Direct synthesis of continuous Sm disilicide films by Sm-ion implantation using a metal vapour vacuum arc ion source

2000 J. Phys.: Condens. Matter 12 9195

(http://iopscience.iop.org/0953-8984/12/44/301)

J. Phys.: Condens. Matter **12** (2000) 9195–9200. Printed in the UK PII: S0953-8984(00)13924-4

Direct synthesis of continuous Sm disilicide films by Sm-ion implantation using a metal vapour vacuum arc ion source

X Q Cheng, H N Zhu, R S Wang and B X Liu†
Advanced Materials Laboratory, Department of Materials Science and Engineering,
Tsinghua University, Beijing 100084, China
E-mail: `dmslbx@tsinghua.edu.cn` (B X Liu)

Received 16 May 2000, in final form 15 September 2000

Abstract. Samarium-ion implantation was carried out to synthesize Sm disilicide films on silicon wafers, using a metal vapour vacuum arc ion source, and the continuous $SmSi_2$ films were directly obtained with neither external heating nor post-annealing. Diffraction and surface morphology analysis confirmed that the Sm disilicide films formed had good crystalline structure under appropriate experimental conditions. Also, the mechanism of formation of the $SmSi_2$ phase is discussed, in terms of the temperature rise caused by ion beam heating and the ion dose imparted in the process of implantation.

Rare-earth (RE) metal silicides have attracted considerable attention because they can form the lowest Schottky barrier height (0.3–0.4 eV) on an n-type silicon surface [1–3], and because of their potential applications in the fabrication of infrared detectors. Accordingly, various techniques have been developed to synthesize RE metal silicides, such as solid-state reaction (SSR) and ion beam synthesis (IBS). It was reported that in SSR, the interaction between the RE metals and single-crystalline silicon behaved as a 'critical temperature' phenomenon, i.e. below the critical temperature (300–350 °C), the interaction was very sluggish, whereas above the critical temperature, the interaction was explosive and out of control [4–6]. Furthermore, the RE metal silicide layers formed by SSR were typically dominated by some pits [7], which have a detrimental effect on their electronic performance. The conventional IBS technique, generally consists of two steps. Firstly, high doses of metal ions were implanted into Si wafers which were simultaneously heated to a temperature of 400 ± 50 °C. Secondly, a post-annealing was conducted after implantation to form the RE metal silicide layers, which were frequently discontinuous [8]. In 1995, continuous buried RE metal silicide layers with good crystallinity were obtained by the channelling IBS technique [9], in which the necessary high-temperature (1000 °C) post-annealing may affect the properties of the integrated circuits.

In the mid-1980s, a new ion source was invented, namely the metal vapour vacuum arc (MEVVA) ion source [10], and was later employed by the authors' group to successfully synthesize metal silicides on Si wafers, such as C54-$TiSi_2$, β-$FeSi_2$, $CoSi_2$, $NiSi_2$ and $ZrSi_2$ [11–15]. Continuing on from this, we investigate, in the present study, the possibility of directly synthesizing Sm disilicide layers on silicon wafers by high-current Sm-ion implantation using a MEVVA ion source.

---

† Author to whom any correspondence should be addressed.

0953-8984/00/449195+06$30.00

The silicon wafers used in this study were of n-type Si(100) with resistivities of 30 to 50 Ω cm. The wafers were cut into 1 × 1 cm^2 samples. The samples were cleaned by a standard chemical procedure and then dipped in a dilute HF solution; this was followed by a rinse in deionized water. The cleaned samples were then loaded onto a steel-made sample holder in the target chamber of the MEVVA implanter with a vacuum level of 2×10^{-3} Pa and held at an extracting voltage of 40 kV. During implantation, there was no deliberate heating of the samples. As the implantation system has no analysis magnet, the extracted samarium ions were analysed and found to consist of 2% Sm^{1+}, 83% Sm^{2+} and 15% Sm^{3+}. The samples were implanted with current densities varying from 8.8 to 35.2 μA cm^{-2} to nominal doses ranging from 5×10^{16} to 2×10^{17} ions cm^{-2}. X-ray diffraction (XRD) analysis was performed to identify the MEVVA-synthesized Sm disilicide, using a D/max-RB diffractometer operated with Cu radiation of wavelength 1.541 78 Å at 40 kV and 120 mA. A step-scan method was used with 0.02° per step and a stopping time of three seconds. Rutherford backscattering spectrometry

