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High-performance Short-channel Germanium nMOSFETs without Phosphorus Diffusion in n^+/p Source/Drain Junctions

Cheng-Ting Chung[1], Guang-Li Luo[2], Bo-Yuan Chen[2], Che-Wei Chen[1], Wei-Chih Chen[1] and Chao-Hsin Chien[1,2]

[1] Department of Electronics Engineering & Institute of Electronics, National Chiao-Tung University, Hsinchu 300, Taiwan
[2] National Nano Device Laboratories, Hsinchu 300, Taiwan

Tel: +886-3-5726100ext7660, E-mail: *glluo@ndl.narl.org.tw*

1. Introduction

In order to boost CMOS operation speed, high mobility materials have been widely investigated. Germanium is one of the candidates since it provides both higher electron and hole mobility than silicon. However, n-type dopant activation is the main problem for fabricating short-channel Ge nMOSFETs although long-channel devices ($L_g \geq 4\mu m$) with high electron mobility have been demonstrated [1-4]. Phosphorus and arsenic possess high diffusion coefficients in Ge due to concentration-enhanced-diffusion mechanism, therefore shallow n^+ source/drain and short-channel N-channel Ge device is hard to be achieved [5]. The saturated electrical activated concentration of phosphorus in Ge is about $5\times10^{19}cm^{-3}$. Excess n-type dosages actually can not give any benefits, and only cause more physical damage, more interstitial defects, and thus higher thermal budget must be used to repair it accompanying with severe diffusion.

In this work, medium dosage of phosphorous (close to solubility of P in Ge) was adopted to form Ge n^+/p junctions. By using this condition, we found the phosphorus can be easily activated without any diffusion. The Ge N^+/P junctions exhibit high rectifying ratio and low leakage. With improved junctions, 500nm gate-length Ge nMOSFETs with high I_{on}/I_{off} ratio and excellent subthreshold swing (S.S) were demonstrated.

2. Experimental

P-type Ge substrates with resistivity of 1.6-2.1Ω-cm and (100) orientation were used to fabricate mesa diodes and self-aligned gate-first NMOSFETs. Boron was implanted and annealed to provide well doping of $\sim5\times10^{17}$ cm^{-3}. For mesa diodes, phosphorus was implanted at dose of 2×10^{14} or 1×10^{15} cm^{-2} at 20keV. Rapid thermal annealing (RTA) at 500℃ for 30sec was used to activate dopants. The detail process flow was shown in Fig.1 For nMOSFETs, the substrates were dipped in diluted HF to remove native oxide. GeO_2 passivation layer was grown in O_2 ambient at 550℃ for 3 min and then Al_2O_3 was deposited by ALD for 80cycles. Next, TiN was deposited by PVD and defined as gate using lithography and dry etching. Phosphorus was implanted at dose of 2×10^{14} cm^{-2} at 20keV as source and drain. Annealing in N_2 ambient was performed at 500℃ for 30sec to activate dopants. Fig.2 shows the process flow and mask used. Secondary ion mass spectrometry (SIMS) was used to analyze the P dopant profile before and after RTA. I-V characteristics of junctions and devices were measured using HP4156C semiconductor parameter analyzer.

3. Results and Discussion

We used 20keV implantation energy to investigate diffusion depth for different dosage implantation. Fig.3 shows the phosphorus distribution before and after RTA at dose of 2×10^{14} and 1×10^{15} cm^{-2}. For 2×10^{14} cm^{-2} dosage, the peak concentration was about $\sim6\times10^{19}$ cm^{-3} which is close to the saturated electrical activated concentration of phosphorus in Ge. The dopant distribution was almost unchanged after 500℃ annealing. However, 1×10^{15} cm^{-2} dosage sample demonstrated typical box-shape distribution and the junction depth was more than 100nm after RTA. Concentration-enhanced-diffusion occurred obviously for 1×10^{15} cm^{-2} dosage. Fig.4 shows the IV characteristics of the n^+/p junctions. For 2×10^{14} cm^{-2} dosage, the defects could be easily repaired at 500℃ for 30sec and 2.55×10^4 on/off ratio at ±1V was achieved. The ideal factor was only ~1.08 which also indicated defects were much reduced during RTA. However, high reverse junction leakage was observed for 1×10^{15} cm^{-2} dosage sample, which means the damages caused by high dosage were harder to be repaired, and the remained defects would produce higher generation current. These results imply that overdose dopants in Ge will only cause deeper junction depth and higher junction leakage during RTA, and the excess dopants will remain electrically inactivated [6].

