THE INFLUENCE OF TITANIUM CAPPED ALUMINUM ON N+/P JUNCTION LEAKAGE

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ABSTRACT

In this paper the effects of aluminum capped with titanium on the barrier properties of tungsten/10%titanium (W/10%Ti) are studied. Also, various methods aimed at improving the barrier properties of W/10%Ti are evaluated. It is found that the amount of silicon in the aluminum alloy influences the ability of the W/10%Ti in preventing junction spiking. Use of an aluminum alloy with increased amounts of silicon result in less junction leakage. The cause of this is the intermetallic formed between the aluminum and the titanium which has a high solid solubility for silicon. That is, after silicon is removed from the alloy by the intermetallic, silicon is consumed from the substrate. This results in contact pitting and junction leakage. The amount of junction leakage is dramatically improved by "stuffing" the barrier metal. This is done by annealing the W/10%Ti in a forming gas ambient to form oxy-nitride compounds on the boundaries of the grains. Other methods that improve the barrier are to thicken it and to deposit a thin layer of titanium beneath it.

INTRODUCTION

The capping of aluminum interconnect lines with titanium has many benefits. Among these benefits are hillock suppression, increased electromigration resistance and use as an antireflective coating. Unfortunately there are also disadvantages to using aluminum layered with titanium. This study was undertaken when a dependence of p-n junction leakage current on aluminum alloy content was observed. In particular, the amount of junction leakage was seen to increase when the weight percent on silicon in the aluminum alloy was decreased. It is well reported in the literature that refractory metal capped aluminum adversely affects p-n junction leakage [1,2,3]. However, the fact that aluminum alloy composition also has a strong effect is not well known. This study will report on the affect of alloy content and the mechanism by which junction leakage is degraded. The need to maintain junction integrity necessitates the use of an effective diffusion barrier. Tungsten/10wt.%titanium (W/10%Ti) was used in this study as the diffusion barrier between the aluminum and the silicon. Various methods of improving barrier quality were evaluated as part of this study.

EXPERIMENTAL

All metals were sputtered in a Varian 3180. The metallization consisted of the W/10%Ti barrier followed by Al/x%Si/0.5%Cu

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(with x=1.0 or 1.5) capped with either 200A or 500A of titanium. The W/10%Ti deposition rate was about 30A/sec. The test structure used for this evaluation consisted of a string of 14,500 n+ contacts. The junction leakage current was measured by applying 10volts between the back of the wafer and the contact string. The wafers were processed as follows,

1. LOCOS isolation
2. N+ S/D implant
3. N+ S/D anneal
4. BPSG deposition and flow
5. Contact mask and etch
6. Metal sputter (various schemes)
7. Metal-1 mask and etch
8. Planarization
9. Via mask and etch
10. Metal-2 sputter
11. Metal-2 mask and etch
12. Anneal

RESULTS

The first part of this experiment compared Al/Si/Cu alloys with differing amounts of silicon. Figure 1 shows junction leakage histograms for the two alloys with differing W/Ti thicknesses. Similar results were obtained when the aluminum was capped with 500A of titanium instead of 200A. The explanation for this is that neither amount of titanium is totally consumed by this process. As will be discussed later though, the thickness of the titanium layer does affect electromigration induced failures. Figure 1 shows that junction leakage is lower at all W/Ti thicknesses for the alloy with the higher silicon content. For comparison, Figure 2 shows junction leakage for silicon contacted by the aluminum alloy with 1.5% silicon only. Of course with this amount of silicon solid phase epitaxial growth of silicon into the contact areas could be a problem. The figure merely baselines the amount of leakage current to be expected from a "good" contact scheme. At the temperatures encountered in this experiment either amount of silicon (1.0% and 1.5%) satisfies the solubility requirement for silicon in aluminum. The problem comes when the aluminum is capped by titanium. The intermetallic (Al5Ti7Si12) formed between the aluminum and the titanium has a large silicon solid solubility. This causes much or all of the silicon in the aluminum alloy to be taken up by the intermetallic. The impact on junction leakage is dramatic, as seen by comparing Figure 1b (0A W/Ti) and Figure 2. Figure 3 shows a SIMS analysis of aluminum capped with titanium. This sample, after deposition, saw temperatures of 400C for approximately 90min. The silicon concentration in the sputtering target is about 8.7E20cm-3. As Figure 3 shows in the center of the metal film at the end of process the concentration is about 1.5E19cm-3. The cause of this difference can be explained in part by considering the solubility of silicon at the metal deposition temperature. The solid solubility of silicon in aluminum at the aluminum deposition temperature is about 0.10% [4]. The excess silicon above this solubility limit will precipitate, presumably at the aluminum-W/Ti interface. However, this solubility limit is about 5.8E19cm-3. The additional reduction in concentration must be due to the intermetallic. The conclusion is that if the silicon solubility of the intermetallic is not satisfied it will consume silicon from the substrate. This in turn necessitates the use of an effective diffusion barrier.

