

## **THERMAL STABILITY STUDY ON TITANIUM DISILICIDE (TiSi<sub>2</sub>) THIN FILMS WITH TITANIUM NITRIDE (TiN) CAPPING USING ATOMIC FORCE MICROSCOPY**

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### **ABSTRACT**

*Titanium disilicide (TiSi<sub>2</sub>) has largely been used as gates and interconnects in semiconductor devices due to its low resistivity and good thermal stability. This work aimed to study the thermal stability of titanium disilicide thin film capped with titanium nitride based on measurements using the atomic force microscope (AFM) and four-point probe apparatus. Capped and uncapped silicide thin film samples, produced from the same initial thickness of Ti film (60 nm) on (111)-Si substrate but subjected to different rapid thermal processing schemes to form the silicide, were annealed at 950°C at varying annealing times (10, 20, 30, 40, 50 and 120 minutes). Morphological changes associated with thermal degradation were determined using both the AFM and scanning electron microscope (SEM). The changes in both the film's surface roughness and sheet resistance were also monitored over these annealing times. Results indicate significantly higher root mean square (RMS) surface roughness and sheet resistance in the uncapped sample after 120 minutes annealing implying better thermal stability in the capped than in the uncapped sample. The efficacy of TiN in increasing the thermal stability of TiSi<sub>2</sub> is attributed to originate from a retardation of material diffusion in the silicide layer. Also, atomic force microscopy was successfully applied to understand the thermal stability of the TiN-capped silicide.*

### **I. Introduction**

Titanium disilicide is considered as one of the most useful silicides for silicon integrated circuit applications<sup>[1]</sup>. It is mainly used as material for gates and interconnects (via the polycide or salicide technology) in semiconductor devices. It is also used as a diffusion barrier, ohmic contact, and Schottky barrier<sup>[2-4]</sup>. In the formation of titanium disilicide from a starting film of Ti on silicon, the ultimate phase desired is the equilibrium C54-TiSi<sub>2</sub> phase which has the lowest resistivity among other reported Ti-Si phases such as TiSi, Ti<sub>5</sub>Si<sub>3</sub> and the metastable C49-TiSi<sub>2</sub> phase<sup>[3]</sup>. These other phases tend to be formed at lower annealing temperatures and are also associated with the presence of impurities such as oxygen.

As applications for TiSi<sub>2</sub> continue to be developed, it is becoming more imperative that its key properties be studied and improved. Many of the studies on silicides focus on the film's resistivity and thermal stability. Thermal stability, which is the film's resistance to degradation during prolonged high temperature treatment, will

become a more critical consideration in the future when thinner and shallower lines of the silicide will be needed in the semiconductor device<sup>[5]</sup>.

When silicides are subjected to long term annealing treatments, they degrade and undergo a morphological transformation described as agglomeration. Agglomeration is a spontaneous transformation where a uniform thin film layer may break up into a non-uniform and possibly discontinuous layer<sup>[6]</sup>. Agglomeration is observed to occur in polycrystalline thin films and its mechanism depends much on material diffusion. This phenomenon generally leads to a degradation of several properties, the most important being electrical conductivity. Agglomeration may be so severe as to lead to complete cut-off of electrical conduction in a conduction line.

A number of studies has already been done on the thermal stability of titanium silicide<sup>[7-10]</sup>. These works have successfully identified several factors that may improve the silicide's thermal stability. One of the factors cited is the presence of a deposited thin film capping on the titanium silicide film. The presence of this cap improves thermal stability by increasing mechanical constraint against deformation of the silicide, reducing surface energy, and most importantly, reducing surface diffusion in the silicide.

Scientists have traditionally used sheet resistance measurements to quantify thermal stability of thin films<sup>[10]</sup>. Thermal stability has been reported in terms of the time at which a 30% rise in the silicide's sheet resistance has occurred. The work of Amorsolo et al. pioneered on another technique to quantify thermal degradation<sup>[10]</sup>. They used the atomic force microscope to monitor the change in the silicide's surface roughness over different annealing times. Their findings indicate an initial linear rise of the silicide's surface roughness over time, after which it levels off when a critical saturation roughness level is reached. Thermal stability is then quantified as the time it takes for the surface roughness to reach this peak.

