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Ion beam synthesis of buried $CoSi_2$ layers in Si(100) (Co^+ energy = 170 keV, dose = 1.7×10^{17} ions cm^{-2}) is studied as a function of implantation temperature (250→500 °C) and beam current density (1.6→3 $\mu A\ cm^{-2}$). Conventional cross-section transmission electron microscopy and Rutherford backscattering spectrometry are used to correlate the experimental conditions with the amount of pinholes in the silicide layer and the flatness of the $CoSi_2$/Si interfaces after annealing. Optimum implantation conditions yielding a pinhole-free buried silicide layer with flat interfaces are obtained.

Ion beam synthesis (IBS) of $CoSi_2$ refers to a process, in which a buried epitaxial silicide layer in silicon is formed after annealing of a high-dose Co^+ implantation in Si.[1] Typically, the implantations are carried out at elevated temperatures T_i (300–500 °C) to retain crystallinity during implantation.[1–4] Recently, several groups have started to investigate the influence of varying the implantation temperature in the above specified range.[5,6] On the basis of Rutherford backscattering spectrometry (RBS) and channeling measurements, the authors in Ref. 5 concluded that an optimum implantation temperature T_i exists around 350 °C. In Ref. 6 we were led to similar conclusions. Moreover, cross-section transmission electron microscopy (XTEM) observations on as-implanted and annealed samples gave us more insight in the underlying physical mechanisms. From this, it was concluded that beam current density (i.e., implantation time) probably also plays a critical role. Preliminary data (resistivity measurements) indicated that with increasing beam current density better silicide layers could be synthesized. In this letter we will give more experimental data on the influence of beam current density using RBS and XTEM analyses.

The experimental details are given elsewhere[6] and are briefly summarized in the following. Co ions were implanted into 4 in. Si(100) wafers at different temperatures T_i (250, 290, 350, 425, and 500 °C) with an energy of 170 keV and a dose of $1.7\pm0.1\times10^{17}$ at cm^{-2}. Two series were implanted, each with a different beam current density: 1.6 $\mu A\ cm^{-2}$ (set 1) and 3 $\mu A\ cm^{-2}$ (set 2, only at 350, 425, and 500 °C). Because of the limited Co^+ beam current in our machine we implanted only a small area on the wafer: 25 cm^2 (set 1) or 4 cm^2 (set 2). The surface normal was tilted by 7° with respect to the incident beam direction to reduce channeling effects. The implantation temperature T_i was controlled by external heating. Temperature measurements were carried out with a thermocouple on the wafer with the ion beam off. We have checked experimentally that beam heating effects during the high-beam current density implantations raise the sample temperature by no more than 40 °C. Therefore, the experiments carried out at different beam currents (set 1 and set 2) are still comparable as far as implantation temperature concerns. The post-implantation anneal treatments were carried out in a heatpulse 610 (AG) furnace, in the sequence 30 min 600 °C + 30 min 1000 °C in flowing N_2 ambient.

Let us recall some of our previously obtained results.[6] XTEM observations on samples of set 1 reveal a strong influence of implantation temperature on the size and shape of the $CoSi_2$ precipitates in the as-implanted state. For T_i = 350 °C, precipitate size is seen to vary strongly with depth in a way that is logically linked with the implantation depth profile: very small precipitates in the front and back tail and larger ones near the peak of the distribution. For T_i = 500 °C, all precipitates have become appreciably larger and highly facetted. The gradient in the size distribution is less pronounced. X-ray diffraction (XRD) measurements (Fig. 1) of the $CoSi_2$ lattice constant in a direction normal to the surface allowed us to correlate strain relaxation of precipitates with the precipitates becoming larger and highly facetted. XTEM analysis of the annealed samples of set 1 (Fig. 2) reveals that only at a T_i of 350 °C a pinhole-free buried silicide layer could be formed. At higher implantation temperatures, the buried layer formation process is hindered because the gradi-

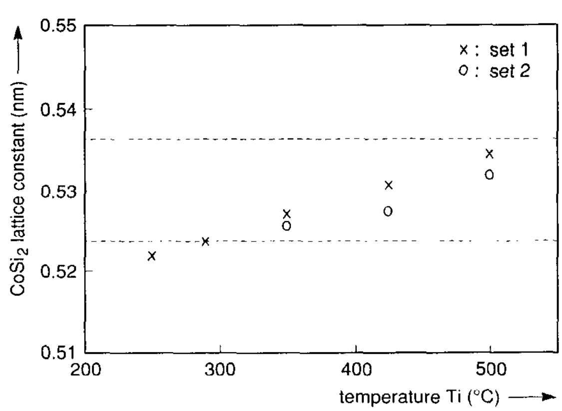

FIG. 1. XRD measurements (from Ref. 6) on as-implanted samples (set 1 and set 2) of the $CoSi_2$ lattice constant perpendicular to the surface as a function of implantation temperature. The upper dashed line indicates the value for $CoSi_2$ powder. The lower dashed line gives the value calculated for tetragonally distorted precipitates that fully match the Si lattice parallel to the surface, assuming conservation of cell volume.