The second portion of the experiment consisted of attempts to improve the barrier properties of W/Ti. The following approaches were taken,

1. Thickening the barrier
2. Stuffing the barrier by
    a) annealing in forming gas
    b) vacuum break after deposition
3. Changing the microstructure of the barrier by
    a) high deposition rate
    b) high temperature deposition
4. Adding a second barrier metal

Figures 4 to 9 show histograms of junction leakage that in addition to being processed through the 30min, 400C anneal, were again processed through the same anneal plus an additional anneal at 450C for 60min. The intention with the 450C anneal was to simulate a worst case packaging process. Unless other noted the barrier thickness was 1400A and the Al thickness was 5500A in Figures 4 to 9. The type of barrier shown in Figure 1 resulted in 90% of the contacts with leakages of 1uA or greater, after the 450C stress . As shown in Figure 4, the thickened barrier works well but the downside is that any increase in metal-1 thickness makes it more difficult to planarize. The attempt at stuffing the barrier in the forming gas anneal was also successful. This method showed excellent barrier properties down to 700A in thickness. The idea here was to stuff the grain boundaries of the W/Ti with nitrogen which would block the diffusion path of silicon and aluminum atoms. An analysis of the W/10%Ti after forming gas anneal with energy dispersive x-ray spectrometry (EDS) prompted an explanation of what actually happened. The EDS spectra show characteristic x-rays from oxygen to be present in annealed samples and not present in samples right after deposition. Nitrogen was not detected in either type of sample. It appears that atmospheric oxygen is pulled into the anneal tube along with the wafers where it is gettered by the titanium in the W/Ti. The effect however with either oxygen or nitrogen is the same in that the grain boundaries of the W/Ti are "stuffed" not allowing diffusion of silicon or aluminum. The vacuum break after deposition split showed less leakage than did the barriers in Figure 1 but worse leakage than the annealed barrier. Leakage was reduced somewhat by increasing the deposition rate or by increasing the deposition temperature. To understand these results consider that the barriers in Figure 1 begin deposition with the substrate at room temperature which quickly rises to around 250C. It is suggested that this procedure results in a barrier metal containing numerous voids [5]. By increasing the deposition temperature (i.e. preheating the substrate) the number of voids are decreased. The same effect is obtained by increasing the deposition rate but the downside is that compressive stress in the film is also increased. And lastly, adding a second barrier to the W/Ti substantially improved the junction leakage as well as favorably affecting the contact resistance values. Titanium has been used successfully as a consumable barrier. However, the barrier properties are lost when the titanium is consumed by reaction with the aluminum. In this experiment though, the titanium was separated from the aluminum by the W/Ti barrier and the resulting leakage was quite low.

RELIABILITY

As was stated earlier, differences in titanium thickness have been shown to influence electromigration median time to fail, or MTF [6]. Electromigration tests were conducted using 150A and 500A Ti caps on both 4000A and 7000A Al/1.5%Si/0.5%Cu films. The W/10%Ti thicknesses were 800A and 2000A. The MTF for the aluminum capped with 500A Ti was about 45% less than aluminum capped with 150A Ti for all case. The lognormal failure distribution for the 800A W/Ti, 7000A Al/Si/Cu test is shown in Figure 10. Thus the Ti should only be as thick as necessary to provide a good antireflective coating.

DISCUSSION

It has been shown that there are various ways of limiting the deleterious effects of silicon consumption by the Al-Ti intermetallic. Even with a good barrier a detailed understanding of the intermetallic is desirable in order to design a process free from concerns of junction leakage. However, on the kinetics of Al-Ti intermetallic formation there is still some disagreement. Some data indicate that the activation energy of the reaction is constant with temperature [7]. Thus the lower the temperature subsequent to metal deposition, the less intermetallic formed and hence the less silicon consumption. Other data suggest that the activation energy increases with temperature up to about 410C [8]. Above this temperature the activation energy is constant and the morphology is characterized by a planar surface at the Al-Ti interface. Below 410C the interface morphology is supposed to be quite irregular with deep penetration of the Ti along the Al grain boundaries. Thus lower temperature processing could have the opposite effect of increasing the amount of silicon consumed by the intermetallic. Undoubtedly a nonplanar interface would also affect the electromigration properties of the metal.

