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 (μ_{FE}) as well as an instability of their threshold voltage (V_{th}). Those 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 μ_{FE} (~100 cm^2/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 μ_{FE} is only ~ 20 cm^2/V·s on the standard Si face. Alternatively, this surface often achieves a higher stability in V_{th}. 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 P$_{H0}$ and P$_{H1}$ 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 doped by the nitridation process [2]. In addition, a large amount of "fixed nitrogen atoms" (over 1×10^{14} 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 H$_2$ (800 °C). These processes greatly improved μ_{FE} from ~ 0 (in the case of dry oxidation) to ~100 cm^2/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-SiO$_2$ 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 P$_{H0/H1}$ centers [1-3], the P$_{bC}$ 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 doublet hyperfine splitting due to a hydrogen atom (^{1}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 V_{th}. From the amount of the V_{th} shift, the concentration of the C-face interface defects was estimated to be $10^{12} \sim 10^{13}$ 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 V_{th} instability and the μ_{FE} degradation on the C face.

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