Suppressing phosphorus diffusion in germanium by carbon incorporation

G. Luo, C.-C. Cheng, C.-Y. Huang, S.-L. Hsu, C.-H. Chien, W.-X. Ni and C.-Y. Chang

A problem in the Ge MOSFET process is that the phosphorus for *n*-type doping in Ge diffuses very fast. It is very difficult to form the shallow source/drain *p*-*n* junctions. It is reported, for the first time, that the phosphorus diffusion in Ge during activation (or annealing) can be suppressed effectively owing to carbon incorporation.

Introduction: The low effective mass and higher mobility of carriers in germanium (Ge) compared to silicon (Si) (two times higher mobility for electrons and four times for holes) has prompted renewed interest in Ge-based devices for high-performance logic, especially as it becomes increasingly difficult to enhance Si CMOS performance through traditional device scaling. However, it has been difficult to fabricate high-quality Ge MOSFETs owing to the lack of a device-quality gate dielectric (stable with low interface state density). In particular, the Ge native oxide is water soluble. Since this makes processing difficult and stability unlikely, other dielectrics have been tried, such as GeON dielectric [1], and high-k materials [2]. For *n*-channel Ge MOSFETs, there is an additional fabrication challenge, namely, owing to the fast phosphorus diffusion during activation [3], the n^+ S/D is very difficult to control. In this Letter, we present a study of phosphorus diffusion in Ge, and demonstrate for the first time that the carbon incorporated in Ge can suppress the phosphorus diffusion effectively during the annealing process.

Experiment: The Ge substrates used in this study are (100) orientation, *p*-type, with a net background at room temperature of $3 \times 10^{14}/cm^3$. The carbon incorporated Ge (or Ge : C) film with a thickness of 1.03 μm was grown on Ge substrate at 400°C by our home-made SiGe UHV/CVD system [4]. The incorporated C is 0.2% in composition. The phosphorus implantation was carried out at energy of 25 keV and dosage of $4 \times 10^{15}/cm^2$. The ion beam was tilted by 7° to the substrate surface normalised to minimise channelling effect. Rapid thermal annealing (RTA) for samples was performed in an N_2 ambient at a temperature of 650°C for 15 s.

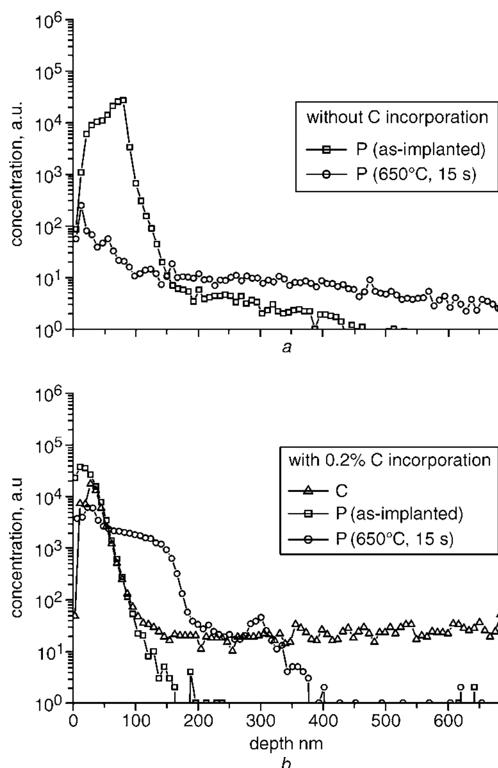

Fig. 1 *SIMS phosphorus profiles for Ge without and with carbon incorporation measured in as-implanted state and after annealing*

a Without carbon incorporation
b With carbon incorporation

Results and discussion: Figs. 1*a* and *b* show second ion mass spectroscopy (SIMS) phosphorus profiles for the Ge with and without carbon incorporation measured in the as-implanted state and after annealing. It can be seen that after annealing the phosphorus in Ge without carbon there is a strong diffusion into Ge substrate, and the peak near the surface almost disappears. However, for the Ge with carbon incorporation, the phosphorus diffusion is suppressed effectively, albeit not completely. A recent report by Uppal *et al.* [5] suggested that the B diffusion in Ge is by an interstitial mediated mechanism. It is possible that the phosphorus diffusion in Ge also depends on the same mechanism. As the boron diffusion can be suppressed by C in Si [6], we speculate that the suppression of phosphorus diffusion in Ge is controlled in a similar way by the competition between the phosphorus and the substitutional carbon atoms for the capture of Ge self-interstitials. The substitutional carbon atoms capturing of Ge self-interstitials should cause the formation of carbon interstitials (C-I) pairs. These pairs reduce the amount of interstitials available for pairing with substitutional phosphorus, thereby reducing the phosphorus diffusion. Reports studying the dopant diffusion in Ge have been very few to date [5]. The above explanation of results requires further experimental and/or theoretical confirmation. Additionally, it is found from Fig. 1*b* that the C SIMS profile has a peak near the surface for the annealed Ge : C sample. We consider that the C tends to segregate from Ge to some degree after high temperature RTP.

We propose that the n^+ S/D with C suppressed phosphorus diffusion can be achieved by two-step implantation after Ge MOSFET gate formation (see Fig. 2): 1. the S/D is implanted with C atoms. The implantation energy is determined by the junction depth of S/D, and the C concentration should be $>10^{19}/cm^3$ (the order of 0.2% C in Ge); 2. the S/D is then implanted with phosphorus and activated by RTP for forming n^+-type doping.

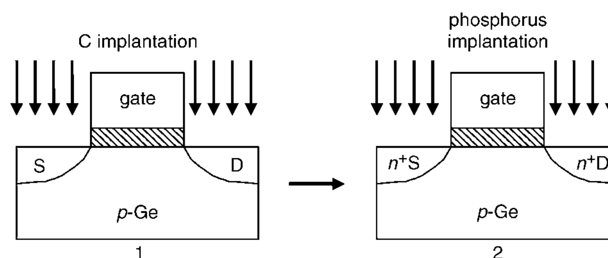

Fig. 2 *Two-step implantation for achieving n^+ S/D with C suppressed phosphorus diffusion: 1. C implantation with its concentration $>10^{19}/cm^3$; 2. phosphorus implantation*

Conclusion: We report, for the first time, that the phosphorus diffusion in Ge during annealing can be suppressed effectively by carbon incorporation. This result can be used to fabricate the shallow n^+ S/D junction for *n*-channel Ge MOSFETs.

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