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Free carrier density enhancement of 4H-SiC Si-face MOSFET by Ba diffusion process and NO passivation

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Abstract

The field-effect mobility was improved in 4H-SiC (0001) MOSFET by Ba thermal diffusion process into the gate oxide and NO passivation. The free carrier mobility and density were evaluated through the Hall effect measurements using the van der Pauw technique at room temperature. Passivation by Ba or NO was found to have no effect on the Hall-effect mobility, but contributes to the improvement of the free carrier density. The free carrier ratio up to 70% was achieved in combination with Ba diffusion and NO passivation.

1. Introduction

The low carrier mobility in the SiC-MOSFET channel region is caused by the high density of interface trapping states. A nitric oxide (NO) post-oxidation anneal (POA) is a widely used process [1]; however, further improvement is required. More recently, Ba-incorporated interfacial layers have been reported to show mobility improvement [2-7], although the drawback is the roughening of the oxide resulting in the gate leakage current. In this work, we employed the Ba diffusion process to suppress the oxide roughening to investigate the mechanism of the μ_{FE} enhancement by Ba incorporation.

2. Experiment

p-type epitaxial layers (N_A = 5×10^{15} cm^{-3}) on 4H-SiC (0001) 4º off-axis substrates were used for n-channel MOSFET fabrication. The source and drain regions were formed by multi-energy phosphorus ion implantation at 600ºC, followed by activation annealing at 1650ºC for 10 minutes with a carbon cap. After a field oxide layer was deposited, a ~25-nm-thick gate oxide was grown by dry oxidation at 1200ºC for 120 minutes. After several kinds of POA, Al was evaporated and patterned for the gate, source and drain pads. By changing POA processes, six types of MOSFETs called Dry, Dry + NO, Ba 0.5 min, Ba 1 min, Ba 3 min and Ba + NO were fabricated, as summarized in Table I. For Ba-incorporated samples, Ba oxide was deposited on the dry oxide surface by BaO_2 sputtering for 0.5, 1, 3 minute(s). The thickness of deposited Ba oxide layers estimated by spectroscopic ellipsometry was ~0.5 nm for a sputtering duration of 1 minute. Subsequently after the Ba oxide deposition, these devices were annealed in Ar at 1100–1200ºC for 30 minutes to distribute the Ba into the interface. For Ba + NO, Ar POA followed by NO POA was performed. Due to the enhanced-oxidation by Ba, the oxide thickness of Ba + NO device is increased to 55.8 nm. Van der Pauw elements having four electrodes were also fabricated for Hall effect measurements to extract the Hall mobility (μ_{Hall}), the field-effect mobility (μ_{FE}) and the free carrier density (n_{free}). The Hall effect measurements were performed with a magnetic field of 0.48 T at room temperature. The total carrier density (n_{total}) was evaluated through the split *C-V* measurements of the gate-channel capacitance at a low frequency of 10 Hz. The free carrier density ratio was calculated by dividing the free carrier density by the total carrier density. V_{th} was defined as the voltage at which the total carrier density reaches 1×10^{10} cm^{-2}.

3. Results and Discussion

The μ_{FE} extracted from the I_d-V_g transfer curves are shown in Fig. 1. In order to eliminate the effect of the oxide thickness variation of each device, the gate overdrive voltage is normalized by the oxide thickness. The peak μ_{FE} increased with the Ba-sputtering time, indicating that increasing amount of BaO_x layer on the thermally grown oxide surface results in the effective diffusion of Ba toward the interface. The Ba 3 min sputtered sample (BaO_x ~ 1.5 nm) showed ~ 60 cm^2/Vs, which is obviously better than NO annealed interface on Si-face. The highest μ_{FE} of 70 cm^{2}V^{-1}s^{-1} was obtained for Ba + NO, which is seven times higher than that for Dry sample.

To investigate the mechanism for the μ_{FE} enhancement observed for Ba and Ba+ NO passivation processes, we measured the μ_{Hall} and n_{free}, as shown in Fig. 2. We found a trend difference between the high (> 1×10^{12} cm^{-2}) and low (< 1×10^{12} cm^{-2}) carrier density regions. When n_{free} is > 1×10^{12} cm^{-2}, μ_{Hall} are almost the same. It should be noted that this region corresponds to the region where the maximum μ_{FE} were obtained. So, the variation of μ_{FE} is not because of the

Table I. Post-gate-oxidation processes and CETs.