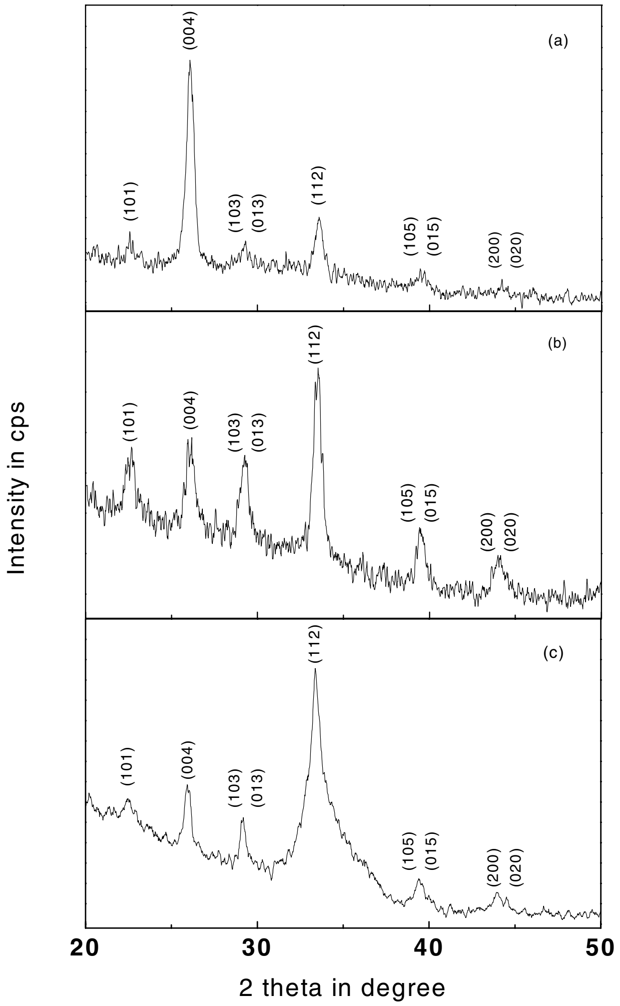

Figure 1. XRD patterns of Si wafers implanted with samarium ions at a current density of 1×10^{17} ions cm^{-2}: (a) 8.8 μA cm^{-2}; (b) 17.6 μA cm^{-2}; (c) 35.2 μA cm^{-2}.

(RBS) was conducted with 2.023 MeV He ions at a 165° scattering angle to measure the depth profile of the implanted Sm in the Si wafers. A scanning electron microscope (SEM) was used to reveal the surface morphologies of the Sm disilicide layers formed on the Si wafers.

After implantation of Sm ions into Si wafers with current densities of 8.8, 17.6 and 35.2 μA cm^{-2} to a dose of 1×10^{17} ions cm^{-2}, x-ray diffraction analysis showed that the SmSi$_2$ phase was indeed formed on these implanted Si wafers and the XRD patterns are shown in figure 1. During implantation, the corresponding temperature rises of the Si substrates were measured, using a thermal couple, to be 190, 290 and 390 °C, respectively; these can be considered as the formation temperatures of the Sm silicide under the respective conditions. It is very interesting that the Sm silicide can be obtained by MEVVA ion implantation over a broad temperature range of 190–390 °C—in contrast to the explosive process and narrow formation temperature regime in SSR mentioned above.

One sees in figure 1(a) that most of the diffraction peaks of SmSi$_2$ appear, although they are very weak except a strong (004) peak, indicating that a strong texture has emerged. In

