

## C54-TiSi<sub>2</sub> fabricated by direct ion beam synthesis

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High current Ti ion implantation using a metal vapor vacuum arc (MEVVA) ion source was employed to fabricate the TiSi<sub>2</sub> in silicon wafers. Implantation was conducted by 80 keV Ti ions to a dose of  $5 \times 10^{17}$  Ti/cm<sup>2</sup> with various ion current densities from 50 to 125  $\mu$ A/cm<sup>2</sup>. It was found that when the ion current density exceeded 100  $\mu$ A/cm<sup>2</sup>, the equilibrium TiSi<sub>2</sub> of C54 structure was uniquely formed with a layer thickness of 80-100 nm. Sheet resistance measurement provided an additional evidence of the formation of the C54-TiSi<sub>2</sub>, as the resistance was below  $3.0 \Omega/\square$ . The formation mechanism of the TiSi<sub>2</sub> was attributed to the simultaneous thermal annealing caused by beam heating during implantation.

### 1. INTRODUCTION

In the last twenty years, the formation of various metal-silicides has been extensively studied by a variety of techniques, such as solid state reaction of thin metal films on single-crystalline silicon substrates upon thermal annealing[1], ion beam mixing[2][3] etc, as the metal-silicides are potential candidate materials in microelectronic devices. Among the silicide-forming metals, titanium has special significance because its disilicide C54-TiSi<sub>2</sub>, which has the lowest resistivity and good thermal stability, is an attractive alternate material to be used as the gate electrode and ohmic contact in the submicron silicon device technology. In this study, ion implantation using a MEVVA ion source[4] was employed to investigate the possibility of forming the equilibrium C54-TiSi<sub>2</sub> layer on silicon wafer, as the MEVVA source can easily provide Ti ions with high current density, which can cause an in-situ thermal heating to induce a direct formation of TiSi<sub>2</sub> without post-annealing. The details of the experimental results and the discussion of the formation mechanism are presented in this paper.

### 2. EXPERIMENTAL PROCEDURE

The Si wafers were p-type Si(111) with 8-13  $\Omega$ cm. The  $1 \times 1$  cm<sup>2</sup> samples were cleaned by a standard chemical procedure and then mounted on a holder in a implanter equipped with a MEVVA source. The implantation voltage was 40 kV (the energy of the Ti<sup>++</sup> ions was then 80 keV), and the ion dose was  $5 \times 10^{17}$  Ti/cm<sup>2</sup>, (consisting of 6% Ti<sup>+</sup>, 82% Ti<sup>++</sup> and 12% Ti<sup>+++</sup>). The ion current density was varied from 25 to 125  $\mu$ A/cm<sup>2</sup>. During implantation, the samples were tilted at 7° to avoid channeling effect. Rutherford backscattering spectrometry (RBS), X-ray diffraction (XRD) and four-point probe resistivity measurement were employed to identify the resulted microstructure in Si.

### 3. RESULTS AND DISCUSSION

Figure 1 is an XRD pattern of a sample implanted with a Ti ion current density of 125  $\mu$ A/cm<sup>2</sup> to a dose of  $5 \times 10^{17}$  Ti/cm<sup>2</sup>. To identify the observed phase, the interplanar spacings of the sample and the reported Ti-silicides (including C54-TiSi<sub>2</sub>, C49-TiSi<sub>2</sub>, TiSi, and Ti<sub>3</sub>Si<sub>2</sub>) are listed in Table I for comparison.