Device	Ba sputtering duration	POA	CET (nm)
Dry	w/o	w/o	24.1
Dry + NO	w/o	NO 30 min	24.3
Ba 0.5 min	0.5 min	Ar	24.9
Ba 1 min	1 min	Ar	25.5
Ba 3min	3 min	Ar	29.3
Ba + NO	3 min	Ar followed by NO	55.8

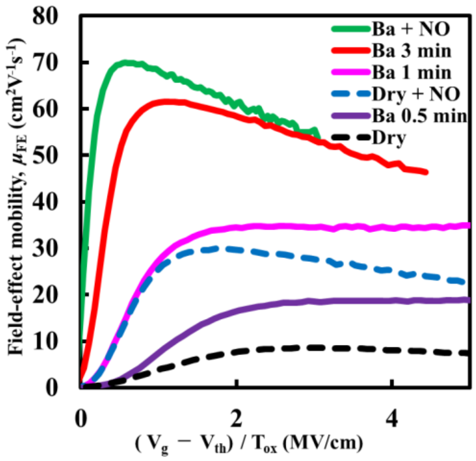

Fig. 1 Field-effect mobility (μ_{FE}) as a function of the gate overdrive voltage divided by the oxide thickness.

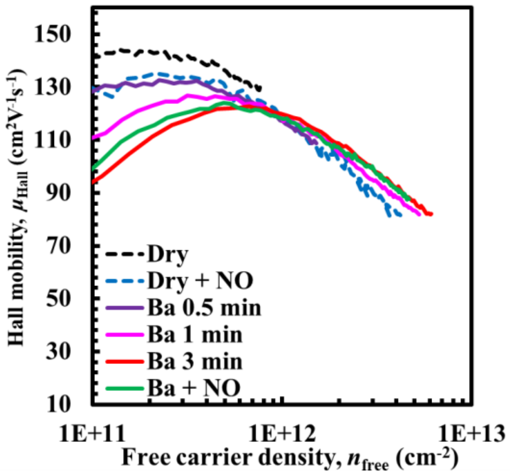

Fig. 2 Hall effect mobility (μ_{Hall}) as a function of the free carrier density n_{free}.

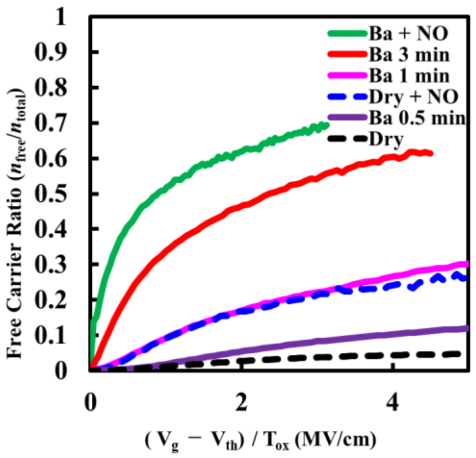

Fig. 3 Free carrier ratio (n_{free}/n_{total}) as a function of the gate overdrive voltage divided by the oxide thickness. ~70% was obtained for Si-face, which is comparable to that on the NO annealed a-face interface [9].

change of free carrier mobility. Recently the existence of unidentified scattering origins at the 4H-SiC MOS interfaces has been suggested [8]. Based on the results in this study, the Ba-diffusion or NO passivation have no significant effect on those scattering origins. On the other hand, when n_{free} is low (< 1×10^{12} cm^{-2}), μ_{Hall} is slightly decreased by Ba introduction. It is speculated that this is due to the Ba-related scattering similar to the NO-process-induced scattering [8] or phonon scattering effects [2].

On the other hand, a clear difference was observed for free carrier ratio (n_{free} / n_{total}), as shown in Fig. 3. n_{free} / n_{total} is increased by Ba diffusion process. Since the μ_{FE} enhancement is not due to the μ_{Hall} enhancement, in this study we conclude that the observed μ_{FE} enhancement can be attributed to the improvement in the free carrier density. The free carrier ratio of the device with both Ba + NO is about 70%, which is the highest among the devices fabricated in this study. The free carrier ratio of 70% is as high as the results of NO-POA on the 4H-SiC a-face [9]; However, it is not equal to the simple summation of the effects of n_{free} enhancements by the Ba diffusion and NO passivation processes. Thus, it is speculated that some of the interface defects are able to be commonly eliminated by each of those processes.

4. Conclusions

In this work, we fabricated 4H-SiC MOSFETs with the Ba-incorporated gate oxide by Ba diffusion process and examined the mobility and free carrier density. The μ_{FE} enhancement mechanisms for Ba or NO processes were commonly the n_{free} increase, whereas they have small impacts on μ_{Hall}. The highest mobility is obtained for Ba + NO device, originating from the free carrier ratio up to 70% in combination of them.

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