Enhanced formation of low-resistivity TiSi_2 contacts for deep submicron devices

L J CHEN*, S L CHENG and S M CHANG

Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu, Taiwan, Republic of China

Abstract. Low resistivity C54-TiSi_2 is currently the most commonly used silicide for metal contacts in ultralarge scale integrated circuits devices. In the present paper, we review recent results of investigations on the effects of stress and high temperature sputtering on the formation of C54-TiSi_2 . Enhanced formation of C54-TiSi_2 on (001)Si by tensile stress and high temperature sputtering is correlated to the growth of thicker amorphous interlayer at the Ti/(001)Si interface. The enhanced transformation is attributed to the presence of higher density of silicide crystallites, which serve as the nucleation sites for the C49-TiSi_2 , in the amorphous layer. As a result, the average grain size of C49-TiSi_2 is smaller which leads to lower $\text{C49- to C54-TiSi}_2$ transformation temperature.

Keywords. TiSi_2 ; stress; high temperature sputtering.

1. Introduction

For self-aligned silicidation process silicides are formed on source, drain and gate regions simultaneously to ease the lithography requirements and to lower the contact resistance. Low-resistivity C54-TiSi_2 is currently the most widely used silicide for the self-aligned technology of ultralarge scale integrated circuits because it possesses the lowest resistivity among all silicides, low contact resistance, and good thermal properties as well as compatibility with the self-aligned silicidation (SALICIDE) process (Wong *et al* 1983, 1986). However it has been found that as the integrated circuit device dimensions scale down to deep submicron region, the high-resistivity $\text{C49- to C54-TiSi}_2$ conversion becomes increasingly difficult; this is attributed to the low density of nucleation sites for the C54-TiSi_2 phase (Lasky *et al* 1991). The desire to form C54-TiSi_2 completely in a submicron structure has led to extensive research in increasing the C54-TiSi_2 nucleation density by using refractory metal (Mo or W) ion implantation (Mann *et al* 1995), Sb additions (Li *et al* 1992), preamorphization of the silicon substrate by ion implantation of Xe (Kuвано *et al* 1990), or by interposing a thin layer of molybdenum (Mouroux *et al* 1996).

For deep submicron multilayer structure, issues related to stress become troublesome in semiconductor device fabrication. Stress can degrade gate oxides in metal-oxide-semiconductor field effect transistors, and cause cracks in interconnect lines (Murarka 1993). A recent finite element calculation showed that the substrate

regions at the oxide edge are compressively stressed to a significant extent (Shen *et al* 1996). The stress level near the silicon substrate surface inside oxide openings is therefore of major concern to the formation of silicides (Nicolet and Lau 1983). Shewmon (1989) showed that the diffusion in the thin films retards under compressive stress. Previous studies also showed that the size effect of oxide opening exerts strong influence on the growth kinetics of silicides (Chang *et al* 1987; Hsu *et al* 1991; Yew *et al* 1996). In a study of the effects of stress on the formation of low-resistivity C54-TiSi_2 , tensile stress has been shown to facilitate the $\text{C49- to C54-TiSi}_2$ transition.

A new and simple Ti SALICIDE process for the reduction in the C54 transformation temperature in sub-quarter micron Si devices was demonstrated recently. An ion implantation step was used to amorphize the surface of Si substrate (preamorphization implantation, PAI), and the substrate temperature was maintained at 450°C during Ti sputtering (high temperature Ti sputtering, HTS). Thicker amorphous TiSi_x layer was formed at the Ti and Si interface in the as-deposited sample with HTS. The growth of interfacial amorphous TiSi_x layer was previously found to relate to the formation of C54-TiSi_2 (Fujii *et al* 1996). However, the detailed mechanism is not well understood. High-resolution transmission electron microscopy (HRTEM) in conjunction with auto-correlation function (ACF) analysis was utilized to determine the structure of the amorphous TiSi_x layer formed in the initial stage prior to the formation of crystalline silicides. Although crystallites $< 1\text{ nm}$ in size may be embedded in the amorphous interlayer and undetectable with direct imaging technique in HRTEM,

