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Ge p-channel Tunneling FETs with steep phosphorus profile source junctions

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Abstract

We have clarified that phosphorus can realize the highest impurity concentration (~7×10^{19} cm^{-3}) and the steepest impurity profile (~10 nm/dec.) in Ge among solid-phase diffusion of the three n-type dopants, P, As and Sb from spin-on glass (SOG). We have demonstrated the operation of Ge p-channel TFETs with steep phosphorus profile source junctions formed by this method. Small SS$_{min}$ of 108 mV/dec. and high ON/OFF ratio higher than 3.5×10^5 were observed at 150K.

1. Introduction

A Tunneling FET (TFET) is one of promising low power devices, because its subthreshold swing (SS) can be less than 60mV/dec. [1]. However, Si TFETs are suffering from low ON current due to the wide bandgap [2]. Therefore, small bandgap materials have been studied for TFET channel materials. Among them, Ge is a promising material for complementary TFETs, because it can be used as both n-type and p-type MOS structure channels. However, there have been very few studies on Ge p-channel TFETs (p-TFETs). One of the key technologies for superior TFETs performance is formation of defect-free and steep impurity profile source junctions. Our group has realized defect-less and steep impurity profile p$^+$-n junctions in InGaAs by Zn diffusion from SOG and has demonstrated InGaAs TFET with low SS and high ON/OFF ratio [3]. On the other hand, Chui *et al.* reported that the diffusion coefficients of implanted P and As in Ge are proportional to the square of each concentration [4], as similar with that of Zn in InGaAs [3]. For that reason, we can expect that P and As provide the steep impurity profiles in Ge, as Zn in InGaAs. However, the examination of P and As profiles in Ge junctions formed by diffusion from SOG and the applications to TFETs have not been reported yet. In this study, we compared diffusion of three n-type dopants (P, As and Sb) from SOG into Ge to judge which dopant is proper for source junctions of p-TFETs. In addition, we fabricated Ge p-TFETs with source junctions formed by diffusion of these dopants and evaluated the electrical characteristics.

2. Impurity profiles of n-type dopants and n$^+$-p junction characteristics

P-type (100) Ge substrates with the hole concentration of ~1.0×10^{17} cm^{-3} were used for dopant diffusion experiments. The diffusion condition and the fabrication process were shown in Table 1 and Fig. 1, respectively. Fig. 2 shows the *I-V* characteristics of n$^+$-p diodes after RTA at 650˚C for 1 min. All the diodes show high ON/OFF ratio (>10^5) and ideality factors of nearly 1.0, indicating that their junctions have a low density of defects. The junctions formed by the other conditions also showed high ON/OFF ratio and good ideality factor (not shown). Fig. 3 and 4 show the depth profiles of n-type dopants after RTA. P showed higher impurity concentration and steeper profile than the other dopants. P diffusion by RTA at 600˚C for 1 min showed not only the highest impurity concentration (~7×10^{19} cm^{-3}) but also the steepest profile (~10 nm/dec. at 1.0×10^{19} cm^{-3}). These results mean that P diffusion is proper for TFET source region formation, as expected. However, As does not have so steep a profile as P. This result does not agree with that by Chui *et al.* [4]. We would think that this difference can comes from the influence of the implantation damages on the previous result [4]. The implantation damages may enhance As diffusion in the damage regions and yield the apparent As concentration dependency as a result of the enhanced diffusion coefficient.

3. Ge p-TFETs with source regions formed by SOG

N-type (100) Ge substrates with a donor concentration of ~1.0×10^{16} cm^{-3} were used for TFETs. The fabrication process and the structure of the Ge TFETs are shown in Fig. 5. The RTA (1 min) temperature was 600 and 650 ˚C for P and 650 ˚C for Sb. An Al_2O_3(~2.5nm)/GeO_x(~0.8nm)/Ge with plasma post oxidation gate stack was employed for reducing the MOS interface state density [5]. The measurements were performed with the source and substrate shorted.

