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Low-temperature Microwave Annealing Process for Ge MOSFETs

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Abstract

Ge MOSFETs with all thermal processes preformed by microwave anneal (MWA) has been realized. The full MWA process is ＜390 °C. It significantly outperforms conventional RTA process in 3 aspects: (1) diffusion-less junction, (2) increased Cox and healed gate dielectric/channel interface, and (3) ultrathin 7.5nm nickel mono-germanide with lower sheet resistivity and contact resistivity. Compared to conventional RTA, the MWA gives 50% and 24% drive current enhancement for p- and n-MOSFET, respectively. These data show that the low temperature MWA is a promising thermal process technology for Ge MOSFETs manufacturing.

Introduction

For dopant activation in Ge MOSFETs, RTA process ＞600 °C have been wildly adopted[1-2]. Such high temperature process causes the degradation of gate dielectric/ Ge channel interface, and results in severe dopant diffusion in source/drain region with Ge out-diffusion. In addition, for lowering the contact resistance to germanium, NiGe is the most promising candidate due to its low resistivity [3-4]. In order to thin down the thickness of NiGe, reducing the process temperature is necessary. However, a lower temperature results in a higher silicide resistance due to the small crystallite size. MWA is promising for achieving advanced Ge MOSFETs because of its unique low temperature due to apparent non-thermal energy transfer that is not yet fully understood[5]. The advantages for Ge MOSFETs with MWA are summarized in Fig. 1.

Results and Discussion

Diffusion-Less Junction. The n^+ and p^+ doping are introduced by P and BF_2 implants at a dose of 1×10^{15} cm^{-2}, respectively. The peak temperature of dopant activation by MWA was 390 °C. Fig. 2(a) shows a significant diffusion of P after RTA and no P diffusion after MWA. For boron, comparable diffusion-less concentration profiles after MWA and RTA are observed and presented in Fig. 2(b). The activated levels of P and B after MWA are 2×10^{19} cm^{-3} and 7.5×10^{19} cm^{-3}, respectively. In Fig. 4, the deep junction of P formed by RTA results in the lower Rs. Thus, ultra shallow junctions can clearly be reached by the low temperature MWA.

Gate Dielectric/Channel Interface. The $TiN/Al_2O_3/GeO_2$ structure of the n- and p-MOS capacitors for C-V characterizations were fabricated on (100) bulk Ge. After interfacial layer formation, Al_2O_3 was deposited by ALD. From Figs. 4 and 5, an increase of C_{ox} and a decrease of the interfacial trap density after MWA were observed. The gate capacitance increases after MWA, which is due to less Ge out-diffusion during low temperature MWA than RTA. The device on/off characteristics are in Figs. 6 and 7. Compared to RTA, MWA produces 50% and 24% drive current enhancements for p- and n-MOSFET, respectively. Their off leakage currents are similar to those by RTA processing.

Ultrathin 7.5nm Ni Mono-Germanide. In Fig. 8(a), a 7.5 nm NiGe is produced by MWA which meets the target of year 2022 in the ITRS roadmap[6]. The NiGe layer is fabricated on (100) epi-Ge on Si. Unreacted metal was removed after the 1st anneal. Afterward, the 2nd anneal was performed. The TEM images show an ultrathin NiGe layer with a smooth interface fabricated by MWA at two different microwave power levels during the 2nd anneal. Fig. 8(c) shows the result of RTA germanide anneal. The NiGe thickness by RTA is about 2 nm thicker than by MWA. The temperature ramp up curves of MWA for NiGe formation are shown in Fig. 9. The temperature ramped at 2 to 6 °C/sec depending on the microwave power. In Fig. 10, Rs of NiGe by two-step MWA or RTA are summarized. Lower Rs could be obtained by increasing the MWA power with shortened process time, which lowers the peak temperature by 40 °C compared to RTA. In Fig. 11(a), the XRD spectrum for the anneal condition of MWA 145 °C + MWA 270 °C shows strong (111) preferred crystal orientation. In Fig 11(b), an increasing power with shortened process time of 2nd step annealing leads to a larger crystallite size. In addition, by lowering the 1st step annealing temperature of RTA for reducing the thickness of NiGe, a low intensity of RTA 150 °C + RTA 330 °C shows that it is hard to achieve both the well-defined crystalline structure and the scaling of the NiGe layer. However, the MWA results show that a thinner and lower Rs of NiGe layer was obtained because of the increased crystallinity at low temperature.

