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Improvements in Both Thermal Stability of Ni-Silicide and Electrical Reliability of Gate Oxides Using a Stacked Polysilicon Gate Structure

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A process design is presented for improving the thermal stability of Ni-silicide (nickel-silicide) using a stacked polysilicon gate structure. The Ni-silicide formed has low sheet resistance up to 800°C on a silicidation process. Additionally, the metal-oxide-semiconductor (MOS) capacitors fabricated using these proposed gate structures demonstrate higher electrical reliability for gate oxides than those of nonstacked films. That is, the gate oxides of the MOS capacitors were only slightly degraded after silicidation step at 800°C. In conclusion, the Ni-silicide formed on those stacked polysilicon gates are attractive in fabricating ultralarge scale integration (ULSI) circuits because both the thermal stability of Ni-silicide and the reliability of gate oxides are improved simultaneously.
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Silicides coupled with heavily doped silicon films are widely used as low resistance gate electrodes and local interconnects. Among them, nickel-silicide (NiSi) can be formed at lower temperature with small extent of silicon consumption as compared with both $TiSi_2$ and $CoSi_2$.[1] Additionally, NiSi can maintain a thin and narrow silicide layer with low sheet resistance. However, the intrinsic properties of NiSi film can be readily degraded during post-thermal processes.[2-4] Thus, it is important to study the impact of post-thermal processes on NiSi's thermal stability to preserve its performance in terms of low resistance.

The morphological degradation of Ni-silicide depends strongly on both the grain size and the relative thickness (silicide layer *vs.* polysilicon layer) of the underlying layer silicon.[5-7] The thermal stability of silicide increases relatively, if the size of the silicon grain increases, the thickness of silicide increases, and the layer of silicon film grows thinner. Therefore, it is desirable to make Ni-silicide film reasonably thick to improve thermal stability and to possess the lowest series resistance. Meanwhile, thickness of silicon film should also be deposited reasonably thin to increase the thermal stability and to simplify the complexity of integrating the entire process. However, the thickness of those films should be carefully designed to prevent silicide protrusions from extending over the silicon film or penetrating into the gate oxide during subsequent thermal processes. To ensure the thermal stability of Ni-silicide and gate oxide reliability, it is important to design appropriate thickness of silicon and silicide in improving the thermal stability and suppressing Ni penetration.

To improve the thermal stability of Ni-silicide, the underlying layer silicon deposited using disilane gas was used here. Disilane has been favorably used in fabricating high-quality low-temperature thin-film transistors. The results in this experiment indicate that the Ni-silicide formed on this silicon film has higher thermal stability, but there is a lack of effect on suppressing Ni penetration. From the standpoint of suppressing Ni penetration, a film stack containing two silicon structures was constructed for the first time to attain both NiSi thermal stability and gate oxide reliability (suppressing Ni penetration) simultaneously. This film structure did improve both thermal stability and gate oxide reliability.

Experimental

n-Type (100) wafers were first grown with a 500 nm field oxide and patterned to isolate the devices. Then, all samples were Radio Corporation of America (RCA) cleaned and grown with a 10 nm thermal oxide at 950°C in an O_2 ambient after the photoresist was stripped. Afterward, the wafers were deposited in a stacked silicon film 200 nm thick. There are two kinds of film stacks prepared in this experiment: (*i*) DS sample, a 100 nm silicon film deposited using disilane gas at 460°C in low pressure chemical vapor deposition (LPCVD) ambient followed by a 100 nm silicon film deposited using silane gas at 620°C without exposing samples to atmosphere, and (*ii*) DA sample, a 100 nm silicon film deposited using disilane gas at 460°C in LPCVD ambient followed by a 100 nm silicon film deposited using silane gas at 550°C without exposing samples to atmosphere. In comparison, the 200 nm thick silicon films deposited using silane at 620°C (S) and 550°C (A) along with film deposited using disilane at 460°C (D) were also prepared. Furthermore, to study how the silicon film thickness affects the thermal stability of the Ni-silicide, silicon films, 100, 200, and 300 nm thick, respectively, were also prepared using silane at 620°C.

After silicon gate was deposited, the samples were then BF_2 implanted with a dose of $5 \times 10^{15}/cm^2$ at energy of 40 keV. These samples were then rapid thermal annealing (RTA) annealed at 950°C in an N_2 ambient for 30 s. Basically, all the films had been transformed into polycrystalline silicon with similar grain sizes by observing images from transmission electron microscope (TEM). The samples were then RCA cleaned and a 30 nm Ni film was deposited using an electron-beam evaporator. Following the deposition of Ni, the samples were RTA annealed from 350 to 850°C in an N_2 ambient for 30 s. The selective chemical etcher ($H_2SO_4{:}H_2O_2 = 3{:}1$) was used to etch the remaining Ni without attacking Ni-silicide. Four-point probe was then used to measure the sheet resistance of the Ni-silicide thin film.

