

Investigating the behavior of arsenic during silicide formation using Scanning Electron Microscopy (SEM), Rutherford Backscatter Spectrometry (RBS) and Secondary Ion Mass Spectrometry (SIMS) in interconnects of new integrated circuit technologies.

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Abstract:

This paper presents a study on Arsenic behavior during high-temperature silicide production, focusing on sub-microcrystalline titanium. The investigation involved oriented monocrystalline silicon discs implanted with Arsenic through an oxide layer. The results showed strong migration of Arsenic in the titanium silicide, impacting formation kinetics. The study identified various mechanisms contributing to dopant redistribution, such as diffusion in Si, TiSi₂, and Ti, evaporation from the titanium surface, and movement of dopants due to interface shifting. The solubility of Arsenic in different phases and segregating coefficients play essential roles in driving these redistribution processes. The findings have significant implications for optimizing CMOS scaling and miniaturization, guiding the development of self-aligned silicide structures to enhance CMOS device performance and support continued socio-economic progress through advanced integrated circuit technologies.

Keywords: Arsenic ; Rutherford Backscattering Spectrometry (RBS); titanium-silicides; Scanning electronics microscopy; rapid thermal annealing ; Secondary Ion Mass Spectrometry (SIMS);

I. introduction :

Used to provide electrical contact between metal lines and specific regions of the device structure, silicide structures are a key component of semiconductor devices[1-3]. Critical to global socio-economic progress, continuous CMOS scaling has been the main catalyst for the miniaturization of integrated circuits (ICs). The optimum silicide uses a minimum amount of Si, provides a low resistance path from the device regions to the metal lines, has a consistent integration path with the other features of the device, and is stable over both the thermal budget of the device fabrication and over the lifetime of the device[2-5]. However, with MOSFETs reaching their fundamental limits and the interconnect bottleneck dominating IC power and performance, scaling to sub-20nm technologies is proving challenging[5-7].

It is highly desirable to adopt a self-aligned silicide structure on the source and drain contact areas as well as on the gate in sub-micron CMOS devices in order to reduce lithographic needs and to minimize contact and junction resistances[5-6]. In these self-aligned CMOS devices, metal silicides are produced on highly doped n⁺ and p⁺ regions with incredibly thin connections. To achieve the lowest possible contact resistance, it is essential to understand the behavior of the dopant during the high-temperature silicide manufacturing process[6-7]. To avoid junction shorts, silica grain growth must also be thoroughly characterized[5-7].

Due to an imperfect C49-C54 transition, scaling down the dimensions has made TiSi₂ exhibit increased sheet resistance in the narrowest runners[8-12].

The most resistant form of titanium, titanium disilicate (TiSi₂), which occurs at relatively low temperatures, was researched using RBS, SIMS, and SEM in this work. Sub-Microcrystalline titanium was studied over a wide temperature range. Additionally, a mechanism for how recrystallization occurs at various temperatures has been established.

II. Experimental studies:

Titane sheet with a thickness of 335–405 m was formed on n-type arsenic doped Si(111) wafers (0.01-0.1 cm⁻¹) (SILTRONIX). The Si wafers were cleaned with organic solvents and etched with a buffered HF solution (10%) to remove native oxides from the Si surface before being put in the evaporation chamber. Physical vapour deposition (PVD) was used to deposit the Ti film.

The evaporation chamber is a 22 cm diameter by 25 cm tall stainless steel cylinder.

It was feasible to achieve a base pressure of 2×10^{-6} mbar with the help of a primary pump (ALCATEL 2012A) and a turbo-molecular pump (EDWARDS EXT255H), while the working pressure was changed to 2×10^{-4} mbar. A working pressure of 2×10^{-4} mbar was changed. A BOC EDWARDS manometer from BOC EDWARDS was used to monitor gas pressure. A mass flow controller situated close to the target was used to introduce the working gas (argon) into the chamber.

At a distance of 50mm from the substrate, the magnetron target, which is a 50mm-diameter pure nickel disc, was put at the top of the chamber and connected to the RF via a matching box. The power density was 6W.cm⁻².

The film was annealed in an oven at an extremely high speed for 7 to 25 seconds at a temperature between 650 and 750 °C.

With an implantation depth of about 100 angstroms, the implantation energy and dose are 30 Kev, 2.1015at/cm². The samples are annealed in flash

RTP using lamps at 1300°C for 20s to minimize or eliminate implantation-induced lattice defects, followed by deoxidising the wafers. Titanium is deposited by magnetron sputtering under argon pressure to produce titanium layers with a thickness of 600 Angstroms. The substrates are kept at room temperature during sputtering.