ACKNOWLEDGEMENTS

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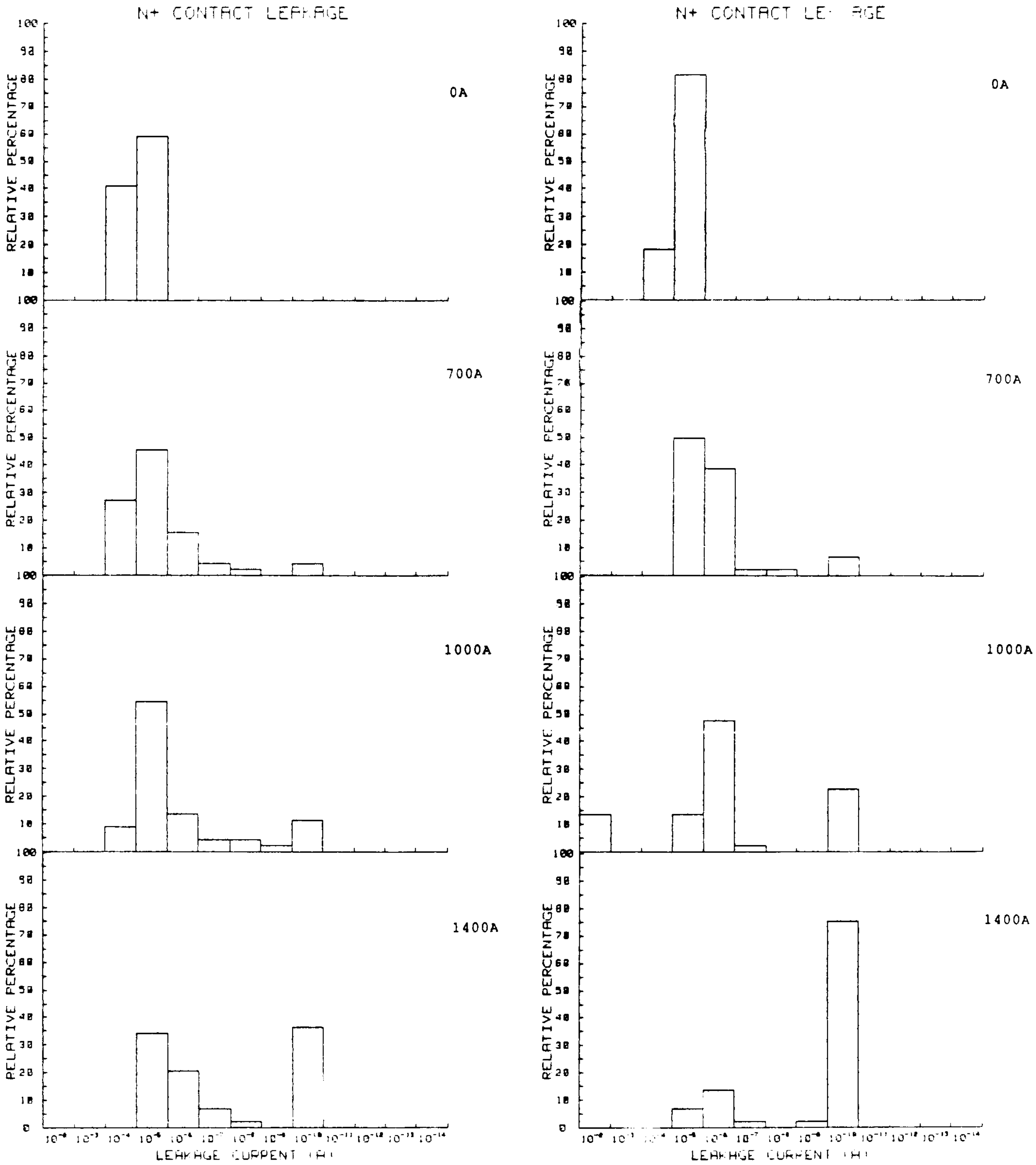

(a) Al/1.0%Si/0.5%Cu

(b) Al/1.5%Si/0.5%Cu

Figure 1. Junction leakage for W/10%Ti (thickness as indicated in figure), Al (5500A) and Ti (200A) metal systems.

