Reliability improvement by the suppression of keyhole generation in W-plug vias

Jong Hun Kim, Kyosun Kim, Seok Hee Jeon, and Jong Tae Park*

Department of Electronics Engineering, University of Incheon
#177 Dohwa-dong Namgu, Inchon, 402-749, Korea

Abstract

This paper describes a mechanism of failures in W-plug vias due to the keyhole generation, and presents the process conditions which enhance the reliability of W-plug vias. For a high aspect ratio via-hole, one of the limiting factors in the reliability of the W-plug is the generation of the keyholes. We have investigated the sensitivities of corresponding technologies and conditions to the generation of the keyholes during the plug process. They include deposition technologies of TiN and deposition conditions of W. Based on the SEM observation and the electromigration failure test, the process conditions of TiN and W have been optimized.

1. Introduction

The tungsten (W) filled via plug process is commonly used in multilevel interconnection of VLSI/ULSI devices. The via-hole formation is one of the most important processes among the interconnection technologies. For a high aspect ratio via-hole, the poor step coverage of TiN was known to result in the creation of keyholes and volcanoes in W-plug vias [1]. The one-step TiN deposition using IMP PVD yields a thicker film layer at the top corners of via openings, and thus leads to incomplete plug filling – that is usually interpreted as keyholes, wormholes, plug-coring or voids [2-5]. When the standard commercial abrasive of Al₂O₃ is used for CMP-W, an oxidizer is mixed into the slurry to oxidize the W surface, and thus creates the keyholes in seams [6]. The elimination of keyholes in the plug is very important for the reduction of via resistance and the enhancement of electromigration reliability [7]. To suppress the generation of keyholes, a CVD-W process with high pressure and low temperature [8], a two-step process for TiN [2] and a new CMP-W process with slurry of MnO₂ [6] have been suggested.

In this work, we present the generation mechanism of keyholes as a two-step process. The keyholes are generated in the deposition of W due to
the overhang of TiN at the top corners of vias, and enlarged at the CMP-W process due to the slurry chemistry. The most optimized deposition conditions of TiN and W have been suggested to suppress the generation of keyholes near the seam and to enhance the reliability of the W-plug.

2. Sample fabrication

Fig.1 shows the cross-sectional structure of prepared samples. N⁺ or P⁺ poly silicon was deposited on an oxide layer. The 0.65um SiO₂ interlayer was deposited by the plasma-enhanced CVD, and planarized by resist etch-back. The 0.18um diameter via-hole was formed by reactive ion etching. Then 360Å of Ti was deposited by IMP PVD to react with the underlying material and lower the contact resistance.

The Ti film was deposited using power of DC 1.6kW, AC 200W and RF 2750W at 200°C. The argon gas flow was kept at 58sccm. Table 1 shows the description of splits in the sample fabrication. The 300Å TiN for samples S1, S5 and S6 was deposited by IMP PVD at 200°C and 15mTorr. The TiN film was deposited using power of DC 4kW, AC 400W and RF 2.5kW at 200°C. The argon and nitrogen gas flows were kept at 25sccm and 28sccm, respectively. The 100Å of TiN for samples S2, S3 and S4 was deposited by CVD using the reaction of ammonia and tetrakis dimethylamino titanium (TDMAT) at 380°C and 5Torr. The reaction of TDMAT with NH₃ to produce the TiN film is as follows:

$$6\text{Ti(N[CH₃]₂)₄ + NH₃} \rightarrow 6\text{TiN +24HN(CH₃)₂ +N₂}$$

The thickness of TiN has been adjusted for the equal resistance of IMP PVD and CVD.

The 0.18um SiO₂ interlayer was deposited by the plasma-enhanced CVD, and planarized by resist etch-back. The 0.18um diameter via-hole was formed by reactive ion etching. Then 360Å of Ti was deposited by IMP PVD to react with the underlying material and lower the contact resistance.

A two-step blanket CVD-W process was performed for a better step coverage and nucleation. A thin layer of W was first nucleated using the silane reduction reaction as follows:

$$2\text{WF₆ + 3SiH₄} \rightarrow 2\text{W + 3SiF₄ + 6H₂}$$

Then, the hydrogen reduction reaction was used to deposit the reminder of the blanket-W film.

$$\text{WF₆ + 3H₂} \rightarrow \text{W + 6HF}$$

Table 2 shows the description of process parameters according to the tungsten deposition technologies.

