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Dose rate effects in focused ion beam synthesis of cobalt disilicide

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The influence of the dwell-time in focused ion beam synthesis has been investigated. Cobalt disilicide layers have been produced by 70 keV Co^{2+} implantation into silicon and have been investigated by Rutherford backscattering spectroscopy and scanning electron microscopy. At an implantation temperature of about 400 °C it is only possible to form continuous $CoSi_2$ layers using sufficiently short pixel dwell-times. This result is explained by an enhanced damage accumulation for longer dwell-times. © *1998 American Institute of Physics.* [S0003-6951(98)03421-4]

Cobalt disilicide is one of the promising silicides for future device metallization and the development of new metal–semiconductor devices. $CoSi_2$ is perfectly suited for silicon technology due to its cubic CaF_2 lattice structure with a mismatch of only -1.2% relative to the silicon lattice. It shows metallic behavior with a resistivity of only 15 $\mu\Omega$ cm and has a Schottky barrier height of 0.64 eV in contact to *n*-type silicon. To our knowledge the production of high-quality buried $CoSi_2$ layers on Si(111) and Si(100) is only possible by ion beam synthesis (IBS)[1] or allotaxy.[2] Allotaxy is a combination of epitaxial growth of the host material (silicon) and the controlled deposition of a precipitating compound by coevaporating a second component (cobalt) at a substrate temperature of about 500 °C. Subsequent annealing leads to a continuous buried layer, but the patterning has to be done after the layer preparation, e.g., by local oxidation.[3] When using IBS, at sufficiently high ion energy a high dose cobalt ion implantation results in a buried distribution of $CoSi_2$ precipitates. To avoid target amorphization a substrate temperature of about 400 °C is required. During subsequent annealing, the precipitates ripen and coalesce to form a continuous buried $CoSi_2$ layer. For a detailed description of the IBS process, see, e.g., Ref. 4. In the case of IBS the patterning of the layer can simply be done by implantation through a mask. However, e.g., for prototyping of new devices, a maskless implantation is also possible with a focused ion beam (FIB) system. The FIB offers the additional possibility of changing the implantation parameters, like the dose or the energy, on any single area of the silicon wafer. Aoki *et al.*[5] showed the possibility of forming $CoSi_2$ layers by high dose implantation using a FIB. Later Bischoff *et al.*[6] formed $CoSi_2$ layers with a FIB successfully.

However, broad beam and FIB implantation cannot be directly compared due to the large difference of the characteristic current densities. For conventional implantation typical current densities are about 10 $\mu A\,cm^{-2}$, compared to about 1 $A\,cm^{-2}$ and more for FIB. For the extremely high current densities associated with FIB, one might further anticipate dose-rate effects in the case of continuous writing and dwell-time effects for the patterning by pixels. The present letter will present a clear indication of such a dwell-time effect and discuss it in terms of damage accumulation and dynamic annealing.

Implantations for $CoSi_2$ formation have been performed with the IMSA-100 FIB system[7] using a mass separated 70 keV Co^{2+} beam with a total ion current of about 0.7 nA, extracted from a $Co_{36}Nd_{64}$ liquid metal ion source (LMIS) and focused to a spot size of about 300 nm. The corresponding current density is about 1 $A\,cm^{-2}$. The tilt angle was 0° and the target material was *n*-Si(111) heated to a temperature of 400 °C. The beam was scanned meanderlike on an area of $40\times40\ \mu m^2$ using subsequent pixels with a distance of 80 nm. The total dose was about 10^{17} ions/cm^2, corresponding to 3×10^1 and 3×10^3 frames at dwell times of 100 and 1 μs, respectively. The switching of the beam between subsequent pixel positions takes 0.1 μs. For characterization, Rutherford backscattering spectroscopy (RBS) of the as-implanted samples has been performed with a nuclear microprobe[8] using a 3 MeV Li^{2+} beam with a spot size of about 5 μm. The annealed samples (60 min at 600 °C and 30 min at 1000 °C in a nitrogen atmosphere) have been investigated by scanning electron microscopy (SEM) after the silicon top layer had been removed by CF_4 reactive ion etching (RIE) for 6 min. Exact knowledge of the thickness of the silicon top layer is not necessary because $CoSi_2$ acts as an etch stop for CF_4 RIE.[9]

