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Investigation of Low-Energy Tilted Ion Implantation for FinFET Extension Doping

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1. Introduction

One of the most important issues in the high-performance FinFET fabrication is the reduction of parasitic source-drain (SD) resistance (R_p) that is mainly determined by the narrow fin extension [1]. For reducing the R_p, highly tilted angle and low-energy ion implantation (I/I) has been used to introduce impurities into the fin extension effectively [2-5]. However, the highly tilted I/I technique becomes difficult with shrinking device size owing to the ion shadowing by adjacent fins or photoresist edges [3, 4]. In the case of a low tilted angle I/I, on the other hand, the implant atoms easily scatter out from the fin extension regions [6], which results in the dopant loss. Hence, the optimization of fin extension I/I process is strongly required.

In this paper, the I_{ON}-I_{OFF} and R_P of the n$^+$-poly-Si gate n-channel FinFETs fabricated by changing extension I/I conditions including dose (D) and tilt angle (θ) are systematically compared and discussed.

2. Experimental results and discussion

Si-fin channels were fabricated by using the orientation-dependent wet etching on the (110) SOI wafers [7]. The n$^+$-poly-Si gate length (L_g) was ranged from 50-175 nm. In the I/I process, arsenic (As) for fin extension with a fixed low-energy of 5-keV and phosphorus (P) for SD electrodes are used as shown in Fig. 1. For impurity activation, RTA was performed at 900 °C for 2 s. An ideal rectangular Si-fin channel is confirmed from the STEM image as shown in Fig. 2.

At first, we evaluated the I_{ON}-I_{OFF} at a fixed V_d = 1 V. Since the actual V_{th} is around -0.2 V as shown in Fig. 3(a), in the evaluation of the I_{ON}-I_{OFF}, the V_g range is shifted to the negative direction by 0.4 V. Next, we evaluated the R_p by using the Terada's method [8] and by its modified implementation [1]. Figure 3(b) shows the on-state resistance ($R_{ON} = V_d/I_d$) at V_d = 0.05 V. The y-intercepts provide the R_p at a given gate overdrive. We chose V_g-V_{th} = 0.6 V, and extracted the R_p for all devices. The I_{ON}, I_{OFF} and R_p were normalized by $2H_{fin}$.

Figures 4(a) and 4(b) show the measured I_{ON}-I_{OFF} and R_p for the devices by changing θ from 0 to 60°. It is clear from Fig. 4(a) that the I_{ON} increases with increasing θ, indicating the superiority of the highly tilted angle I/I. Somewhat lower I_{ON} and marked fluctuation in I_{OFF} and R_p are observed at θ= 0°, which will be discussed later.

Figures 5(a) and 5(b) show the measured I_{ON}-I_{OFF} and R_p for the devices by changing D from 1E14 to 8E14 cm^{-2}. Note that the best I_{ON}-I_{OFF} performance and lowest R_p are obtained when the D is chosen to be 4E14 cm^{-2}. In the case of lower D of 1E14 cm^{-2}, the total impurities introduced into the fin extension regions should be smaller than those in the case of D = 4E14 cm^{-2}, which reasonably results in a higher R_p. On the other hand, with further increasing D, in contrast, the I_{ON}-I_{OFF} and R_p are deteriorated. It is speculated that the D = 8E14 cm^{-2} is high enough to cause amorphization, and the re-crystallization of the defected amorphous fin extension is insufficient, which results in the poor impurity activation and fluctuations in I_{ON}-I_{OFF} and R_p [5].

Figures 6(a) and 6(b) show the measured I_{ON}-I_{OFF} and R_p for the devices by changing D from 4E14 to 1.07E15 cm^{-2}. It should be noted that the D = 1.07E15 cm^{-2} at θ = 0° is chosen so that the implanted impurities to the extension regions are equivalent to that in the case of D = 4E14 cm^{-2} at θ = 60°. Note that no performance improvement is observed even if D increases to 1.07E15 cm^{-2}, and the R_p fluctuation is enhanced compared with that in the case of D = 4E14 cm^{-2} at θ = 60°. This result implies that the implanted atoms scatter out from the upright thin fin extensions randomly [6]. As a result, the net impurities remained in the fin extension regions are different each other, which result in the marked fluctuations in R_p as shown in Fig. 6(b).