Conclusion

For the first time, Ge MOSFETs with all thermal processes performed by microwave has been realized. Diffusion-less junctions were achieved in Ge was induced by MWA. Compared to the conventional RTA, all MWA processing yields 24% and 50% drive current enhancements for n- and p-MOSFET, respectively due to increased of C_{ox} and better gate dielectric/Ge interface. Finally, a record ultrathin 7.5 nm nickel mono-germanide thickness is achieved by two-step low temperature MWA process.

References:

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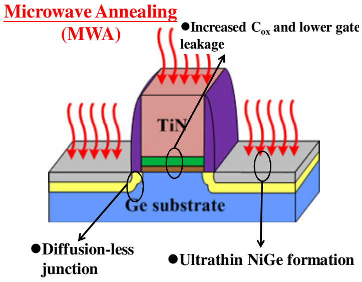

Fig. 1 Schematic diagram of low-temperature microwave anneal (MWA) processed Ge MOSFETs.

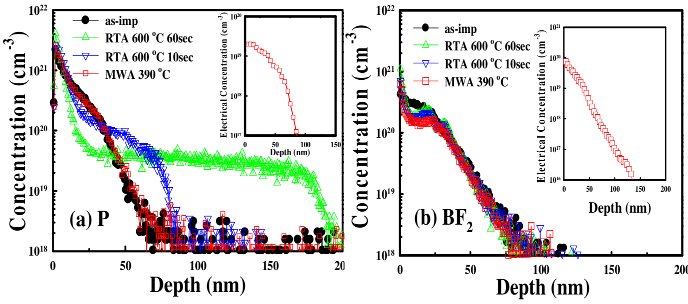

Fig. 2 SIMS and SRP profiles of (a) P and (b) BF_2 at 1×10^{15} cm^{-2} in (100) Ge. The P distribution after MWA is identical to as-implanted, but not after RTA. All boron distribution profiles are close to as-implanted. The insets show the activated levels of P and B by SRP are 2×10^{19} cm^{-3} and 7.5×10^{19} cm^{-3}.

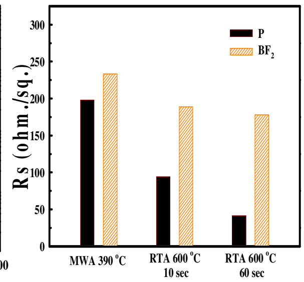

Fig. 3 The comparisons of the R_s between MWA and RTA in (100) Ge. The deep junction of P formed by RTA results in the lower Rs.

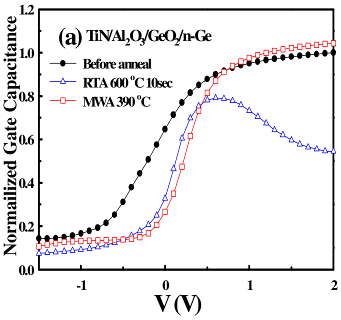

Fig. 4 p-MOS CV characterizations.D_{it} and EOT are improved with MWA dopant activation process. RTA process degrads the CV and increases the gate leakage.

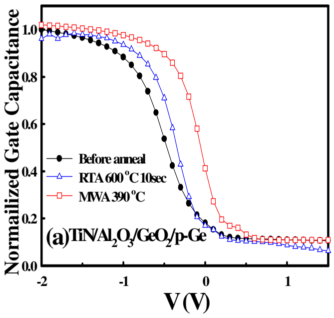

Fig. 5 n-MOS CV characterizations. MWA produced higher gate capacitance and much less gate leakage than RTA.

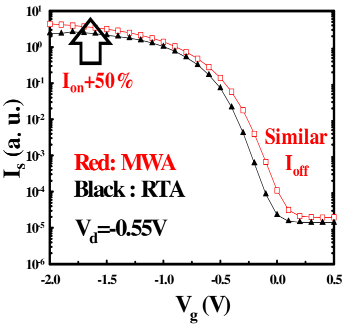

Fig. 6 I_s-V_g of Ge p-MOSFET at V_d= -0.55V. A 50% drive current enhancement was achieved.

