

The Process Window of a-Si/Ti Bilayer Metallization for an Oxidation-Resistant and Self-Aligned TiSi₂ Process

Yung-Song Lou, *Student Member, IEEE*, Ching-Yuan Wu, *Member, IEEE*,
and Huang-Chung Cheng, *Member, IEEE*

Abstract—The dependences of both oxidation-resistant and self-aligned silicidation properties on the thicknesses of top amorphous-Si (a-Si) and Ti metal in an a-Si/Ti bilayer process are presented. It is shown that a thin silicide layer formed during the reaction between a-Si and Ti films becomes a stable oxidation and nitridation barrier for oxygen- and nitrogen-related impurities. Moreover, the formation sequence of the silicide phase depends on not only the annealing temperature but also the thickness of Ti film. In addition, the preferential orientation of the silicide phase after annealing at high temperature also shows a strong dependence of the thickness of Ti film, which is attributed to the difference of the grain size in the polycrystalline silicide film. The allowed process window for the a-Si thickness can be determined experimentally and a reproducible and homogeneous self-aligned TiSi₂ film can be easily obtained by using the a-Si/Ti bilayer process in SALICIDE applications despite of high-level contaminations of oxygen impurities in both the as-deposited Ti film and the annealing ambient.

I. INTRODUCTION

AS MOS devices are scaled down to submicrometer dimension, the self-aligned silicidation (SALICIDE) technology becomes one of the best approach to solving the serious problems resulting from the increase of the parasitic series resistances including the contact resistance and the diffusion sheet resistance [1]–[6]. TiSi₂ is the most attractive material for this technology because of its comparatively low resistivity ($\approx 20 \mu\Omega \cdot \text{cm}$) and refractory nature. However, due to its high chemical reactivity with ambient impurities (e.g., N₂, O₂, and H₂O) during either vacuum deposition or thermal annealing, the quality of the formed silicide depends immensely on process control. Recently, a novel TiSi₂ process using a-Si/Ti bilayer metallization [3], which exhibits both oxidation-resistant and self-aligned silicidation features, has been demonstrated to be highly effective in solving the oxidation and nitridation problems for Ti silicidation in

an oxygen-contaminated N₂ environment. This method is shown to be attractive for preparing a reproducible and homogeneous TiSi₂ film while eluding any special equipment or any complicated process. Another interesting aspect concerning the application of the bilayer metallization in the SALICIDE process is that the selective formation property can be retained despite the additional thin a-Si layer over the Ti film. Since the use of the top a-Si layer as a protective layer may provide a new approach for silicide formation, it becomes very important to study the limitation of the a-Si film thickness associated with the oxidation-resistant and self-aligned silicidation properties and the effects of a-Si thickness variation on the kinetics of TiSi₂ formation during thermal annealing.

In this paper, the effects of different a-Si thicknesses on silicide formation and selective etching properties in an a-Si/Ti bilayer process are studied in detail. According to the measured sheet resistances, SEM topography, and AES depth profiles of the annealed a-Si/Ti on Si and SiO₂, the allowed process window for the a-Si film thickness is obtained experimentally. Within the proposed process window, a complete conversion of Ti into TiSi₂ can be achieved even for both the as-deposited Ti film and the annealing ambient contaminated with oxygen impurities. Moreover, X-ray diffraction analysis reveals that both the silicide formation sequence and the orientation of the silicide phase are dependent on the thickness of the as-deposited Ti film. Finally, a simple empirical rule for determining the thickness ratio of the a-Si film to the Ti film is obtained for the a-Si/Ti bilayer process in SALICIDE applications.

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

The (100), 5–15- $\Omega \cdot \text{cm}$, n-type Si wafers were used in this experiment. After a standard cleaning process, the Si substrates were etched in a diluted HF solution immediately prior to loading into the vacuum system. The thin titanium film was deposited by an electron gun with a base pressure of about 5×10^{-6} torr, subsequently the a-Si film was evaporated without breaking the vacuum. The samples were annealed in N₂ ambient for 40–50 min at different temperatures between 400 and 900°C. It should be noted that no special equipment was used to minimize

Manuscript received October 2, 1990; revised August 6, 1991. This work was supported by the National Science Council, Republic of China, under Contract NSC-79-0414-E009-01. The review of this paper was arranged by Associate Editor S. J. Fonash.

The authors are with the Advanced Semiconductor Device Research Laboratory and the Institute of Electronics, National Chiao-Tung University, Hsin-Chu, Taiwan, ROC.

IEEE Log Number 9200226.

the oxygen content in the flowing N_2 ambient before introducing it to the furnace.

A. Oxidation-Resistant Silicidation Properties

The measured sheet resistances as a function of the annealing temperature for various a-Si thicknesses on 500-Å Ti film are shown in Fig. 1. The variations of the sheet resistance with the annealing temperature apparently show the same features for different a-Si/Ti bilayer systems, e.g., a high sheet resistivity value for the as-deposited sample, a sharp decrease of the sheet resistivity for the increased annealing temperature, and a minimum sheet resistivity of less than $2 \Omega/\square$ for samples annealed above 750°C . These phenomena reflect that an additional a-Si layer on Ti film does not affect the basic reaction kinetics between Ti and the Si substrate during heat treatment, despite the slight difference in sheet resistance for the cases with annealing temperature below 700°C . For the samples with a-Si thickness of less than 30 \AA or greater than 100 \AA , the measured sheet resistances are shown to be higher than those with the a-Si thickness between 50 and 100 \AA . This can be correlated with the effects of the reaction between Ti and a-Si and the redistribution of oxygen impurities during silicide formation. The AES depth profile for the as-deposited a-Si/Ti bilayer is shown in Fig. 2, in which a strong oxygen peak at the Ti/Si-substrate interface, marked with O_i in the figure, suggests the presence of native oxide and the adsorption of oxygen impurities during film deposition. The adsorption of oxygen impurities can be confirmed by the poor vacuum of about 5×10^{-6} torr during deposition or the observation of a rapid change in vacuum pressure at the beginning of Ti evaporation. The high oxygen content is responsible for the high sheet resistance value observed from the as-deposited samples.