In this work, medium implantation dosage (2×10^{14} cm^{-2}) was used to fabricate gate-first Ge nMOSFETs (gate length= 500nm) and the device characteristics are shown in Fig.5 and 6. Since reverse junction leakage was suppressed, the I_{on}/I_{off} ratio was about $\sim1.67\times10^5$ for source current (I_S) and $\sim1\times10^4$ for drain current (I_D) at V_D=0.05V. With GeO_2 surface passivation, the subthreshold swing (S.S) can be improved by reduced interface states. In a previous report, S.S was also affected by reverse junction leakage. Higher reverse junction leakage will cause higher I_{SUB}; therefore drain off current will increase and deteriorate S.S [4]. In this work, low S.S. value of ~100mV/dec is obtained and there was no significant difference between S.S (I_D) and S.S (I_S).

4. Conclusion

Excess dosage of n-type dopants in Ge by implantation can not give any benefits to formation of n^+/p junctions, and only cause more damage, more severe diffusion during RTA. In this work, medium dosage of phosphorus (2×10^{14} cm^{-2}, 20KeV) was adopted to form S/D of Ge nMOSFETs. Because the P concentration was controlled to be close to its solubility in Ge, the P dopants could be easily activated under 500℃, 30sec, meanwhile no diffusion occurred. Based on this condition, Ge nMOSFETs with gate-length of 500nm were fabricated by gate-first process. Due to the high-quality junctions and gate-stack, high device Ion/Ioff ratio of 1.67×10^5 and S.S value of 100mV/dec were achieved without obvious drain induced barrier lowering.

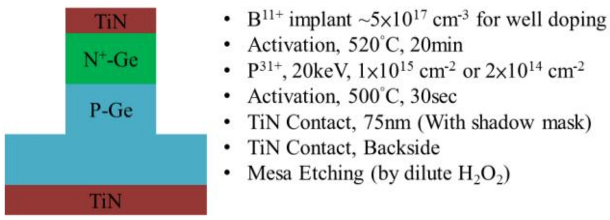

Fig. 1 Process flow of fabricating mesa diodes. TiN hard-mask was patterned by shadow mask. Dilute H_2O_2 was used to etch Ge.

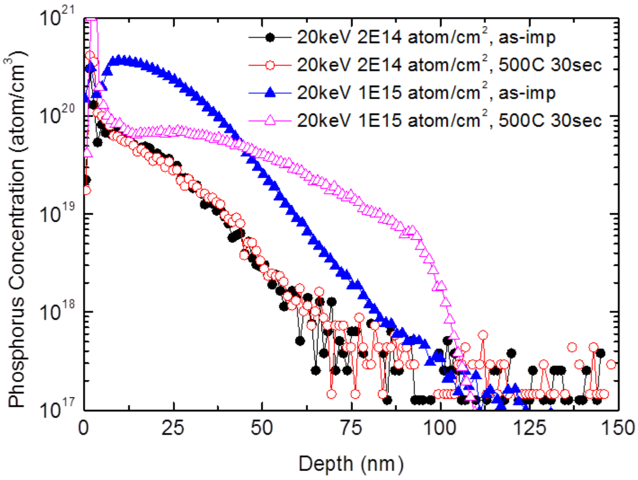

Fig. 3 SIMS results of phosphorus distribution before and after RTA at dose of 2×10^{14} and 1×10^{15} cm^{-2}. Concentration-enhanced-diffusion was occurred obviously in higher dosage.