III. Results :

1- Scanning electronics microscopy (SEM) analysis :

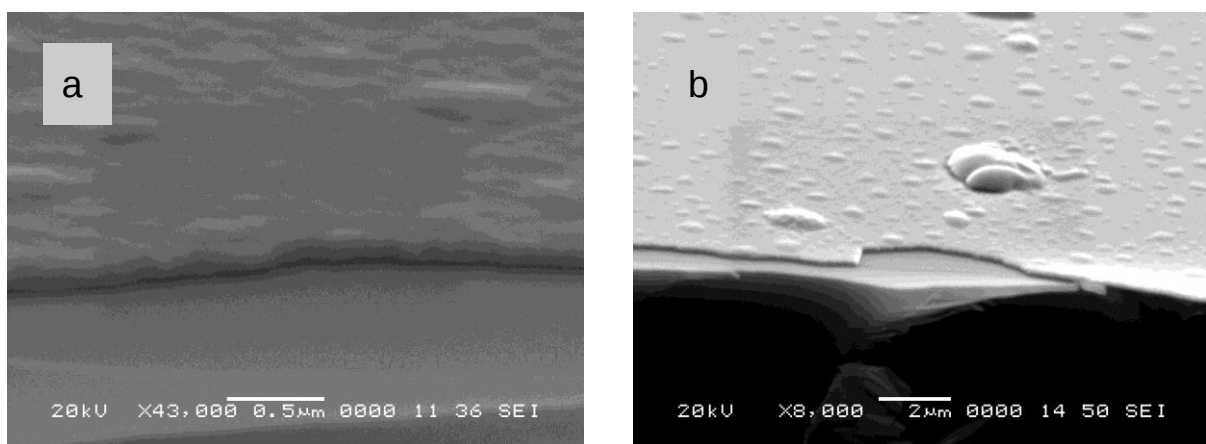


Figure 1 : SEM images of Titanium-silicides we can see the boundary between silicides and Silicon substrate.

The reaction starts at the Ti-Si interface and continues at the Ti-silicide interface until all the titanium in Figure 1 "a" is consumed. The reaction extends to the boundaries of the titanium layer.

This reaction is associated with large dopant dispersion and shifts in the silicon crystal lattice in all cases.

2-Rutherford Backscattering Spectrometry (RBS) analysis:

Figure 2 shows the RBS spectra of the Ti-Si film after annealing at 650°C for 7 seconds on an "As" grown Si substrate. The Ti and Si signals of the 150 nm thick TiSi₂ layer. It should be noted that the Ti and Si peaks of the TiSi

layer extend from the surface, whereas the "As" peak appears only at a depth of about 28 nm from the surface. RBS spectra of As profiles taken at two different Ti-silicide production temperatures are shown in Fig. 2(b): (c) 13 s and (d) 20 s. All samples were subjected to 650 °C vacuum annealing. The arrowheads in the figure and the depth scale at the top of the figure indicate the surface positions of As calculated from the feedback kinematic coefficient.

After annealing at 650°C, except for a depth shift of about 15 nm due to the deposited top Ti layer (15 nm thick), the As profile showed a typical distribution and segregation at the Ti-Si interface Fig. 2(d).

The profile was almost identical to that of the as-deposited samples which had not been annealed. However, As atoms were redistributed near the Ti-Si interface due to Ti silicide formation and a second As peak was observed at or near the surface due to As segregation after 7s annealing [Fig. 2(b)]. As shown in Figure 2 (c), the redistribution of As atoms extended further into the Ti silicide after a 9s anneal. There was also an increase in the size of the surface As peak. Two Ti silicide phases may be present at this annealing stage, as indicated by the RBS spectra of the Ti and Si profiles (not shown). The surface As peak is nearly gone, as shown in figure 2(d).