Figs. 3 and 4 show the AES depth profiles for a-Si/Ti bilayer on Si with different a-Si thicknesses on 500-Å Ti layer after annealing at 650°C and 750°C , respectively. Since the a-Si thickness of 30 \AA is insufficient to prevent further contamination of oxygen impurities from the annealing ambient, the incomplete expulsion of oxygen impurities initially contaminated in Ti during silicide formation may occur. The encroached oxygen impurities together with the residual oxygen impurities in silicide, as marked with O_{II} in Fig. 3(a), will accumulate at the TiSi_2/Si -substrate interface. Since Si atoms are the predominant moving species during TiSi_2 formation [7], the O_{II} layer will act as a diffusion barrier for Si flux from the Si substrate and can thus impede the further growth of TiSi_2 . It should be noted that the formed diffusion barrier is so stable that even after annealing at a high temperature of 750°C , the oxygen peak O_{II} can be still observed, as shown in Fig. 4(a). So, the higher sheet resistance shown in Fig. 1 for a-Si/Ti bilayer with the a-Si thickness of less than 50 \AA is attributed to the ineffective transformation of Ti into TiSi_2 caused by the presence of interface impurities.

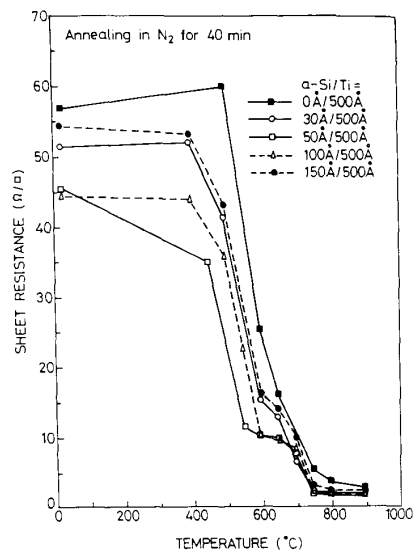


Fig. 1. Measured sheet resistances as a function of annealing temperature after annealing in an oxygen-contaminated N_2 ambient for 40 min.

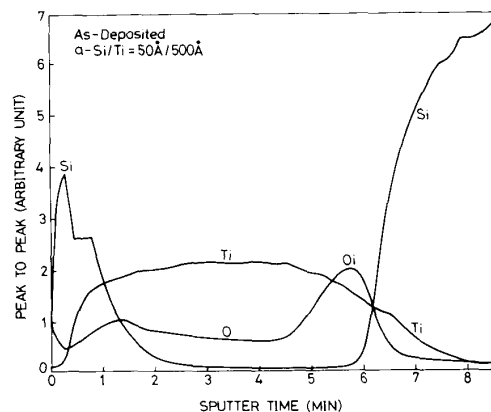
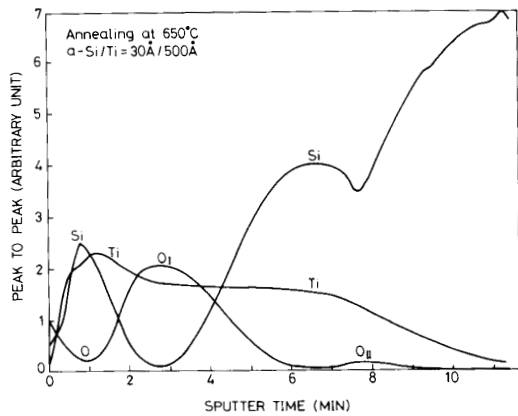
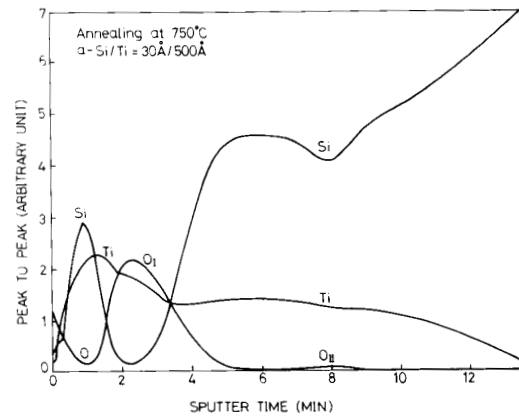


Fig. 2. The AES depth profiles for the as-deposited 50-Å a-Si/500-Å Ti bilayer structure on bare Si.

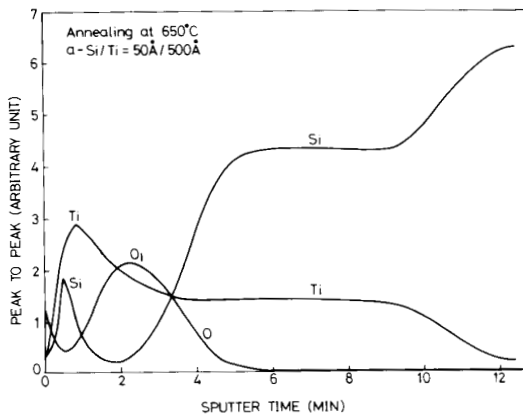
The AES depth profile for the 50-Å a-Si/500 Å Ti bilayer case after annealing at 650°C is shown in Fig. 3(b), in which a prominent oxygen peak O_i is located in front of the silicide layer and the interface oxygen O_i peak shown in Fig. 2 disappears. This behavior is the well-known "oxygen snow-plow effect" during silicidation. If the accumulated oxygen content O_i reaches a critical level, the suppression of further growth of the TiSi_2 phase by blocking the outward diffusion of Si atoms from the Si substrate will occur. Therefore, for the case of a-Si/Ti bilayer with a-Si thickness between 50 and 100 \AA , the measured sheet resistances shown in Fig. 1 are almost kept unchanged for annealing temperature between 600 and 650°C . With a moderate a-Si thickness, a higher annealing temperature ($\geq 700^\circ\text{C}$) can be used to expel the oxygen impurities out of silicide and thus to completely resolve a-Si into Ti to form the TiSi_2 phase, as shown in