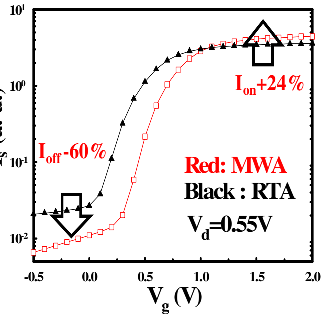

Fig. 7 I_s-V_g of Ge n-MOSFET at V_d = 0.55V. A 24% drive current enhancement and lower leakage current are achieved.

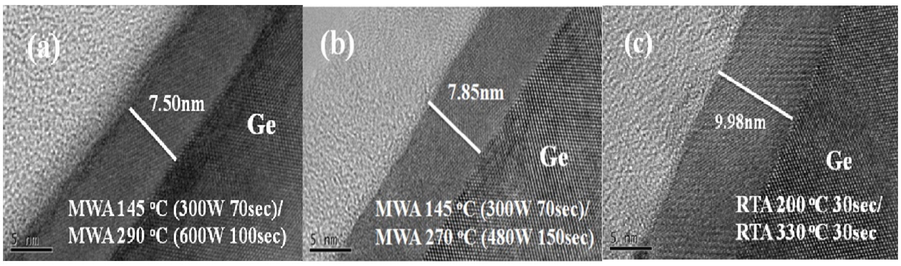

Fig.8 HR-TEM images of NiGe by two-step MWA process (a) and (b) using lower power in the 2nd step than (a) and by two-step RTA (c).

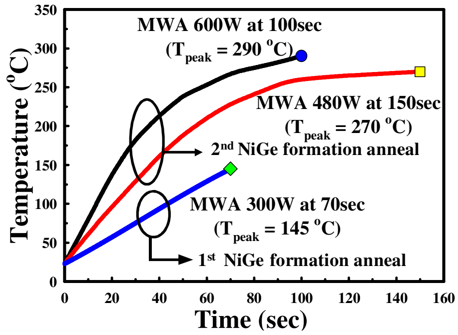

Fig. 9 The temperature profiles of MWA for NiGe formation.

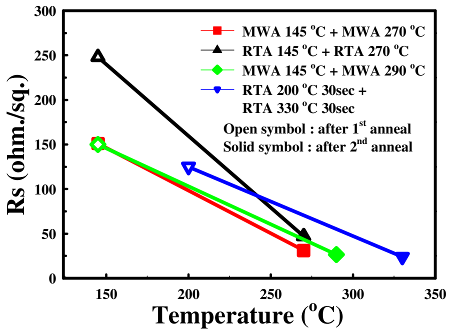

Fig. 10 Rs of Ni germanide after 1st anneal (open symbol) and after 2nd anneal (solid symbol).

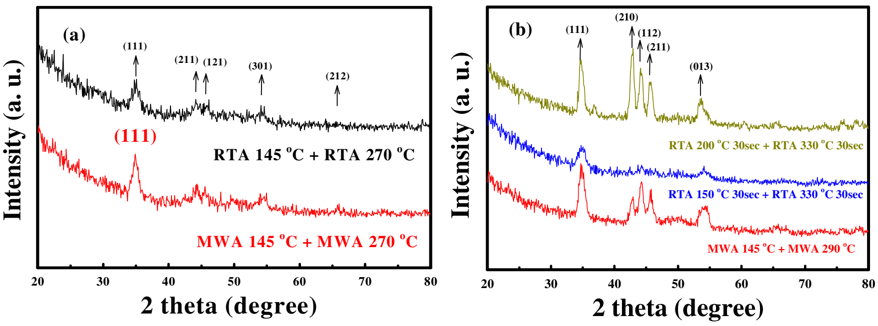

Fig. 11 XRD 2θ-scan of nickel germanide formed by MWA or RTA. MWA 145 °C + MWA 270 °C produces the relatively strong (111) preferred crystal orientation with low anneal temperature.