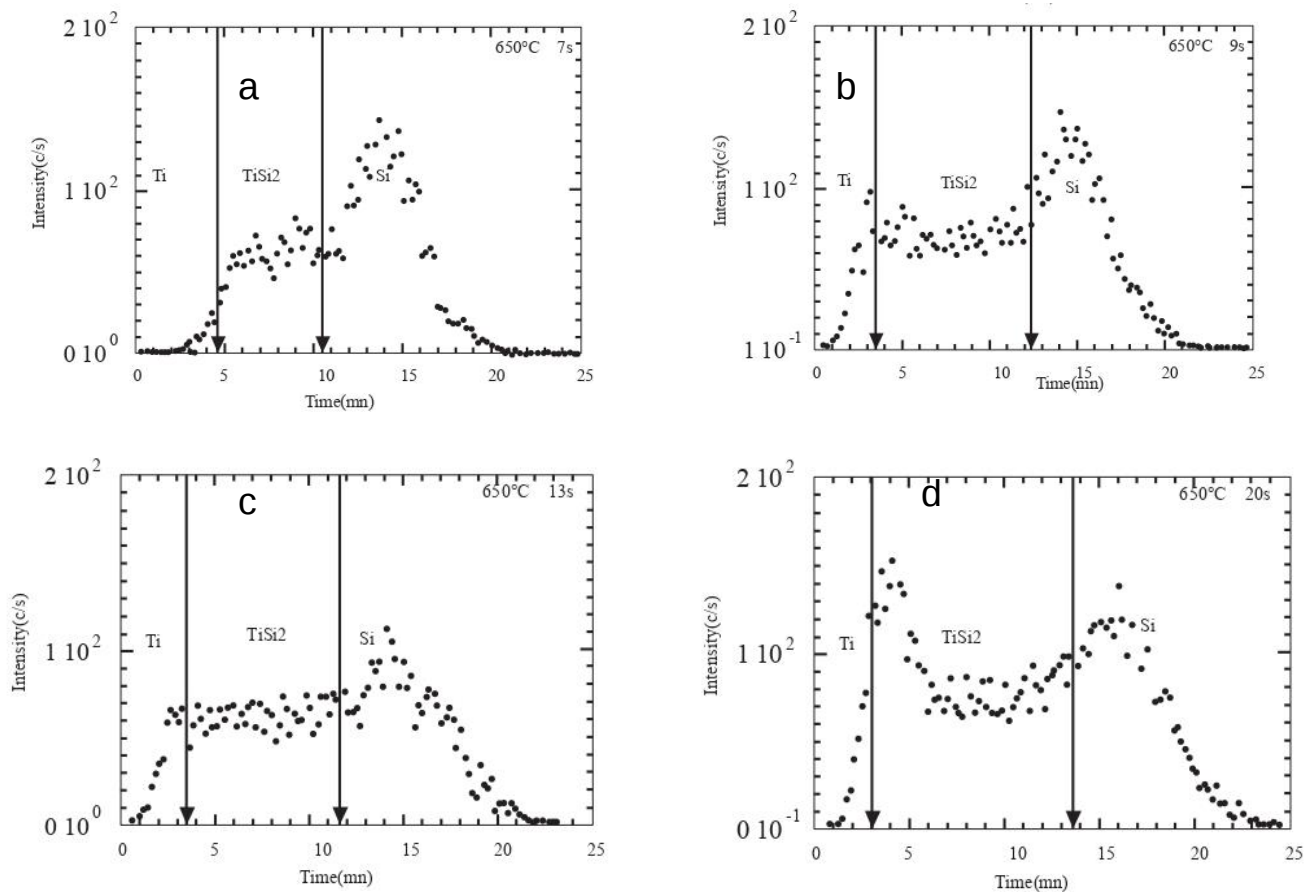


figure 2 : RBS spectra for Ti-silicides rapid thermal annealing (7-20s) at 650 °C.

3-Secondary Ion Mass Spectrometry (SIMS):

Figure 3 displays the 1-D chemical profiles that were discovered by SIMS studies of the silicide samples following 650°C drive-in annealing. The two studies lead to the emergence of several traits.

Initially, there is First, the upper portion of the Ti_xSi_y contains an N-rich area. At 7 nm depth and in the direction of the Si substrate, the N concentration peaks

at 4%. At a concentration of 1.5%, the As dopants remain at the Si surface and extend for about 6 nm into the silicide zone. Since the Ti does not diffuse into the Si in the other direction (As also has a very low diffusivity in Ni [12-25(13)]), this suggests that approximately 6 nm of Si was removed during drive-in annealing.

Oxygen accumulation within the silicide is not detectable. Analysis of the SIMS plot at the TiN-Ni_xSi_y interface shows a SiN peak measured at a mass-to-charge ratio of 42.

