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TEM Analysis and Failure Mechanism Studies of Bromine-Induced Defects in Wafer Fabrication

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ABSTRACT

In wafer fabrication, the contamination of halogen is commonly encountered, such as fluorine, chlorine, bromine. These contaminants can seriously impact product's quality and yield. In the previous works, we have studied F and Cl-induced metal corrosion and failure mechanisms. In this paper, we will apply TEM analysis technique to study Br-indued corrosion and failure mechanism. Moreover, we will introduce a model of "Br-chain chemical reaction" to explain why even a little bit of Br contamination, it can cause very bad corrosion results, and the formation of the worm-like defects at the side of Al metal lines in wafer fabrication.

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Introduction

Contamination issues are inevitable topics during semiconductor manufacturing, although modern fab production is normally conducted in the high-grade clean-room environments. There are many possible sources of the contamination, like chemical residues left over from etch/cleaning processes, from gas leakage, and cross-contamination from manufacturing tool chambers/wafer SMIF pods/FOUPs, etc. Among various contaminants, halogen contamination is one of the most critical issues. The halogens like fluorine (F), chlorine (Cl), bromine (Br) can readily lead to the direct chemical corrosion of the interconnect metal lines and bond pads such as Al, forming aluminium halide defects. Therefore, the halogen contamination issues can directly impact not only device failure, but also potential device reliability.

We have studied F and Cl induced metal corrosion and failure mechanisms and we reported for the Br-indued metal corrosion and the associated mechanism [1-4].

In our previous papers we studied the F-induced corrosion and defects, classification of defects and mechanism caused by fluorine contamination, characterized of the defects and established a chemical model [1-2]. Then some methods to prevent fluorine contamination and corrosion so as to improve line yield in wafer fabrication.

In our previous paper the Cl-induced corrosion and the defects in the Via holes were studied [3]. Immediacy and severity chlorine chemical reactions are brought up, which is to explain why sometimes a little bit of chlorine element contamination can cause very serious and very bad corrosive effects. For this reason, we proposed the theory that chlorine element can produce chain-chemical reactions. Applying this theory the worm-like Cl-induced defects were studied.

In our previous paper we studied Br-induced corrosion and defects on Al metal lines [4]. Auger, SEM/EDS and Ion Chromatography were used for failure analysis and studies of failure mechanism. We found that if we applied the low acceleration voltage SEM/EDX analysis, for example 5 kV, we could only obtain the Br Lα characteristic line of Bromine. Since the Br Lα characteristic line overlaps with the Al Kα characteristic line of Aluminum, it is difficult to distinguish them. Therefore, the accelerated high voltage must be applied to measure the Br Kα characteristic line of Bromine and confirm the existence of Bromine contamination.

In this work, we report a further study on the Br-induced corrosion and defects formation by TEM (transmission electron microscopy) and EDS, by which further details of the defect microstructure and composition of Br-corrosion induced defects were investigated. The correlated process issues and the corrosion mechanism were discussed.

The Br-Induced Corrosion and Defects

In the current study, the inline yield defect density reported that several lots of wafers were affected by a high-density of defects. Based on the map, the defects were present on Al metal lines. Inline SEM analysis showed that the defects existed mainly along the sidewall of Al metal lines, as shown in Figure 1 (a). High-magnification SEM analysis revealed that the defects were worm-like, likely growing from the sidewall of the Al metal, rather than from the surface of the Al surface, as shown in Figure 1 (b).