The work by Amorsolo et.al, however, studied only uncapped silicides. This paper presents the results of an investigation on the mechanisms of thermal degradation of titanium silicide with a titanium nitride (TiN) capping. In this study, the techniques employed by Amorsolo et al were adapted for studying the thermal stability of titanium silicide with a TiN cap. The main analytical techniques that were used to evaluate thermal degradation were atomic force microscopy (AFM) and four-point probe sheet resistance measurements. AFM was used to measure surface roughness and gather objective evidences of thermal degradation such as grain boundary grooving and pit formation. The AFM images were then correlated to sheet resistance measurements on the silicide. Scanning electron microscopy (SEM) technique was also used to view the degraded film and the results of this analysis were correlated to the AFM images and sheet resistance measurement results.

## II. Materials and Methods

### 2.1 Sample History

Two types of samples were utilized. The first sample (capped) possessed a thin layer of TiN cap on TiSi<sub>2</sub> while the second sample (uncapped) had only TiSi<sub>2</sub> on silicon. In both samples, the silicide was fabricated by initially depositing 60 nm Ti, via sputtering of Ti metal target, on (111) phosphorus-doped single crystal silicon wafer with diameter of 10 cm. In the capped sample, the TiN was formed during a silicidation rapid thermal anneal (750°C for 60 seconds) of the Ti-Si substrate in a nitrogen ambient. In the uncapped sample, the Ti-Si wafer was subjected to rapid thermal annealing in argon ambient at 650°C for 60 seconds. In both samples, the thickness of TiSi<sub>2</sub> is estimated to be in the vicinity of 140-150 nm (based on the reported density of TiSi<sub>2</sub> and experimentally confirmed by AFM measurement of the step height of an etched sample). However, the thickness of the silicide is expected to be slightly less in the capped sample since some of the titanium was consumed to create the nitride during the silicidation anneal.

### 2.2 Initial Characterization and Annealing of Samples

Both wafers were initially tested to determine several of its characteristics. The composition of each sample was determined using an X-ray diffractometer system. Also, the energy dispersive spectrometer (EDS) was used to further confirm the elements present in each sample. The thin film's sheet resistance was measured using the four-point probe. Surface topography was viewed using the scanning electron microscope (SEM) and AFM. Surface roughness was also measured using AFM.

After the rapid thermal annealing treatments to convert the Ti film to TiSi<sub>2</sub> (with and without TiN cap), each type of wafer was cleaved to square pieces, each measuring 1 cm x 1 cm. The samples chosen for thermal stability testing were those that were found to have the most identical set of sheet resistance readings considering possibility of non-uniformity across the 10-cm wafer because of thermal gradients during the rapid thermal silicidation anneal as a result of such factors as the wafer edge effect and cooling effect of flowing gas. Samples for the annealing treatments in connection with thermal stability testing were then cleaned using acetone to eliminate contaminants. Each annealing run made use of two samples, one capped and one uncapped, which were both placed in a ceramic wafer boat and loaded into a conventional tube furnace. The furnace chamber was closed and argon gas was injected to purge it. Purging was done at a gas flow rate of 4.0 L/min for 10 minutes.

After purging, the temperature controller was set to 950°C. When the chamber temperature was equal to the desired temperature, the timer was started. Annealing times chosen were the following (in minutes): 10, 20, 30, 40 and 50. In addition, annealing was also done at 120 minutes to get an insight on roughening behavior at much longer time. At the end of annealing, the furnace temperature was set to 25°C and the chamber was opened. The samples were retrieved from the chamber and allowed to cool in air.

### 2.3 *Post-Anneal Characterization of Samples*

After annealing, samples were subjected to different characterization techniques to qualify and quantify the amount of thermal degradation that occurred in each. Sheet resistance of annealed samples was measured using a four-point probe analyzer. Surface topography was analyzed using a field emission scanning electron microscope (FESEM). Magnification settings utilized were 5,000X and 10,000X. These magnifications were chosen since low magnifications allow relatively larger areas of the wafer to be examined. Finally, the atomic force microscope (AFM) was used in tapping mode to measure surface roughness as well as to view surface topography at higher resolutions. Scan area was chosen at 50  $\mu\text{m}$  x 50  $\mu\text{m}$ . Measurement of surface roughness was done in offline mode using the Nanoscope III program. The root mean square (RMS) roughness was used as a figure of merit for the surface roughness.