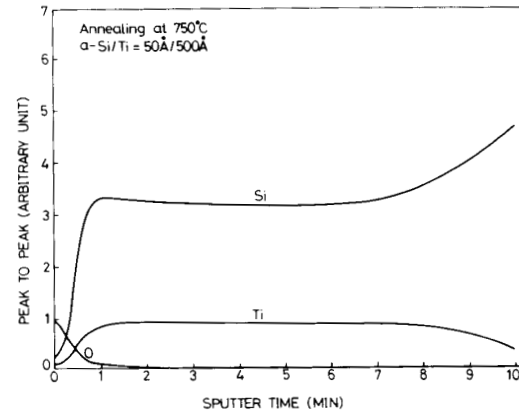
(a)



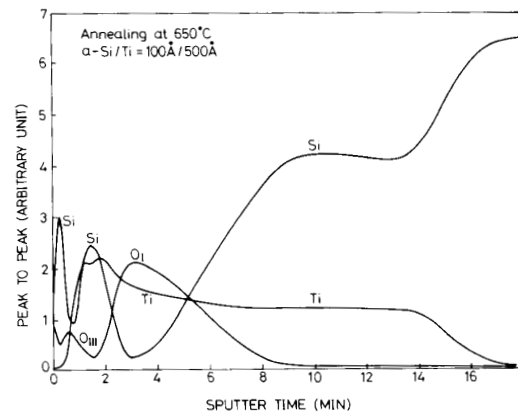
(a)



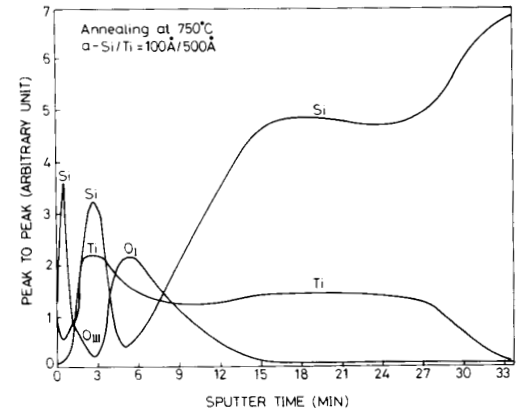
(b)



(b)



(c)



(c)

Fig. 3. AES depth profiles for the a-Si/Ti bilayer structure on bare Si with (a) 30-Å, (b) 50-Å, and (c) 100-Å a-Si film on 500-Å Ti metal after annealing at 650°C.

Fig. 4. AES depth profiles for the a-Si/Ti bilayer structure on bare Si with (a) 30-Å, (b) 50-Å, (c) 100-Å a-Si film on 500-Å Ti metal after annealing at 750°C.

Fig. 4(b). This result indicates that the thin a-Si layer can effectively prevent the Ti film from the contamination by O₂/H₂O impurities in the annealing ambient, and this fact also gives an explanation for the lowest sheet resistance obtained for the cases annealed at 750°C.

For the case of 150-Å a-Si bilayer annealed at 650°C, it is interesting to note that a new oxygen peak, marked as O_{III} in Fig. 3(c), occurs just under the unconsumed a-Si in addition to the oxygen peak O_I. This new oxygen peak is believed to be produced by the snow-plow effect through

the reaction between a-Si and Ti. The formation of a thin silicide layer between O_I and O_{III} , probably $TiSi$, will play an important role in the silicidation process with higher annealing temperatures. As mentioned previously, the pile-up of oxygen impurities can prevent the outdiffusion of Si atoms, and the formation of $TiSi_2$ is retarded. From this point of view, it is clearly seen from Fig. 3(c) that the transport of Si atoms from the top a-Si layer to the sandwiched thin silicide layer is easier than that from the Si substrate. Moreover, the exhaustion of the top a-Si layer will reduce the total effective sheet resistance in an a-Si/ $TiSi_2$ couple, thus the formation of the sandwiched silicide layer is associated with the anomalous plateau region which appears between 600 to 650°C, as shown in Fig. 1. Since the abundant supply of Si atoms from the top a-Si film results in the growth of the intermediate silicide layer for various annealing temperatures, and the ratio of the Si peak to the Ti peak of the sandwiched silicide layer is varied from ≈ 1 for the case annealed at 650°C (Fig. 3(c)) to ≈ 1.5 for the case annealed at 750°C (Fig. 4(c)). From the Si-Ti binary phase diagram, it is reasonable to expect that an alternation of the silicide phase from $TiSi$ to $TiSi_2$ occurs. Due to the stability of the silicide layer formed on the Si substrate, the accumulated oxygen impurities O_I cannot be pushed out even after annealing at the high temperature of 750°C.

From the measured sheet resistance and AES depth profiles, the formation of thin silicide layer between a-Si and Ti may stabilize the Ti surface; the capped a-Si layer can successfully act as a protective layer. Although the real phase of this stable layer is too thin to be identified, using the intentional deposition of a thick a-Si film on Ti metal, the formation of the stoichiometric-like silicide between two oxygen peaks, e.g., either $TiSi$ at 650°C or $TiSi_2$ at 750°C, may support the possibility of such a reaction. Moreover, this observation is consistent with the previous report [8] that the Ti film reacts faster with a-Si than with the Si substrate and the formation temperature of the $TiSi_2$ phase could be as low as 525°C. The presence of interface impurities is attributed to different reaction behaviors. Therefore, the oxygen distribution of the as-deposited a-Si/Ti/Si substrate system, as shown in Fig. 2, significantly shows different amounts of accumulated oxygen impurities at the a-Si/Ti and Ti/Si substrate interfaces. These facts give us another reason to expect that the formation of a thin silicide layer between a-Si and Ti may act as an isolation barrier at a lower annealing temperature.