A 500 nm Al film was deposited on the Ni-silicide films. Aluminum (Al), NiSi, and polysilicon films were then patterned to form the top electrodes (gate) of the metal-oxide-semiconductor (MOS) capacitors. After native oxide at the back side was removed, a 500 nm Al film was deposited on the back side of the samples. Finally, all samples were sintered at 400°C in an N_2 ambient.

Results and Discussion

Figure 1 shows the average and error bars extracted from 20 points of measured sheet resistance of the Ni-silicide films, which were formed by depositing 30 nm Ni on six silicon substrates with various RTA temperatures. These six silicon substrates are described as follows: (*i*) S, 200 nm silicon film deposited using silane gas at 620°C, (*ii*) D, 200 nm silicon film deposited using disilane gas at 460°C, (*iii*) A, 200 nm silicon film deposited by silane gas at 550°C, (*iv*) c-Si, (100) p-type crystalline silicon bulk, (*v*) DS, 100 nm D silicon film (underlayer) followed by depositing 100 nm S silicon film (upper layer), and (*vi*) DA, 100 nm D silicon film (underlayer) followed by depositing 100 nm A silicon film (upper layer). The S and A samples have lower thermal stability than that of the D sample or the stacked samples.

The differences of thermal stability among S, A, and D samples can be explained by the X-ray diffraction pattern (XRD) profiles of the S, A, and D samples, all samples were BF_2 implanted and RTA annealed at 950°C for 30 s, as shown in Fig. 2. The profiles show

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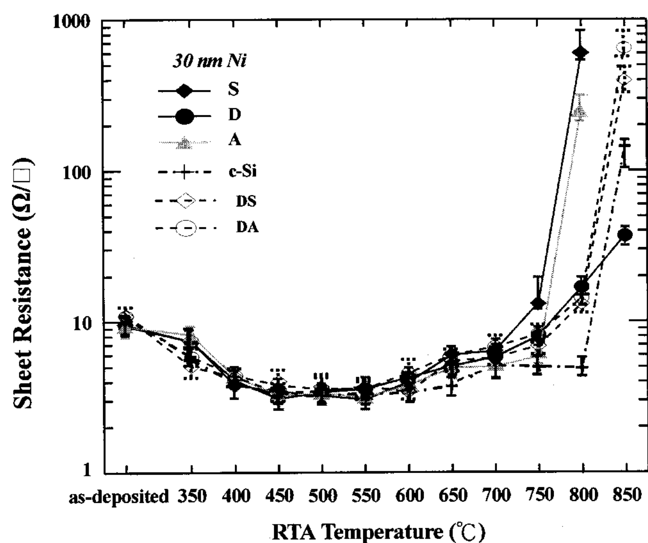

Figure 1. The sheet resistance of Ni-silicide formed with various RTA silicidation temperatures. The Ni-silicides were prepared by depositing 30 nm nickel on five polysilicon films and single-crystalline silicon. Then, they were rapid thermal annealed with various temperatures in an N_2 ambient for 30 s.

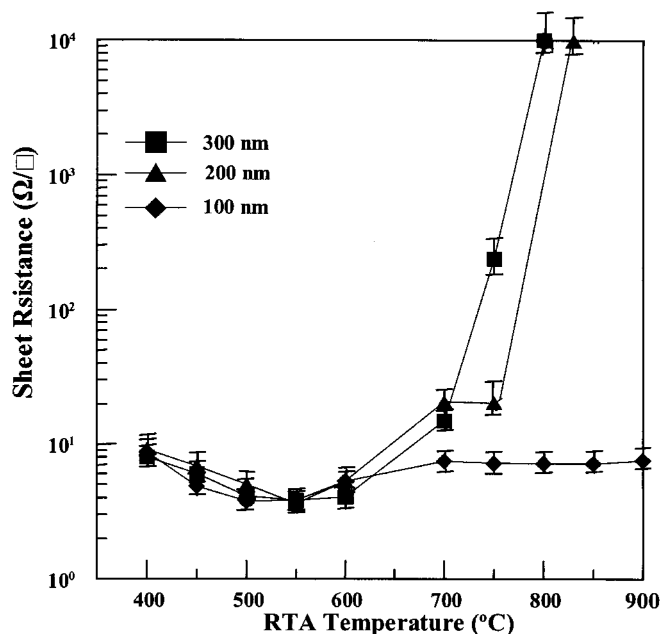

Figure 3. The sheet resistance of Ni-silicide formed on 100, 200, and 300 nm thick polysilicon with various silicidation temperatures.

that the disilane polysilicon film has only one peak at ⟨111⟩ whereas the silane polysilicon and amorphous silicon have two peaks: ⟨111⟩ and ⟨220⟩ orientations. This indicates that polysilicon film containing mono-oriented grains could suppress the agglomeration of Ni-silicide film.

