Vth. These different behaviors are most probably due to different types of Dit on the C and Si faces. However, their origins have not been clarified yet, despite many researches over a decade.

In this paper, we study the microscopic nature of the C- and Si-face 4H-SiC MOS interfaces by means of electrically detected magnetic resonance (EDMR) spectroscopy. This technique is an electrical detection of ESR (electron spin resonance), having access to a microscopic information of the Dit. In fact, we found a large amount of intrinsic interface defects on the C face. Their density is so large that they can associate with a big difference between the C and Si faces. The C-face interface defects are formed from carbon atoms. We discuss their nature and their strong influences on the electrical properties of the C-face MOS interfaces.

EDMR STUDIES

We have already studied Si-face 4H-SiC MOSFETs using EDMR spectroscopy at 4K to room temperature. We have detected low-temperature EDMR signals in channel currents of the MOSFETs. These signals were attributed to minor carbon-related centers (the P2H and P1H centers) at either nitrided-oxide MOS interfaces or dry-oxide MOS interfaces with/without hydrogen treatments [1-3]. They were most probably related to shallow Dit on the Si face. In the nitrided-oxide MOSFETs, we have also found nitrogen shallow donors in the channel region, which were hoped by the nitridation process [2]. In addition, a large amount of “fixed nitrogen atoms” (over 1×10¹² cm⁻²) were also found, which were chemically stable and remained after the removal of the oxide layer [4]. Such nitrogen’s behaviors are the key to understand the nature of nitrided Si-face MOS systems.

Next to the above studies, we applied the same EDMR technique to C-face 4H-SiC MOSFETs. They were prepared by wet oxidation and post oxidation anneal by H2 (800 °C). These processes greatly improved μFE from ~ 0 (in the case of dry oxidation) to ~100 cm²/V-s. The threshold voltage was ~ 1.5V. In these MOSFETs, an electrical current was driven via the MOS interface from the source to either the drain or the well.

Using such a current, a strong EDMR signal of S (an electron spin) = 1/2 was successfully detected, when the gate was strongly negatively biased. This signal should correspond to a deep Dit, because under the negative gate bias, the surface potential or Fermi level (E_F) at the SiC-SiO₂ interface should be shifted toward the midgap. In principle, singly occupied energy levels, which are visible in ESR and EDMR spectroscopy, are generated near the E_F level.

The observed defect is characteristic of the C face, because it was completely absent on the Si face. This is a type of new carbon-related defect, judging from its ESR signatures. Its identification is currently in progress. We should mention that it is different from the previous ESR and EDMR centers such as our P2H0 centers [1-3], the Pn_c centers [5], the Si-vacancy center [6], and the C-cluster center [7].

Looking at the details, the C-face interface defect consists of two components, one of which was accompanied with a doubler hyperfine splitting due to a hydrogen atom (H, nuclear spin = 1/2). Besides, both types were increased by γ-ray irradiation to the MOSFETs. Generally, the γ-ray irradiation can break hydrogen bonds, leaving un-terminated defects at there. These results indicate that the C-face interface defects reacted with one or more hydrogen atoms.

The EDMR signal of the C-face interface defects was extremely strong as compared to previous EDMR signals, suggesting that their concentration is very high on the C face. In fact, such a high concentration was associated with an appreciable negative shift in Vth. From the amount of the Vth shift, the concentration of the C-face interface defects was estimated to be 10¹² ~ 10¹³ cm⁻². They also influenced on the channel mobility of the MOSFETs. We consider that they bring different chemical and electrical natures of the Si and C faces, and they are the key defect to explain the Vth instability and the μFE degradation on the C face.