*Author for correspondence

periodic structure can be observed in some of the ACF images which revealed the formation of crystalline nuclei and short-range ordering in the amorphous interlayers (Frank 1980; Fan and Cowley 1985; Liang and Chen 1994). ACF analysis has been applied to the HRTEM images of amorphous interlayers formed in the interfacial reactions of ultrahigh vacuum (UHV) deposited V, Zr, and Mo thin films on (111)Si (Liang and Chen 1994; Chen *et al* 1998). The results demonstrated the usefulness of the ACF analysis of atomic images in amorphous interlayers formed in the initial stage of reactions in metal thin films on silicon.

In this study we have investigated the effects of stress and high temperature sputtering on the formation of TiSi_2 on (001)Si by stress and sheet resistance measurements, grazing incidence X-ray diffractometry, transmission and scanning electron microscopy.

2. Experimental

2.1 Effects of stress on the formation of titanium silicide

Single crystal, 2–3 $\Omega\text{-cm}$, (001)Si wafers were used in the present study. Following a standard cleaning procedure, SiO_2 films were deposited by plasma enhanced chemical vapour deposition (PECVD) or thermally grown in wet oxygen ambient condition at 1000°C. After the SiO_2 film was deposited, the oxide film on the front side of the wafer was subsequently removed. A 200 nm thick Co film was deposited onto the back side of some of the blank (001)Si wafers first, then annealed in a rapid thermal annealing (RTA) apparatus from 800–900°C for 120 s to form CoSi_2 layer. The stresses induced by the SiO_2 and CoSi_2 film at the backside of the sample were determined by a scanning laser beam reflection technique (Murarka 1993b). The radius of curvature of each of the silicon wafers was measured prior to the deposition of the film and following the deposition.

All of the stressed samples (samples B, C, D, E) were cleaned by a standard RCA process and then dipped in a dilute HF solution ($\text{HF}:\text{H}_2\text{O}=1:50$) before loading into an electron gun evaporation chamber. Ti thin films, 30 nm thick, were then deposited onto the front side of the stressed (001)Si wafers. Heat treatments were carried out in the RTA apparatus from 450–1000°C for 30–60 s in N_2 ambient. Selective removal of unreacted metals and formed TiN were carried out in an etchant solution ($\text{H}_2\text{O}_2/\text{NH}_4\text{OH}/\text{H}_2\text{O}$) at 65°C.

A JEOL JEM2010 transmission electron microscope (TEM) operating at 200 keV was used for microstructure examination. Grazing incidence X-ray diffractometry (GIXRD) was carried out for phase identification. The incident angle of X-ray was fixed at 0.5°. Sheet resistance measurements were performed using a standard four-point probe.

2.2 Enhanced formation of C54- TiSi_2 in high-temperature-deposited Ti thin films on preamorphized (001)Si

Boron-doped (001)Si wafers, 6" diam., 1–20 $\Omega\text{-cm}$ in resistivity, were first cleaned by standard RCA process followed by the growth of 10 nm thick thermal (pad) oxide layer. The wafers were implanted by 70 keV, $3 \times 10^{15}/\text{cm}^2$ As^+ through the pad oxide layer. These implanted wafers were annealed at 900°C in a diffusion furnace for 30 min in N_2 ambient condition to activate the implanted As^+ and eliminate the residual defects. PAI treatment was carried out by 70 keV, $3 \times 10^{14}/\text{cm}^2$ As^+ . The thicknesses of implantation amorphous layers in PAI samples were about 50 and 34 nm in as-deposited, and annealed at 500°C for 30 s samples, respectively.