Fig. 6 shows the I_d-V_d characteristics of a Ge p-TFET with P diffusion at 600˚C. The high ON current of 1.7 µA/µm was obtained at V_d=-1.5V and V_g=-2.0V. Fig. 7 shows the I_d-V_g characteristics of all the Ge p-TFETs. P-TFETs with P diffusion at 600 ˚C exhibited the highest ON current due to the high impurity concentration and the steep impurity profile, though the ON/OFF ratio was low (~100) and SS$_{min}$ was not low because of the high OFF current. Fig. 8 shows the I_d-V_d characteristic of the Ge p-TFET with P diffusion at 600˚C at 20K. The observed NDR-like characteristics indicate that the current is dominated by band-to-band tunneling (BTBT). Fig. 9 and 10 show the temperature dependence of I_d-V_g and SS-I_d characteristics, respectively, of the TFET with P diffusion at 600˚C. At 150 K, SS$_{min}$ of 108 mV/dec. and ON/OFF ratio higher than 3.5×10^5 were obtained. Under 150 K, SS$_{min}$ is almost saturated around ~110mV/dec.. Fig. 11 shows the I_d-q/kT characteristics of the TFET at V_g=-1.6 V and V_g=-0.7 V. The low (0.037 eV) and high (0.28 eV) activation energies were obtained at V_g=-1.6 V and -0.7 V, respectively. These results indicate that BTBT is dominant at V_g=-1.6V, while defect related thermal excitations can strongly affect the current at V_g=-0.7 V.

4. Conclusions

It has been found that P shows the highest impurity concentration (~7×10^{19} cm^{-3}) and the steepest profile (~10nm/dec. at 1.0×10^{19}cm^{-3}) among solid-phase diffusion of P, As and Sb in Ge. We have demonstrated the operation of Ge p-TFETs with steep P profile source junctions formed by diffusion from SOG. SS$_{min}$ of 108 mV/dec. and ON/OFF ratio higher than 3.5×10^5 were observed at 150 K.

Acknowledgements

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References

[1] A. Seabaugh et al., Proc. IEEE 98, 2095, 2010 [2] T. Krishnamohan *et al.*, IEDM, pp. 947, 2008. [3] M. Noguchi *et al.*, IEDM, pp. 683, 2013. [4] C.-O. Chui *et al.*, Appl. Phys. Lett., 83, pp. 3275, 2003. [5] R. Zhang *et al.*, IEEE TED, 59, 2, pp. 335, 2012.

Table I
Diffusion condition used for SIMS and n^+-p diode

Dopant	Diffusion temp. (°C)	Diffusion time
P	600	10s
P	600	1min
P	650	1min
As	500	1min
As	600	1min
As	650	1min
Sb	650	1min