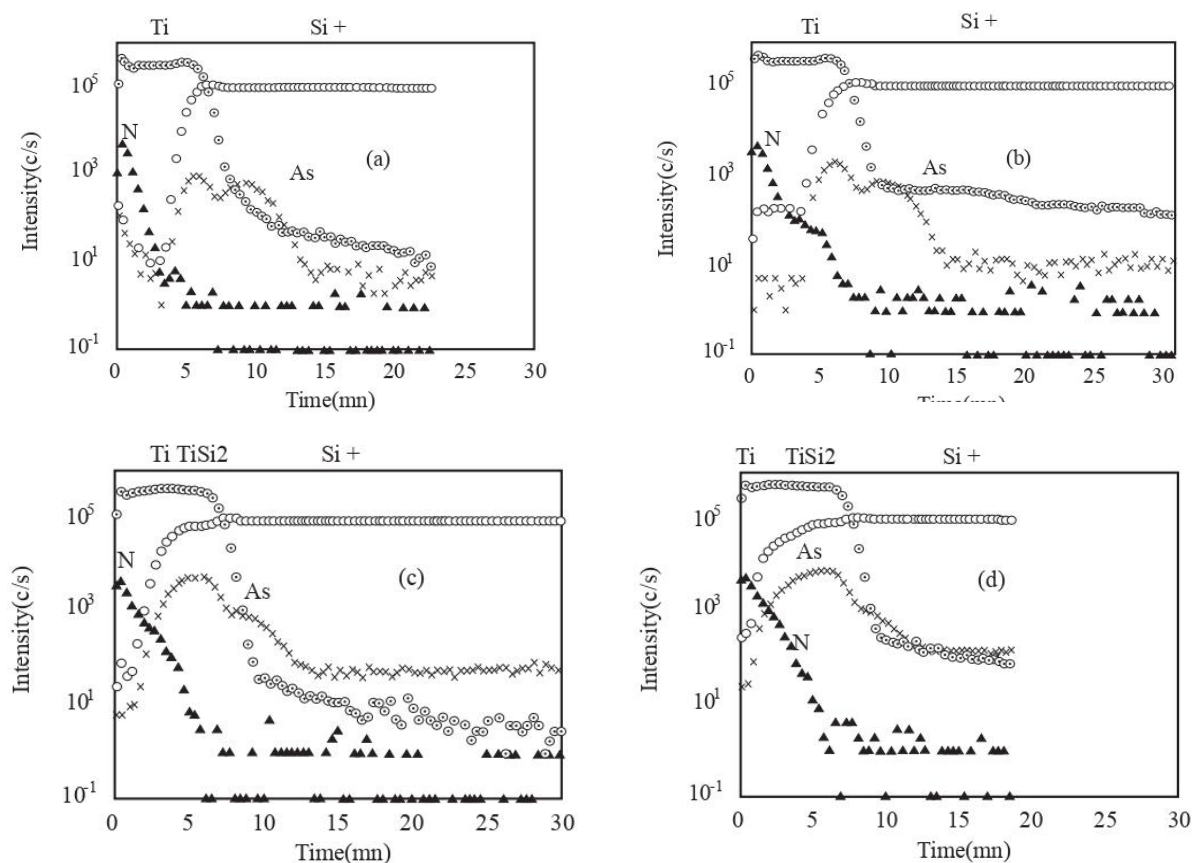
This could mean that the silicide surface has undergone a slight nitridation. It is possible to measure the Ti and Si concentrations throughout the silicide, and neither analysis shows an equal distribution of the two elements. The silicide is Ti rich at the TiN contact, dips to Ti₃Si₂ at the silicide's center, and then Ti content decreases as it approaches the Si substrate. The 1-D chemical profiles of the silicide sample after the phase-forming anneal are shown in Figure 3(b).

Analyzing the same characteristics as those covered in Figure 3(c) is possible. First, Pt segregates at the TiN/Ni interface as the Pt concentration decreases to less than 1% throughout the silicide. At the TiSi - Si contact, precisely at a distance of 0.4 nm on the silicide side of the interface, the As dopant atoms peak. The snow-plow effect of the Ti metal rapidly diffusing into the Si is probably to blame for this buildup. The As separates at the silicide-Si interface rather than combining with the silicide. Once more, there is no discernible oxygen buildup within the silicide. Since the silicide was not exposed to oxygen during the deposition or annealing processes, this is not surprising.

At the TiN - silicide contact, the SiN peak can be seen once more, however this time it is much more diffuse than in Figure 3(d). Throughout the silicide, the

concentrations of Ti and Si are measured. After the drive-in anneal, the SIMS analysis is shown in Figure 3(d).