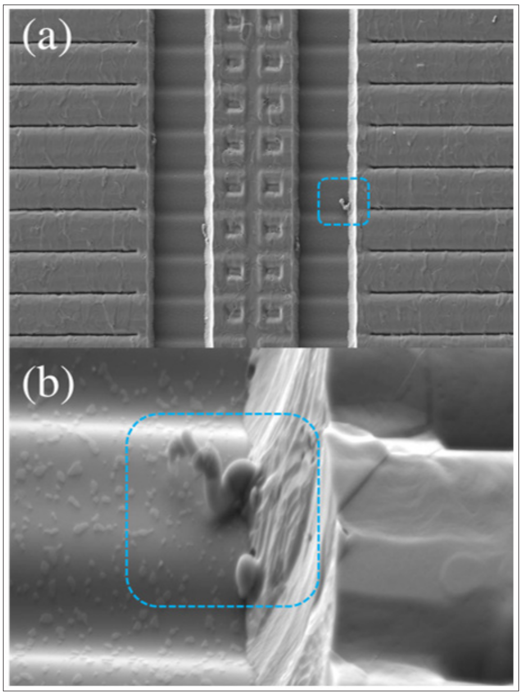

Figure 1: Low-magnification SEM image (a) and high-magnification SEM image (b) shows a worm-like defect in the sidewall of Al metal.

In order to understand detailed microstructure and composition of the defects and the correlated Al sidewall, cross-section FIB-TEM/EDX analysis was performed in the defect region.

As it is well known, the failure of semiconductor devices often results from abnormalities in terms of phase, microstructure and composition of the process layers and structures. With high spatial resolution and as a platform integrating various spectroscopy micro-analysis techniques, TEM is well-recognized as a powerful tool for semiconductor IC failure analysis, compared with other physical analysis techniques, like SEM and Auger.

TEM/EDX Analysis Results and Discussions

The cross-section TEM analysis was performed by sampling a thin lamella region across the worm defect and Al metal line, as shown in Figure 2(a). TEM sample was prepared by using focus ion beam (FIB, Thermofisher Helios 600i) at 30kV with final FIB cleaning at 5kV. The thickness of TEM lamella was around 100nm. TEM-EDS analysis was performed with Tecnai F20 TEM (Thermofisher) at 200kV with an EDAX Si (Li) EDS system.

Figure 2 (b) show a low-magnification TEM image in the defect region. The defect was formed at the bottom corner of the Al metal with smooth surface. No direct root or structure correlation in between the worm-defect and Al metal, and Al sidewall next the defect was smooth. EDS micro-area analysis in Figure 3 indicated that the worm defect region was Br-rich (Point-1).

While in the bottom corner of the Al metal, a particle residue was observed, embedded in between Al metal and PSG (phosphor doped Si glass) layers, as shown by the TEM image in Figure 2 (c), and EDS analysis in Figure 4 and Figure 5 showed that the particulate defect was mainly Si-rich, tallying with the typical diffraction contrast of the polycrystalline structure observed under TEM (white dash line circled region, Figure 2 (c)). The Si-rich particle defect should be introduced before Al metallization. With such residue particle embedded at the Al/PSG interface, it is highly possible that there exist interfacial voids or gap in Al/PSG interface, which may easily trap some chemical residue, like Br in this case, inducing the Al metal corrosion in the region. Therefore, this could be major process weakness leading to the Br-induced Al corrosion.

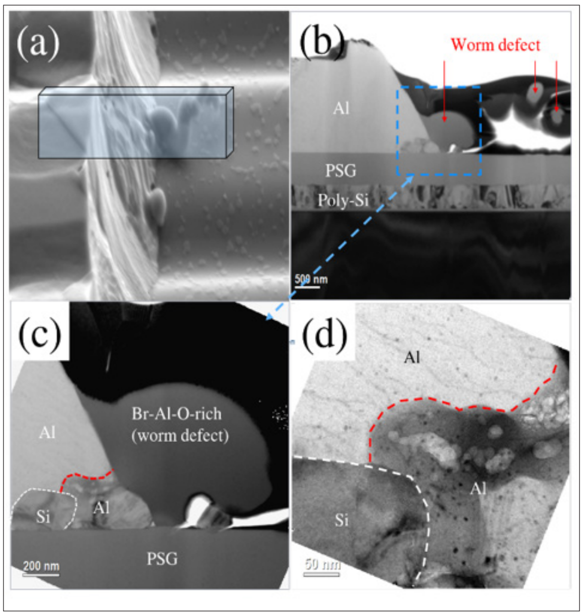

Figure 2: (a) cross-section FIB-TEM location (across the worm defect); (b) low-magnification TEM image of the worm-defect and its neighbouring structures; (c) high-magnification TEM image of the defect region, showing the presence of Si-rich residue in between Al and PSG layers, and (d) the high-magnification TEM image of the Si-rich residue particle and the abnormal contrast in Al metal next to the worm defect, possible the growth origin of the worm defect.