Prior to loading into the sputtering deposition system, thermal oxide was removed from all samples by a dilute HF dip. A 30 nm thick Ti layer was deposited by sputtering. The base pressure of the sputter deposition system was maintained at 5×10^{-9} torr. The sputtering rate of Ti was 2 nm/s. During sputtering, the substrates were maintained at 450°C or room temperature. A 30 nm thick TiN capping layer was then deposited on the Ti layer. The capping layer was used to improve the uniformity of TiSi_2 , and avoid the oxidation of Ti on Si surface (Smith *et al* 1990; Chen *et al* 1996). All samples were then treated by RTA in N_2 ambient condition at different temperatures for 30 s sample in a heating apparatus. Sheet resistance was measured by a conventional four-point probe measurement system. Glancing-angle X-ray diffraction method was used to determine the phases formed after annealing.

For HRTEM observation, a JEOL 4000EX TEM operating at 400 kV with a point-to-point resolution of 0.18 nm was used. No objective aperture was inserted into the beam path during the imaging of the cross-sectional TEM (XTEM) samples. The thickness of cross-sectional samples for HRTEM investigation was estimated from the simulated images of crystalline Si atoms. ACF was used to determine the local ordering in the amorphous TiSi_x layer from the scanned images of HRTEM micrographs. ACF analysis was carried out on templates of $0.983 \times 0.983 \text{ nm}^2$ cut along the interlayer in the HRTEM micrographs. In order to avoid wraparound effect to exhibit false ACF-processed images, the templates were patched on double in size square regions with a homogeneous background which is set to be equal to the average values of the original intensity.

3. Results and discussion

The laser beam method for substrate curvature measurement was used to measure the stress induced by the film at the backside of the sample. This method allows

the stress of the film to be calculated using Stoney's equation (Murarka 1993a), which relates the curvature of the sample to the stress of the film. Stress measurement showed that compressive stresses of 100–550 MPa and tensile stresses of 690–870 MPa were present in the SiO_2 films, and the CoSi_2 films at room temperature, respectively. Therefore, compressive and tensile stresses were induced by the SiO_2 films and the CoSi_2 film on the front sides of silicon substrate, respectively.

Figure 1 shows the sheet resistance data of Ti (30 nm) on blank-(001)Si (sample A), SiO_2 -100 MPa (sample B), SiO_2 -550 MPa (sample C) compressively stressed Si and CoSi_2 -690 MPa (sample D), CoSi_2 -870 MPa (sample E) tensilely stressed Si samples after different heat treatments. The data clearly demonstrates the impact of the stress on the C49- to C54- TiSi_2 transformation. A sharp drop in sheet resistance was found for Ti on E samples at 700°C. On the other hand, for Ti on A, B, C and D samples, as the annealing temperature was increased to 750°C, 750°C, 800°C and 750°C, respectively, a sharp drop in sheet resistance was found, indicating that appreciable C49- to C54- TiSi_2 transformation occurred. The increase in sheet resistances for Ti on blank-(001)Si and stressed samples after annealing at high temperatures were correlated to the formation of island structure of C54- TiSi_2 .

From the grazing angle XRD analysis, the low-resistivity C54- TiSi_2 was observed to be the only silicide phase formed in 700°C annealed E samples and 750°C annealed A, B and D samples. For Ti on D samples after annealing at 700°C, C54- TiSi_2 was found to coexist with the dominant polycrystalline C49- TiSi_2 phase. On the other hand, even after annealing at 750°C, both C49-

and C54- TiSi_2 were found to form in C samples. The corresponding XRD spectra are shown in figure 2.

Figures 3a-e show XTEM micrograph of A, B, C, D and E samples, respectively, after annealing at 800°C for 30 s. From figures 3a-e, it is clearly seen that the thicknesses of C54- TiSi_2 in D and E samples (under tensilely stressed samples) are thicker than those in A, B and C samples (blank and under compressively stressed samples). The thicknesses of C54- TiSi_2 thin films were measured to be 54, 36, 28, 55 and 60 nm for A, B, C, D and E samples, respectively. In addition, the thicknesses of TiSi_2 films were found to decrease with the compressive stress level and increase with the tensile stress level. These results are correlated with the differences in sheet resistance of TiSi_2 among A, B, C, D and E samples in figure 1.

