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Suppression of Surface States inside Conduction Band and Effective Mobility Improvement of Ge nMOSFETs by Atomic Deuterium Annealing

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Introduction

Ge has been attracting a lot of interests as one of future high mobility channel materials to further enhance the performance of present Si MOSFETs [1]. Recently, Ge nMOSFETs with high peak mobility have already been demonstrated by using thermal oxidation GeO_2/Ge [2, 3] and plasma post oxidation Al_2O_3/GeO_x/Ge gate stacks [4]. However, the weak temperature dependence of the effective electron mobility and the strong degradation in high normal field region are typically observed for Ge nMOSFETs, which reduce the effectiveness of Ge nMOSFETs. It has been confirmed that the surface states inside conduction band (CB) of Ge results in an over estimation of inversion carrier density (N_s), which is responsible for the rapid effective mobility degradation in high normal field region [5].

In order to passivate these traps in CB of Ge, PDA is carried out for the Al_2O_3/GeO_x/Ge gate stacks in different ambient of N_2, Forming gas, H_2, atomic H, D_2 and atomic D. It is found that the atomic deuterium (D) PDA shows effective passivation to the N_{ss} inside E_c of Ge, resulting in an enhancement of effective electron mobility for Ge nMOSFETs.

Experiments

(100) Ge nMOSFETs were fabricated with a gate-last process. After pre-cleaning of Ge wafers, active areas were defined by etching field oxides of sputtered SiO_2. Ion implantation was carried out for S/D formation. After activation annealing, Al_2O_3(6 nm)/GeO_x(1.2 nm)/Ge gate stacks were fabricated using plasma post oxidation of 1-nm-thick Al_2O_3/Ge structures and 2nd-ALD of 5-nm-thick Al_2O_3. As a result, these gate stacks show an EOT of ~3.6 nm. PDA was carried out at 400 ^{o}C for 30 min in different ambient of N_2 and atomic D. The atomic H and D were generated by cracking D_2 through tungsten filaments. Al gate metals were deposited by thermal evaporation and patterned. Finally, Al contacts were formed for S/D and back electrode.

Results and discussion

Fig. 1 shows the I_d-V_g characteristic of Ge nMOSFET with N_2 PDA, which exhibits normal transistor operations. The normal operations of Ge nMOSFET are also confirmed (data not shown). Hall measurement and split-CV method were employed to evaluate the Hall and effective electron mobility, as well as the inversion carrier density as a function of gate bias, in these Ge nMOSFETs. The surface state densities (N_{ss}) in these Ge nMOSFETs are extracted from the difference between N_s obtained from Hall measurement and split-CV method, as shown in Fig. 2. It is found that N_{ss} inside CB of Ge is reduced by ~40% with atomic D PDA, leading to the increased free electron concentration and improvement of effective electron mobility. Fig. 3 shows the Hall and effective electron mobility in Ge nMOSFETs with N_2 and atomic D PDA, respectively. Similar Hall mobility is observed in Ge nMOSFETs with different PDA ambient. On the other hand, the effective electron mobility increases by 25% with atomic D PDA against that with N_2 PDA, attributing to increased N_s due to suppression of N_{ss}. As a result, a record high mobility for Ge nMOSFETs, 488 cm^2/Vs at N_s=8×10^{12} cm^{-2}, is obtained with atomic D PDA.

Conclusion

It is found that N_{ss} inside CB can be effectively passivated by PDA in atomic record D ambient. Record high effective electron mobility in high N_s region, 488 cm^2/Vs at N_s=8×10^{12} cm^{-2}, has been obtained for Ge n-MOSFETs with atomic D PDA.

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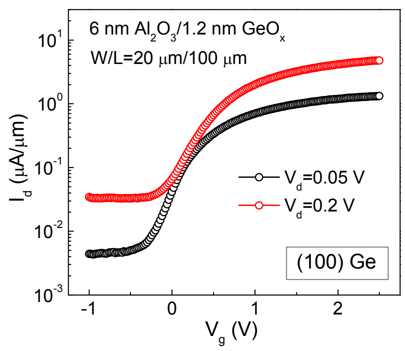

Fig. 1. The I_d-V_g curves of the (100) Ge nMOSFETs with N_2 PDA.

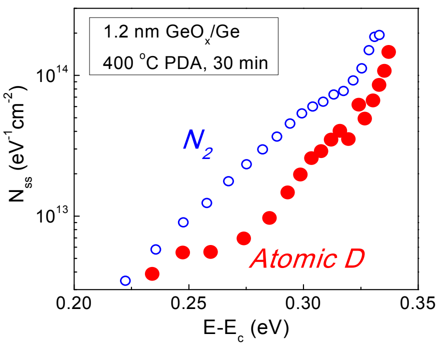

Fig. 2. The N_{ss} at GeO_x/Ge interfaces with N_2 and atomic D PDA, as a function of energy.

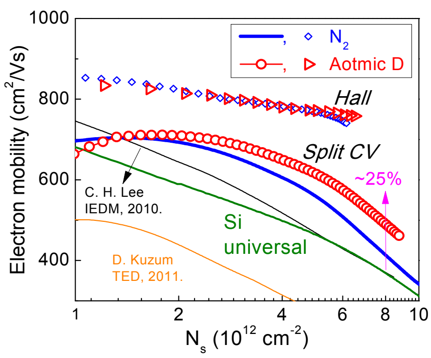

Fig. 3. The mobility of Ge nMOSFETs with N_2 and atomic D PDA, compared with previous reports.