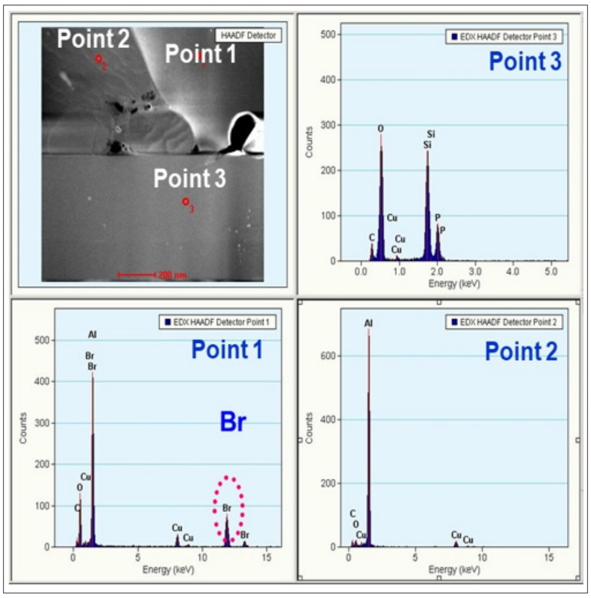

Figure 3: EDS micro-area analysis in the worm defect region

Further zoom-in TEM analysis indicated the presence of voiding-like structure with non-uniform contrast in the Al metal next to the worm defect, as shown by the TEM image in Figure 2 (d) (red dash line circled region). Such abnormal contrast might be the signature related to the Al metal corrosion although EDS analysis did not show appreciable Br in this region. It is possible that Al corrosion started in this corner region with the Si residue defect and Br trapping. This led to the continuous chemical corrosion process, and final formation of the worm defect in the corner sidewall region.

Failure Mechanism Studies

Based on the above TEM-EDX analysis results, the worm defect was formed due to Br-induced Al metal corrosion. In terms of the chemistry, we need to understand the chemical mechanism behind the formation of the worm-shaped defect, i.e. the process by which the chemical reaction proceeded continuously to form the worm-shaped defect.

Br-Induced Corrosion

Br and Al chemical reaction could form Al bromide:

$$Al + xBr^- \rightarrow [AlBr_x]^{(x-3)-} \quad (X = 3, 6) \qquad (1)$$

$$Al + 3Br^- \rightarrow AlBr_3 + 3e^- \qquad (2)$$

$$2Al + 6Br^- \rightarrow Al_2Br_6 + 6e^- \qquad (3)$$

[OH] Enhance Corrosion

Using TEM analysis, besides of bromine & aluminum, high oxygen was also detected. We think that as long as [AlBrx](x-3)- and Al2Br6 are formed on the Al metal wire, water (H2O) vapor and oxygen (O2) in environment will further chemically react and form [OH-] ions, which will cause further [OH] enhance corrosion, and form Al(OH)3, and then Al2O3 :

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad (4)$$

$$Al \rightarrow Al(OH)_3 \xrightarrow{-H_2O} Al_2O_3 \qquad (5)$$

It then reacts with bromine chemically and physically to form oxybromide → AlxBryOz :

$$[AlBr_x]^{(x-3)-}/Al_2Br_6 + Al_2O_3 + Al \rightarrow Al_xBr_yO_z \qquad (6)$$

(The worm-like defects)

From Figures 2-3, one can see that TEM analysis detected Br, O and Al, which supports the above failure mechanism and chemical reaction model proposed.