## III. Results and Discussion

### 3.1 *Characterization of Control Samples*

As far as physical appearance is concerned, the capped (TiN-TiSi<sub>2</sub>) sample was similar to the uncapped sample except for their respective colors. The former possessed a golden color at the surface while the latter appeared to be silvery or mirror-like. The golden color at the surface of the capped sample is already indicative of the presence of TiN as gold is TiN's characteristic color. This information would eventually be confirmed using X-ray diffractometry.

Four-point-probe sheet resistance measurements of the capped sample gave a mean value of 1.99 ohm/sq. This sheet resistance reading converts to a resistivity of about 30.2  $\mu\text{ohm-cm}$ . This value is higher than the expected resistivity for C54-TiSi<sub>2</sub> (13-25  $\mu\text{ohm-cm}$ <sup>[10]</sup>), which was the expected phase in the sample after the 750°C silicidation anneal treatment. This may then be explained by the presence of the high-resistivity TiN (~ 40  $\mu\text{ohm-cm}$ ) cap which contributed to the total resistivity of the film. It was noted that the TiN formed did not totally insulate the TiSi<sub>2</sub> below it, otherwise the resistivity measured would correspond to that of TiN. This is due to the fact that the probe used in the four-point probe technique actually penetrates the composite thin film and is able to have electrical contact with both layers of TiN and TiSi<sub>2</sub>. Thus, the total resistivity measured is due to the contribution of both materials in parallel.

On the other hand, the uncapped sample was measured to possess a mean sheet resistance of 5.83 ohms/sq. This corresponds to a resistivity of 75  $\mu\text{ohm-cm}$  which agrees well with some of the reported resistivity for C49-TiSi<sub>2</sub> of 50-70  $\mu\text{ohm-cm}$ . This is as expected since the metastable C49 phase is normally formed at silicidation anneals of 600 to 650°C<sup>[10]</sup>.

An important information that may be obtained from the sheet resistance measurement on the capped sample is the estimation of the TiN capping's thickness. As mentioned above, the capped sample's measured sheet resistance is due to the

contribution of the two layers (TiN and TiSi<sub>2</sub>) and may be treated as resistances in parallel. Using the equation for this case and the relationship of resistivity with sheet resistance, the silicide and nitride thicknesses to obtain a sheet resistance equal to the value measured in the capped sample (2.1 ohms/sq) may then be calculated. The estimated C54-TiSi<sub>2</sub> thickness is about 122.5 nm while that of TiN is 9.7 nm. The estimate for thickness of the TiN cap is deemed to be realistic considering that silicidation anneal in nitrogen was done for 60 seconds only. However, it should also be remembered that the above calculation is based on the assumption that the Ti converts to TiSi<sub>2</sub> and TiN only. The actual presence of other phases (unreacted Ti and/or other intermediate Ti-Si phases) in the silicide could affect the proposed estimated values. The presence of unreacted Ti metal, for example, could add to the total resistivity of the thin film and further lower the actual thickness of the TiSi<sub>2</sub> layer. However, should this occur, further annealing at longer times, such as during thermal stability testing, will be expected to convert all other transition silicide phases and unreacted metal to the equilibrium C54 phase expected. This will be accompanied by a drop in the composite film's sheet resistance to a minimum level.

X-ray diffraction results were properly indexed and the capped sample was found to possess diffraction peaks consistent with the C54-TiSi<sub>2</sub> phase. This finding further reinforces the conclusions made from the four-point probe results. A peak corresponding to Ti was also observed in the pattern. The presence of Ti in the silicide has been observed in previous studies<sup>[11]</sup> and is due to the incomplete reaction of Ti with silicon during the silicidation process. This unreacted Ti is expected to be converted to silicide after the succeeding annealing steps. The capped sample's pattern also revealed the presence of a peak at around  $2\theta = 36^\circ$  which was absent in the uncapped sample. This peak is actually characteristic of TiN ( (111) plane and  $d = 2.44 \text{ \AA}$ ). The peak's presence in the capped sample's pattern only proved that the nitride is indeed present in this sample and the broadness of the peak also indicates the presence of only a very thin layer of the material which is supported by calculations based on sheet resistance. On the other hand, the uncapped TiSi<sub>2</sub> sample revealed diffraction peaks consistent with both C49 and C54-TiSi<sub>2</sub>. There was difficulty encountered with indexing the uncapped sample's XRD pattern especially since only two peaks appeared for C49-TiSi<sub>2</sub>. Unfortunately, these two peaks coincided with those of the C54 phase. However, since a high sheet resistance reading was obtained from this sample, then it may be concluded with confidence that a majority of the peaks' intensity is due to the presence of C49 phase. Still, one cannot discount the fact that C54 phase may also be present since other peaks consistent with it were observed in the pattern. The presence of C54 phase in the uncapped wafer is not an anomaly. Literature confirms that even at 600°C, the silicide is already partially converted to the C54 phase<sup>[11]</sup>.

