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Origin of Low Channel Mobility and Threshold Voltage Instability of SiC-MOSFETs

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Abstract

The origins of low channel mobility and threshold voltage (V_{th}) instability of silicon carbide metal-oxide-semiconductor field-effect transistors (SiC-MOSFETs) were investigated by both electrical and physical characterizations. Hall measurements and split C-V measurements revealed that the difference of field effect mobility of wet oxide and dry oxynitride interfaces was mainly due to the ratio of the mobile electron density to the total induced electron density. High resolution Rutherford backscattering spectroscopy (HR-RBS) analysis and elastic recoil detection analysis (ERDA) showed the nanometer-scale compositional profile of the SiC-MOS interfaces for the first time. These analyses with cathode luminescence (CL) spectroscopy and transmission electron microscopy (TEM) complementarily show that oxygen vacancies increase the electron trap density and that the excess hydrogen or nitrogen causes the V_{th} shift.

1. Introduction

SiC power devices are now employed in a variety of power systems, including power supplies, photovoltaic converters, air conditioners, and motor controls for elevators and railcars, because of their dramatic reduction of switching loss. While continual improvement is being achieved for the development of SiC-MOSFETs, their system still suffers from high channel resistance and instability of their threshold voltage.

To elucidate the origins of low channel mobility and instability of V_{th}, both electrical and physical measurements were conducted and correlated with each other on controlled samples through the same device fabrication process.

2. Experimental

We provided three typical samples of n-channel MOSFETs fabricated on SiC (0001) and SiC (000-1) with post-oxynitridation process (Si-face Oxynitride and C-face Oxynitride, respectively) and SiC (000-1) with wet oxidation process (C-face Wet Oxide). The gate oxidation and the post-oxynitridation have been reported in the literature [1, 2]. We conducted gate-controlled Hall measurements, split C–V measurements and I_D–V_G measurements on these MOSFETs [3]. We estimated the instability of V_{th} by measuring the V_{th} shift during 10 min stressed under 2 MV/cm at 200 °C.

CL spectra were recorded at the electron beam acceleration voltage of 5 kV, which is suitable to analyze the interface with 70 nm SiO_2 film [4]. The oxide films were thinned less than 10 nm by etching in hydrofluoric acid for the following physical analyses. For TEM, these thinned films were processed by focused ion beam etching. HR-RBS was carried out with 450 keV He^+ ions, which were irradiated to the samples at 32° and detected at 77° by a high-resolution energy analyzer. Hydrogen at the interface was analyzed by using ERDA with 450 keV N^+ ions.

3. Results

The total induced electron density (n_{total}) and the mobile electron density (n_{mobile}) were measured as a function of gate voltage by split C–V measurements and Hall measurements, respectively, on Si-face Oxynitride in Fig. 1 (a). The trapped electron density (n_{trap}) was estimated to be $n_{total} - n_{mobile}$ in Fig. 1 (b). The Hall factor, which is the ratio of Hall mobility (μ_H) to drift mobility, was assumed to be unity here, because it becomes close to unity if scattering is due to strongly screened ionized impurities or neutral impurities [5]. Though several methods have been presented to estimate the interface states [6], n_{trap} seems to directly correspond to the integrated density of electron traps, because the Fermi level at the Hall measurement is close to that on-state of MOSFETs.

Figure 2 shows μ_H and effective mobility (μ_{eff}) on Si-face Oxynitride. The μ_{eff} was calculated from I_D–V_G transfer characteristics of MOSFETs and n_{total}, measured by split C–V measurements. The difference of μ_H and μ_{eff} in Fig. 2 is not actually due to literal mobility but mainly due to the amount of mobile electrons.

Table 1 shows μ_H and field effect mobility (μ_{fe}), which is often used instead of μ_{eff} to show the performance of MOSFETs, and the mobile electron ratio of n_{mobile} / n_{total} and V_{th} shift. The difference of μ_{fe} of Wet Oxide and Ox-

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ynitride interfaces is shown to be mainly due to the difference of n_{mobile} / n_{total}.