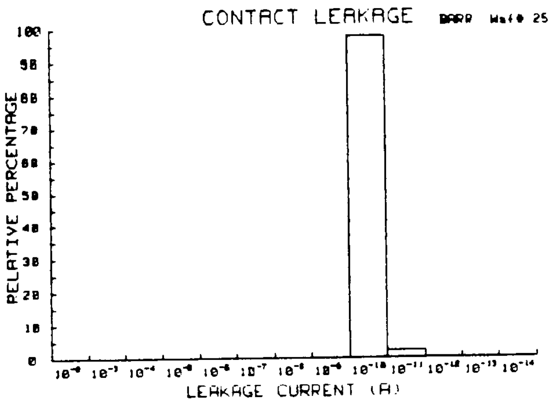

Figure 2. Leakage current for Al/1.5%Si/0.5%Cu contact to silicon. Leakage limited to 100pA or less.

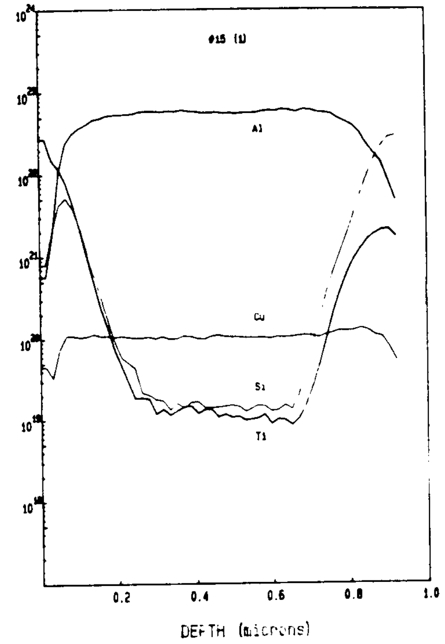

Figure 3. SIMS analysis of 800A W/10%Ti, 8000A Al/1.5%Si/0.5%Cu and 500A Ti after approximately 90min at 400C.