As seen in Fig. 1, the SEM images of the annealed samples show that continuous $CoSi_2$ layers can only be formed using sufficiently short pixel dwell-times. When the dwell-time is increased, the layers exhibit holes and are completely disintegrated at a dwell-time exceeding 100 μs. To decide whether this effect is due to annealing, SEM analysis of as-implanted samples has been performed. The results prove that the disintegration is already present in the as-implanted samples. To obtain more information about the as-implanted state of the samples RBS measurements have been performed, as shown in Fig. 2, revealing a deeper distribution of the cobalt atoms for the short dwell-times than for the long ones. The change from continuous to disrupted layers is correlated directly with a shift of the as-implanted profiles of the cobalt atoms.

The reason for the shift of the cobalt profiles can be a

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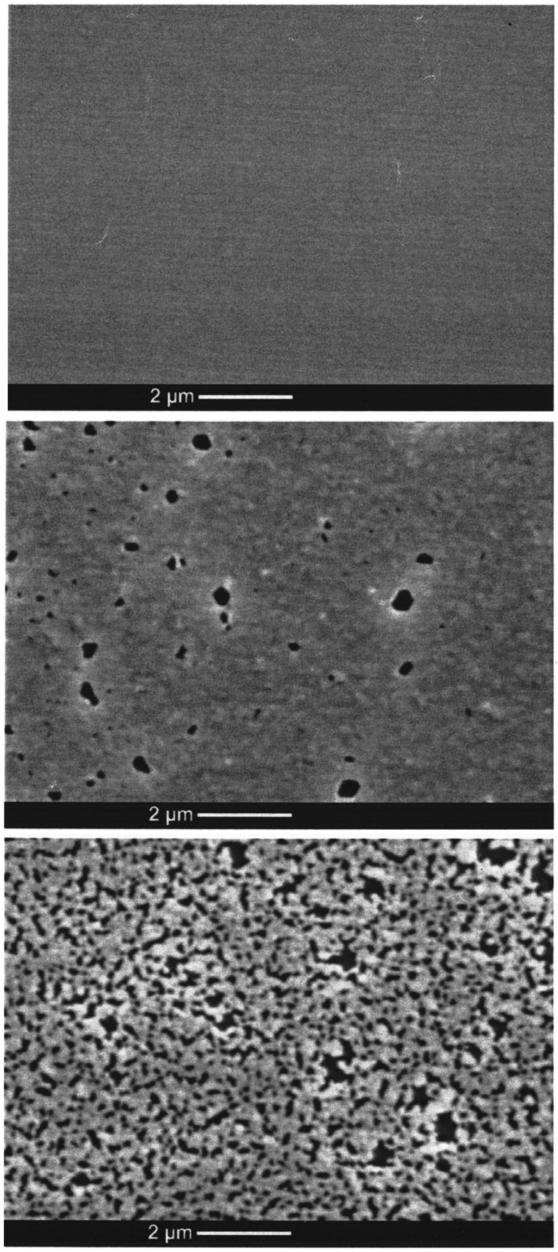

FIG. 1. In this series of plane view SEM images the influence of different dwell-times is shown. The first image shows a $CoSi_2$ layer fabricated with a short pixel dwell-time of 1 μs. The layer is continuous and smooth. On the next image the dwell-time is increased to 50 μs and the layer shows some holes and an enhanced roughness. When the dwell-time is increased to 100 μs the layer is totally disintegrated as it can be seen on the last image. Experimental parameters are: Si(111) substrate, dose of 10^{17} cm^{-2}, beam spot size of 300 nm, current density of 1 A cm^{-2}.