AFM analysis on the untreated samples revealed the topography of both wafers. In general, the capped sample's surface appeared to be relatively flat with some hills and pits. The uncapped sample on the other hand appeared to possess a generally hilly surface. RMS roughness measurements gave an almost identical value (23.4 nm for the capped sample while 23.6 nm for the uncapped). This confirms that the two samples again possessed almost similar surface morphologies. However, what needs to be

quantified is the contribution of the TiN layer to the capped silicide's total surface roughness. Fortunately, the effect of the presence of TiN on the silicide's total roughness has already been studied by Karlin et al<sup>[11]</sup>. It concluded that TiN's impact on the silicide's roughness is negligible and that other factors (such as film thickness and grain size) bear greater effect on roughness than this.

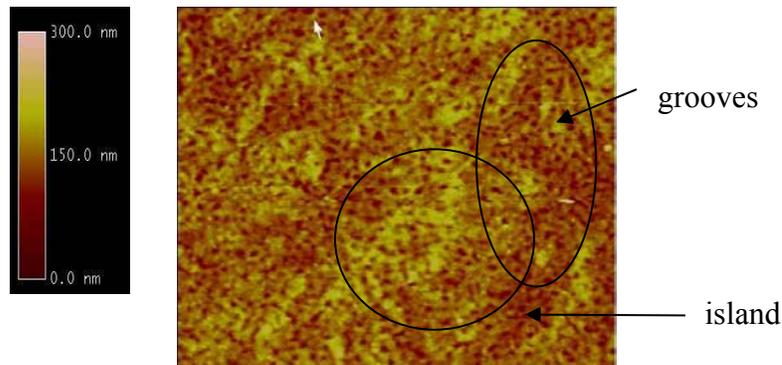
SEM images of control samples confirm what AFM analysis of the samples showed; i.e both possessed almost identical morphologies. On the other hand, EDS analysis also confirmed the presence of titanium and silicon in both samples. Since EDS is only capable of elemental analysis, the compound form of the elements present will not be established. However, this was already amply verified using XRD analysis. An important result of this analysis is the affirmation of the presence of nitrogen in the capped sample and its absence in the uncapped. Although EDS does not directly verify the form of nitrogen in the capped sample, it strongly complemented the results of the XRD analysis.

## 3.2 *Characterization of Annealed Samples*

### 3.2.1 *AFM Morphology Analysis*

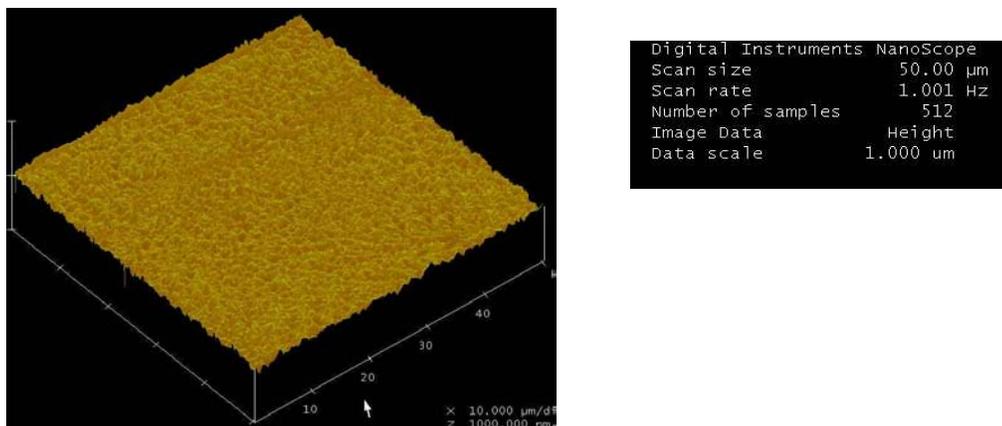
AFM analysis on the annealed sample showed the continuously changing surface of both wafers. At annealing times of 10 and 20 minutes, the annealed samples' morphologies were very much comparable with that of control samples. This is an indication that agglomeration had not yet started for both samples after 10 minutes annealing at 950°C. Indeed, the sheet resistances of the samples were at their lowest after this treatment, another sign that agglomeration had not yet set in.