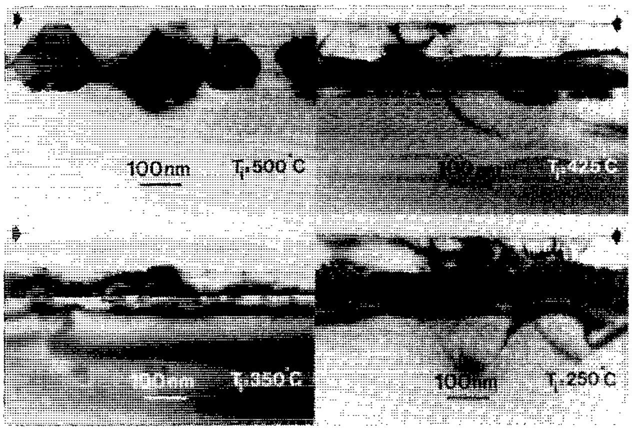

FIG. 2. Bright-field XTEM images (from Ref. 6) of annealed Co-implanted Si(100) samples (Co^+ energy = 170 keV, dose = $1.7 \pm 0.1 \times 10^{17}$ at cm^{-2} and low-beam current density of 1.6 $\mu A\ cm^{-2}$) for different implantation temperatures T_i. Black arrows indicate the position of the Si surface.

ent in precipitate stability over the implanted depth (i.e., the driving force for creating an anisotropic diffusion of Co atoms from the tails towards the peak of the implanted distribution) has become too small. At lower implantation temperatures, radiation damage probably becomes too large.

Obviously, in order to produce high quality buried silicide layers one must prevent that during the Co implantation the $CoSi_2$ precipitates become too large. Since precipitate growth is related to the diffusion of Co atoms, this can be accomplished in two ways: set an upper bound to the implantation temperature (as we showed above) or reduce the implantation time. The latter means that we expect that better silicide layers can be produced using higher ion-beam current densities. For instance, we hope that the facetted $CoSi_2$/Si interfaces observed after annealing a sample implanted at the optimum $T_i = 350$ °C with

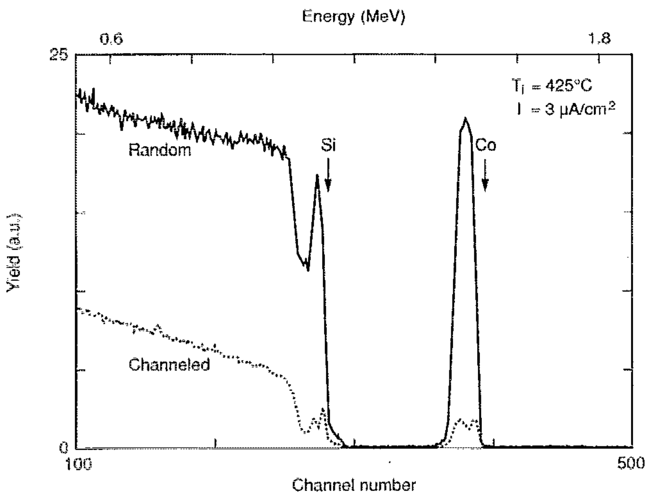

FIG. 3. Random (solid line) and channeled (dotted line) RBS measurements on an annealed Co-implanted Si(100) sample (Co^+ energy = 170 keV, dose = 1.75×10^{17} at cm^{-2}, $T_i = 425$ °C and beam-current density = 3 $\mu A\ cm^{-2}$) using a 2 MeV He^+ ion beam.

TABLE I. RBS minimum yield values (χ_{min}) of the Co signals of the implanted samples after high-temperature annealing.

