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Origin of Enhanced Impact Ionization in Strained-SiGe pMOSFETs

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1. Introduction

The use of a buried SiGe channel material has attracted considerable attention for improving pMOSFETs performance owing to the high hole mobility [1]-[3]. The improvement in the hole mobility results from the modification of the band structures and the holes confinement in the SiGe channel away from the SiO_2/Si interface. However, a serious reliability issue is that the impact ionization efficiency (IIE) is widely believed to be enhanced by the strain in the SiGe channel due to a decrease in the bandgap energy and/or the high hole mobility. Although the strain-enhanced IIE has already been reported [4]-[6], knowledge of the physical origin of the IIE in the strained SiGe channel is still poor. Moreover, the opposite explanation for the IIE in the SiGe channel is also proposed [7].

The aim of this paper is to explore the IIE in strained-SiGe pMOSFETs. From the relationship between the IIE and the electric field in the pinch-off region, the present understanding of the IIE can be substantially improved.

2. Experimental

The strained-SiGe pMOSFETs used in the paper had a 10 nm-thick strained $Si_{0.7}Ge_{0.3}$ channel and a top 4 nm-thick Si cap layer, as shown in Fig. 1. Then, the low-temperature tetraethylorthosilicate (TEOS) with the thickness of 30 nm was deposited as the gate dielectric material to prevent the relaxation of the strained SiGe channel. For comparison, the bulk-Si pMOSFETs, here called as the control-Si device, were also fabricated using the same CMOS process. Two different gate areas (WxL) of 200x100 and 25x10 um^2 were utilized to determine the effective hole mobility and the IIE, respectively.

3. Results and Discussion

The effective hole mobility was extracted from a well-known split capacitance-voltage (C-V) method. Compared to the control-Si device, the strained-SiGe pMOSFETs have a high effective hole mobility of about 220 cm^2/Vs at the low effective electric field, as shown in Fig. 2. This result is also comparable with the value reported in Ref. [2],[3].To ensure most of the holes confinement in the SiGe channel, an integrated system engineering (ISE) simulator is used to provide the information regarding the hole concentration in the SiGe channel and parasitic Si cap layer, as shown in Fig. 3. The modest gate overdrive V_G-V_T (=-1.5 V) is chosen to eliminate a significant amount of parasitic hole conduction through the top Si cap layer. At the same V_G-V_T=-1.5 V, the drain current (I_D) and substrate current (I_B) as a function of drain voltage (V_D) for control-Si and strained-SiGe pMOSFETs are plotted together in Fig. 4, showing the increase in I_B with increasing I_D. Through the source terminal floating [5], the excess diode leakage current has markedly smaller effect on the I_B caused by impact ionization process, as shown in Fig. 5. Furthermore, for the 30 nm-thick gate oxide, the influence of gate leakage current (I_G) on the IIE can be neglected. Thus, the impact ionization multiplication coefficient M-1 is approximately the ratio of the I_B to I_D, i.e., M-1≈I_B/I_D. M-1 as a function of V_D, M-1(V_D), shows a significantly increased IIE in Fig. 6. Due to the I_B associated with the maximum electric field E_m near the drain, it is necessary to translate M-1(V_D) into M-1(E_m). According to the lucky electron model [8], M-1(E_m) is described as

$$\text{M-1} \approx \frac{I_B}{I_D} \propto E_m \exp\left(\frac{-\varphi_i}{q\lambda E_m}\right), \qquad (1)$$

where φ_i is the threshold energy for impact ionization and λ is the mean free path. Moreover, E_m can be expressed as

$$E_m = \frac{V_D - V_{dsat}}{l}, \qquad (2)$$

where V_{dsat} is the voltage at the pinch-off point and l is the effective pinch-off length. E_m in Eq. (2) can be indirectly assessed through V_D-V_{dsat}. As predicted by Eqs. (1) and (2), the slope of the ln[$I_B/I_D(V_D-V_{dsat})$] versus 1/(V_D-V_{dsat}) plot is represented by $-\varphi_i l/\lambda$. To differentiate between the contribution of these components (λ, φ_i, and l) to the IIE, a comparison of the slope change between the control-Si and the strained-SiGe pMOSFETs is made, as shown in Fig. 7. First, under a high electric field, λ is assumed to be insensitive to the strain. This assumption is also supported by our previous studies [5],[6]. In addition, another parameter l is proportional to the gate oxide ($t_{ox}^{1/3}$) [9] and only plays a minor role in the IIE because compared to control Si, the t_{ox} variation due to the increase in the Si cap layer is estimated to be about 1.3 nm. Finally, the slope change of about 25% obtained from Fig. 7 is close to the expected value of the bandgap energy change of about 21% at the strained $Si_{07}Ge_{0.3}$ channel [10]. This result strongly supports the argument that the strain-enhanced IIE is mainly attributed to the narrowing of the bandgap energy.

4. Conclusions

Enhanced IIE in strained-SiGe pMOSFETs has been investigated. From the relationship between the IIE and the E_m, the strain-enhanced IIE is found to strongly support the argument about the narrowing of bandgap energy. The obtained result is also expected to be

applicable to other strained Si devices.