different damaging and dynamic annealing behavior of the silicon target for different dwell-times. If the use of short dwell-times results in a less damaged silicon target, channeling of the cobalt atoms occurs and sputtering is reduced. In this case the reason for the insufficient formation of the $CoSi_2$ layer is a too high degree of damage of the silicon matrix for the formation of a continuous $CoSi_2$ layer at long dwell-times. Another effect could be pure diffusion of the cobalt atoms, and then the transition from continuous or disrupted layers would be due to kinetics of Ostwald ripening and coalescence. The combination of both effects is also possible, e.g., that the diffusion behavior is changed due to dif-

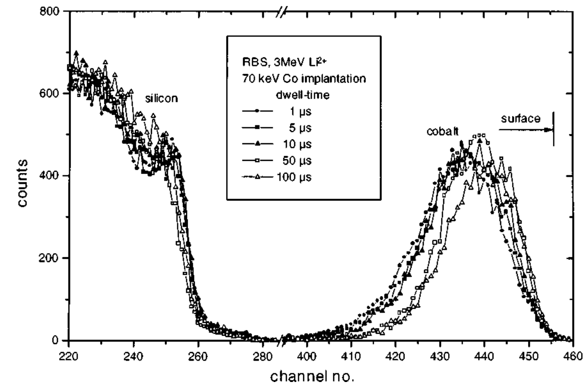

FIG. 2. RBS spectra obtained from a nuclear microprobe of as-implanted samples fabricated with different dwell-times. It can be seen that the cobalt distribution shifts deeper into the silicon with decreasing pixel dwell-times. Of special interest is that only the deeper cobalt distributions result in a continuous layer formation.

ferent target damaging. To determine whether damage effects are responsible for the different layer formation channeling RBS measurements have to be performed.

A direct measurement of the lattice damage by channeling RBS was not possible for our layers because of the limited FIB implantation area using stoichiometric doses. The application of the nuclear microprobe with a small spot size for channeling RBS measurement is not possible because of self-damaging effects.

Instead, low cobalt doses (2×10^{16} cm^{-2}) were implanted into larger areas with a diameter of 300 μm using a 35 keV Co^+ beam and a substrate temperature of 430 °C to investigate the early state of the layer formation. (For this energy, a slightly higher temperature is required to form a continuous layer for 1 μs dwell-time at sufficiently high doses, in accordance with results from broad-beam experiments.[10]) The total implantation time for every pixel was 250 μs. Implantations were performed using 1 μs dwell-time and 250 repetitions, and 250 μs dwell-time in one cycle. RBS and channeling RBS spectra were measured with a van de Graaff accelerator using a 1.7 MeV He^+ beam with a spot size of about 1 mm. In order to suppress the signal from the unimplanted area the wafer was masked with an AZ 4562 photoresist after implantation, a hole with a 500 μm diameter was opened at the irradiated area using standard optical lithography. This reduces the size of the unimplanted silicon which contributes to the measurement. For the evaluation of the spectra a constant helium beam profile was assumed across the 500 μm hole. The results are shown in Fig. 3. A comparison of the measurements shows that the use of short dwell-times results in a lower damage of the target. Additionally it can be seen that for the implantation using 1 μs dwell-time the silicon surface layer remains crystalline. For a dwell-time of 250 μs the surface layer is amorphous, with respect to channeling. Thus, we conclude that different dwell-times result in a different degree of damage due to dynamic annealing.

There are some further arguments which support the idea that the different behavior of the layer formation is due to the fact that the different dwell-times result in different degrees of damage of the silicon target. Jebasinski[11] has shown for broad beam experiments that channeling implantation of co-