Figure 7 summarizes the θ dependence of average R_p at a fixed D = 4E14 cm^{-2}. The smallest R_p is obtained to be 0.64 kΩ-μm when the I/I condition is chosen to be D = 4E14 cm^{-2} & θ = 60°. This value is comparable with the R'_p = 0.53 kΩ-μm by the solid-phase-diffusion of phosphors from PSG, which is conformal and damage-free process [7]. This indicates that above I/I condition is almost optimized.

3. Conclusion

The low-energy tilted I/I for FinFET source-drain extension doping has been investigated thoroughly by fabricating a series of n$^+$-poly-Si gate n-channel FinFETs with different I/I conditions. It is experimentally found that the best extension I/I condition is D = 4E14 cm^{-2} & θ = 60°. With further increasing D, the device performance deteriorates due to the incomplete re-crystallization of amorphous regions in the fin extensions. In the case of θ = 0°, the marked increment and fluctuations in R_p are observed owing to the implant atoms scattering out randomly from each fin extension.

Acknowledgements

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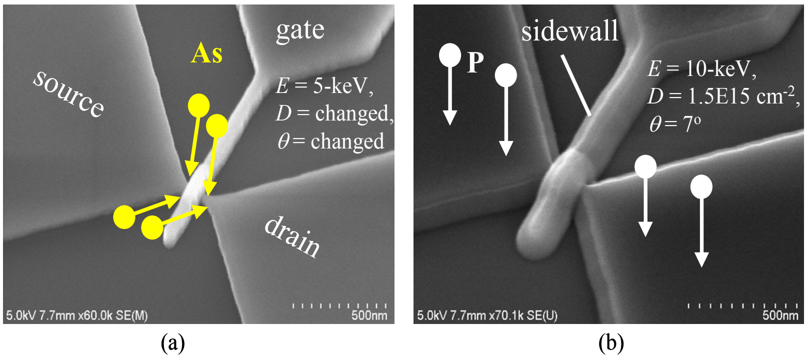

Fig. 1. SEM images of the fabricated FinFETs after (a) n^+-poly-Si gate formation by ICP-RIE and (b) sidewall spacer formation. In the I/I process, arsenic (As) for extension with a fixed low-energy of E = 5-keV and phosphorus (P) for source-drain electrodes are used.

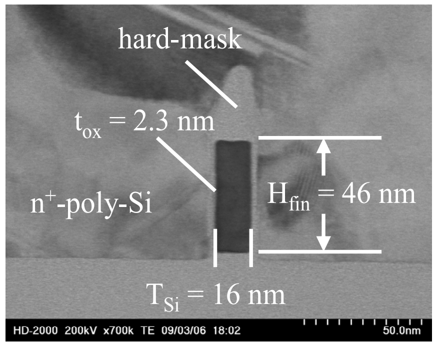

Fig. 2. Cross-sectional STEM image of the fabricated n^+-poly-Si gate FinFET by using the orientation-dependent wet etching.

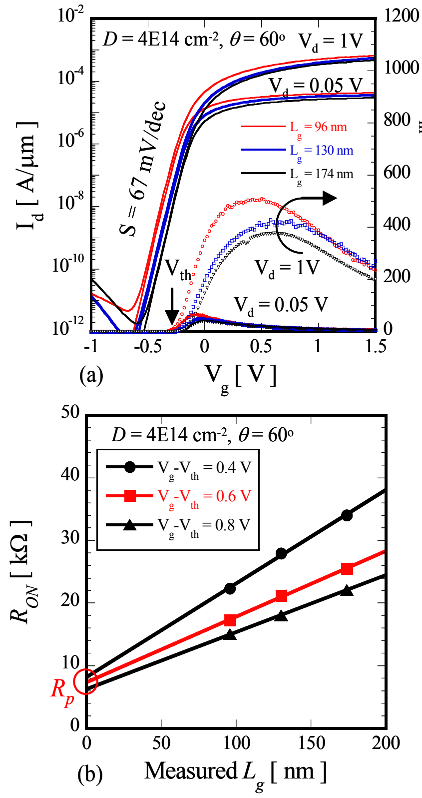

Fig. 3. (a) I_d-V_g & g_m-V_g (b) R_{ON}-L_g characteristics of the fabricated FinFETs.