The difference of poly-Si grain size that affects the thermal stability of Ni-silicide was reported in Ref. 11. It was believed that polysilicon film with larger grain size could result in a better thermal stability. However, the difference of thermal stability among those samples was not caused by the difference of poly-Si grain size because the grain sizes observed among these films are about 100 nm. The properties of the polysilicon films strongly depended on the orientations of grains.[9,10] In our experiment, the D sample has a much lower sheet resistance and smoother surface roughness, which was measured by atomic force microscope (AFM), therefore, it is reasonable to believe that the orientation difference could also affect the thermal stability of the formed Ni-silicide. The smoother surface of the D poly-Si film could be caused from the surface energy of the mono-oriented grains. It is known that the migration of Si atoms at the surface was strongly dependent on the surface energy, which was determined by the orientations of the Si grains.[12] That is, during depositing or thermal treatment, the Si atoms will migrate from high surface energy sites to low energy sites. Hence, roughness is enhanced in the many-oriented grains of poly-Si. The surface energy of the silicon grains and the Ni-silicide grains could also affect the

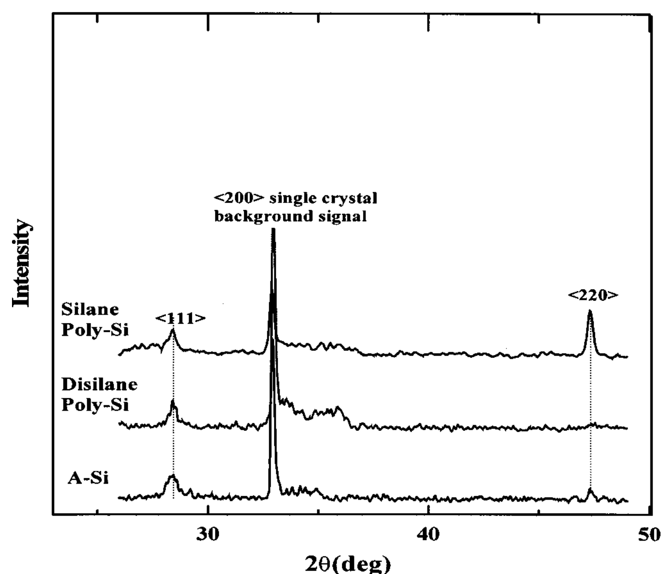

Figure 2. XRD profiles of the S, D, and A for three different types of polysilicon films.

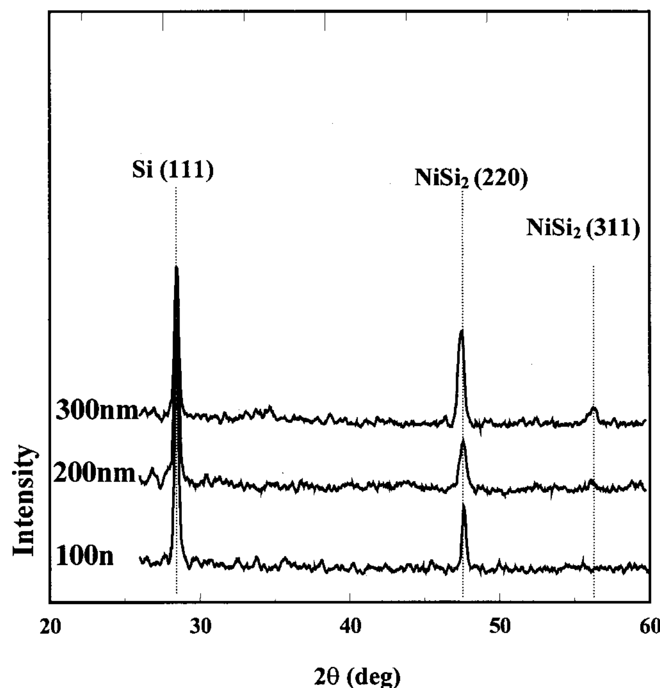

Figure 4. XRD profiles of the Ni-silicide formed at 800°C on 100, 200, and 300 nm thick polysilicon films.