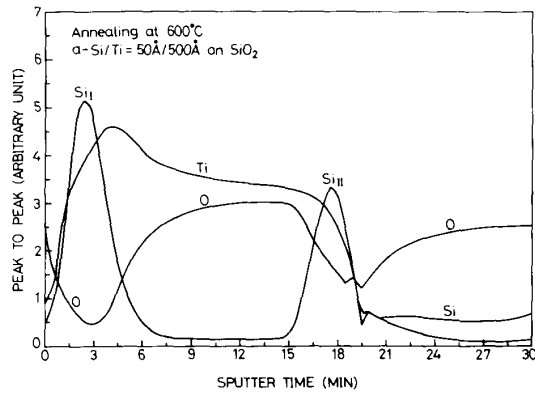
Another interesting question is whether a thicker a-Si film is preferable for the a-Si/Ti bilayer process. Due to the abundant supply of Si atoms from the a-Si film, the surface silicide layer will act as an "anti-snow-plow" barrier during thermal annealing, and thus a large amount of oxygen impurities may still remain within the silicide film after the silicidation process. The presence of oxygen impurities in either Ti film or silicide layer will impede the grain growth and thus increase the impurity scattering [7], so the buried oxygen impurities are believed to con-

tribute to the higher sheet resistance value for the a-Si/Ti bilayer with a-Si thicker than 100 Å after thermal annealing, as observed in Fig. 1.

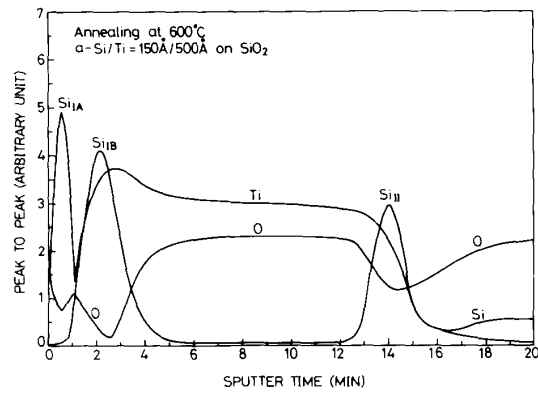
B. Self-Aligned Silicidation Properties

The selectivity of the etching behavior strongly depends on the products on SiO_2 after thermal annealing. The AES depth profiles for 50-Å a-Si/500-Å Ti bilayer on 3000-Å-thick SiO_2 after annealing at 600 and 650°C are shown in Fig. 5(a) and (b), respectively. By comparing the AES depth profile of the as-deposited sample with that of the annealed one, it is clearly seen that not only the oxygen profile is drastically redistributed within the Ti film, but also a new and sharp Si peak at the Ti/ SiO_2 interface, as marked by Si_{II} in Fig. 5, appears in addition to the top a-Si peak marked by Si_I . The reaction between Ti and a-Si or between Ti and SiO_2 is rather complicated after thermal annealing; however, the disappearance of oxygen peak O_I and the uniform distribution of oxygen impurities in Ti are presumably known to be due to the interaction between Ti and SiO_2 . Ti film could react with the SiO_2 substrate after thermal annealing with the thin Ti_5Si_3 layer formed between the SiO_2 substrate and the top TiO_x layer [9], [10], as shown in Fig. 5. Moreover, the reaction between a-Si and Ti will also result in a thin silicide layer formed on the top surface of TiO_x after annealing at 600°C. According to the Si-Ti binary phase diagram, a metal-rich silicide phase, which may be a mixture of Ti_5Si_3 and Ti_3Si , seems to appear at the top surface if the annealing temperature is raised to 650°C. It is interesting to note that the thin Ti_5Si_3 layer on the SiO_2 substrate is not a stoichiometric one. Since the oxygen content is observed within Ti_5Si_3 , a mixed phase of silicide and metal oxide or a ternary compound is more suitable to describe this product. With a moderate thickness of a-Si film on Ti, the removal of the a-Si/Ti bilayer after annealing at 650°C can be fully accomplished because the final products over SiO_2 , which include the top metal-rich silicide layer, the middle titanium oxide layer, and the bottom oxygen-embedded silicide layer, are all removable in conventional $NH_4OH/H_2O_2/H_2O$ (NHH) or H_2SO_4/H_2O_2 (HH) solutions.

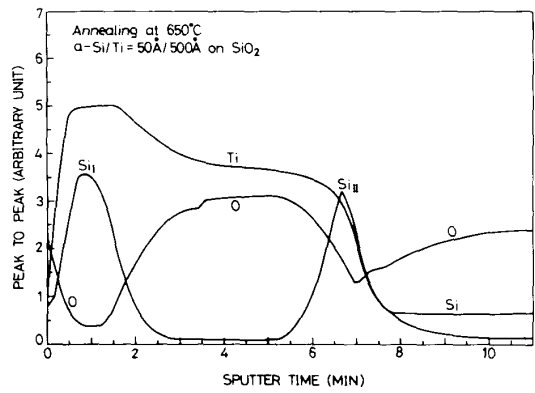
The AES depth profiles for the 150-Å a-Si/500-Å Ti bilayer on SiO_2 after annealing at 600 and 650°C are shown in Fig. 6(a) and (b), respectively. Due to the reaction between a-Si and Ti, the top a-Si peak has been split into two distinct peaks as marked by Si_{IA} and Si_{IB} in Fig. 6(a). This reaction is similar to that on bare Si, as shown in Fig. 3(c). The further growth of a top Si-rich silicide layer, probably $TiSi_2$, can be achieved by increasing the annealing temperature to 650°C, as shown in Fig. 6(b). During the formation of the Si-rich silicide layer, the supply of Si atoms from the a-Si film is certainly enough, and the supply of Ti atoms by breaking the Ti-O bond to favor a-Si-Ti bonding also seems to be easier. This may be due to the fact that the titanium oxide is not a fully stoichiometric product after annealing at 600°C.