For Ti, on blank and stressed samples after annealing at 450°C for 30 s, the thicknesses of a-interlayers were measured to be 4, 5 and 6 nm for C, A and E samples, respectively. In addition, for C, A and E samples annealed at 450°C for 60 s, the thicknesses of a-interlayers were found to increase to 4.5, 6.5 and 7 nm, respectively. No crystalline titanium silicide phases were observed in all of the annealed samples. Examples are shown in figure 4. The results clearly showed that the compressive stress hinders the migration of Si through the Ti/Si interface,

Figure 1. Sheet resistance of titanium silicides versus annealing temperature curves for A, B, C, D and E samples.

Figure 2. GIXRD spectra of (a) 750°C annealed Ti/blank-Si, (b) 750°C annealed Ti/ SiO_2 -100 MPa stressed-Si, (c) 750°C annealed Ti/ SiO_2 -550 MPa stressed-Si, (d) 700°C annealed Ti/ CoSi_2 -690 MPa stressed-Si samples, and (e) 700°C annealed Ti/ CoSi_2 -870 MPa stressed-Si samples.

so that the thickness of α -interlayer is thinner. In contrast, the tensile stress promotes the Si diffusion, therefore, the tensile stress present in the silicon substrate was found to enhance the growth of the α -interlayer.

Based on the GIXRD analysis and XTEM observation, the compressive stress presented in the silicon substrate was found to retard significantly the transformation of C49- to C54-TiSi₂. In contrast, the tensile stress presented in the silicon substrate was found to promote the growth of C54-TiSi₂ phase. Furthermore, the thicknesses of TiSi₂ films were found to decrease and increase with the compressive and tensile stress level, respectively. In silicide formation, compressive stress is generated in the silicide by the migration of silicon atoms into titanium film. Observed results can therefore be attributed to the hindrance of the migration of Si through the Ti/Si interface by the presence of compressive stress, so that the formation of TiSi₂ films were retarded. In contrast, the tensile stress promotes the Si diffusion. As a result, the formation of TiSi₂ during annealing is facilitated and as also increase in thickness of TiSi₂ films.

In previous studies (Fujii *et al* 1996; Kikkawa *et al* 1996), the phase transformation of titanium silicide from C49 to C54 was significantly influenced by the presence of amorphous interlayer. The thicker α -interlayer, indicating a higher degree of intermixing between Ti and Si, provided more nucleation sites for phase transformation of C49- to C54-TiSi₂. As a result, the tensile stress present in the silicon substrate leads to the formation of a thick α -interlayer, which increases the nucleation density of the C54-TiSi₂ phase, so that the transformation of C49 to C54-TiSi₂ phase is enhanced. These results are correlated with the sheet resistance measurement and GIXRD analysis described in previous sections.

Based on the sheet resistance measurement, GIXRD analysis, and XTEM observation, the compressive stress present in the silicon substrate was found to retard significantly the transformation of C49- to C54-TiSi₂. In contrast, the phase transformation of TiSi₂ from C49 to C54 was facilitated in tensilely stressed samples. The results are attributed to the tensile stress present in the silicon substrate which leads to the formation of a thick

Figure 3. XTEM images, 800°C, 30 s of Ti (30 nm) on (a) blank-Si, (b) SiO₂-100 MPa stressed-Si, (c) SiO₂-550 MPa stressed-Si, (d) CoSi₂-690 MPa stressed-Si, and (e) CoSi₂-870 MPa stressed-Si samples.

Figure 4. XTEM images, 450°C, 60 s of Ti (30 nm) on (a) SiO₂-550 MPa stressed-Si, (b) blank-Si and (c) CoSi₂-870 MPa stressed-Si samples. α represents amorphous interlayer.

a-interlayer, which in turn increases the nucleation sites for the C54- TiSi_2 phase.

