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Dopants redistribution during titanium-disilicide formation by rapid thermal processing

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Redistribution of implanted As (5×10^{15} cm^{-2}, 150 keV) and Sb (1×10^{15} cm^{-2}, 200 keV) due to $TiSi_2$ formation by rapid thermal processing was investigated by means of backscattering spectroscopy. By choosing properly the rapid thermal processing parameters, low resistance uniform silicides layers (typically 14 $\mu\Omega$ cm) were obtained, and dopant loss by out-diffusion and redistribution of the dopant were made negligible. High peak concentrations of dopant within silicon substrate, beneath the silicide, were obtained for all processing times.

Metal silicides have been used as gate electrodes and interconnects in advanced metal-oxide-semiconductor (MOS) very-large-scale integrated (VLSI) structures because of their low resistivities.[1] As device dimensions are scaled down, the parasitic resistances, namely, gate resistance and source/drain diffusion and contact resistance, increase and limit device performance. Thus, it is highly desirable to have self-aligned silicides on source and drain contact regions as well as on the gate, in order to ease the lithographic requirements and to lower contact and interconnect resistances. In these self-aligned structures, metal silicides are formed on highly doped n^+ and p^+ silicon with very shallow junctions. Therefore, it is essential to understand the dopant redistribution during high-temperature silicide formation. It has been shown recently that titanium-disilicide, which has the lowest resistivity among the refractory metal silicides, can be formed by rapid thermal processing (RTP).[2-5] In this communication, we report the behavior of implanted Sb and As atoms during $TiSi_2$ formation by RTP, and compare the results with the dopant redistribution during furnace annealing.[6-10]

In our experiments p-type B-doped silicon wafers with a nominal resistivity of 1.8–2.2 Ω cm and $<100>$ orientation were used. The samples were chemically cleaned before the As^+ or Sb^+ implantation at room temperature, with energies of 150 keV (dose $=5\times10^{15}$ cm^{-2}) and 200 keV (dose $=1\times10^{15}$ cm^{-2}), respectively. The silicon surface layer amorphized by dopant implantation was recrystallized epitaxially by furnace annealing at 600 °C during 30 min in a N_2 atomsphere. A 40-nm-thick Ti film was subsequently deposited on each sample using a resistively heated tungsten boat, at a base pressure of 1×10^{-5} Pa. Following the evaporation, the RTP was performed by a graphite heater similar to the one reported by Fulks *et al.*[11] The pressure in the RTP chamber during the high-temperature cycle was 1×10^{-3} Pa. The samples were annealed at 850 °C during times between 10 and 60 s. This processing time is the total period of time during which the samples are exposed to the heater. It includes the heating period of the sample (around 10 s), but not the cooling period, since the samples are suddenly taken away from the graphite heater, to the thermally shielded region, after the selected time of exposure.

The composition, the thickness of the silicide layers and the dopant profiles before and after silicide formation were determined by 2-MeV helium backscattering spectroscopy. Sheet resistance was measured using a standard four-point probe method. Low-resistance uniform silicide layers were obtained after about 10-s annealing. For the Sb implanted samples, the measured resistivities of the silicides ranged from around 20 $\mu\Omega$ cm for 10-s annealing to around 10 $\mu\Omega$ cm for 60-s annealing, whereas for the As implants the resistivities of the silicides ranged from around 15 $\mu\Omega$ cm for 10-s annealing to around 13 $\mu\Omega$ cm for 60-s annealing.

In Fig. 1 the backscattering spectra are shown for samples processed during 10 and 60 s. In Figs. 2 and 3 the depth profiles of As and Sb, after each of the sintering conditions, are shown in more detail.

It can be noted that the oxygen peak in the RBS spectra is visible only in the samples processed during 10 s. For longer times of processing, when the Ti film is completely consumed, the oxygen is expelled from the silicide layer. This behavior is consistent with the one observed by Berti *et al.*[12] for furnace annealing. The presence of an appreciable concentration of oxygen at the outermost surface of the titanium film, causes the retention of dopant at the surface of the Sb implanted sample processed for 10 s (see Fig. 3), since oxygen-rich titanium can act as a barrier against out-diffusion of the dopant.

The behavior of implanted Sb and As atoms during $TiSi_2$ formation by RTP, as described respectively in Figs. 2 and 3, is rather similar to that observed for refractory-metal silicides formed by furnace annealing. In both cases the majority of the dopants are located within the silicon substrate beneath the silicide.[6-10] Measurements similar to the ones presented here were reported previously by Maex *et al.*[13] The results of both works are comparable, although there are specific differences in the RTP parameters, and in the fact that Maex *et al.* did not quote the dopant concentrations after RTP, apart from chemically removing the $TiSi_2$ layer before determining the As profiles.