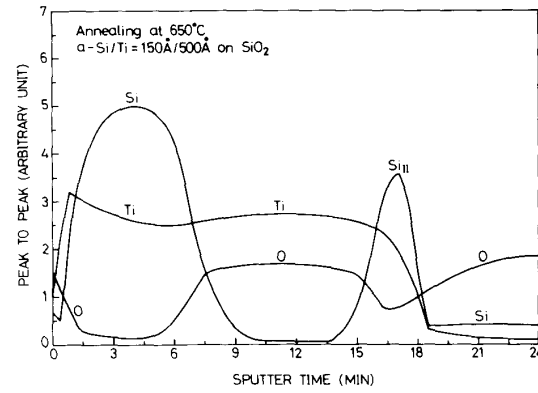
(a)



(a)



(b)



(b)

Fig. 5. AES depth profiles for the a-Si/Ti bilayer structure on SiO₂ with 50-Å a-Si film on 500-Å Ti metal after annealing at (a) 600°C and (b) 650°C.

Fig. 6. AES depth profiles for the a-Si/Ti bilayer structure on SiO₂ with 150-Å a-Si film on 500-Å Ti metal after annealing at (a) 600°C and (b) 650°C.

As compared with the result of a-Si/Ti bilayer on Si after thermal annealing, the residual a-Si peak shown in Fig. 4(c) clearly indicates that it is more difficult to release Ti atoms from the dense and stable TiSi₂ layer even after annealing at the high temperature of 750°C.

The high oxygen content and the uniform oxygen distribution within Ti metal after thermal annealing not only indicate the presence of the titanium oxide layer but also provide another "barrier" effect for Si flux. It is found that the outdiffusion of Si atoms has been impeded by oxygen impurities contained in the Ti metal. This feature is useful for SALICIDE applications because it will suppress the lateral silicide growth across the sidewall oxide and further eliminate the bridging effect, despite the fact that Si atoms are recognized to be the moving species during a thermal reaction.

Fig. 7 shows the edges between the grown TiSi₂ region and the SiO₂ region after annealing at 650°C and etching in NHH solution. Although the selective etching can be performed for the case of 30-Å-thick a-Si film on Ti metal, the serious surface roughness of the silicided region and the local etching pits on SiO₂ can be observed, as shown in Fig. 7(a). As discussed in Section II-A, the

thin a-Si layer of 30 Å cannot resist the invasion of ambient oxygen impurities, thus the incomplete silicidation on the Si region will result in a coarse surface, and the reaction between Ti and SiO₂ is locally enhanced to induce the etching cavities. With a moderate thickness of the a-Si film on Ti metal, e.g., 50 Å, a well-defined edge after etching in NHH solution can be obtained, as shown in Fig. 7(b). Therefore, this gives direct evidence to support the concept that the lateral silicide growth can be suppressed by the presence of the metal oxide layer (TiO_x) on SiO₂. Moreover, the surface morphology of the silicided region is smoother than that of the 30-Å-thick a-Si case. This result is attributed to the full transformation of the Ti film into TiSi₂ and the complete expulsion of the native oxide and oxygen contamination. As the thickness of a-Si film is increased beyond 100 Å, the product over SiO₂ is hard to be removed even after etching in NHH solution for a long time.

In summary, the minimum a-Si thickness required to prevent Ti metal from oxidation during the silicidation cycle should be greater than 30 Å, while the maximum a-Si thickness should be less than 100 Å for the as-deposited Ti metal of 500 Å in order to obtain satisfactory

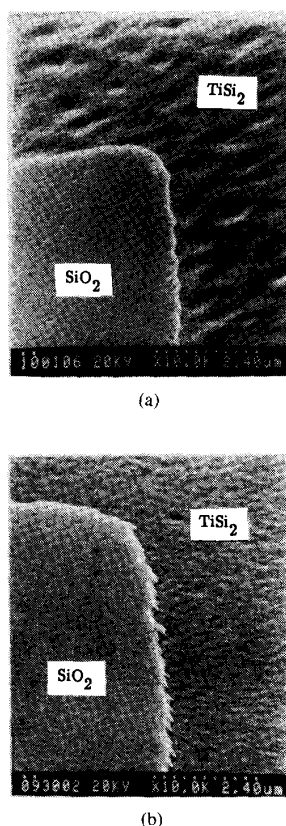


Fig. 7. SEM microphotographs ($\times 10\,000$) showing the topography of TiSi_2 film and the residues on SiO_2 for (a) 30-Å a-Si/500-Å Ti, and (b) 50-Å a-Si/500-Å Ti bilayer structures after annealing at 650°C and etching in NHH solution.

self-aligned silicidation properties for SALICIDE applications.

III. THE PROCESS WINDOW FOR a-Si THICKNESS

Fig. 8 shows variations of the X-ray diffraction spectra with annealing temperature for a 50-Å a-Si/500-Å Ti bilayer structure, in which the corresponding (h, k, l) values are used to identify each peak. Clearly, the observed phase formation sequence agrees with the measured temperature behavior of the sheet resistance, as shown in Fig. 1, and gives a more detailed understanding on the AES depth profiles, as shown in Figs. 3 and 4. The (h, k, l) values of the TiSi_2 phase indicate that the crystallographic structure is orthorhombic with $a = 8.267$ Å, $b = 4.799$ Å, and $c = 8.550$ Å. On the other hand, the behavior of the X-ray intensities for TiSi and TiSi_2 as a function of the annealing temperature also shows a similar tendency as reported in the previous study [7], e.g., TiSi and TiSi_2 are first detected after annealing at 600°C, and only TiSi_2 exists after annealing at 800°C. These results imply that the final crystallographic structure and the phase growth with respect to the annealing temperature can be basically retained in an a-Si/Ti bilayer process.