At higher annealing times, AFM images of both samples showed the appearance of holes and island-like formations coming out at the surface of the wafers. The dark portions in the image may be considered as subsided or grooved regions of the surface. This phenomenon is often described as thermal grooving. The light regions may be imagined as elevated regions (hills) rising out of the surface. Thermal grooves and islands are further illustrated in Figure 1. Grooves and islands were observed to continuously enlarge and impinge on each for the wafers subjected to longer heat treatment regions. All of these observations are in conformance with literature<sup>[8,11]</sup> and relates to the silicide's morphological changes associated with agglomeration.

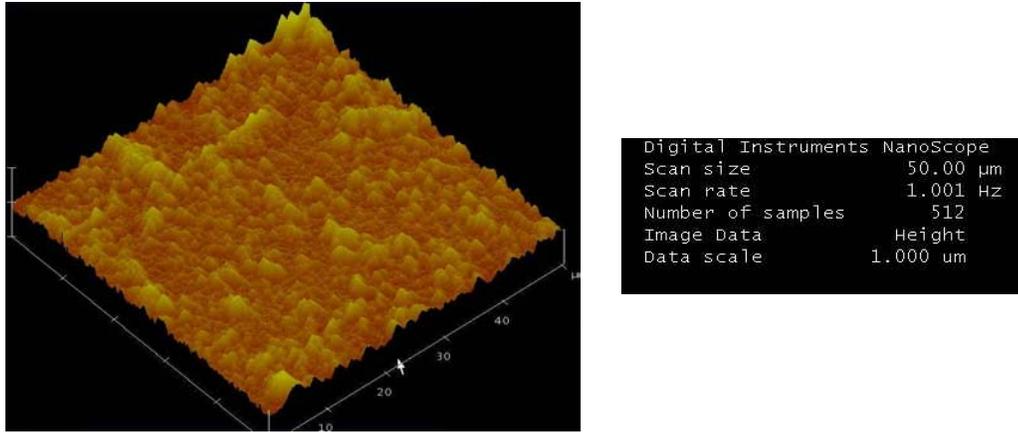


**Figure 1.** 2D AFM image showing regions on the film considered as grooves and islands.

A particularly significant observation made from the images is the drastic roughening of the uncapped sample's morphology after the 40 minutes and beyond annealing treatments. The emergence of rising topography in the AFM became evident and this was confirmed by surface roughness measurement. The capped sample in this annealing regime showed some changes related to agglomeration but not as drastic as that observed in the uncapped sample (compare morphology after 120 minutes annealing; Figure 2 and Figure 3)). This observation indicates a morphologically more stable state in the capped than in the uncapped wafer and may be taken as an indication of better thermal stability in the former. The observed increase in thermal stability may only be explained by the presence of the nitride cap. Again, this protection is attributed to the nitride's stopping of material diffusion in the silicide wafer.



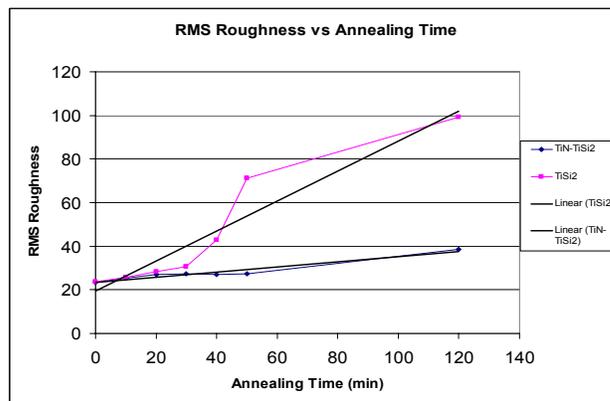
**Figure 2.** 3D AFM image of capped sample after 120 minutes annealing  
Scan size is 50 x 50 μm<sup>2</sup>.



