Dopant Activation in Single-Crystalline Germanium by Low-Temperature Microwave Annealing

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***Abstract*—Phosphorus activated in germanium epitaxy atop Si wafer by low-temperature microwave annealing technique was investigated in this letter. Compared to the conventional RTA process, the temperature of phosphorus activation could be 120 °C to 140 °C which is an improvement in temperature reduction at the same sheet resistance. According to the SRP, up to 150 °C reduction in maximum temperature at the same activation concentration (about 2×10^{19} cm^{-3}) could be achieved. Through adjusting the microwave power and process time, sheet resistance could be decreased while suppressing dopant diffusion. In addition, the inserted susceptor wafers above and below the processing wafer also suppressed the dopant diffusion and improved film roughness.**

***Index Terms*—Germanium, low temperature, microwave anneal, phosphorus, rapid thermal anneal (RTA).**

I. Introduction

GERMANIUM (Ge) HAS been considered a potential material as replacement for silicon because of its higher mobility for electron and hole than Si. However, the thermal instability of Ge and GeO_x during the fabrication process limits the fabrication temperature of Ge-based devices. Recently, high-k materials and metal gates have become a solution for continuous scaling down of Ge-based devices. The deposition of high-k material can be achieved by atomic layer deposition at very low temperature (170 °C–340 °C). This spurs consideration of germanium as a replacement material for the Si channel [1]. However, the ability of dopant activation is another issue for the fabrication of Ge-based devices [2], [3]; dopant diffusion in Ge film is observed in rapid thermal processing (RTP) method. According to Satta *et al.* [4], rapid thermal annealing, even at 500 °C for 60 s, leads to severe implanted dopant diffusion for high-dose phosphorus in Ge film. However, lower annealing temperature is used; the lower activation percentage causes higher contact resistance, reducing the drain current.

Low-temperature dopant activation method has been developed by Park *et al.* [5]. They have successfully used the metal-induced crystallization (MIC) process to activate dopants in amorphous germanium at about 360 °C [5]. However, for n-type doped Ge film, good results leading to low resistivity may be obtained only with cobalt. Other metal impurities work as acceptor-like traps which capture the electrons, resulting in resistivity increases. Further, the low metal diffusion coefficient in n-type doped germanium is a disadvantage for cobalt MIC processing. Accordingly, microwave annealing may be an alternative to other rapid thermal processing methods in silicon processing [6], [7]. Microwaves could repair the damage caused by high-dose boron implantation. Further, the dopant is activated by the microwave initiation of solid-phase epitaxial regrowth at 500 °C. In addition, we have demonstrated boron activation on the Si/Ge/Si structure by microwave annealing [8].

In this letter, we used microwave annealing to activate the phosphorus in single-crystalline Ge epitaxial film at low temperature. The major factors in the microwave process are power, frequency, and loads inside the chamber, while a less important factor is temperature. We demonstrated microwave annealing by controlling the power magnitude and the loads inside the chamber in order to compare it with the conventional RTP method.

II. Experiments

Several Ge epitaxial films were prepared for dopant activation experiments. A 10-nm Si layer was deposited with SiH_4 as the buffer layer on 6-in p-type Si (100) substrates with resistivity of 15–25 $\Omega - \mathrm{cm}$ by UHVCVD at 550 °C. Then, a 200-nm Ge epitaxial layer was deposited by UHVCVD at 420 °C, followed by P^{31} (25 keV, 1×10^{15} cm^{-2}) implantation at room temperature. Additional wafers with a layer of AlSiCu and tungsten thin film, both 200 nm thick, deposited on thermal oxide, were also prepared for microwave testing.

The splits underwent microwave annealing at 5.8 GHz with a power of about 600–1400 W in a 5.57×10^6 cm^3 chamber for 100 to 600 s. A 10-min N_2 purge from the top of the chamber was performed before the microwave was started, and the N_2 flow was maintained until the process was completed. The processing time was measured from when the microwave power

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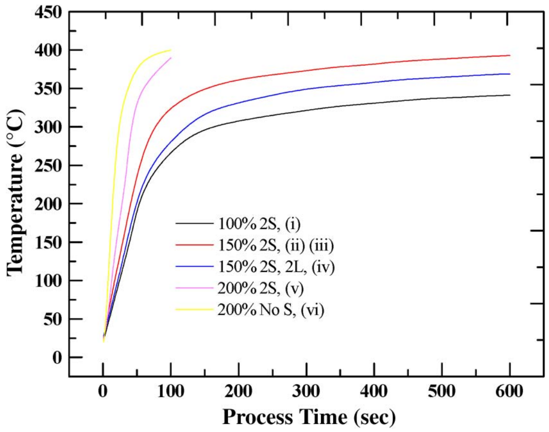


Fig. 1. Temperature versus process time during microwave annealing in different setting conditions; S is the represented susceptor, and L is the represented load wafer.