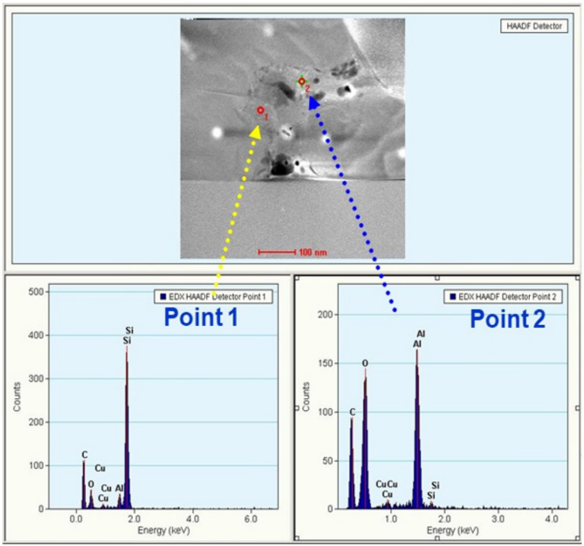

Figure 4: EDS micro-area analysis in the particle residue region (next to the worm defect)

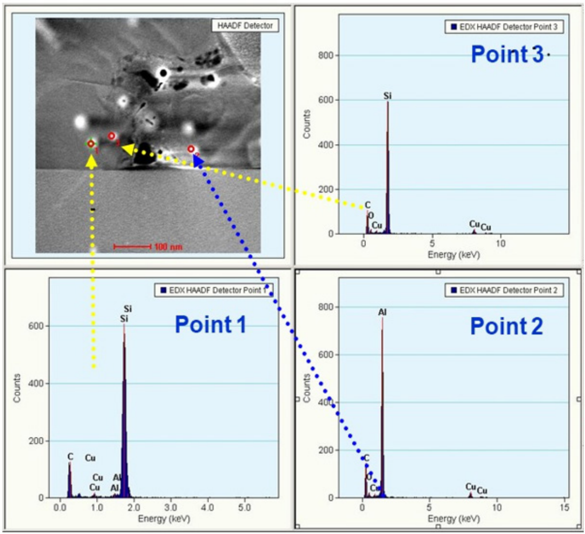

Figure 5: EDS micro-area analysis in the particle residue region (next to the worm defect).

Br-Chain Chemical Reaction

In our research, we found that Br-induced corrosion, sometimes even a little bit of Br contamination, can cause very bad results. What is the actual cause? We must understand it clearly and establish a corresponding chemical model to explain it reasonably.

Through studies, we proposed the "Br-chain chemical reaction". Thus the Br-induced corrosion failure model is reasonably explained.

$$2Al + 6Br^- \rightarrow Al_2Br_6 \xrightarrow{+6\,H_2O} 2Al(OH)_3 + 6Br^- + 6H^+ \quad (7)$$

$$2Al(OH)_3 \xrightarrow{-3H_2O} Al_2O_3$$

$$[AlBr_x]^{(x-3)-}/Al_2Br_6 + Al_2O_3 + Al \rightarrow Al_xBr_yO_z \quad (8)$$

AlBr3 or Al2Br6 come into contact with water vapor, leading to the generation of Br- ions once again, which can then chemically react with Al again to produce more aluminium tribromide, thereby initiating a continuous cycle known as the "Br-chain chemical reaction".

Finally, it forms the aluminium oxobromide (AlxBryOz) which could be grown alongside the sides of Al wires, particularly on wide Al metal lines in wafer fab.

Conclusion

TEM/EDX analysis techniques was used to further study Br-induced corrosion and the failure mechanism. The poor interfacial integrity in between Al metal and PSG layer might be the root cause of the Br-rich chemical residue trapping, leading to the Al metal corrosion and the formation of the worm-shaped defect. Moreover, a "Br-chain chemical reaction" model is proposed and explained the formation of the worm-like defects at side of Al metal lines in wafer fabrication [5].

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