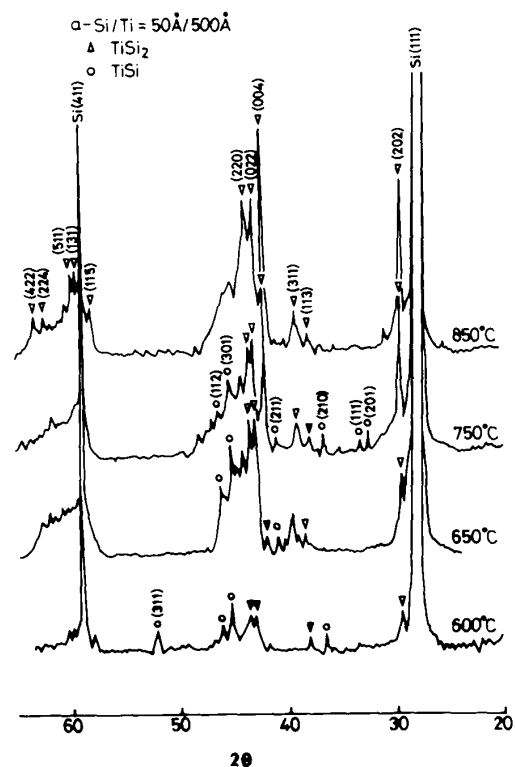


Fig. 8. Variations of X-ray diffraction spectra with annealing temperature for a 50-Å a-Si/500-Å Ti bilayer structure.

Besides the effect of the annealing temperature, the formation sequence of the silicide phase is dependent on the thickness of the as-deposited Ti film. Fig. 9 shows the X-ray diffraction spectra obtained from 50-Å-thick a-Si film on either 500-Å- or 2000-Å-thick Ti metal after annealing at 650°C. In addition to the TiSi phase, several weak peaks of the TiSi_2 phase are obtained for the case of thinner Ti film. However, only the TiSi phase is found from the bilayer structure with the thicker Ti film. The diffusion-limited reaction described by the Arrhenius equation can be used to explain this observation. It has been reported [8] that the TiSi film is formed first, then after the full consumption of Ti for TiSi formation, TiSi is taken over by the formation of TiSi_2 . However, such a phase formation sequence only occurs for well-controlled deposition and annealing conditions. The accepted view in our case is that the complete conversion of Ti into TiSi has been retarded by accumulated oxygen impurities at the Ti/ TiSi interface during TiSi formation. Accordingly, the continuous supply of Si atoms from the Si substrate will result in the formation of TiSi_2 if the as-deposited Ti film is thinner. On the other hand, for the case of thicker Ti film, the amount of Ti atoms is large enough during TiSi formation according to the Arrhenius relation with the same annealing time. Thus TiSi exists after annealing at 650°C because the Si flux is all exhausted in the formation of TiSi .

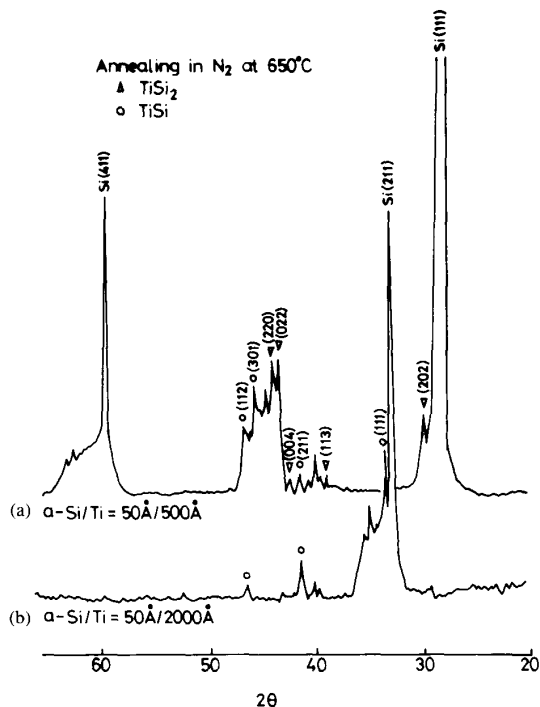


Fig. 9. X-ray diffraction spectra for (a) 50-Å a-Si/500-Å Ti and (b) 50-Å a-Si/2000-Å Ti bilayer structures after annealing at 650°C.

It is interesting to note that the (h, k, l) value of the final silicide phase after annealing at 850°C also shows a dependence on the thickness of the as-deposited Ti film. The normalized X-ray intensities of the observed TiSi_2 peaks with different (h, k, l) values at a fixed metal thickness are shown in Fig. 10, in which the preferential orientation dependence of the silicide phase on film thickness is clearly obtained, e.g., the arbitrary intensity of the silicide phase for $\text{TiSi}_2(311)$ increases, but that of $\text{TiSi}_2(004)$ decreases as the metal film becomes thicker, and that of $\text{TiSi}_2(004)$ increases to a maximum value at the Ti thickness of 1000 Å and then decreases with increasing Ti thickness. After high-temperature annealing, the silicide phase of $\text{TiSi}_2(311)$ is the one most frequently observed either for 1000-Å-thick Ti film on poly-Si annealed in H_2 or vacuum [7] or for 1000-Å-thick Ti film on n-Si annealed by the quartz-halogen method in vacuum [11]. However, this phase is also observed to be the major peak only when the thickness of the as-deposited Ti film is larger than 2000 Å. Another behavior worth noting is that the dominant peaks of the silicide phases are all $\text{TiSi}_2(004)$ with the same bilayer structure (say, 1000-Å-thick Ti) after annealing in either N_2 ambient or vacuum. This result indicates that the final silicide phase is independent of the annealing ambient in an a-Si/Ti bilayer process because the thin a-Si layer acts as a barrier for ambient impurities.