The general trend observed here was that the concentration of As and Sb present within the silicon substrate decreases with increasing processing time. However, the dopant loss by out-diffusion and the redistribution of the

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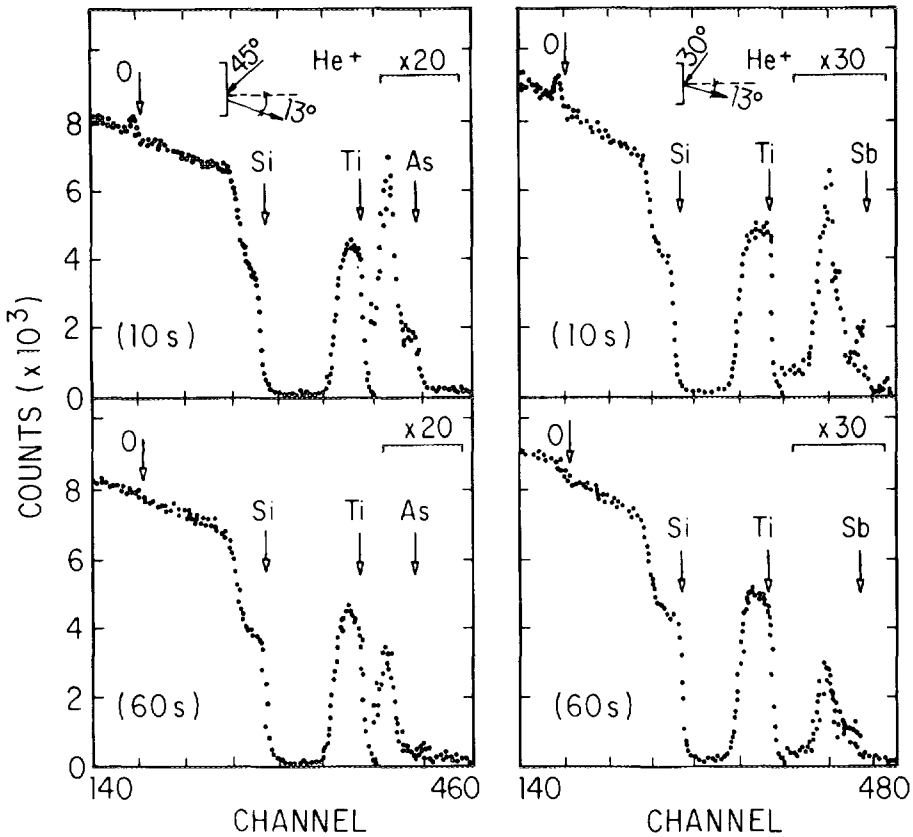

FIG. 1. 2-MeV helium backscattering spectra of the $TiSi_2$ layer formed after sintering at 850 °C during exposure times of 10 and 60 s. Surface positions of dopants, titanium, silicon, and oxygen, are shown by arrows.

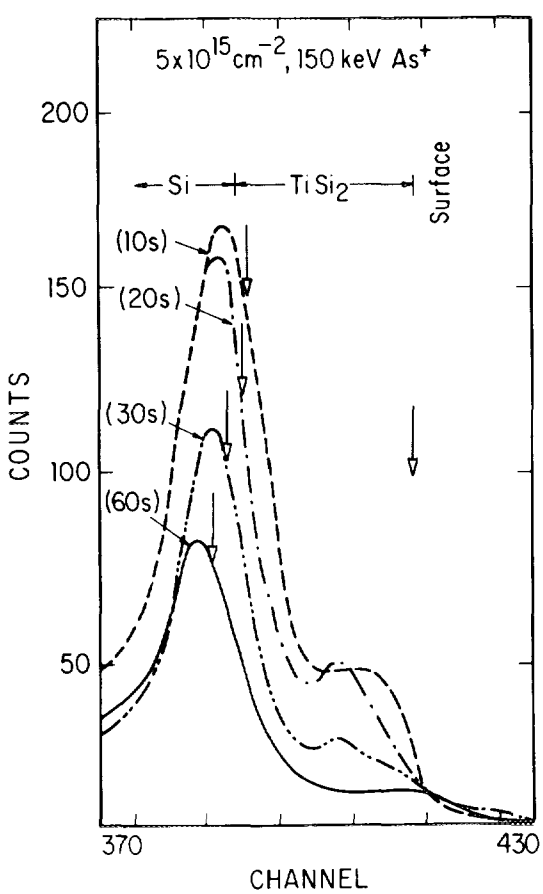

FIG. 2. 2-MeV helium backscattering spectra of As profiles in the silicon substrates at different annealing times. The arrows indicate the position of the outermost surface and the position of the silicide-silicon interface. The peak concentration of As in silicon after 850 °C, 10-s processing is 4×10^{20} cm^{-3}.