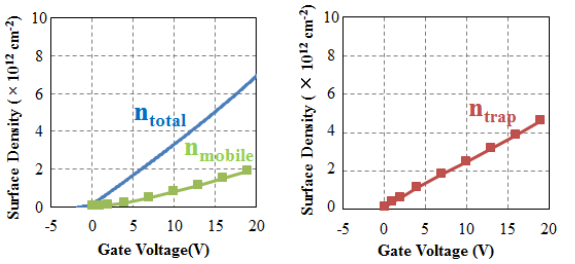

Fig. 1 (a) n_{toal}, n_{mobile}, and (b) n_{trap} as a function of gate voltage on Si-face Oxynitride.

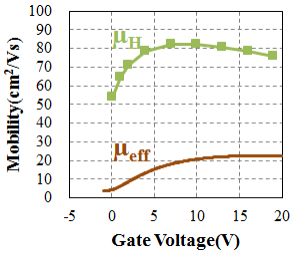

Fig. 2 μ_H and μ_{eff} as a function of gate voltage on Si-face Oxynitride.

Table 1 μ_{fe}, μ_H, n_{mobile} / n_{total}, and V_{th} shift.

	μ_{fe} (cm^2/Vs)	μ_H (cm^2/Vs)	n_{mobile} / n_{total} (%)	V_{th} Shift (V)
C-face Wet Oxide	64	98	56	0.26
C-face Oxynitride	35	79	25	0.21
Si-face Oxynitride	32	81	25	0.08

Figures 3 show the CL spectra of C-face Wet Oxide, C-face Oxynitride, and Si-face Oxynitride. The peak at 460 nm originates from oxygen vacancies, while the peak at 680 nm originates from non-bridging oxidation holes [4]. The CL peak at 390 nm originates from a bound exciton of 4H-SiC, which shows that the CL spectra come from both SiO_2 and 4H-SiC regions. Non-bridging oxidation holes and complex defects are dominant in C-face Wet Oxide, where oxygen vacancies are minimal as compared in both C-face Oxynitride and Si-face Oxynitride.

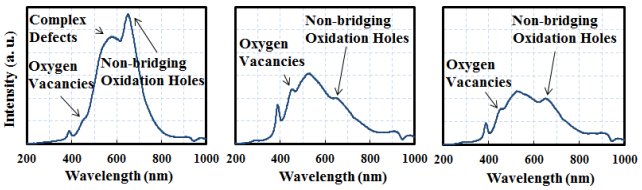

Fig. 3 CL spectra of (a) C-face Wet Oxide, (b) C-face Oxynitride, (c) Si-face Oxynitride.

The thickness of the thinned SiO_2 films was measured by TEM and used to fit the RBS analyses, shown in Fig. 4. Fig. 4 (b) and (c) show that the deficiency of oxygen at the interface of C-face Oxynitride and Si-face Oxynitride, which may increase the interface state density. In C-face Wet Oxide and C-face Oxynitride, there are excess hydrogen and nitrogen, respectively, whose concentrations are less than the detection limit in Si-face Oxynitride. Theses impurities can migrate or interact with vacancies in SiC and cause the instability of V_{th}.

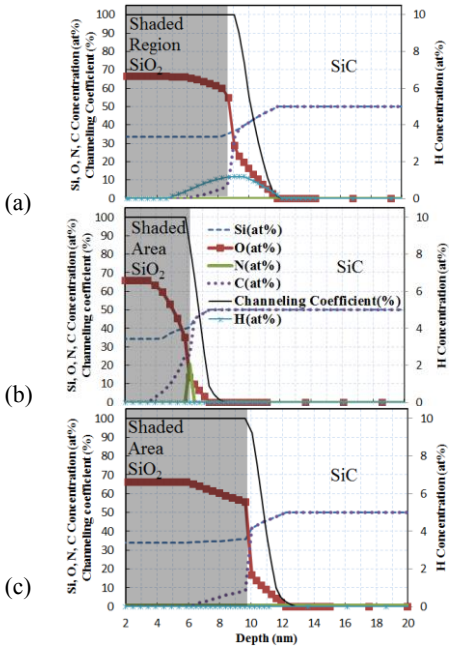

Fig. 4 RBS analyses and ERDA of (a) C-face Wet Oxide, (b) C-face Oxynitride, and (c) Si-face Oxynitride.

4. Conclusions

The origins of low channel mobility and instability of V_{th} of SiC-MOSFETs were investigated by Hall measurements, split C–V measurements and various physical characterizations (CL, TEM, RBS, and ERDA). And we present that oxygen vacancies increase the electron trap density and that the excess hydrogen or nitrogen causes the V_{th} shift.

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