It is reasonable to expect that the preferential orientation of the final silicide phase may be changed by adjust-

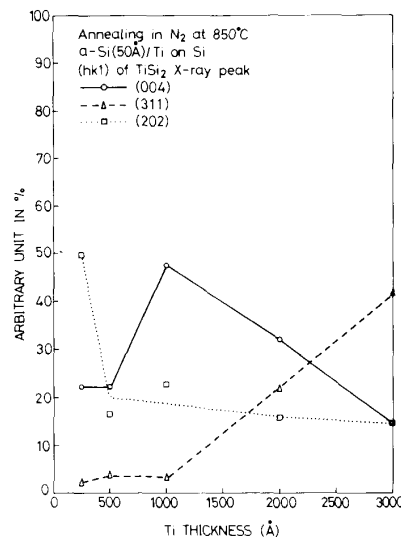


Fig. 10. Normalized X-ray intensities in percentage for the prominent TiSi_2 phases as a function of thickness of the as-deposited Ti film for 50-Å a-Si/Ti bilayer structures after annealing at 850°C.

ing the silicide thickness which is proportional to the thickness of the as-deposited Ti film. It is found that the grain size of the polycrystalline silicide film and the oxygen contamination in silicide are closely related to the formation of the final silicide phase. It is reasonable to expect that some of the oxygen impurities mostly adsorbed during vacuum deposition have been retained and gettered to the grain boundaries during thermal annealing and, as a consequence, will impede the grain growth and thus modify the orientation of the silicide phase. Although these oxygen impurities are beyond the AES detection limit (≈ 0.01 to 0.1%), this explanation can be confirmed by comparing the vacuum pressure during deposition in our work ($\approx 5 \times 10^{-6}$ torr) with that of the reported conditions ($\approx 10^{-7}$ – 10^{-8} torr).

The allowed process window for a-Si thickness between 30 and 100 Å has been defined under constant Ti thickness of 500 Å in an a-Si/Ti bilayer process. It is now interesting to investigate the variations of this process window with the Ti film thickness. Various a-Si/Ti pairs with different thicknesses of the a-Si and Ti films were prepared and annealed at 650°C in N_2 for 40 min. Using the sheet resistance measurement, the AES depth profiles, the X-ray diffraction spectra, and the selective etching methods, the results were grouped into four types according to the characteristics of the oxidation-resistant and self-aligned silicidation properties: fully oxidized, partly oxidized, good for both oxidation-resistant silicidation and selective etching, and good for oxidation-resistant silicidation but poor for selective etching. Fig. 11 shows the experimental results, in which a straight line with a slope equal to 10.37 is obtained by using a least squares fit to the middle points of the a-Si process window. It is clearly seen that the a-Si process window is enlarged with increasing thickness of the Ti metal because

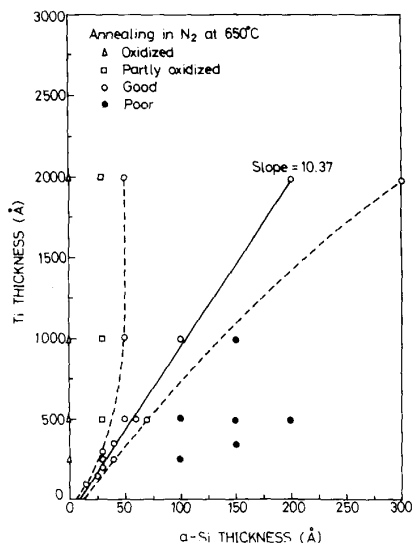


Fig. 11. Annealing behavior for different a-Si/Ti bilayer structures on both Si and SiO₂ after annealing at 650°C.

the products on either Si or SiO₂ have been changed with variations of Ti thickness. Moreover, the slope of the least squares fit gives a very important processing concept for the application of a-Si/Ti bilayer technology: the a-Si/Ti bilayer can provide excellent oxidation-resistant and self-aligned silicidation properties when the thickness ratio of the a-Si film to the Ti film is chosen to be about 1/10 even for the case of the as-deposited Ti film thickness of less than 500 Å.

IV. CONCLUSIONS

The effects of a-Si thickness on the oxidation-resistant and self-aligned silicidation properties in the a-Si/Ti bilayer process during thermal annealing have been studied in detail. The allowed process window for the a-Si thickness between 30 and 100 Å has been deduced for the case of Ti metal 500 Å thick. Within this process window, the Ti metal can be fully converted into TiSi₂ even in an oxygen-contaminated ambient, and the excess oxygen impurities originally contained within the Ti metal can be completely removed to produce a homogeneous and reproducible silicide film. Moreover, the self-aligned feature, which is an important consideration for SALICIDE applications, can be maintained. In addition, the lateral silicide growth on the SiO₂ film can be retarded by the released oxygen impurities collected in the Ti film over the SiO₂ region.

It has been shown that the formation sequence of the silicide phase depends not only on the annealing temperature but also on Ti-film thickness. These results are due to the nature of the diffusion-limited reaction during silicide formation and the pile-up of excess oxygen impurities within the silicide layer. Furthermore, the final silicide phase after annealing at high temperature shows a strong dependence of preferential orientation on the Ti

film thickness. This is attributed to the difference of grain size in the polycrystalline silicide film. Finally, the process window is found to be enlarged with the increasing thickness of Ti film, and the optimal thickness ratio of the a-Si film to the Ti film is about 1/10. Thus a simple and practical rule is experimentally obtained for the a-Si/Ti bilayer process in SALICIDE applications.

ACKNOWLEDGMENT

The authors wish to thank Dr. H. H. Tseng for his helpful discussions and his pioneering research on the a-Si/Ti bilayer process in the Advanced Semiconductor Device Research Laboratory.