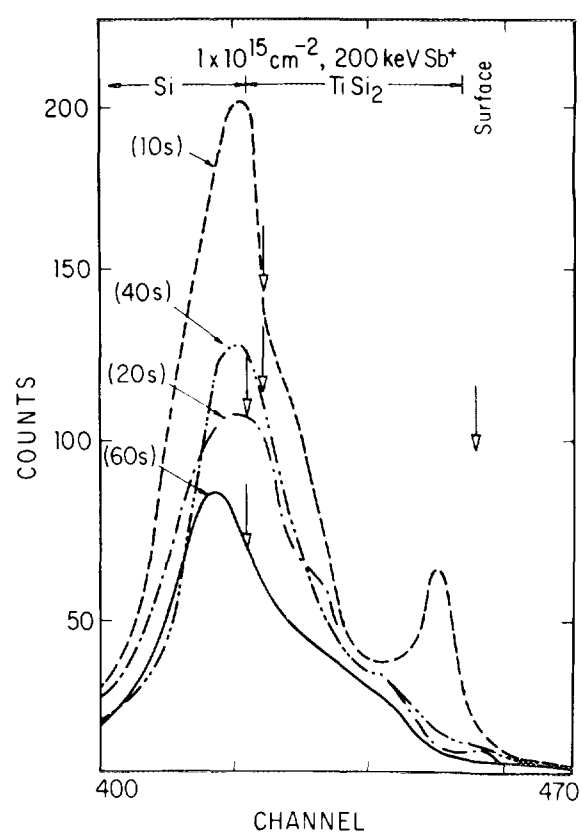

FIG. 3. 2-MeV helium backscattering spectra of Sb profiles in the silicon substrates at different annealing times. The arrows indicate the position of the outermost surface and the position of the silicide-silicon interface. The peak concentration of Sb in silicon after 850 °C, 10-s processing time is 9.1×10^{19} cm^{-3}.

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implanted profiles are negligible in the case of 10-s processed samples for both kinds of dopants. Even for the larger processing time (60 s) at which the titanium layer has been completely consumed, peak dopant concentrations of 4.1×10^{19} cm^{-3} and 1.2×10^{20} cm^{-3} of Sb and As, respectively, have been obtained.

The mechanism for dopant redistribution and loss during silicide formation has been discussed by Amano *et al.*[7] The process is usually initiated by silicide formation, followed by the incorporation of the dopant initially present in the silicon layer, which is consumed for the silicide formation. After incorporation into the silicide, the dopant can diffuse towards the outermost surface where it precipitates or eventually evaporates.

The behavior of As atoms is somewhat different from that of the Sb atoms. As shown in Fig. 2, As atoms are distributed homogeneously within the growing $TiSi_2$ layer. This is different for Sb atoms, whose distribution is nonuniform. At least for one sample (10-s annealing) Sb dopants are trapped at the surface in the nonreacted metal film. As atoms, on the other hand, were not observed to be trapped at the metal surface. These results are in good agreement with the results obtained by Amano[7,10] and Rèvèsz[6] for the dopant redistribution during $TiSi_2$ formation by furnace annealing.

In summary, the dopant redistributions during titanium disilicide formation by RTP (850 °C, 10–60 s) were monitored by RBS. It was observed that an appreciable amount of dopant remains within the silicon substrate. In this way, shallow junctions, adequate for VLSI, were obtained with junction depths of 150 nm for As- and 180 nm for Sb-implanted silicon. Furthermore, low resistivity (typically 14 $\mu\Omega$ cm) uniform and smooth thin films of $TiSi_2$ were obtained on silicon samples doped with a high concentration of As or Sb.

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Acousto-optic interaction in proton-exchange 128° rotated *Y*-cut $LiNbO_3$ optical waveguides

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The characteristics of proton-exchanged optical waveguides using a new substrate of 128° rotated *Y*-cut $LiNbO_3$ were investigated. The variation of refractive index was found to be $\Delta n \simeq 0.07$, because the crystallographic *c* axis was oblique to the surface normal. As a result, the number of guided modes versus the depth of proton exchange was small compared with that in conventional substrates. Acousto-optic interaction between a guided mode and surface acoustic wave exhibited the diffraction efficiency of about 50% for the acoustic power of 18 mW at 130 MHz. This suggested that after the proton-exchange process, an apparent photoelastic coefficient was still maintained with the reduction factor of $1/\sqrt{3}$.

In terms of dynamic addressing and flexible light modulation, surface acoustic waves (SAWs) play important roles[1] in the optical waveguides used in analog signal processing with such devices as convolver and spectrum analyzers as well as in parallel signal processing with multiplexer and digital correlators. In these cases, mostly, the substrate is a *Y*-cut $LiNbO_3$ plate, wherein the intensity modulation[2] of guided optical waves is carried out by the electric field rather than the strains accompanied with the SAW. However, this substrate has some problems. First, the proton-

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