Figure 5 shows the sheet resistance data of different samples after RTA at various temperatures for 30 s. The unreacted metal and TiN layer were etched off by a solution of $\text{H}_2\text{O}_2 : \text{NH}_4\text{OH} : \text{H}_2\text{O} = 5 : 1 : 1$. The formed phases of samples annealed at different temperature determined by X-ray diffraction are listed in table 1. It is clear that the C49- to C54- TiSi_2 phase transformation temperature was lower in samples with HTS and PAI (HTS + PAI). C54- TiSi_2 was found to be the only silicide phase at 675°C. The transition temperature was higher for samples with room-temperature sputtering (RTS) and without PAI. The transition to C54 phase was not completed until 750°C. On the other hand, the transition to C54 phase was completed at 700°C in both samples with HTS but without PAI (HTS) and RTS with PAI (RTS + PAI). From HRTEM images, the average thicknesses of amorphous TiSi_x layer are about 2, 4, 2 and 5.5 nm, respectively, in as-deposited RTS, HTS, RTS + PAI and HTS + PAI samples. The thickness of amorphous

TiSi_x layer at the Ti/Si interface was found to increase with the substrate temperature. A few periodic structures were observed in some of the ACF images of outlined regions shown in figure 6a of a HTS + PAI sample. Examples of ACF-processed images are shown in figure 6b. The cross-hatch patterns were found to correspond to Ti_5Si_3 or Ti_5Si_4 from both interplanar spacing and angular measurements. Both Ti_5Si_3 and Ti_5Si_4 were also found in the HTS samples. On the other hand, neither silicide crystallites nor local ordering structures were found in RTS and RTS + PAI samples. Therefore, for HTS and HTS + PAI samples, silicide crystallites were embedded in the amorphous layer. The intermixing of Ti and Si atoms was more extensive and the amorphous TiSi_x layers were thicker than those in RTS samples.

In order to investigate the effects of HTS and PAI further, all the samples were annealed at 500°C to obtain thicker amorphous TiSi_x layer. Well-defined correlated images were more prominent in samples annealed at 500°C than those in as-deposited samples. In the following, data for samples annealed by RTA in N_2 ambient at 500°C for 30 s are presented.

From HRTEM images of RTS and HTS samples, the average thicknesses of the amorphous TiSi_x layer were about 8 and 10 nm, respectively. Analysis of ACF-processed images revealed the presence of Ti_5Si_3 , Ti_5Si_4 , TiSi and C49- TiSi_2 phases. However, the amount and extent of local ordering are higher in samples with HTS than those with RTS.

From HRTEM images of the RTS + PAI and HTS + PAI samples, the thicknesses of the amorphous TiSi_x layers were both measured to be about 13 nm. Multiphases were observed to be present simultaneously in both samples. The density of crystallites is higher in the HTS + PAI samples than those in RTS + PAI samples. HTREM image and ACF-processed images of a HTS + PAI sample are shown in figures 7a and b, respectively. It has been reported previously that Ti_5Si_3 , Ti_5Si_4 , TiSi and C49- TiSi_2 crystallites along with amorphous TiSi_x layer were observed to be present simultaneously in

Figure 5. Sheet resistance data for different samples after 30 s RTA at various temperatures.

Table 1. Phases determined by XRD. The annealing time at each temperature was 30 s.

	Samples			RTA temperature				
	Deposition temperature		PAI treatment					
	RT	450°C		625°C	650°C	675°C	700°C	750°C
RTS	✓			—	—	C49	C49 + C54	C54
HTS		✓		—	C49	C49 + C54	C54	—
RTS + PAI	✓		✓	—	C49	C49 + C54	C54	—
HTS + PAI		✓	✓	C49 + C54	C49 + C54	C54	—	

RTS, room temperature sputtering; HTS, high temperature sputtering; PAI, preamorphization implantation.