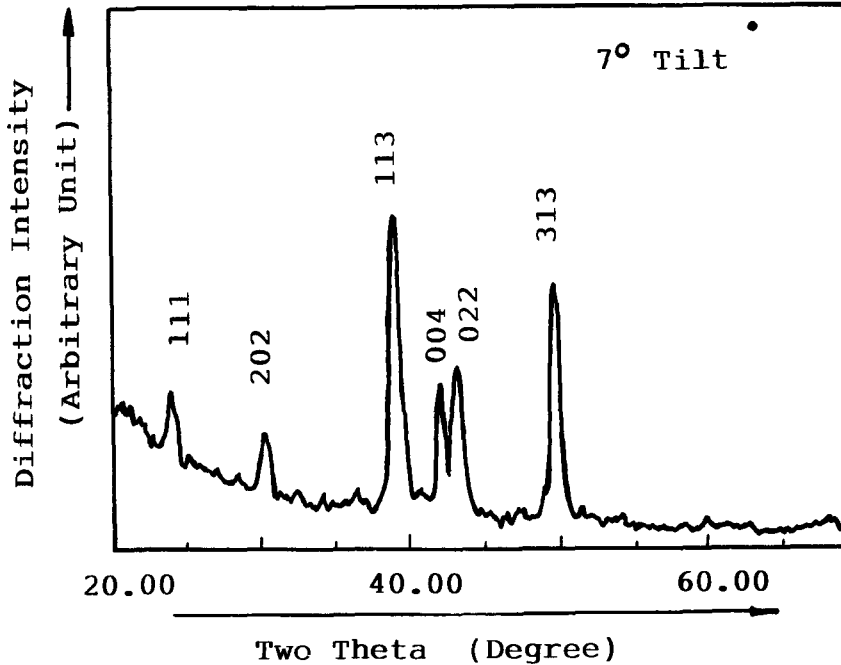


Figure 1. X-ray diffraction pattern of a sample implanted with Ti ions of  $125 \mu\text{A}/\text{cm}^2$  to a dose of  $5 \times 10^{17} \text{Ti}/\text{cm}^2$ .

Table I. The interplanar spacings (nm) of the listed Ti-silicides and the observed for a sample implanted with  $125 \mu\text{A}/\text{cm}^2$  to a dose of  $5 \times 10^{17} \text{Ti}/\text{cm}^2$ .

Observed	$\text{TiSi}_2$ (C54) <sup>a</sup>	$\text{TiSi}_2$ (C49) <sup>b</sup>	$\text{Ti}_3\text{Si}_3$ <sup>c</sup>	$\text{TiSi}$ <sup>d</sup>
0.3732	0.3729(111)			
0.2960	0.2970(202)	0.284(130)	0.3015(111)	
0.2297	0.2300(113)	0.229(060)	0.2388(012)	0.2335(102)
0.2135	0.2136(004)	0.223(131)	0.2202(121)	0.2189(211)
0.2088	0.2092(022)	0.219(150)	0.2149(030)	0.2000(301)
0.1828	0.1831(313)	0.181(200)	0.1861(220)	0.1823(020)

a. JCPDS 33-1384 b. JCPDS 10-225 c. JCPDS 29-1362 d. JCPDS 17-424

Apparently, the observed diffraction peaks can well be identified as (111), (202), (113), (004), (022) and (313) of the  $\text{C54-TiSi}_2$ . A corresponding RBS spectrum shown in Figure 2 demonstrates that a  $\text{TiSi}_2$  layer with a thickness of 80 nm was formed. The sheet resistance as a function of ion

current density is shown in Table II and Figure 3. One sees from the figure that when the current density reached  $100 \mu\text{A}/\text{cm}^2$ , the sheet resistance of the as-implanted sample was below  $3.0 \Omega/\square$ . Increasing the ion current density to  $125 \mu\text{A}/\text{cm}^2$ , the sheet resistance was  $2.4 \Omega/\square$ . The resistivities of these two

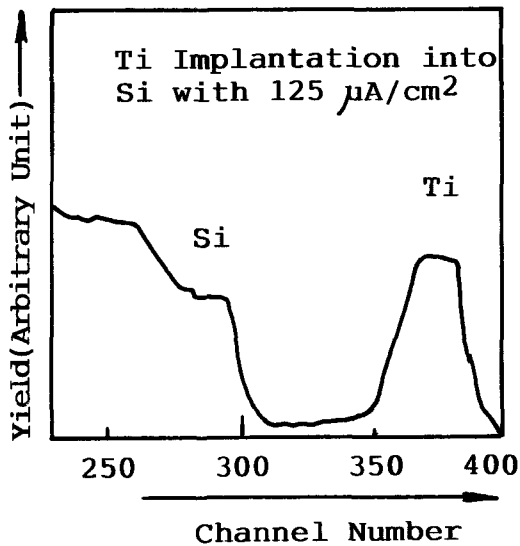


Figure 2. RBS spectrum of a sample implanted with  $125 \mu\text{A}/\text{cm}^2$  to  $5 \times 10^{17} \text{Ti}/\text{cm}^2$ .

TABLE II. Change of sheet resistance as a function of ion current density.

Current density ( $\mu\text{A}/\text{cm}^2$ )	Sheet resistance ( $\Omega / \square$ )
25	65±1
50	60±1
75	46±1
100	3.0±0.1
125	2.5±0.1

samples were calculated to be 36 and 20  $\mu\Omega\text{cm}$ , which fall in a resistivity range of the equilibrium  $\text{C54-TiSi}_2$  phase[5].