The silicide contains a definite oxygen peak. The Pt-rich Ti_xSi_y region's center contains this oxygen peak. It's interesting to observe that while oxygen was initially added at the Ti-Si interface, it traveled away from that interface during the drive-in anneal and into the silicide bulk. This is a crucial and expected property of the silicide. N and Pt are able to diffuse into silicon as a result of Ti's reaction with the interfacial oxide.



IV. Discussion:

According to the SIMS results (Fig. 3(a,b,c,d)) and the RBS results (Fig. 2(a,b,c,d)), there is a strong migration of the dopant (As) in the titanium

silicide and this redistribution influences the kinetics of formation. The growth rate on a doped substrate depends on the arsenic concentration in silicon, leading to the formation of precipitates as in the case of the TiAs product, which acts as a diffusion barrier to silicon, hindering the C49 → C54 phase transformation, according to R. Beyrs [5,12-15].

However, the low boron doses implanted in our structures do not affect formation kinetics. The redistribution is the result of several mechanisms. These include

Dopant redistribution by diffusion in Si, TiSi₂ and Ti.

-Vaporising from the surface (of Ti).

-Moving the dopants by shifting the different interfaces.

The driving forces for this redistribution are mainly due to the following factors

-As solubility in the various phases.

-the segregation coefficients of this dopant at the interfaces.

Furthermore, the diffusion coefficient of As in Ti-Si₂ is of the order of 10⁻¹³ cm²/s at 600°C, which is of the same order as that of Si in Ti-Si₂, which is 2*10⁻¹³ cm²/s at 600°C [8-12].

V. Conclusion:

This study focused on understanding the behavior of dopants during the high-temperature silicide manufacturing process in sub-micron CMOS devices, which play a critical role in providing electrical contact between metal lines and specific regions of the device structure. Continuous CMOS scaling has been instrumental in driving the miniaturization of integrated circuits, contributing significantly to global socio-economic progress. However, the challenges posed by MOSFETs reaching their fundamental limits and the dominance of the interconnect bottleneck in IC power and performance have made scaling to sub-20nm technologies increasingly challenging.

To address these challenges and optimize CMOS device performance, self-aligned silicide structures have emerged as a highly desirable solution. These structures reduce lithographic requirements and minimize contact and junction resistances, particularly in source and drain contact areas, and the gate regions of sub-micron CMOS devices. This research aimed to gain a comprehensive understanding of dopant behavior during high-temperature silicide production, as it is crucial for achieving minimal contact resistance and preventing junction shorts.

The focus of this study was on sub-microcrystalline titanium, specifically titanium disilicate (TiSi₂), which occurs at relatively low temperatures. The research utilized a combination of advanced analytical techniques, including Rutherford Backscattering Spectrometry (RBS), Secondary Ion Mass Spectrometry (SIMS), and Scanning Electron Microscopy (SEM), to investigate the evolution of titanium disilicide at various temperatures.

Experimental studies involved the deposition of titanium films on n-type arsenic-doped silicon wafers, followed by annealing at high temperatures in a controlled environment. The results from SEM analysis revealed the reaction initiating at the Ti-Si interface and progressing to the Ti-silicide interface until all the titanium was consumed. This reaction was associated with significant dopant dispersion and shifts in the silicon crystal lattice.

RBS analysis provided further insights into the redistribution of arsenic (As) dopants during annealing. The migration of As within the titanium silicide significantly influenced the kinetics of formation. The study also detected the presence of TiAs product, acting as a diffusion barrier to silicon and hindering the C49 → C54 phase transformation.

SIMS analyses revealed intricate chemical profiles within the silicide samples, with areas of high Ti content and redistribution of As dopants due to Ti

silicide formation. Oxygen accumulation within the silicide was not observed, indicating that the fabrication and annealing processes were performed under controlled oxygen-free conditions.

The discussion highlighted various mechanisms responsible for dopant redistribution, including diffusion in silicon, TiSi_2 , and Ti, as well as evaporation from the titanium surface and movement of dopants due to interface shifting. The solubility of As in different phases and the segregating coefficients of the dopant at interfaces played key roles in driving these redistribution processes.

In conclusion, this research provides valuable insights into the complex dynamics of dopant behavior during the formation of titanium silicides in sub-micron CMOS devices. The understanding gained from this study is crucial for optimizing self-aligned silicide structures, enhancing CMOS device performance, and supporting continued socio-economic progress through advancements in integrated circuit technology. By addressing the challenges of scaling to sub-20nm technologies, this research contributes to the development of more efficient and advanced semiconductor devices that are vital to the continued evolution of modern electronics.

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