REFERENCES

- [1] C. Y. Ting, "Silicide for contacts and interconnects," in *IEDM Tech. Dig.*, 1984, pp. 110-113.
- [2] M. E. Alperin, T. C. Hollaway, R. A. Haken, C. D. Gosmeyer, R. V. Karnaugh, and W. D. Parmantie, "Development of the self-aligned titanium silicide process for VLSI applications," *IEEE Trans. Electron Devices*, vol. ED-32, pp. 141-149, 1985.
- [3] H. H. Tseng and C. Y. Wu, "A new oxidation-resistant, self-aligned TiSi₂ process," *IEEE Electron Device Lett.*, vol. EDL-7, pp. 623-624, 1986.
- [4] F.-S. J. Lai, L. K. Wang, Y. Taur, J. Y.-C. Sun, K. E. Petrillo, S. K. Chicotka, E. J. Detrillo, M. R. Polcari, T. J. Bucelot, and D. S. Eicherman, "A high latch up-immune 1- μ m CMOS technology fabricated with 1-MeV ion implantation and self-aligned TiSi₂," *IEEE Trans. Electron Devices*, vol. ED-33, pp. 1308-1320, 1986.
- [5] T. E. Tang, C.-C. Wei, R. A. Haken, T. C. Hollaway, L. R. Hite, and T. G. W. Blake, "Titanium nitride local interconnect technology for VLSI," *IEEE Trans. Electron Devices*, vol. ED-34, pp. 682-688, 1987.
- [6] S. P. Murarka, *Silicides for VLSI Applications*. New York: Academic Press, 1983, ch. II.
- [7] S. P. Murarka and D. B. Fraser, "Thin film interaction between titanium and polycrystalline silicon," *J. Appl. Phys.*, vol. 51, no. 1, pp. 342-349, 1980.
- [8] L. S. Hung, J. Gynla, and J. W. Mayer, "Kinetics of TiSi₂ formation by thin Ti film on Si," *J. Appl. Phys.*, vol. 54, no. 9, pp. 5076-5080, 1983.
- [9] R. Pretorius, J. M. Harris, and M. A. Nicolet, "Reaction of thin metal films with SiO₂ substrate," *Solid-State Electron.*, vol. 21, pp. 667-675, 1978.
- [10] C. Y. Ting, M. Wittmer, S. S. Iyer, and S. B. Brodsky, "Interaction between Ti and SiO₂," *J. Electrochem. Soc.*, vol. 131, no. 12, pp. 2934-2938, 1984.
- [11] C. S. Wei, J. Van der Spieqel, and J. Santiago, "Electrical characteristics of fast radiatively processed titanium silicides thin films," *J. Vac. Sci. Technol.*, vol. A3, no. 6, pp. 2259-2263, 1985.



Yung-Song Lou (S'86) was born in Taiwan, Republic of China, on January 24, 1963. He received the B.S. degree from the Department of Electrical Engineering, National Tsing-Hua University, Taiwan, Republic of China, in 1985, and entered the Institute of Electronics, National Chiao-Tung University, for graduate study in Sept. 1985. Now, he is a Ph.D. candidate and engages in the development of self-aligned silicidation (SALICIDE) technologies and their applications in MOS/VLSI fabrication.



Ching-Yuan Wu (M'72) was born in Taiwan, Republic of China, on March 18, 1946. He received the B.S. degree from the Department of Electrical Engineering, National Taiwan University, Taiwan, Republic of China, in 1968, and the M.S. and Ph.D. degrees from the State University of New York (SUNY) at Stony Brook, in 1970 and 1972, respectively.

During the 1972-1973 academic year, he served as a Lecturer at the Department of Electrical Sciences, SUNY, Stony Brook. During the 1973-1975 academic years, he was a Visiting Associate Professor at National Chiao-Tung University (NCTU), Taiwan, Republic of China. In 1976, he became a Full Professor in the Department of Electronics and the Institute of Electronics, NCTU. At NCTU he had been the Director of Engineering Laboratories and Semiconductor Research Center during 1974-1980; the Director of the Institute of Electronics, during 1978-1984; and the Dean, College of Engineering, during 1984-1990. He was a principal investigator of the National Electronics Mass Plan—Semiconductor Devices and Integrated-Circuit Technologies, during 1976-1979, and had been a Coordinator of the National Microelectronics Researches and High-Level Man-Power Education Committee, National Science Council, Republic of China, during 1982-1988. He has been a Research Consultant for the Electronics Research and Service Organization (ERSO), ITRI; a member of the Academic Review Committee, the Ministry of Education; and the chairman of the Technical Review Committee on Information and Microelectronics Technologies, the Ministry of Economic Affairs. His research activities have been in semiconductor device physics and modelings, integrated-circuit designs and technologies. His present research areas focus on the developments of efficient two- and three-dimensional simulators for deep-submicrometer semiconductor devices, design rules, and optimization techniques for deep-submicrometer CMOS devices, and key technologies for deep-submicrometer CMOS devices. He has published over 150 papers in the semiconductor field and has served as a reviewer for international journals such as IEEE ELECTRON DEVICE LETTERS, IEEE TRANSACTIONS ON ELECTRON DEVICE, *Solid-State Electronics*, etc. He received the Academic

Research Award in Engineering from the Ministry of Education (MOE), in 1979; the Outstanding Scholar Award from the Chinese Educational and Cultural Foundation, in 1985. He has received an Outstanding Research Professor fellowship from the Ministry of Education and the National Science Council (NSC), Republic of China, during 1982-1991.

Dr. Wu is a member of the Honorary Editorial Advisory Board of *Solid-State Electronics* and is a board member of the Chinese Engineering Society.



Huang-Chung Cheng (M'90) was born in Taiwan, Republic of China, on September 6, 1954. He received the B.S. degree from the Department of Physics, National Taiwan University, in 1977, and the M.S. and Ph.D. degrees from the Department of Materials Science and Engineering, National Tsing-Hua University, Taiwan, Republic of China, in 1979 and 1985, respectively.

From 1981 to 1982, he served as a research assistant in the Materials Research Laboratory, Industrial Technology Research Institute, Taiwan.

From 1982 to 1984, he was a part-time lecturer in the Department of Mechanical Engineering, National Chiao-Tung University, Taiwan. In 1985, he joined the Department of Electronics Engineering and the Institute of Electronics, National Chiao-Tung University, Taiwan, as an Associate Professor. Since 1986, he has served as a research consultant for United Microelectronics Corp. and Hualon Microelectronics Corp., Taiwan. His present research areas focus on the reliability of thin-gate dielectrics, the contact properties of metals on Si and GaAs semiconductors, the technologies for three-dimensional IC's, and thin-film transistors of different active materials (amorphous, polycrystalline, and laser-recrystallized silicons).

Dr. Cheng is a member of Phi Tau Phi, Republic of China, and a member of the Materials Research Society, USA.