**Figure 3.** 3D AFM image of uncapped sample after 120 minutes annealing  
Scan size is 50 x 50  $\mu\text{m}^2$ .

The two most commonly used figures of merit for the surface roughness are mean roughness, Ra, and the root mean square (RMS) roughness, Rq. The RMS roughness is usually preferred over the mean roughness since it involves the sum of the squares of the deviation from the fitted plane surface, which is always a positive quantity and thus easy to treat mathematically. In this study, the RMS roughness was thus chosen as the measure of the silicide’s surface roughness.

Roughness measurements on both samples revealed the trend that surface roughness increases with time. Indeed this observation conforms with results from the study made by Amorsolo et al <sup>[10]</sup>. Comparing the rate of increase of surface roughness, here one finds that the uncapped sample’s surface roughness increases faster and at a more drastic rate than the capped. For example, at 120 minutes annealing time, the RMS roughness of the uncapped sample (99.2 nm) is already more than twice that of the capped sample (38.7 nm). This would again signify that the nitrated silicide indeed has better thermal stability than the uncapped one.



**Figure 4.** Plot of RMS surface roughness vs time showing higher rates of roughening in the uncapped sample.

The study by Amorsolo et al<sup>[10]</sup> observed that the silicide's surface roughness initially behaves linearly with time, after which the roughness value appears to reach a saturation point where no further increase is observed. It concluded that thermal stability may be judged by how fast this saturation level is reached. Looking at Figure 4, one may indeed notice that the behavior described above is more or less adopted by the uncapped sample's curve. At the early annealing stages (10-30 minutes), the plot indeed appears linear. Beyond the 30 minutes time, the plot seems to gradually curve upwards with the possibility of leveling close to the 120 minutes level. On the other hand, the capped sample's series appears to be fairly linear even up to the 120 minutes level and that the saturation point is not yet in sight. From this aspect, one may again conclude that the capped sample has better thermal stability than the uncapped wafer since roughness saturation seems to occur faster in the latter sample.

To gauge the difference in thermal stability of the capped and uncapped titanium silicide samples, this study focused on the crucial early stages of annealing up to 50 minutes. The run at 120 minutes was done just to get an initial insight on how annealing at longer times could still affect the roughness behavior. More runs from another investigation are needed to get a better picture of how the system will continue to behave at significantly longer annealing times but the data on hand already sufficiently established that the capped sample with a thin nitride layer has indeed slowed down the deterioration of the silicide film based on measurements of surface roughness and sheet resistance.

Empirical mathematical modeling of the surface roughness behavior with time gave a linear equation for both samples. The relatively high  $R^2$  values above 0.9 for the fitted equations indicate a high goodness-of-fit. What can be noticed from the equations is that the slope of the line of the uncapped sample's equation has a significantly higher value than the capped sample. This validates the observation that the rate of surface roughening of the uncapped sample is higher than that of the capped and again points to

**Table 1.**  
Derived mathematical relationship between RMS roughness(y) and annealing time(x) for capped and uncapped samples.

Sample	Equation	$R^2$
Capped sample	$Y = 0.1196x + 23.38$	0.9345
Uncapped sample	$Y = 0.687x + 19.396$	0.9082

better thermal stability in the nitrated sample than in the uncapped one. However, the adequacy of the linear model for the entire range should be taken with caution. The trend in the data, especially after the 40 minutes annealing time, points to a relationship which might exhibit significant curvature for the uncapped sample. Indeed, a silicide sample

produced from the same starting thickness of 60 nm Ti tested by Amorsolo et. al.<sup>[10]</sup> achieved saturation roughness after 40 minutes of annealing. However, in their study, only one specimen was subjected to cumulative thermal stability testing runs and the rapid thermal annealing furnace they used for thermal stability testing was also different from the conventional annealing tube furnace used in this study. The method used in this study involved lower thermal gradients during the ramping stage due to a much slower heating rate which is expected to lower thermal stress effects that could promote degradation. Thus, degradation rates from this study are expected not to be directly comparable with the results from Amorsolo et al. and could even be slower because the conventional annealing used for thermal stability testing involved less severe ramping than what occurs during thermal stability testing using a rapid thermal annealing furnace. The linear equations fitted to the data in this study is deemed to be most applicable to lower annealing times (less than 30 minutes), especially for the uncapped sample which apparently exhibits curvature beyond 30 minutes.