Planarization of the W surface was achieved through a CMP process. The electrochemical oxidation of W to form WO₃ was done by the oxidizing agent H₂O₂ in slurry. The mechanical removal of WO₃ was done by abrasive slurry particles of Al₂O₃.

3. Results and discussion

For the W-plug applications, the contact or via holes must be completely filled. For this to occur, the step coverage must be 100%. Otherwise, keyholes or voids will be formed, and exposed during the subse-
sequent W etchback step. The cross-sectional SEM photographs before and after CMP-W are shown in Fig. 2 to explain the mechanism of the keyhole generation by a two-step process. The deprocessing of SiO₂ has been done to investigate the shape and filling of the W-plug. Even at the condition of high pressure and high gas flow rate in the CVD-W process, the tiny keyholes are generated when TiN is deposited by IMP PVD. However, they are not generated when TiN is deposited by CVD. We can also observe the thicker film layer of TiN at the top corners. The overhang at the top corners of via openings can eventually close off the hole and form the keyhole. Fig. 2 shows that the keyhole becomes enlarged after CMP-W due to the oxidizer that is mixed into slurry. The polishing slurry contains a large quantity of H₂O₂, and etches the keyholes generated in the CVD-W process.

The SEM photographs in Figs. 3 to 8 show the surface and cross-sectional views of plug vias after CMP-W. The surface SEM photographs of samples S1, S2, S5 and S6 show vias with dark center regions indicating keyholes. However, there are no dark regions in samples S3 and S4. The cross-sectional SEM photographs in Figs. 3 and 4 show that the via-holes are not completely filled when CVD-W was performed at low pressure and low gas flow rate. Figs. 7 and 8 indicate that the tiny keyholes generated after CVD-W became enlarged after the CMP-W process as mentioned above. From the SEM photographs of Figs. 5 and 6, we can observe that the keyholes are not generated in W-plug vias. The SEM photographs indicate that the most desirable process conditions to suppress the keyholes are CVD-TiN and CVD-W at high pressure and gas flow rates. It is known that the W-plug itself will not electromigrate under typical test or field conditions, but it is the propensity of aluminum to walk away from ideal blocking boundary [9]. In this experiment, high density current of 1.5MA/cm² was used for acceleration.
Table 3
Results of electromigration failure test

<table>
<thead>
<tr>
<th>split</th>
<th>n-poly TTF(hrs)</th>
<th>p-poly TTF(hrs)</th>
<th>n-poly $\sigma$</th>
<th>p-poly $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>24.3</td>
<td>20.5</td>
<td>0.69</td>
<td>0.67</td>
</tr>
<tr>
<td>S2</td>
<td>22.6</td>
<td>19.9</td>
<td>0.7</td>
<td>0.69</td>
</tr>
<tr>
<td>S3</td>
<td>43.1</td>
<td>39.9</td>
<td>0.42</td>
<td>0.53</td>
</tr>
<tr>
<td>S4</td>
<td>46</td>
<td>43</td>
<td>0.4</td>
<td>0.49</td>
</tr>
<tr>
<td>S5</td>
<td>38.2</td>
<td>36.8</td>
<td>0.5</td>
<td>0.63</td>
</tr>
<tr>
<td>S6</td>
<td>39.1</td>
<td>38</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fig.7 SEM photographs of sample S5

Fig.8 SEM photographs of sample S6

The time to failure (TTF) was measured for 52 chains of W-plugs, and averaged. The summarized results of electromigration failure test in Table 3 show that the incomplete filling of via-holes and the generation of keyholes demonstrate early failures although they do not result in contact opens.

It has been observed that the W-plug on N$^+$ poly silicon is more reliable in terms of electromigration than the one on P$^+$ poly silicon. The SEM photographs and the electromigration failure test lead to the conclusion that the most desirable process conditions to suppress the keyholes are CVD-TiN and CVD-W at high pressure and gas flow rate.

4. Conclusion

The tiny keyholes generated in the W-plug with IMP PVD-TiN become enlarged after the CMP-W process. The via-holes are not completely filled at low pressure and low gas flow rates in the CVD-W process regardless of the deposition technologies of TiN. Based on the results of SEM and electromigration failure test, we conclude that the most reliable conditions for W-plug are the CVD-TiN process and the CVD-W process at high pressure and high gas flow rates.

References