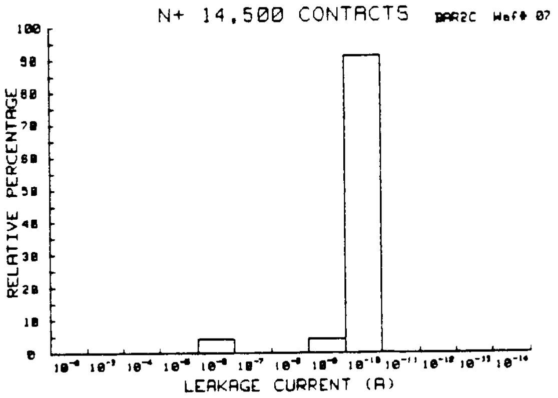

Figure 4. 2800A W/10%Ti

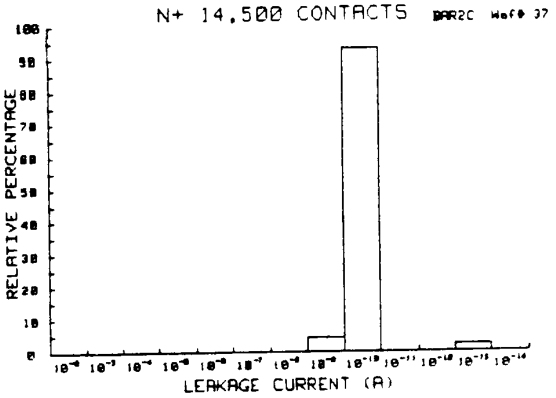

Figure 5. 450C, 60min anneal of the W/10%Ti

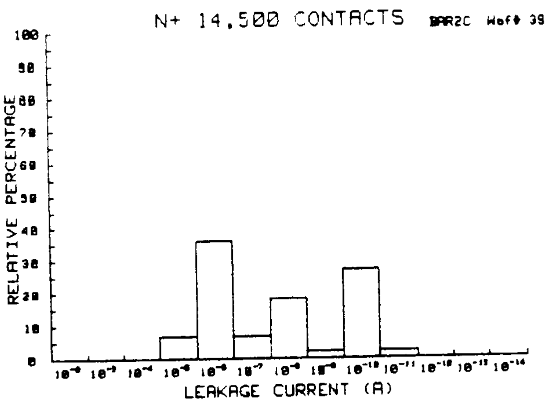

Figure 6. Vacuum break after W/10%Ti sputter

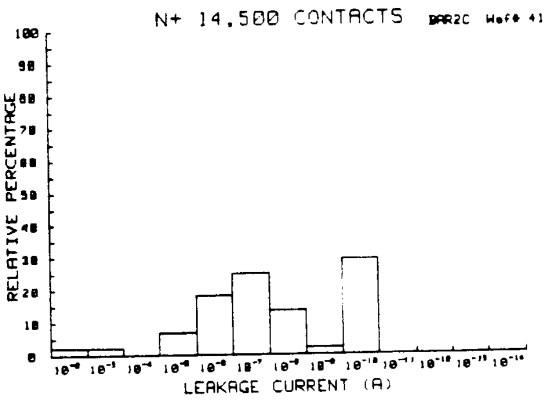

Figure 7. 400C W/10%Ti sputter

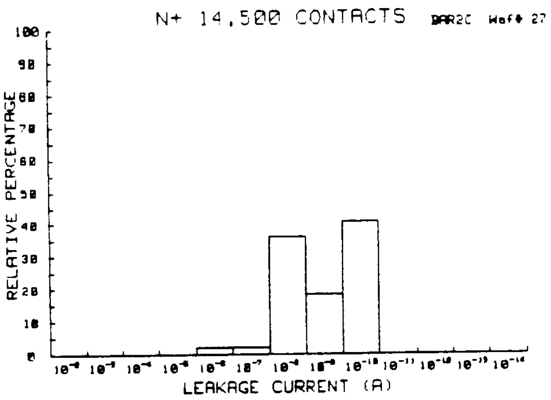

Figure 8. W/10%Ti sputtered at 58A/sec

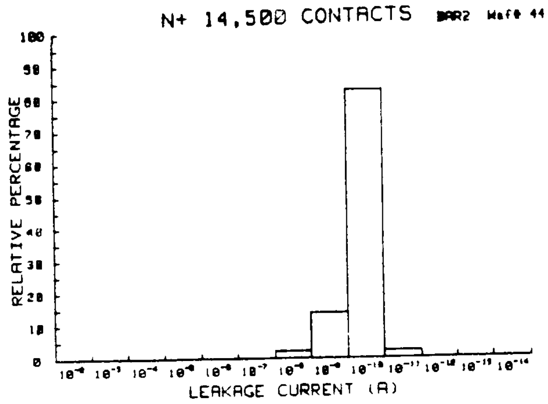

Figure 9. 200A Ti sputtered with vacuum break prior to W/10%Ti sputter

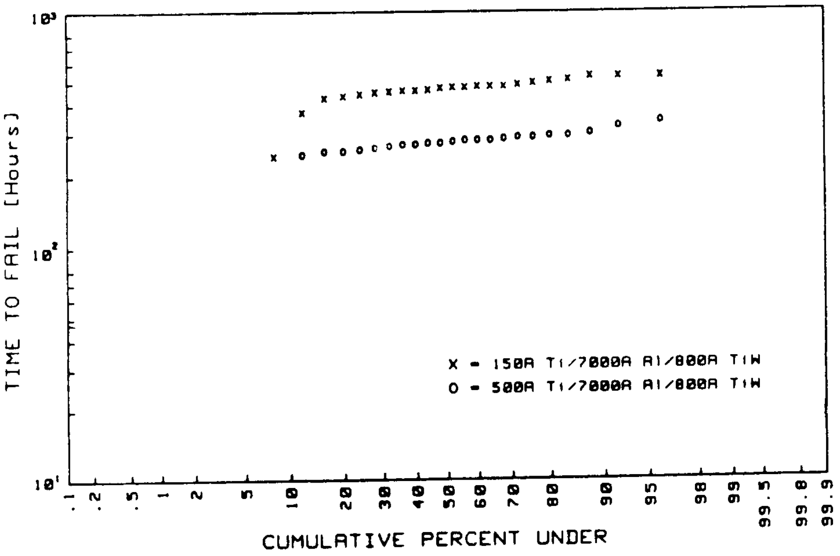

Figure 10. Electromigration median time to fail or MTF