Phase and Composition Control of Ni-FUSI gates by N$_2$ I/I with Double Ni-silicidation

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INTRODUCTION

It has been an urgent challenge to introduce high-k gate dielectrics and metal gates into practical applications. In particular, Ni-filially silicided (Ni-FUSI) gate is attractive replacement for poly-Si due to fundamental limitations of poly-Si/metal oxide stack like Fermi-level pinning effect and consistency to conventional poly-Si process flow [1]. In the FUSI process, phase and composition of Ni-silicide are key factors to control appropriate effective work function, where suitable phases for n- and p-MOS correspond to Si-rich (NiSi$_2$, and NiSi) and Ni-rich silicide (Ni$_5$Si$_3$, Ni$_{12}$Si$_7$ and Ni$_3$Si), respectively [2]. Poly-Si etch back process combined with 2 step annealing is well known CMOS integration scheme [3]. Thinner poly-Si thickness for pMOS (higher thickness ratio of Ni to Si) than that for nMOS makes it Ni-rich silicide with larger work function. However, this technique has considerably difficult controllability for Ni-silicide phases on the CMOS process, because the optimal condition for n-MOS is slightly overlapped with that for p-MOS. To overcome this difficulty, limited and enhanced silicidation techniques are required for n- and p-MOS, respectively, to widen their process window. In this paper, we investigate nitrogen (N$_2$ i/i) implantation into poly-Si prior to Ni-silicidation for nMOS and an additional Ni deposition and annealing (double Ni-silicidation process) for pMOS.

EXPERIMENT

FUSI gate devices were fabricated using a CMP based process [4]. After exposure of poly-Si top by the CMP and etched back processes, the N$_2$ ion implantation to poly-Si for nMOS area was performed (fig. 1). Then, Ni layer was deposited, and followed by the 1$^{st}$ annealing for Ni-silicidation. Continuously, an additional Ni deposition for pMOS area was done with a SiN protection for nMOS area, followed by the 2$^{nd}$ annealing. By this additional Ni deposition and annealing for pMOS, Ni-rich silicide was obtained independently of n-MOS FUSI condition.

RESULTS AND DISCUSSION

Figs. 2 and 3 indicate the amount of reacted Ni thickness measured by XRF on the annealing time and the diffusion coefficient of Ni atoms deduced from their temperature dependence, respectively (100nm-Ni/100nm poly-Si stack). Compared to without N$_2$ i/i, it is found that the reaction of Ni to Si is retarded having larger activation energy and the temperature range for silicidation reaction is shifted to ~20$^\circ$C higher. A cross sectional SEM (XSEM) view of Ni/poly-Si stack after 1$^{st}$ annealing step shows that much amount of un-reacted Si and Ni are remained (fig. 4). It is considered as impacts of N$_2$ i/i into poly-Si that it makes amorphous-Si from poly-Si layer and also Si-N bonds in it. The crystallinity of poly-Si is less impact for the Ni-silicidation because the reacted Ni thickness to poly-Si is almost the same compared to that to amorphous-Si fabricated by low temperature CVD as a reference (data not shown). Although the amorphous phase is less impact to the amount of reacted Ni, XSEM images after 2$^{nd}$ annealing (fig. 5) show that the modulation of grain size is occurred inside the NiSi layer. This seems to come from uniform diffusion of Ni atoms into N$_2$ implanted poly-Si layer. So, we consider that nitrogen atoms bound to Si is main retardative factor on Ni reaction as illustrated in fig. 6. Fig. 7 shows the reacted Ni thickness dependence under various N$_2$ i/i conditions. The reaction is found to be suppressed by higher nitrogen dose and lower implantation energy. Higher i/i energy makes a nitrogen peak deeply inside poly-Si, where poly-Si layer on them is easily reacted with Ni atoms during annealing. Thus, N$_2$ i/i technique enables the FUSI process to be more controllable.

In contrast for pMOS, enhanced silicidation techniques are required for Ni-rich silicidation formation. Here, the double Ni-silicidation process was performed for pMOS area, where Ni deposition and annealing were done on the NiSi layer previously formed by the 1$^{st}$ Ni-silicidation. Fig. 8 shows the reacted Ni thickness dependence on additional Ni layer, where the starting surface was NiSi fabricated from 30nm-Ni/50nm poly-Si stack. Until 30nm as additional Ni thickness, the Ni is further uptaken even on the NiSi but saturated at above ~40nm (total Ni thickness=70nm). Fig. 9 shows that XRD charts of Ni-silicide layer fabricated by (a) conventional FUSI process, i.e., single Ni deposition and annealing, and (b)double Ni-silicidation process to NiSi. Ni-rich silicide phase like Ni$_{31}$Si$_{12}$ is successfully fabricated by this technique. We also investigate electrical properties from the viewpoint of effective work functions (e.W.F.) for Ni-FUSI gate capacitors (fig. 10). According to an increase of Ni composition in Ni-silicide, e.W.F. becomes large, deduced from high-frequency CV curves. Here, double Ni-silicidation process leads to increase the e.W.F. value with an increased Ni composition as shown in inset of fig. 10, which is consistent with physical characterization results. During the double Ni-silicidation for pMOS, a thin Si$_3$N$_4$ capping layer on nMOS protects the reaction of Ni atoms more. This technique will lead to be more widen FUSI process window due to independent process parameters for CMOS FUSI gates.

CONCLUSIONS

We confirmed that N$_2$ i/i into poly-Si retards the reaction of Ni to Si due to Si-N bonds in it. And the grain size of NiSi is found to be modulated, which is effective for uniform FUSI gate formation. Also we performed the double Ni-silicidation process to widen the process window for PMOS. Ni addition to NiSi was successfully done and Ni-rich silicidation formation was confirmed physically and electrically. Combined these techniques will enable to serve the optimized process integration scheme for CMOS devices.
Fig. 1. Process flow of FUSI in this exp. Lower i/i energy and lower dose have impacts to suppress the reaction.

Fig. 2. Reacted Ni thickness dependence on time\(^{1/2}\). 100nm Ni is fully consumed when without N\(_2\) i/i.

Fig. 3. Comparison of activation energy with and without N\(_2\) i/i. N\(_2\) i/i is effective to limit the Ni/Si reaction.

Fig. 4. Cross sectional SEM image of NiSi/poly-Si layer after 1st annealing for with and w/o N\(_2\) i/i.

Fig. 5. Cross sectional SEM images of NiSi after 2nd annealing. N\(_2\) i/i has an impact to grain feature.

Fig. 6. Schematic image of impact of nitrogen in poly-Si layer. Nitrogen retards the reaction of Ni-Si.

Fig. 7. N\(_2\) i/i condition dependence for Ni-silicidation. Higher N\(_2\) dose and lower i/i energy have impacts to suppress the reaction.

Fig. 8. Reacted Ni dependence for additional Ni deposition, where saturated above 40nm Ni.

Fig. 9. XRD charts of conventional FUSI (NiSi) and with double Ni-silicidation process.

Fig. 10. hf-CV curves and effective work function dependence on Ni composition. Si-rich silicides (NiSi\(_2\)) are changed to Ni-rich silicide by double Ni-silicidation process.

REFERENCES