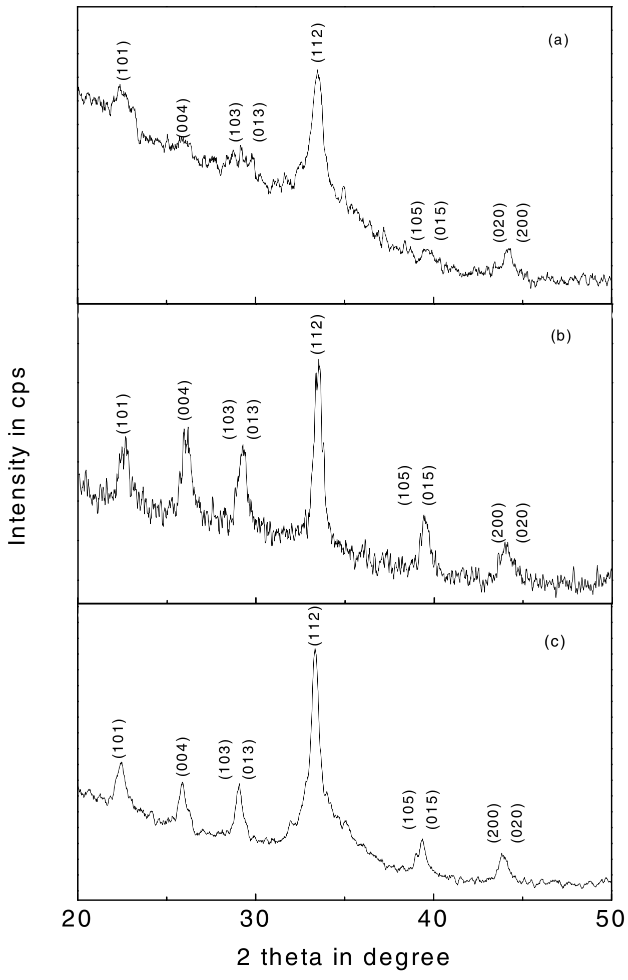

Figure 2. XRD patterns of Si wafers implanted with samarium ions to a fixed dose at a current density of 17.6 μA cm^{-2}: (a) 5×10^{16} ions cm^{-2}; (b) 1×10^{17} ions cm^{-2}; (c) 2×10^{17} ions cm^{-2}.

figure 1(b), almost all of the diffraction peaks from $SmSi_2$ are very strong, meaning that the $SmSi_2$ formed has a good crystalline structure, while in figure 1(c), the XRD pattern is very similar to that displayed in figure 1(b). These results indicated that a formation temperature of 290 °C was high enough for synthesizing the $SmSi_2$ layer on Si wafers with a well-crystallized structure by MEVVA ion implantation.

As regards the effect of the ion dose on the formation of Sm disilicide layers, we discuss a typical case of Sm implantation with a fixed current density of 17.6 μA cm^{-2}, i.e., at a formation temperature of 290 °C, to various ion doses. Figure 2(a) shows an XRD pattern for the Si wafer implanted to a dose of 45×10^{16} ions cm^{-2}. One sees that the diffraction peaks arising from the $SmSi_2$ phase are neither sharp nor strong, indicating that the $SmSi_2$ was not yet crystallized well. On increasing the ion dose up to 1×10^{17} ions cm^{-2}, the crystalline structure of the $SmSi_2$ phase formed was considerably improved, as shown by the XRD pattern in figure 2(b). On further increasing the ion dose up to 2×10^{17} cm^{-2}, the corresponding XRD pattern shown in figure 2(c) becomes quite similar to that displayed in figure 2(b). These results seemed to suggest that an ion dose of 1×10^{17} ions cm^{-2} was about the so-called ‘suited nominal value’ for synthesizing $SmSi_2$ with a well-crystallized structure by MEVVA ion implantation. It is therefore concluded that the optimal experimental parameters for synthesizing the $SmSi_2$ layers on Si wafers by MEVVA ion implantation are an ion current density of 17.6 μA cm^{-2}, corresponding to a formation temperature around 290 °C, and an implantation dose of 1×10^{17} ions cm^{-2}.

Figure 3 shows a RBS spectrum obtained from the sample implanted with the ion current density of 17.6 μA cm^{-2}, corresponding to a formation temperature of 290 °C at a dose of 1×10^{17} ions cm^{-2}. One sees a little flat signal just behind the Si leading edge and a relatively