From the above results provided by XRD, RBS and sheet resistance analyses, it is concluded that the resultant Ti-silicide was indeed of the equilibrium  $\text{C54-TiSi}_2$ . An important factor responsible to the formation of  $\text{C54-TiSi}_2$  by MEVVA ion implantation technique was regarded to the simultaneous thermal annealing during implantation. According to Wittkower and Hirvonen[6],

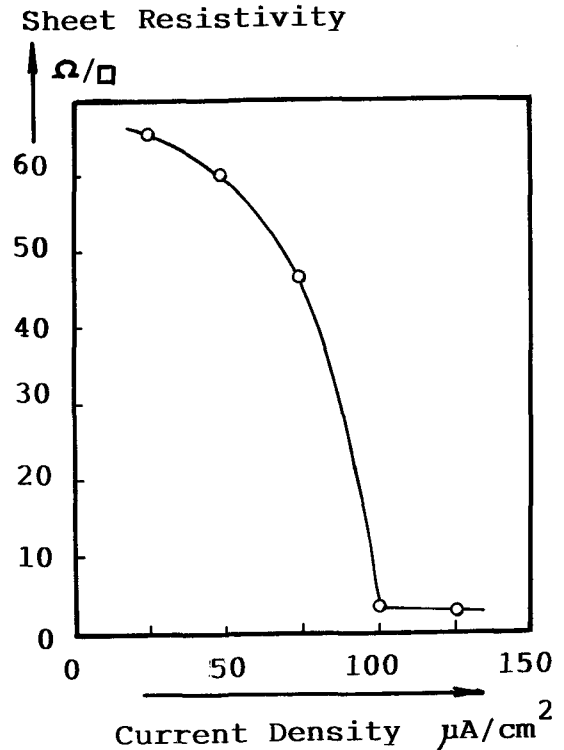


Figure 3. Dependence of sheet resistance as a function of ion current density on the samples implanted with Ti ions to a dose of  $5 \times 10^{17} \text{Ti}/\text{cm}^2$ .

the temperature rise (the time reached this temperature) of the Si wafers during implantation was evaluated to be  $280^\circ\text{C}$ (108 min),  $400^\circ\text{C}$ (54 min),  $480^\circ\text{C}$ (36 min),  $560^\circ\text{C}$ (27 min),  $630^\circ\text{C}$ (22 min), under the corresponding ion current densities of 25, 50, 75, 100, 125  $\mu\text{A}/\text{cm}^2$ , with a fixed dose of  $5 \times 10^{17} \text{Ti}/\text{cm}^2$ . Apparently, the implantation process was not only to provide sufficient Ti atoms, but also accompanied by a thermal annealing caused by beam heating. The temperature required for forming the  $\text{C54-TiSi}_2$  phase was reported to be about  $500^\circ\text{C}$ [7], which meant that the high  $\text{Ti}$  ion current density beyond  $100 \mu\text{A}/\text{cm}^2$  assured a simultaneous thermal annealing at a high enough temperature to form the equilibrium  $\text{C54-TiSi}_2$ . It has been

reported that some other Ti-silicides nucleated before the formation of C54-TiSi<sub>2</sub>[5][7-10] under solid-state reaction. However, in all our implanted samples, none of those Ti-silicides were detected by XRD. It is believed that this phenomenon has to do with the growth kinetics of the Ti-silicides. In principle, all the other Ti-silicides will transform into the equilibrium Ti-silicide, if the Si supply is unlimited and the temperature and time are favored for the formation of C54-TiSi<sub>2</sub>. In our experimental conditions, Si atoms drawn from the Si wafer were always unlimited. For two cases of Ti implantation with the beam current densities of 100 and 125  $\mu\text{A}/\text{cm}^2$ , the simultaneous thermal annealing temperatures and times are both favored to the C54-TiSi<sub>2</sub> formation according to the above calculation. While for the samples implanted by lower current densities, no visible x-ray diffraction lines of any Ti-silicide were observed, indicating that no titanium silicide, at least no big enough grains of titanium silicide, had been formed.

#### 4. CONCLUSION

C54-TiSi<sub>2</sub> with low resistivity was formed in the as-implanted samples by direct Ti ion implantation using high current MEVVA ion source, under an extract voltage of 40kV, a dose of  $5 \times 10^{17}$  Ti/cm<sup>2</sup>, and a current density exceeding 100  $\mu\text{A}/\text{cm}^2$ . The satisfaction of a kinetic condition for C54-TiSi<sub>2</sub> phase to nucleate and grow was resulted by a in-situ thermal annealing process caused by high current beam heating effect. It was expected that the other metal-silicides of interest could also be fabricated by the

similar implantation technique. In fact, the equilibrium WSi<sub>2</sub>, the  $\alpha$ -FeSi<sub>2</sub> and  $\beta$ -FeSi<sub>2</sub> phases were formed by this research group upon relative metal ion implantation using MEVVA ion source, and the results will soon be published.

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