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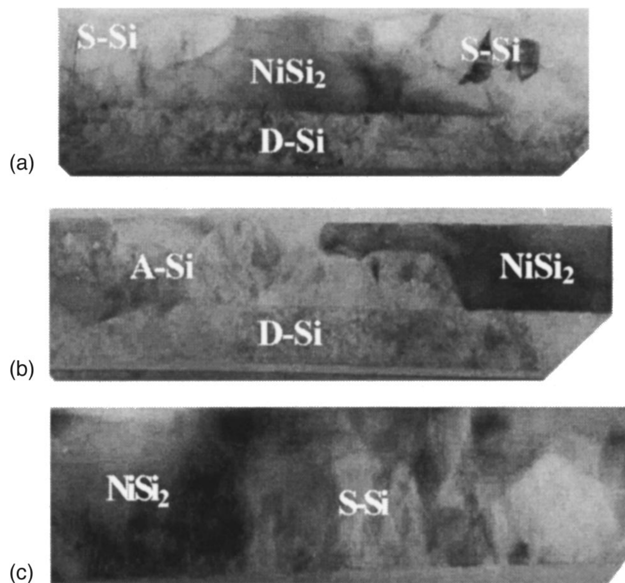

Figure 5. TEM images of the Ni-silicide formed at 800°C on (a) DS silicon film, and (b) DA silicon film, and (c) S silicon film.

agglomeration of the Ni-silicide; therefore, the surface energy of the mono-oriented grains could suppress the agglomeration of the Ni-silicide.

Moreover, the structure containing the film stack has superior thermal stability than that of the S or A samples, which could be further explained using the results demonstrated in Fig. 3-5.

The figures also show that the thermal stability of D is higher than that of c-Si above 850°C, although that of D is lower than that of c-Si under 800°C. This could be explained by the XRD data and the results presented in Fig. 3. For the D sample is mono-oriented poly-Si grains and the c-Si is single-crystalline silicon, the agglomerating temperature could be higher for the c-Si sample. However, after agglomeration the D sample has better thermal stability because the thinner poly-Si films have better thermal stability as shown in Fig. 3.

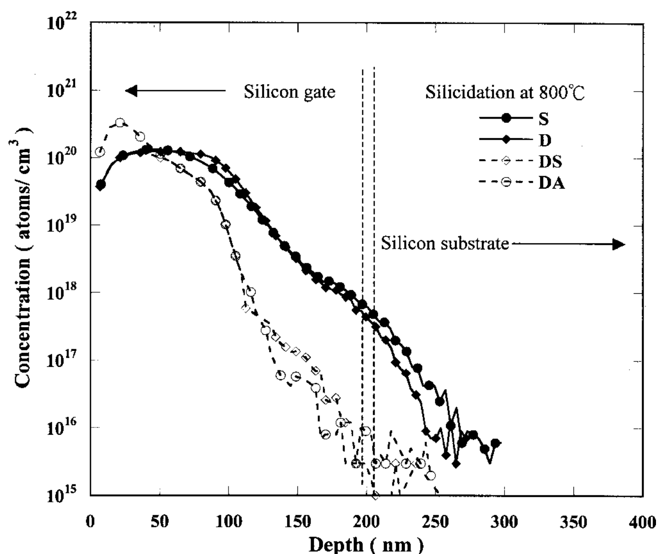

Figure 6. SIMS profiles of the Ni-silicide formed at 800°C on S, D, DS, and DA films.

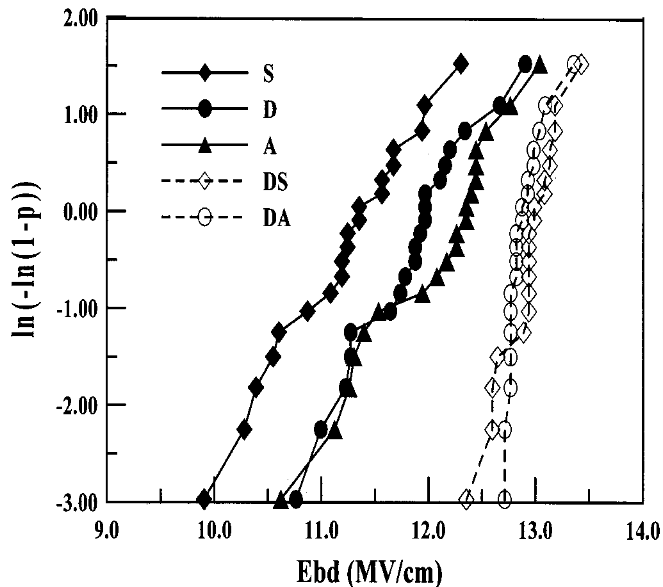

Figure 7. Weibull plot of E_{bd} of the MOS capacitors with Ni-silicide gates formed at 800°C on S, D, A, DS, and DA silicon films.