T_i(°C)	χ_{min}(%) 1.6 $\mu A\ cm^{-2}$	3 $\mu A\ cm^{-2}$
350	10.0%	10%
425	13.5%	9%
500	18.5%	12%

low-beam current density (Fig. 2) can be improved. Therefore, samples were implanted with a two times higher beam current density (set 2). XRD measurements (Fig. 1) already indicated that indeed in this way precipitate growth could be reduced. This is concluded from the fact that samples implanted with the higher beam current density show less strain relaxation in the silicide precipitates. Figure 3 shows a typical RBS measurement on an annealed sample of set 2, implanted at $T_i = 425$ °C. Similar measurements were carried out for other annealed samples of set 2 and set 1 implanted in the temperature range 350–500 °C (not shown). For each spectrum we determined the minimum yield value of the Co signal. To obtain a more reliable indication of the crystalline quality of the structures, the minimum yield was defined as the ratio between the integrated channel yield and the integrated random yield. These values are summarized in Table I. The uncertainty in these minimum yield values is typically less than 5%. These data show that for $T_i = 350$ °C, beam current density variations from 1.6 to 3 $\mu A\ cm^{-2}$ do not result in any

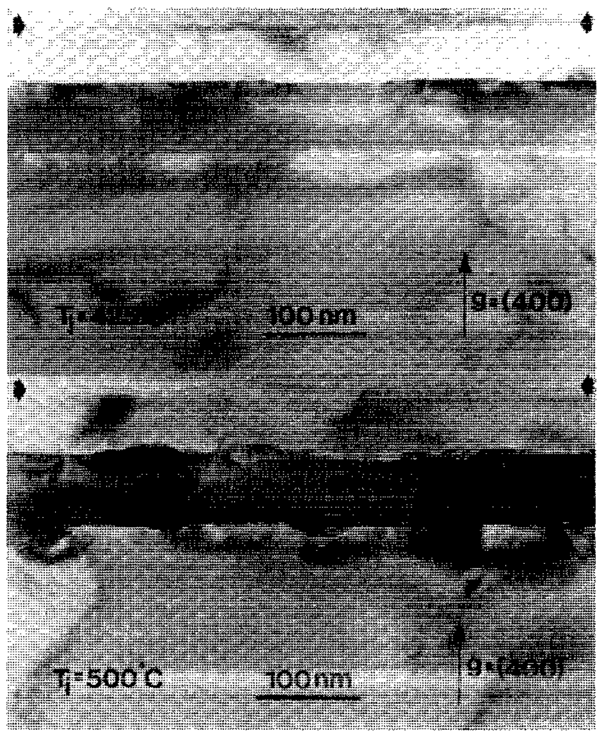

FIG. 4. Bright-field XTEM images of annealed Co-implanted Si(100) samples (Co^+ energy = 170 keV, dose = 1.75×10^{17} at cm^{-2} and high-beam current density of 3 $\mu A\ cm^{-2}$) for different implantation temperatures T_i. Black arrows indicate the position of the Si surface.

measurable difference in the Co minimum yield. However, for the higher implantation temperatures the minimum yield is greatly improved for the highest beam current density. These minimum yield variations reflect differences in the microstructure of the annealed samples. For instance, for $T_i = 500\,^\circ\text{C}$, in case of the implantation with a low-beam current density, annealing of this sample did not result in buried layer formation. Instead, a series of large isolated precipitates was formed (Fig. 2). In case of the implantation with a high-beam current density a buried silicide layer is formed with, however, a highly facetted $CoSi_2$/Si interface (Fig. 4). According to Table I the best silicide layer is formed at $T_i = 425\,^\circ\text{C}$ with a high-beam current density of 3 μA cm^{-2}. XTEM observations on this sample (Fig. 4) demonstrate that the silicide layer is pinhole free (also confirmed by plan-view TEM) and has a very flat $CoSi_2$/Si interface. In fact, this interface is much better as compared to what is observed after annealing the sample implanted with a lower beam current density at 350 °C (Fig. 2). The interfacial steps have not totally disappeared, but the stepheight is strongly reduced (typically less than 3 nm).

In summary, we have shown that, when the Co implantation dose exceeds the critical dose for buried silicide layer formation, the quality of the silicide layer strongly depends on implantation temperature and ion-beam current density. We have obtained good quality silicide layers (pinhole free and nearly flat $CoSi_2$/Si interfaces) at an implantation temperature of 425 °C and a beam-current density of 3 μA cm^{-2}. We did not investigate higher beam current densities since, in our case, temperature variations over the implanted area would become too large. Nevertheless, we think that, if one can control the implantation temperature within about 20 °C, it may lead to even further improvements of the material properties.

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