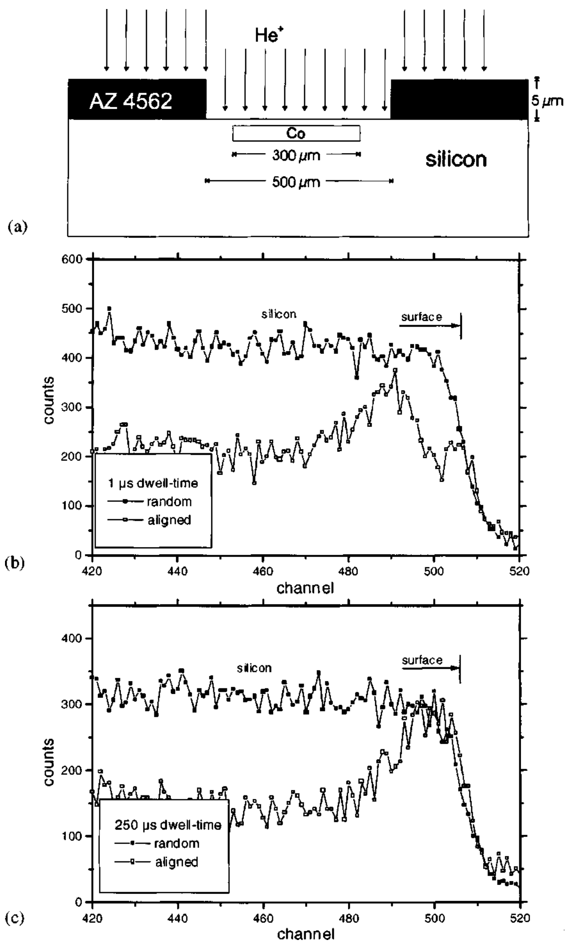

FIG. 3. (a) Schematic view of the sample preparation with small implanted areas using a conventional RBS/channeling setup. (b) RBS/channeling spectra of an as-implanted sample. Implantation with a low dose 35 keV Co^+ FIB into Si(111) at 430 °C and a dwell-time of 1 μs. The aligned spectra is multiplied with the ratio of the total area of the opened hole in the resist to the implanted area (=25/9). (c) Same as in (b) except a dwell-time of 250 μs. The damage level for 1 μs dwell-time implantation is reduced in contrast to that of 250 μs.

balt is possible even at those high doses of about 10^{17} cm^{-2}. In addition, broad beam implantation of cobalt in random direction (7° tilt angle) was successfully simulated[12] by high dose TRIM (HDTRIM),[13] indicating that the implantation profiles are governed by collisional effects rather than diffusion. A similar dwell-time effect was also found for GaAs. Low-dose Ga FIB implantation with different dwell-times has been investigated[14] on GaAs wafers at room temperature and the corresponding samples were analyzed by RBS channeling. The samples implanted with longer dwell-times showed a higher degree of damage than those with short dwell-times. Tamura *et al.*[15] showed for FIB implantation of boron into silicon that the electrical activity after annealing is higher for samples implanted with a slow scanning speed. This is an indication of a higher damage for longer dwell-times. The same was found by Madokoro *et al.*[16] for FIB implantation of phosphorus into silicon.

Thus, the damage of the silicon lattice has a strong influence on the $CoSi_2$ layer formation. For long dwell-times the damage accumulation of the silicon lattice during the cobalt implantation prevents the formation of continuous $CoSi_2$ layers. For short dwell-times the results are comparable to broad beam ion implantation where the thermally induced defect annihilation prevents an amorphization of the silicon wafer. It is also helpful to compare the present results to ion beam induced crystallization and amorphization experiments performed by Linnros *et al.*[17] with pulsed ion beams. As explained by Jackson[18] at a low pulse frequency the results are comparable to experiments with a constant beam with the same current. For high pulse frequencies the results correspond to experiments with a constant beam but with the averaged current of the pulsed beam. If this knowledge is transferred to our results, although the conditions are rather different, this means that for short dwell-times the effective ion arrival rate per pixel is reduced. In comparison with long dwell-times, when the steady-state case is assumed, the effective current density for the 40×40 μm^2 implanted areas with short dwell-times is a factor of 2.5×10^5 smaller (for 1 μs). This means that the effective current density is now on the order of $\mu A\ cm^{-2}$ which is comparable to the current density of broad beam ion implantation.

In summary 70 keV Co^{2+} was implanted with a focused ion beam system into a heated silicon target to form continuous cobalt disilicide layers. A strong influence of the dwell-time on the $CoSi_2$ layer formation was found. For sufficiently short dwell-times it was possible to form continuous $CoSi_2$ layers while for long dwell-times it was shown that the increased damage accumulation of the silicon target prevented the formation of a continuous $CoSi_2$ layer.

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