Figure 3 shows the average and error bars extracted from 20 points of measured sheet resistance of the Ni-silicide formed on polysilicon film with various thicknesses. It can be seen that the thinner the polysilicon film, the higher is the thermal stability of Ni-silicide. The underlying layer of silicon film with less thickness could suppress Ni-silicide agglomeration. This interpretation is supported by the XRD profiles in terms that indicate the 300 nm film stack has strong $NiSi_2$ ⟨311⟩ phase and this orientation is not found in the 100 nm sample as shown in Fig. 4 after 800°C 30 s RTA treatment. However, the $NiSi_2$ ⟨311⟩ phase is also shown in the 200 nm sample, but it is much weaker than the 300 nm one. These $NiSi_2$ grains with different orientation should be the main reason that makes Ni-silicide discontinuous and sheet resistance greater.

Figure 5 shows the TEM images of (a) DS, (b) DA, and (c) S samples. These samples are silicided by RTA at 800°C for 30 s.

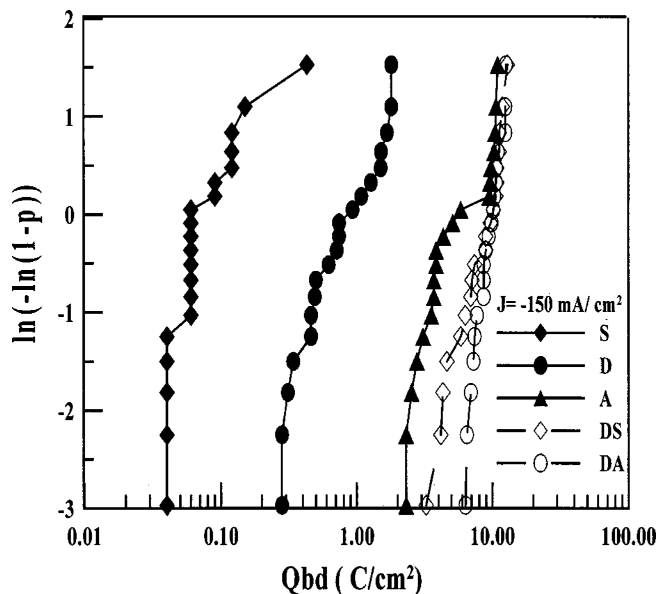

Figure 8. Weibull plot of Q_{bd} of the MOS capacitors with Ni-silicide gates formed at 800°C on S, D, A, DS, and DA silicon films.

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Ni-silicide extends mainly within the upper layer of silicon film for double-layer structures. Ni-silicide extends through the entire film for S sample. These results explain why samples with film stack structure have better thermal stability than S and A samples do. That is, Ni-silicide agglomeration of the stacked samples mainly occurred in the upper silicon film. According to the result shown in Fig. 3, the stacked films would have better thermal stability.

Figure 6 shows the SIMS profiles of the Ni-silicide formed on S, D, DS, and DA samples. All samples are silicided by RTA at 800°C for 30 s. We can find that the stacked samples have a much sharper profile than either the S or D sample. This indicates that the structures of the film stack could suppress Ni penetration with the assistance of polysilicon films; therefore, these structures improve the reliability of the gate oxide. The mechanism of suppression could be attributed to the fact that Ni molecules are trapped as they migrate through the interface of the film stack. This phenomenon is similar to the occurrence reported by Wu *et al.* describing the boron penetration suppressed by stacked gate structure.[8] These profiles also support that the Ni-silicide was formed only in the upper layer of the stacked film.

Figures 7 and 8 show the Weibull plots of breakdown electric field E_{bd} and charge to breakdown Q_{bd} distributions for S, D, A, DS, and DA Ni-silicide gate MOS capacitors with the gate oxide thickness being 10 nm and the silicidation temperature processed at 800°C. These plots obtained here indicate that the stacked samples have higher E_{bd} and Q_{bd} distributions than those of nonstacked samples. This may arise from the results presented in the Fig. 6 that the stacked gate structures suppress Ni penetration into oxides.

Conclusions

The Ni-silicide formed on stacked polysilicon gates is attractive in fabricating gates of MOS capacitors. Devices using gate structures proposed here can acquire better thermal stability and higher electrical reliability; that is, the samples could maintain low resistance, high E_{bd} and high Q_{bd} distributions with 800°C RTA silicidation. In this paper, we also demonstrated the mechanism relating to these improvements.

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