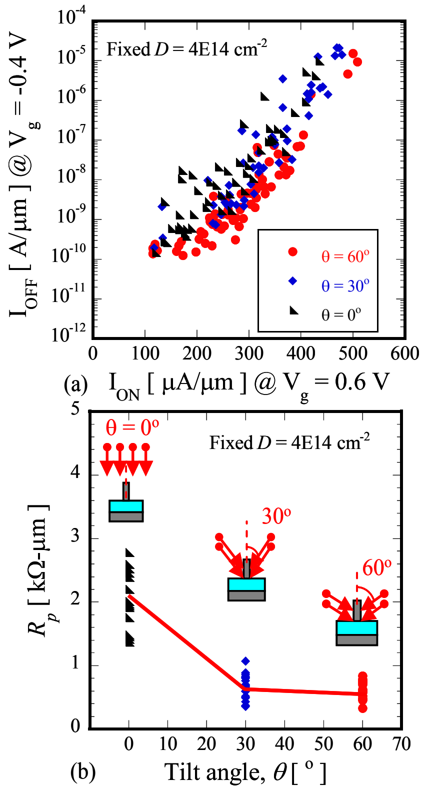

Fig. 4. (a) I_{ON}-I_{OFF} plot at V_d = 1 V and (b) normalized R_P as a function of θ.

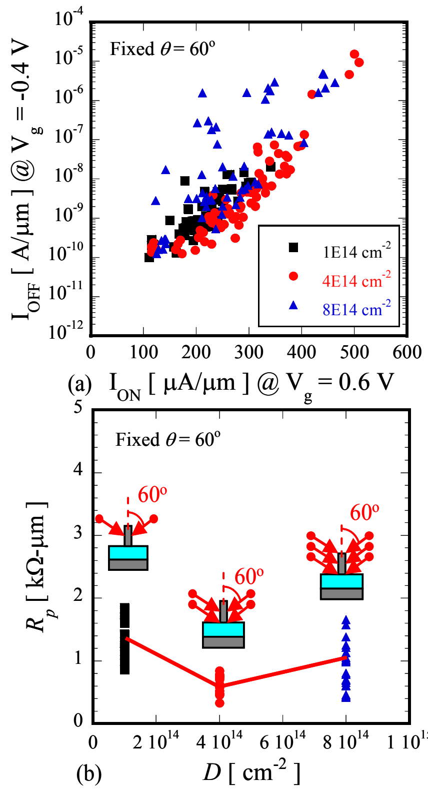

Fig. 5. (a) I_{ON}-I_{OFF} plot at V_d = 1 V and (b) normalized R_P as a function of I/I dose.

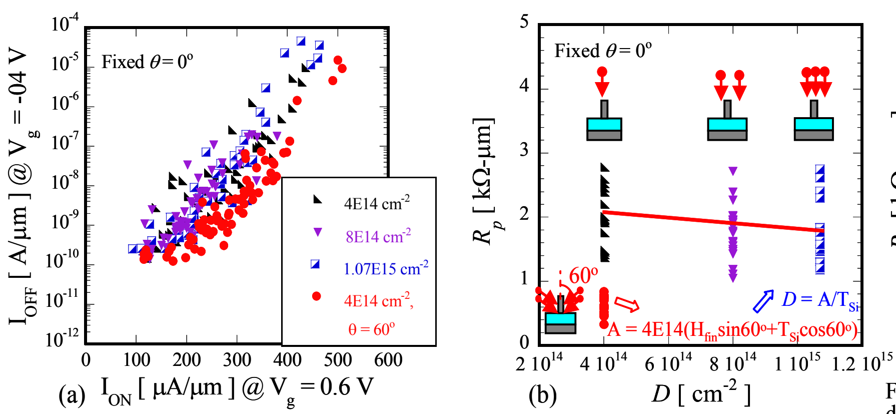

Fig. 6. (a) I_{ON}-I_{OFF} plot at V_d = 1 V and (b) normalized R_P as a function of I/I dose at a fixed θ = 0°. Data for D = 4E14 cm^{-2} & θ = 60° are also plotted for comparison.

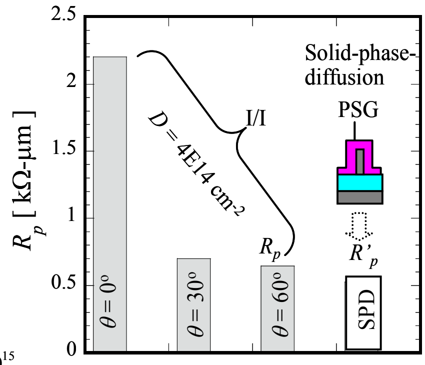

Fig. 7. Summary of average R_p values at a fixed dose of D = 4E14 cm^{-2} with the θ as a parameter. The R'_p by solid-phase-diffusion (SPD) from PSG is also plotted for comparison.