TABLE I
CONDITIONS OF MICROWAVE ANNEALING AND RTA FOR INVESTIGATING THE DOPANT DIFFUSION MECHANISM

	RTA1	RTA2	i	ii	iii	iv	v	vi
Power(%)	N	N	100	150	150%	150	200	200
Susceptor (pc.)	N	N	2	2	2	2	2	N
Load wafer (pc.)	N	N	N	N	N	2	N	N
Process time (sec.)	60	60	600	600	300 two cycles	600	100	100
R_s ($\Omega/\square$)	235	120	316.3	162.3	215.4	276.3	200.1	133.2
T_{max}(°C)	450	550	341.3	392.8	373	368.9	390	400

was turned on until the power was turned off, without regard to temperature, different from the approach used in rapid thermal anneal (RTA). The temperature profile versus time by microwave is shown in Fig. 1. As one added susceptors or loading wafers above and below the process wafer inside the microwave chamber, the maximum temperature and temperature ramping slope would decrease because the susceptor and loading wafers also soak up the microwave power inside the chamber [9]. Therefore, the heating slope would be lower with susceptors. Finally, SIMS, SRP, and sheet resistance (R_s) were measured, and cross-sectional transmission electron microscope (TEM) images were also compared. The splits without microwave treatment were activated by RTA in a heat-pulse AG601i RTA system at 450 °C and 550 °C, respectively.

III. RESULTS AND DISCUSSIONS

The conditions of the different microwave processes and R_s are displayed in Table I. The microwave magnetron emitted 600–700 W of power when it was fully turned on (100%). The R_s of sample (i) is 316.3 $\Omega/\square$.

The R_s by RTA was also summarized in Table I. Comparing to RTA at 550 °C for 60 s (RTA2), the microwave power used on sample (i) appears to be too low to activate sufficient dopants. After increasing the power to 150% for advanced activation, the R_s of sample (ii) is much lower than that of sample (i). However, the SIMS profile in Fig. 2 shows that the diffusion of phosphorus in sample (ii) is nearly as severe as under RTA at 550 °C for 60 s, although the R_s of sample (ii) is low. Hence, two approaches to suppressing dopant diffusion while maintaining lower R_s are investigated. First, in sample (iii), the time that the wafers stay in the saturated temperature is reduced by splitting the total process time into two cycles, of 300 s each. Second, in sample (iv), the load wafers are added to soak up the power inside the chamber. As a result, sample (iv) has a higher R_s because of the insufficient power applied to the wafer, as with sample (i). Sample (iii) gets an acceptable R_s value and less dopant diffusion than sample (ii). Higher power and a shorter processing time thus appear to be necessary for good activation and less dopant diffusion.

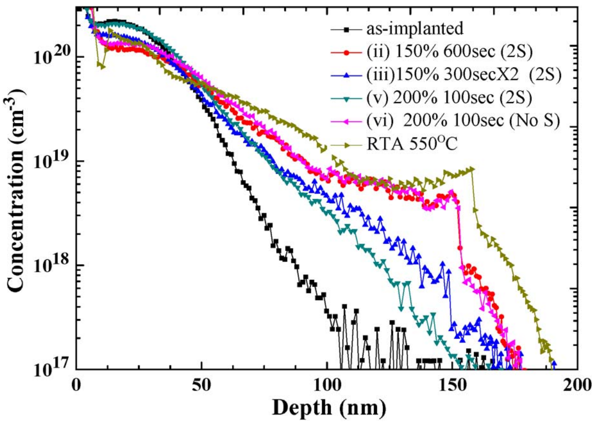


Fig. 2. SIMS profiles of implanted P in Ge before and after microwave annealing in different conditions and RTA at 550 °C for 60 s.

With magnetron power at 200% fully turned on for 100 s, as shown in Table I, sample (v) has less dopant diffusion and a lower sheet resistant value than sample (iii). Only about 10.7% of dopants in sample (v) diffused into the bulk region, and the peak of the phosphorus concentration of sample (v) remains at the level of the as-implanted sample. In addition, from Fig. 3 of the SRP depth profiles, one can conclude that the lower R_s magnitude of sample RTA2 among all splits was due to dopant diffusion. The maximum electrical concentration between microwave annealing and RTA was almost the same (2×10^{19} cm^{-3}). In addition, the depth of the electrical dopants by microwave anneal was 50 nm shallower than that by RTA at 550 °C for 60 s, and the minimum resistivity near the Ge surface is about 10^{-3} ohm-cm. Therefore, microwave could well activate the P^{31} dopant inside the Ge film, and the dopant diffusion could be suppressed due to its lower temperature anneal process.