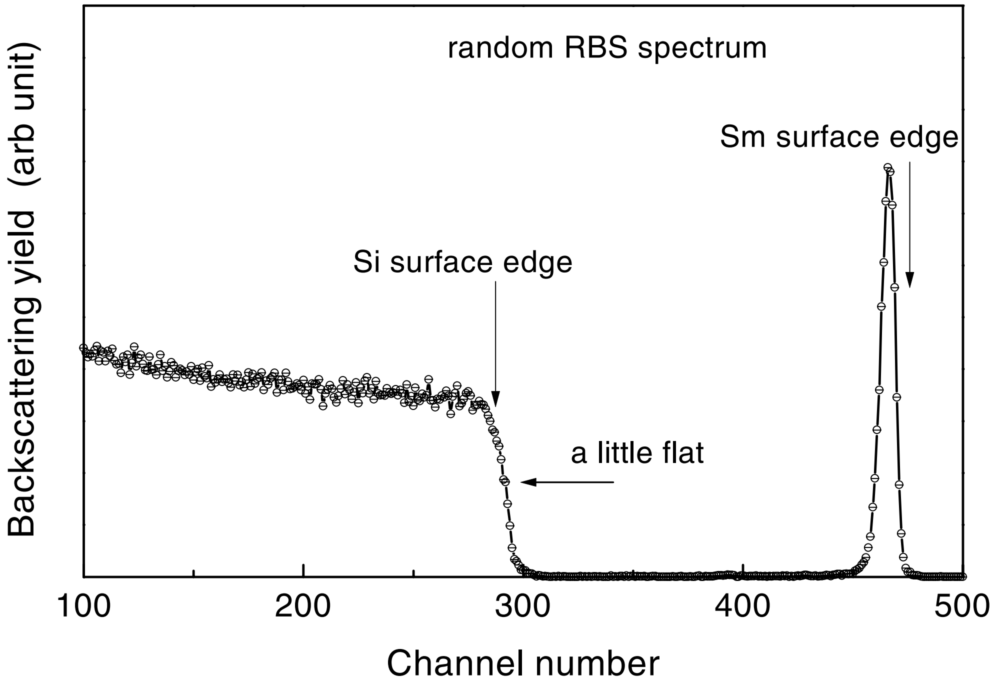

Figure 3. The RBS spectrum of the sample implanted at a current density of 17.6 μA cm^{-2} to an ion dose of 1×10^{17} ions cm^{-2}.

sharp signal from Sm, indicating that the Sm disilicide layer formed is very thin. The interface between the $SmSi_2$ formed and the Si wafer is quite sharp, as there is no apparent tail at the low-energy edge of the Sm signal. From the spectrum, the thickness of the Sm + Si mixture layer is deduced to be about 35 nm which is much less than that deduced from a TRIM calculation according to the nominal implantation dose. This can probably be attributed to the effect of sputtering upon high-current Sm ions interacting with the substrate. Also, the composition profile of the Sm deduced from the spectrum conforms to a Gaussian distribution and the average stoichiometry of Sm:Si is between 1:1.99 and 1:2.03 at the distance of 4.5 nm from the surface, which corresponds quite closely to that of the equilibrium $SmSi_2$ phase. It is known that irradiation could enhance diffusion of Sm to a greater depth in the Si wafer; the

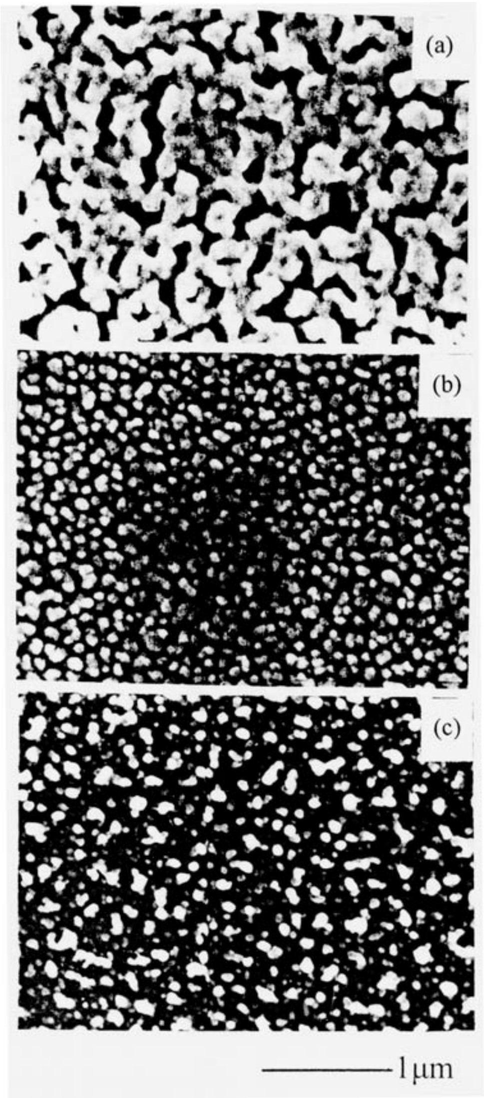

Figure 4. Surface morphologies of the samples with samarium ions implanted at 1×10^{17} ions cm^{-2} into Si wafers as observed by SEM: (a) 8.8 $\mu A\ cm^{-2}$; (b) 17.6 $\mu A\ cm^{-2}$; (c) 35.2 $\mu A\ cm^{-2}$.

