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DC and AC Characteristics of RPCVD Grown Modulation-doped SiGe pMOSFETs

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1. Introduction

Recently, the utilization of a SiGe strained channel in pMOSFET is receiving a great attention because carriers can transport faster in the SiGe quantum-well (QW) channel [1,2]. In SiGe pMOSFETs, a thin Si capping layer (<100Å) is normally required in order to grow a better quality thermal gate oxide, preventing Ge oxidation and segregation [2,3]. This Si cap layer, however, tends to form a parallel channel at the SiO_2/Si interface lowering the hole mobility [4]. Proposed techniques to minimize this effect are the use of a deeper QW in the valence band (i.e. a larger Ge mole-fraction in the SiGe) [3,4], and the modulation doping of dopants below and/or above the channel [2,3,5]. The key role of the both methods is to increase the carrier density in the SiGe QW channel. The use of a high Ge content in the channel, however, is not so advantageous in the aspect of fabrication process because the high-quality thermal gate oxidation is less applicable due to the elevated possibility of Ge segregation [6]. Regarding the modulation doping technique, its effects on DC and AC characteristics of the SiGe pMOSFET have been rarely investigated experimentally.

2. Device Fabrication

The SiGe/Si QW growth by reduced pressure CVD (RPCVD) started with a 50Å Si seed, and then a modulation doping of boron followed it. For the in-situ boron modulation doping, 1000ppm B_2H_6 in H_2 was used as a dopant gas, and the sample surface was exposed to the further diluted B_2H_6 in H_2 (100:1 dilution) at 600°C without Si/SiGe growth. The doping density was controlled by the exposure time (t_{exp}). The SIMS profile in Fig.1 shows that the FWHM of the boron peak is 5nm for the doping densities of 3×10^{18}–$1\times10^{19}cm^{-3}$. Thus, two different modulation doping doses of $1\times10^{12}cm^{-2}$ (when t_{exp}=15sec) and $5\times10^{12}cm^{-2}$ (t_{exp}=40sec) were selected for the first (sample A) and second (sample B) sample, respectively, and no doping is for the third (sample C). After this, 100Å thick Si spacer, 200Å $Si_{0.8}Ge_{0.2}$ channel, and 70Å Si cap layers were grown sequentially on the wafers without an intentional doping. Then, a low-temperature gate oxidation (~800°C) with H_2/O_2 mixture was done for all the wafers, including a Si control sample. The gate oxide and the unconsumed Si capping layer thickness were measured to be 70±5Å and 30±5Å, respectively.

3. Results and Discussion

Fig. 2 shows the both $-I_{ds}$ and G_m vs. V_{gs} of the SiGe and Si pMOSFETs. Although it demonstrates the larger $|I_{ds}|$ and G_m of the SiGe pMOSFETs than those of the Si-control, the sample C shows a relatively smaller improvement than the samples A and B. This indicates that the QW channel does not sufficiently form without a modulation doping when the relatively low Ge content (20%) is utilized because the shallower QW results in a poorer hole confinement [3]. Between the modulation-doped samples, the sample A exhibits 22% and 6% higher $|I_{ds}|$ at V_{gs}=-3V and maximum G_m, respectively, comparing to the sample B. The sample B seems to suffer from the enhanced impurity scattering due to its higher modulation doping level even if the doped region is spaced from the channel. In addition, it is seen that all the SiGe pMOSFETs here exhibit an excellent turn-off characteristics, with the I_{on}/I_{off} ratio of over 10^8. This result implies that the modulation doping dose could be chosen to improve the carrier transport only without degrading I_{off}. Fig. 3 shows the output characteristics of the Si and SiGe pMOSFETs in this study.

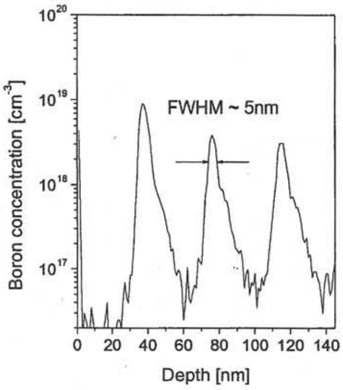

Fig. 1 SIMS profile of the modulation doping of boron performed by RPCVD.

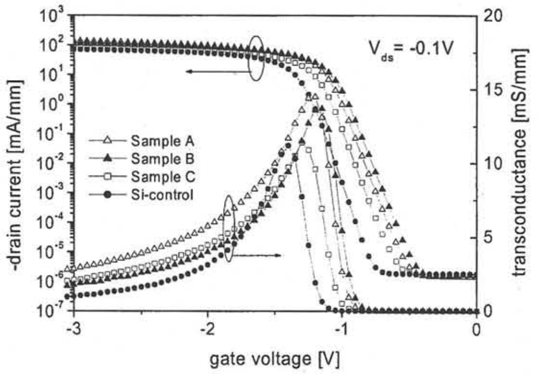

Fig. 2 $-I_{ds}$ and G_m vs. V_{gs} of the SiGe and Si pMOSFETs.