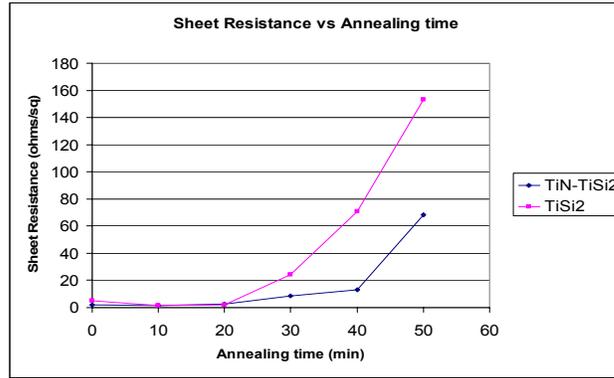
### 3.2.2 Sheet Resistance Measurements

The primary manifestation of the silicide's instability is the increase in sheet resistance with annealing temperature. Again, this increase is often attributed to agglomeration and spheroidization of the silicide. Also, it is important to monitor the time and temperature at which a 30% increase in sheet resistance occurs as this becomes the indicator of thin film degradation<sup>[12]</sup>.

**Table 2.**  
Results of sheet resistance measurements for the silicide samples at different annealing times.

Annealing Time (minutes)	Sheet Resistance (ohms/sq)	
	Capped Sample	Uncapped Sample
0	1.99	5.83
10	0.50	0.38
20	0.56	0.41
30	1.78	4.87
40	3.05	16.77
50	14.10	33.54

The measured sheet resistance of the wafers at different annealing times are listed in Table 2. Sheet resistance measurements on annealed samples showed that after 10 minutes of annealing, there was an observed drop in the sheet resistance of the two wafers (Figure 5). This decrease in sheet resistance at low annealing times in both wafers signifies the continuation of the conversion of  $\text{TiSi}_2$  from C49 to the C54 phase. Indeed, the measured resistivity values for the two samples after the 10-minute anneal correspond to that of the C54 phase (12-25  $\mu\text{ohm-cm}$ ). Also, although the  $\text{TiN-TiSi}_2$  was initially believed to be already composed of C54- $\text{TiSi}_2$ , the drop in its sheet resistance only proved that the  $\text{TiN-TiSi}_2$  sample still possessed some unconverted silicide. This correlates well with the results of XRD analysis on the etched capped sample.



**Figure 5.** Plot of sheet resistance vs annealing time showing higher rates of rise in sheet resistance in the uncapped sample.

The uncapped sample was also found to possess slightly lower levels of sheet resistance than the capped wafer at the 10 and 20 minutes regime (see Table 2). This observation may be explained by the conversion of the C49- $\text{TiSi}_2$  phase to the low-resistivity C54- $\text{TiSi}_2$  phase.

On the other hand, the silicide in the capped sample at that point was already feeling the effects of the thermal treatment; i.e. degradation was under way. This is essentially due to the fact that the silicide in this sample has already converted to its final form (C54) and the next eventual step is for it to agglomerate.

After the 20 minutes annealing time, a sharp rise in the sheet resistances of both samples may be seen; even greater than 30% from its lowest values. From this, one can conclude that degradation has occurred in both samples between the 20-minutes and 30-minutes annealing treatment as the 30% drop in sheet resistance falls in this regime (this will again be discussed in the next section). Annealing treatments beyond the 30-minute time showed the continuous increase of the sheet resistance.

The rise in sheet resistance after the 20 minutes annealing time in both wafers may be correlated to the morphological changes occurring at the surface as observed in the AFM images. As the surface was observed to roughen and degrade, the sheet resistance also rose. The rise in sheet resistance may be explained by the gradual break up of the film and the formation of discontinuous  $\text{TiSi}_2$  islands. When these islands are formed, silicon becomes exposed and contributes to the total increase in the resistance of the wafer.

The more important information obtained from these results may be perceived by comparing the rate at which sheet resistance rose in each sample. Here, one finds that the sheet resistance rise in the uncapped sample is more drastic than in the capped sample. This indicates that the capped sample has better thermal stability and again proving the ability of the TiN to protect  $\text{TiSi}_2$  against thermal degradation.