References

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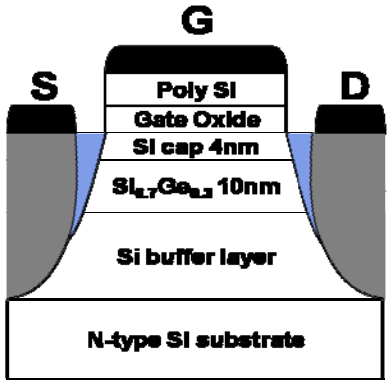

Figure 1 Schematic illustration of strained-SiGe pMOSFETs.

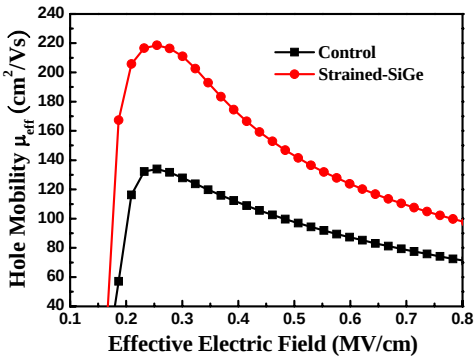

Figure 2 Typical effective electric field dependence of effective mobility of control-Si and strained-SiGe pMOSFETs.

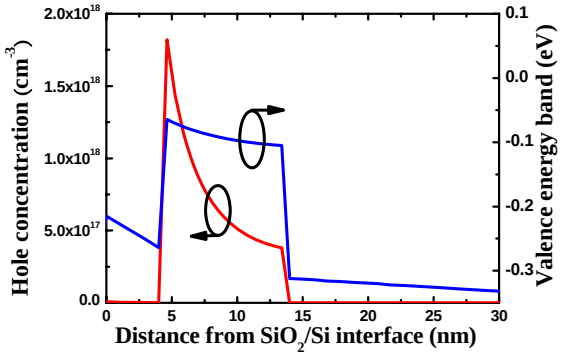

Figure 3 Schematic illustration of hole distribution and valence energy band.

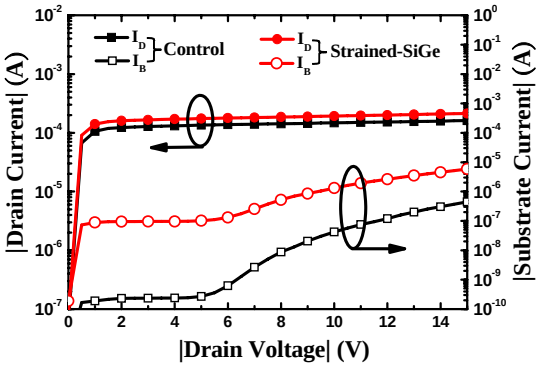

Figure 4 Comparison of drain and substrate currents in control-Si and strained-SiGe pMOSFETs.

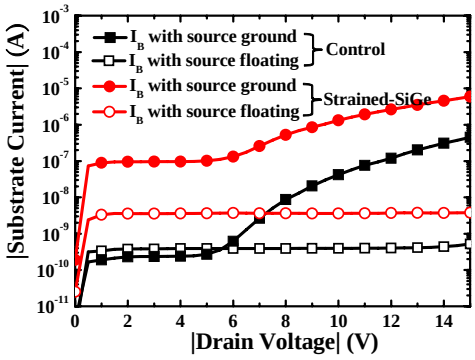

Figure 5 Comparison of substrate currents in control-Si and strained-SiGe pMOSFETs with source terminal grounded and floating.

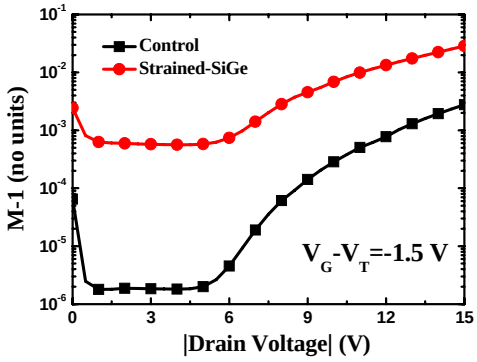

Figure 6 Impact ionization multiplication coefficient ($M-1=I_B/I_D$) as a function of V_D corresponding to Fig. 4.

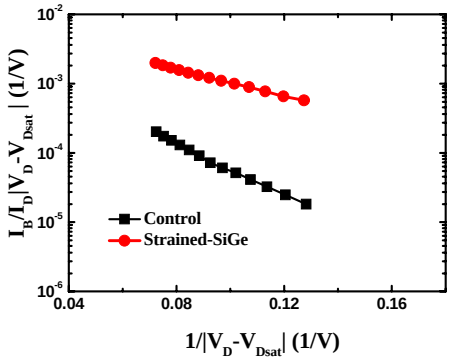

Figure 7 $1/|V_D-V_{dsat}|$ dependence of $I_B/I_D|V_D-V_{dsat}|$ in strained-SiGe pMOSFETs. The result of control-Si pMOSFETs is also shown for comparison.