Ti/(111)Si samples annealed at 475–500°C (Wang and Chen 1991). In the present study, embedded crystallites of Ti_3Si_3 , Ti_5Si_4 , TiSi and C49-TiSi_2 were found from the ACF analysis.

Comparing RTS and HTS samples, it can be seen that although the amorphous TiSi_x layer is thicker in the samples with HTS, the increase in thickness is not very significant (8 nm vs 10 nm). For both HTS + PAI and RTS + PAI samples, the thicknesses of the amorphous TiSi_x layers are about 13 nm. Therefore, the increase in thickness of amorphous TiSi_x layer is due to PAI for most part. The dominant effect of HTS is to increase the density of crystallites in the amorphous TiSi_x layer. The combined effects of HTS and PAI result in a thick amorphous TiSi_x layer with higher density of embedded crystallites than those in other samples. In a parallel study, the average grain size of C49-TiSi_2 in 650°C annealed for 20 s samples was found to decrease with the substrate heating temperature (Yang 1997). It has been shown that the nucleation of C54-TiSi_2 takes place preferentially at triple grain junctions or grain boundaries of C49-TiSi_2 (Ma *et al* 1995). The phase transformation temperature was previously found to be lower for small-grained C49-TiSi_2 films than that of the large-grained films (van Hontum *et al* 1987). It is thought that with higher density of crystallites in the amorphous TiSi_x layer, more nucleation sites are available for the formation

of crystalline C49-TiSi_2 . As a result, the average grain size of C49-TiSi_2 is smaller which leads to lower C49- to C54-TiSi_2 transformation temperature. A previous study on the growth of TiSi_2 from codeposited amorphous TiSi_x interfacial layers supported the attribution of the observed reduction in the C54-TiSi_2 nucleation temperature in the HTS process to the formation of a thick interfacial TiSi_x layer (Tung *et al* 1997). The results strongly suggested that the presence of silicide crystallites in the amorphous TiSi_x layer leads to the favourable TiSi_2 formation.

4. Summary and conclusions

Effects of stress and high temperature sputtering on the formation of TiSi_2 on (001)Si have been investigated by stress and sheet resistance measurements, grazing incidence X-ray diffractometry, transmission and scanning electron microscopy.

The phase transformation of titanium silicide from C49 to C54 phase was significantly influenced by the stresses present in the silicon substrate. From XTEM observation,

Figure 6. (a) Cross-sectional HRTEM image of interface between 450°C deposited Ti on preamorphized (001)Si. (b) ACF-processed images of the outlined regions shown in (a).

Figure 7. (a) HRTEM image of a PAI + HTS sample annealed at 500°C for 30 s. (b) ACF-processed images of the outlined regions shown in (a).

the thicknesses of a-interlayers were found to be thicker and thinner in the tensile and compressively stressed samples, respectively. The thicker a-interlayer, indicating a higher degree of intermixing between Ti and Si, provided more nucleation sites for phase transformation of C49- to C54- TiSi_2 . Therefore, tensile stress present in the silicon substrate was found to facilitate the C54- TiSi_2 formation. On the other hand, compressive stress present in the silicon substrate was found to retard significantly the transformation of C49- to C54- TiSi_2 .

The phase transformation of C49- to C54- TiSi_2 is enhanced in the high temperature deposited Ti thin films on pre-amorphized (001)Si. The increase in the thickness of amorphous TiSi_x layer is due to the PAI for the most part. The dominant effect of HTS is to increase the density of crystallites in the amorphous TiSi_x layer. The enhanced transformation is attributed to the presence of higher density of silicide crystallites, which serve as the nucleation sites for the C49- TiSi_2 . As a result, the average grain size of C49- TiSi_2 is smaller which leads to lower C49- to C54- TiSi_2 transformation temperature.

Acknowledgement

This research was supported by the Republic of China National Science Council through a grant No. NSC87-2215-E-007-029.