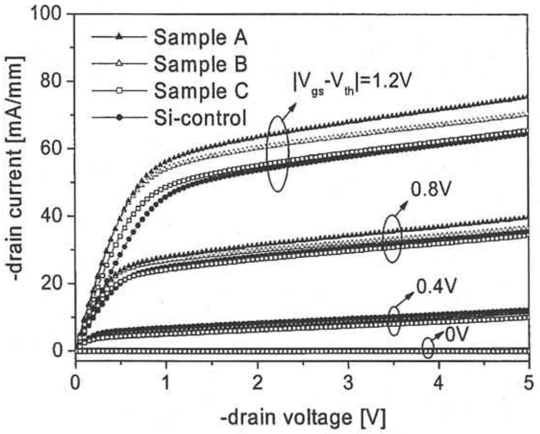

Fig. 3 Output characteristics of the SiGe and Si pMOSFETs.

Fig. 4 compares the threshold voltage (V_{th}) and drain-induced barrier lowering (DIBL) of the Si and SiGe pMOSFETs. As illustrated, the SiGe FETs generally have more positive V_{th}'s than the Si control FET, and the modulation doping shifts the V_{th} further positive. The smaller $|V_{th}|$ of the SiGe FET with a higher modulation doping dose has been expected because the holes are mainly located in the QW channel at a lower $|V_{gs}|$, resulting in the quicker turn-on of the QW channel than the surface one [7]. Regarding DIBL, the higher modulation doping dose reduces DIBL more, meaning that the higher carrier density in the buried QW channel further decreases the portion of the subthreshold current flowing through the surface channel. Through the modulation doping with a dose of $5x10^{12}cm^{-2}$ in sample B, the DIBL is reduced to 21.6mV/V, which is almost half of the Si-control FET's (42.8mV/V).

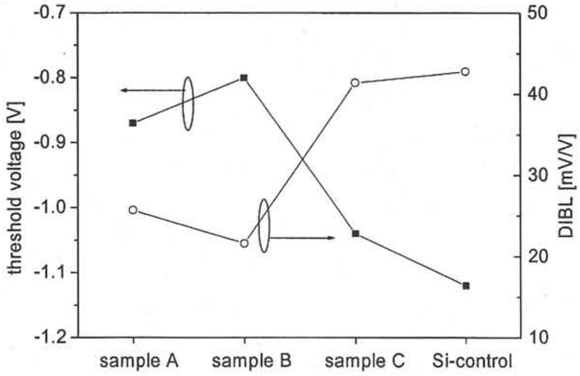

Fig. 4 Comparison of V_{th} and DIBL of the Si and SiGe pMOSFETs

Fig. 5 shows the unity-gain cut-off frequency (f_T) vs. V_{gs} of the Si and SiGe pMOSFETs, and generally larger f_T's of the modulation-doped FETs are demonstrated due to their higher G_m's. However, a slightly lower f_T of the sample B is observed as in the case of G_m since the f_T is directly proportional to G_m. In addition, f_T of the modulation-doped SiGe FET reveals a relatively weak dependence on V_{gs}, comparing to the undoped SiGe FET (sample C), meaning that the carrier density in the SiGe channel is relatively high at a lower $|V_{gs}|$ if modulation-doped. This is considered another advantage of the modulation-doping because it ensures a larger gate-voltage swing.

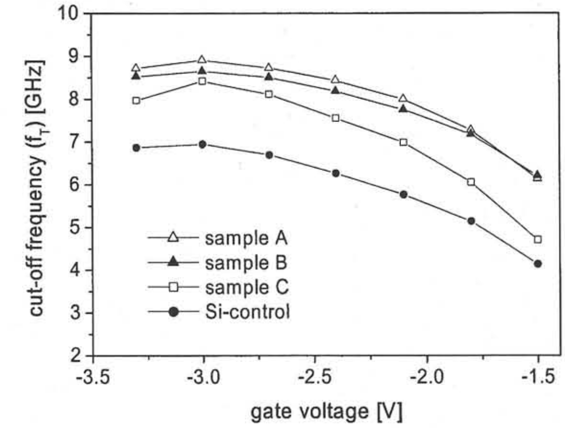

Fig. 5 Dependence of f_T on gate-voltage for the Si and SiGe pMOSFETs at V_{ds}=-3V.

4. Conclusion

In conclusion, the influence of boron modulation doping on DC and AC characteristics of SiGe channel pMOSFETs has been investigated. Through the well-controlled boron modulation doping by RPCVD, DC and AC properties of the device are improved, without degrading I_{off}. Although the lower modulation doping dose of $1x10^{12}cm^{-2}$ provides a larger G_m, I_{on}, and f_T, the higher doping dose of $5x10^{12}cm^{-2}$ is particularly advantageous in reducing DIBL.

Acknowledgment

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