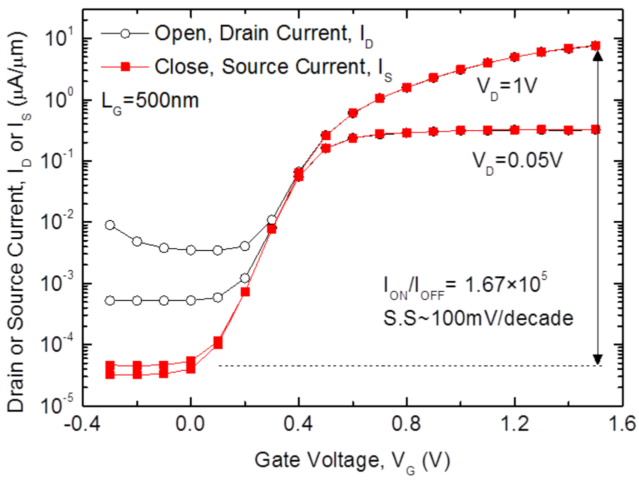

Fig. 5 I_D-V_G characteristics of the nMOSFETs. I_{on}/I_{off} ratio was about ~1.67×10^5 for I_S and ~1×10^4 for I_D at V_D=0.05V. Low S.S. value of ~100mV/dec is obtained

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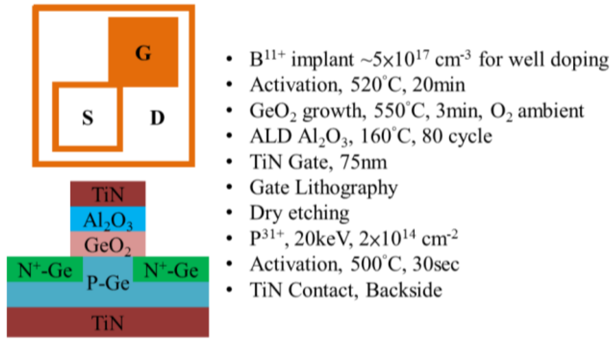

Fig. 2 Process flow of fabricating Ge nMOSFETs. One-mask process was used in this work. The channel length was 500nm.

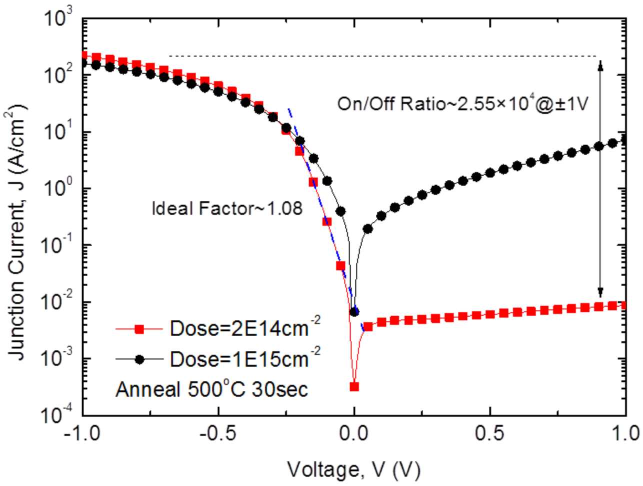

Fig. 4 IV characteristics of the n+/p junctions. 2.55×10^4 on/off ratio at ±1V and ideal factor ~1.08 was achieved by 2×10^{14} cm^{-2} dosage. For 1×10^{15} cm^{-2} dosage, high reverse junction leakage was obtained.

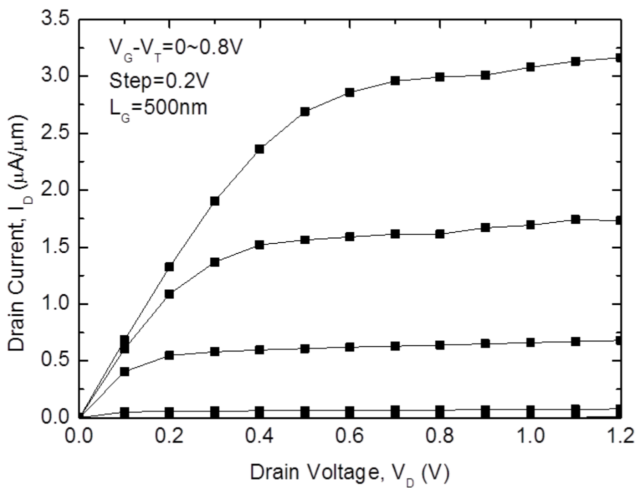

Fig. 6 I_D-V_D characteristics of the nMOSFETs. The channel length was 500nm and implantation dosage was 2×10^{14} cm^{-2}.