References

- Chang C S, Nieh C W and Chen L J 1987 *Appl. Phys. Lett.* **50** 259
- Chen L J, Lin J H, Lee T L, Luo C H, Hsieh W Y, Liang J M and Wang M H 1998 *Microsc. Res. Tech.* **40** 136
- Chen W M, Pozder S, Limb Y, Sitaram A R and Fiordalice B 1996 *Mater. Res. Soc. Symp. Proc.* **429** 163
- Fan G Y and Cowley J M 1985 *Ultramicroscopy* **17** 345
- Frank J 1980 *Computer processing of electron microscopy images* (Berlin: Springer) p. 187
- Fujii K, Tung R T, Eaglesham D J, Kikuta K and Kikkawa T 1996 *Mater. Res. Soc. Symp. Proc.* **402** 83
- Hsu H F, Chen L J and Chu J J 1991 *J. Appl. Phys.* **69** 4282
- Kikkawa T, Fujii K and Inoue K 1996 *Proc. inter electron device and mater. symp.*, Hsinchu, Taiwan (Taiwan: Mater. Res. Soc.) **A3-5** 125
- Kuwano H, Phillips J R and Mayer J W 1990 *Appl. Phys. Lett.* **56** 440
- Lasky J B, Nakos J S, Cain O J and Geiss P J 1991 *IEEE Trans. Electron Dev.* **ED-38** 262
- Liang J M and Chen L J 1994 *Appl. Phys. Lett.* **64** 1224
- Li X-H, Carlsson R A, Gong S F and Hentzell H T G 1992 *J. Appl. Phys.* **72** 514
- Ma Z, Allen L H and Allman D D J 1995 *J. Appl. Phys.* **77** 4384
- Mann R W, Miles G L, Knotts T A, Rakowski D W, Clevenger L A, Harper J M E, D'Heurle F M and Cabral C Jr 1995 *Appl. Phys. Lett.* **67** 18
- Mouroux A, Zhang S-L, Kaplan W, Nygren S, Ostling M and Petersson C S 1996 *Appl. Phys. Lett.* **69** 12
- Murarka S P 1993a *Metallization theory and practice for VLSI and ULSI* (Boston: Butterworth-Heinemann) p. 74
- Murarka S P 1993b *Metallization: theory and practice for VLSI and ULSI* (Boston: Butterworth-Heinemann) p. 82
- Nicolet M A and Lau S S 1983 *Formation and characterization of transition-metal silicides*, in *Materials and process characterization* (eds N G Einspruch and G B Larrabee) (New York: Academic Press) p. 329
- Shen Y L, Suresh S and Blench I A 1996 *J. Appl. Phys.* **80** 1388
- Shewmon P G 1989 *Diffusion in solid* (Warrendale, PA: The Metallurgical Society) 2nd edition, p. 84
- Smith P L, Osburn C M, Wen D S and McGuire G 1997 *Mater. Res. Soc. Symp. Proc.* **160** 299
- Tung R T, Fujii K, Kikuta K, Chikaki S and Kikkawa K 1997 *Appl. Phys. Lett.* **70** 2386
- van Hontum H J W, Raaijmakers I J M M and Menting T J M 1987 *J. Appl. Phys.* **61** 3116
- Wang M H and Chen L J 1991 *Appl. Phys. Lett.* **59** 2460
- Wong C Y, Wang L K, McFarland, P A and Ting C Y 1983 *J. Appl. Phys.* **60** 243
- Wong C Y, Lai F S, McFarland P A, d'Heurle F M and Ting C Y 1986 *J. Appl. Phys.* **59** 2773
- Yang H Y 1997 *Formation of self-aligned TiSi_2 on (001)Si; inside 0.1–0.6 μm openings prepared by electron beam lithography*, MS Thesis, National Tsing Hua University, Hsinchu, Taiwan, Republic of China
- Yew J Y, Chen L J and Nakamura K 1996 *Appl. Phys. Lett.* **69** 999