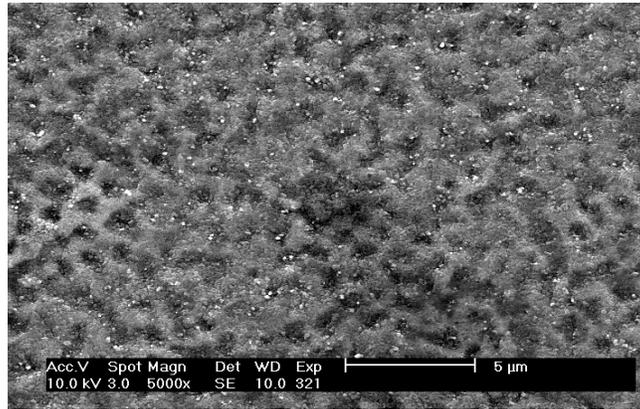
### 3.2.3 SEM Analysis

The series of SEM images obtained in the annealed wafers again show the morphological changes occurring at the surface and further verify the results of AFM analysis.

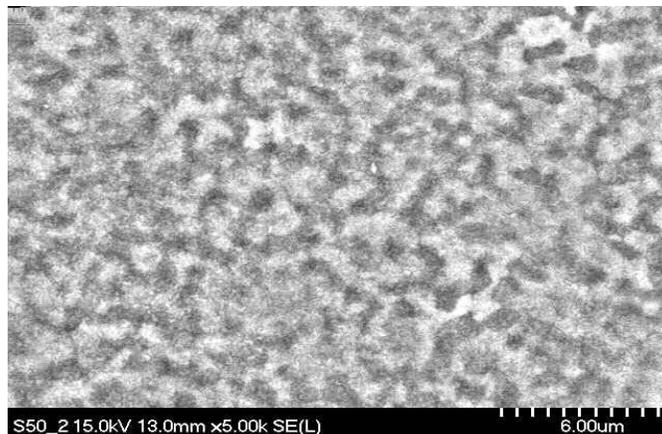
After the first annealing treatment (10 minutes), both samples appear grooved with the  $\text{TiSi}_2$  sample bearing finer grooves. However, it was noticed that the morphology of both samples are very much similar to that of the control samples. Again, this is in agreement with AFM observations and would indicate that agglomeration has not yet set in.

The images obtained after the 20 minutes anneal treatment show most of the phenomenon associated with agglomeration. By combining the images obtained with the AFM and scanning electron microscope, the morphological degradation occurring at the silicide's surface may be described as occurring through several stages. Surface degradation starts with pit or hole formation. This stage is followed by hole enlargement and its impingement with neighboring holes. The final stage corresponds to island formation and break up of the film. This finding conforms well with observed stages in the thermal degradation of silicide<sup>[8, 13]</sup>.

On the other hand, comparing the rate of morphological degradation occurring in the two samples (e.g. Figure 6 and 7) would lead to the conclusion that surface degradation occurs faster and more severely in the uncapped sample. This again correlates well with the conclusions derived from previously discussed results.



**Figure 6.** SEM image of capped sample after 50 minutes annealing (Scan area:17.5 x 22.5 um, 5000X )



**Figure 7.** SEM image of uncapped sample after 50 minutes annealing (Scan area:17.5 x 22.5 um, 5000X )

#### **IV. Conclusions**

AFM and SEM analysis on annealed samples showed a changing morphology of the silicide upon prolonged exposure at high temperature. Island formation resulted from progressive degradation of the surface. Agglomeration appears to start with thermal grooving and pit formation followed by hole enlargement and impingement with neighboring holes. Finally, break up of the films occurs with the formation of discontinuous silicide islands. Morphology analysis further points to the fact that surface degradation was more severe in the uncapped than in the capped sample.

Surface roughness was observed to increase with annealing time at 950°C. The early stage of roughening appears to be linearly dependent with time. A higher rate of roughening, indicated by a higher slope of the curve, was also observed in the uncapped sample. On the other hand, sheet resistance measurements on the annealed samples showed increasing resistance values with annealing times. The rise in sheet resistance is correlated with morphological degradation and island formation at the silicide surface.

All results point to the fact that the thermal stability of the capped silicide is better than the uncapped sample. The action of TiN is explained to be a diffusion retarder, limiting the amount of mass diffusion in the silicide and leading to lower rate of agglomeration.

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g gravitational acceleration constant	[m/s <sup>2</sup> ]
R dimensionless distance defined by Eq. 3	[ - ]
δ Thickness of liquid film defined by Eq. 20	[ m ]

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w subscript referring to water

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