Sm:Si ratio at a distance is therefore decreased and less than the above value. Meanwhile, the sputtering effect could also reduce the Sm:Si ratio as some Sm atoms were sputtered out of the Si surface. In fact, the actual Sm dose retained in the sample is about 4×10^{16} ions cm^{-2}, basically because of the above sputtering effect.

Figure 4 shows a group of morphologies observed for some samples implanted to a fixed dose of 1×10^{17} ions cm^{-2} with varying formation temperatures. At the lowest formation temperature of 190 °C, a network pattern consisting of $\mathrm{SmSi_2}$ phase (the bright regions) was observed on the Si surface, as shown in figure 4(a). Apparently, this morphology was related to an early stage of the growth as well as to the texture of $\mathrm{SmSi_2}$(004). When the formation temperature was increased to 290 °C, the $\mathrm{SmSi_2}$ film with very fine grains embedded in the Si substrate was still continuous as shown in figure 4(b). On further increasing the formation temperature up to 390 °C, the grains of $\mathrm{SmSi_2}$ did not grow homogeneously, and some bigger grains grew upwards in a cylindrical form, as shown in figure 4(c). It is well known that the crystals grow faster at higher temperature; therefore it was as expected that it was a high formation temperature of 390 °C that resulted in the observed morphology of figure 4(c). Also, regardless of their different morphologies, the $\mathrm{SmSi_2}$ layers formed had measured sheet resistances in the range of 90–105 $\Omega/\square$, which is the same range as for those synthesized by the SSR technique. It is important to note that there were no pitting defects seen on the Si surface, whereas such pitting was often observed on the RE metal silicides synthesized by SSR.

In summary, we have shown that equilibrium $\mathrm{SmSi_2}$ films on Si wafers can be directly synthesized by a single-step process of Sm-ion implantation using a MEVVA ion source and that under optimal experiment conditions, continuous $\mathrm{SmSi_2}$ films with a good crystalline structure can be obtained.

Acknowledgments

The financial aid from the National Natural Science Foundation, the Ministry of Science and Technology (Grant No G20000672-07) of China and the Administration of Tsinghua University is gratefully acknowledged.

References

[1] Knapp J A and Picraux S T 1986 *Appl. Phys. Lett.* **48** 466
[2] Siegal M P, Kaatz F H, Graham W R, Santiago J J and d'Spiegel J V 1989 *Appl. Surf. Sci.* **38** 162
[3] Duboz J Y, Badoz P A and d'Avitaya F A 1989 *Appl. Phys. Lett.* **55** 84
[4] Baglin J E E, d'Heurle F M and Petersson C S 1980 *Appl. Phys. Lett.* **36** 594
[5] Thompson R D, Tsaur B Y and Tu K N 1981 *Appl. Phys. Lett.* **38** 535
[6] Baglin J E E, d'Heurle F M and Petersson C S 1981 *J. Appl. Phys.* **52** 2841
[7] Lau S S, Pai C S, Wu C S, Kuech T F and Liu B X 1982 *Appl. Phys. Lett.* **41** 77
[8] White A E, Shprt K T, Dynes R C, Garno J P and Gibson J M 1987 *Appl. Phys. Lett.* **50** 95
[9] Wu M F, Vantomme A, Hogg S, Pattyn H and Langouche G 1998 *Appl. Phys. Lett.* **72** 2412
[10] Brown I G, Gavin J E and MacGill R A 1985 *Appl. Phys. Lett.* **47** 1358
[11] Zhu D H, Tao K, Pan F and Liu B X 1993 *Appl. Phys. Lett.* **62** 2356
[12] Liu B X, Zhu D H, Lu H B, Pan F and Tao K 1994 *J. Appl. Phys.* **75** 3847
[13] Zhu D H, Chen Y G and Liu B X 1995 *Nucl. Instrum. Methods* B **101** 394
[14] Gao K Y and Liu B X 1997 *Nucl. Instrum. Methods* B **132** 68
[15] Gao K Y, Zhu H N and Liu B X 1998 *Nucl. Instrum. Methods* B **140** 126