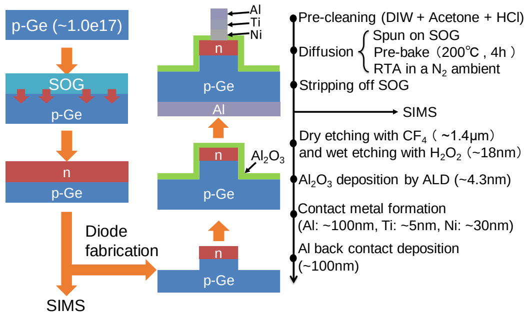

Fig. 1 Fabrication process of samples for SIMS and n^+-p diode

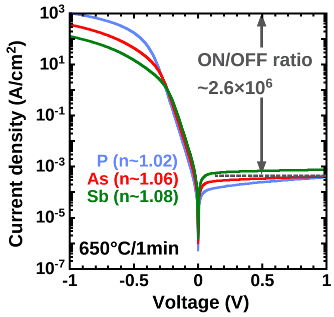

Fig. 2 *I*-*V* characteristics of n^+-p diodes after RTA at 650˚C for 1min

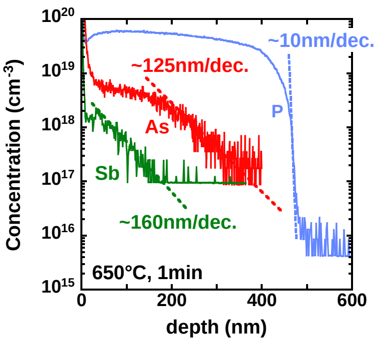

Fig. 3 Chemical impurity profiles of n type dopants after 650˚C/1min RTA

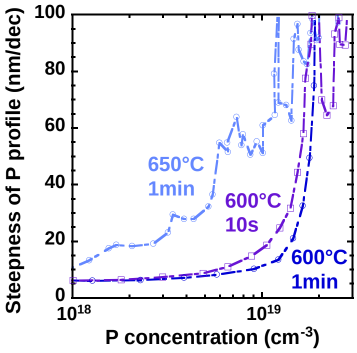

Fig. 4 Steepness of P profile vs P concentration after three RTA conditions

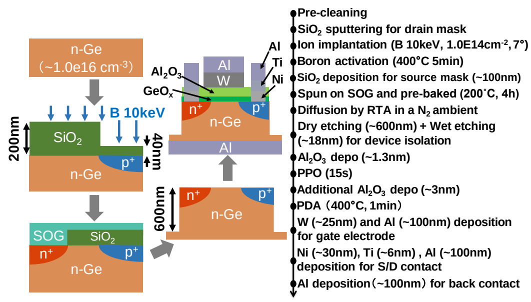

Fig. 5 Fabrication process of the Ge TFET

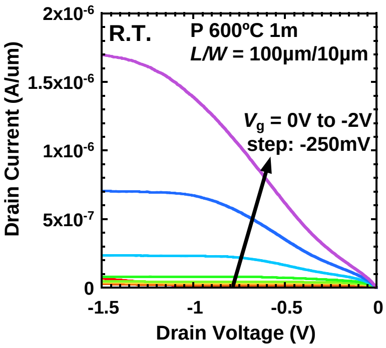

Fig. 6 I_d-V_d characteristics of the Ge TFET with P diffusion at 600˚C

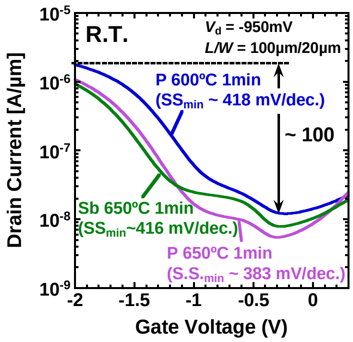

Fig. 7 I_d-V_g characteristics of all Ge TFETs

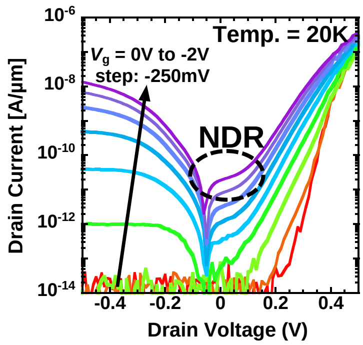

Fig. 8 I_d-V_d characteristics of the Ge TFET with P diffusion at 600˚C at 20K

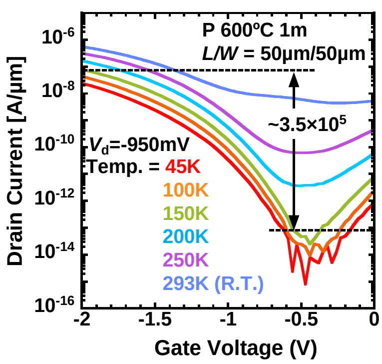

Fig. 9 The temperature dependence of I_d-V_g characteristics of the Ge TFET with P diffusion at 600˚C

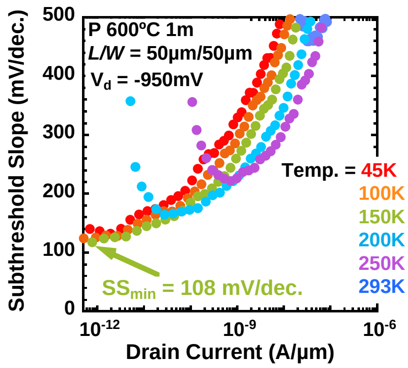

Fig. 10 The temperature dependence of SS-I_d characteristics of the Ge TFET with P diffusion at 600˚C

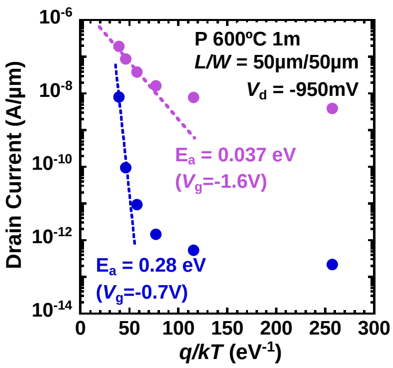

Fig. 11 I_d-q/kT characteristics of the Ge TFET with P diffusion at 600˚C at V_g=-1.6V and V_g=-0.7V