The comparison of the dopant profile of samples (v) and (vi), in Fig. 2, shows that the susceptor can significantly suppress dopant diffusion. Two important issues are suggested by the temperature profiles of the samples with and without the susceptors (Fig. 1): reduction in the maximum temperature of about 10 °C to 20°C and the rate of temperature increase at the beginning of the process. The susceptor and loading wafers appear to cause a slower temperature increase. Based on the experiments above, there appear to be three possible mechanisms which lead to dopant diffusion which include the

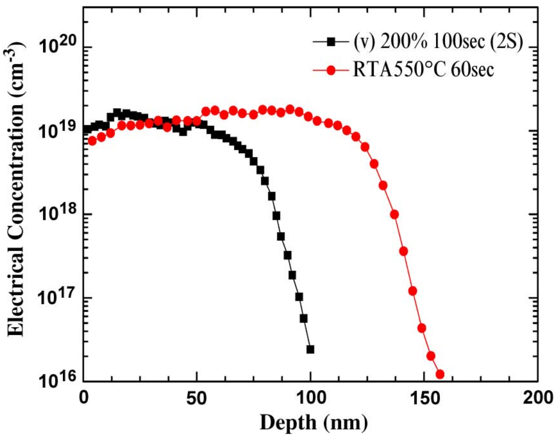
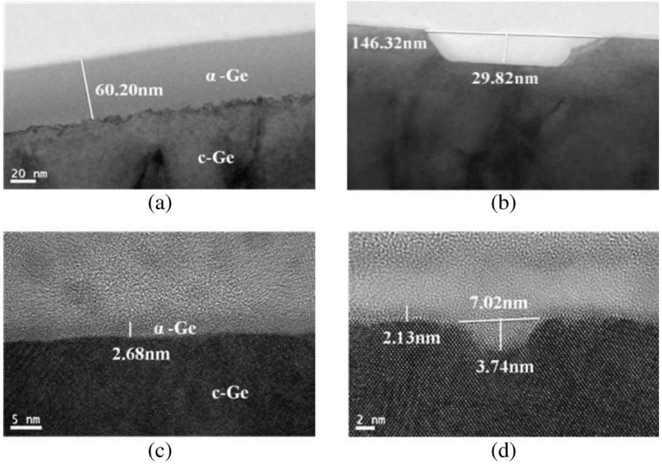


Fig. 3. SRP depth profiles of P in Ge from sample (v) and RTA2.



(a) (b)

(c) (d)

Fig. 4. TEM of (a) as-implanted, (b) RTA2, (c) sample (v), 200% for 100 s with susceptors, and (d) sample (vi) without susceptors.

following: 1) the power magnitude; 2) the processing duration time at the saturated temperature; and 3) the temperature ramp rate at the beginning of the process.

In Fig. 4(a), a 60-nm amorphous region was created by ion implantation. In Fig. 4(b), after RTA at 550 °C for 60 s, the surface was damaged because of germanium out diffusion. It caused a critical issue of device fabrication. The microwave process has the ability to repair the bombardment damage by ion implantation and drove dopants into the lattice site. An amorphous region of 2–3 nm deep is found on the surface of the germanium of sample (v), as shown in Fig. 4(c). In addition, without susceptors, there are pin holes on the germanium surface, as shown in Fig. 4(d). This may be due to the rate of temperature increase at the beginning of the process. Susceptors soak up part of microwave power. It causes a slower temperature increase at the beginning of the process. Therefore, by adding susceptors, the process wafer was treated in more uniform temperature ambient because of thermal coupling effect [9].

Finally, the AlSiCu and tungsten films also underwent microwave treatment, and the resistivity value remained the same after the microwave annealing process. These metals are not damaged by microwave annealing.

IV. CONCLUSION

This work has demonstrated that phosphorus in single-crystalline germanium thin films can be activated by microwave annealing. The SRP and SIMS analyses showed that the severe dopant diffusion and the dopant activation level by microwave annealing, as compared to that by RTA, can be suppressed. Moreover, the TEM images showed that radiation damage occurring during the implantation process can be repaired by microwave annealing. This appears to be due to the lower temperature during processing than in conventional RTA processing. In addition, higher power may be used to obtain a sufficient activation level, while shorten the process time, and susceptors are needed for suppressing dopant diffusion and stimulating germanium out diffusion. Microwave annealing also appears to be compatible with metallic processing.

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