Modelling of The Reservoir Effect on Electromigration Lifetime

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1. Introduction
As device dimension continue to shrink and clock frequencies continue to increase, electromigration is becoming an increasingly important aspect of Integrated Circuit (IC) reliability. The electromigration behaviour in W-plug/metal stripe structures is different from in conventional metal-strip structures because there is a “blocking boundary” which is formed by immobile W-plug in the contact/via. The electromigration failures occur much more readily in near area of W-plug than in metal-strip structures because metal ions are forced away from the contacts/vias by a electrical current, while the metal ions cannot flow through the blocking boundary to fill the vacancies around the contacts/vias area. Much work has reported that the electromigration lifetime of multiple levels interconnect is influenced by the presence of a “reservoir” around the contacts/vias. Reservoirs are metal parts that are not or hardly conducting current that act as a source to provide atoms for the area around the blocking boundary where the atoms migrate away due to the electrical current. The lifetime of interconnect systems can be prolonged by using the reservoirs, which is called “reservoir effect”. Several authors have experimentally shown the reservoir effect [1-8,11]. The reservoir can be created by an increase of the overlap, the number of contacts/vias and the end-cap (reservoir area); 1c and 1d have the same overlap but different in reservoir area but difference in direction layout; 1a, 1e and 1f have the same reservoir area and number of contacts but differ in contact placement.

When fully understood, the reservoir effect can be used in circuit designs. To increase the present understanding, 2D simulation has been performed into the effects of reservoirs. The stress build-up during electromigration in the contact area can be simulated for several configurations separating the effect of overlap, total reservoir area, the reservoir layout directions (vertical and horizontal), number of contacts/vias and the contact/via placement. It is very useful for IC-design rules to estimate which parameters are important for IC reliability. In this study, we considered the critical stress that the metal line can sustain before void formation as failure criterion. The failure time is determined by the time to reach the critical stress.

2. Simulation Structures and Condition
In this work, the simulation structures were designed with various aspects such as the overlap, the reservoir area, the reservoir layout directions (vertical and horizontal), the number of contacts/vias and the contact/via placement directions. The structures as shown in figure 1a, 1b, and 1c have the same overlap, different end-cap (reservoir area); 1c and 1d have the same reservoir area but difference in direction layout; 1a, 1e and 1f have the same overlap but difference in number of contacts; 1c, 1d, 1e and 1f have the same reservoir area but difference in number of contacts; 1e and 1f have the same reservoir area and number of contacts but differ in contact placement.

At each structure, the width and length (from the edge of cathode to the edge of anode) of the metal lines were kept as 3µm and 72µm respectively. The size of contact/via is 1µm × 1µm.

![Fig. 1: Simulation structures for the single and two via contact configurations with varying reservoir area and overlap. The reservoir is located upstream with respect to the electron flow.](image-url)
The reservoir area is in this paper defined as the amount of aluminium surrounding via or upstream from the electron wind (including the contact). A current of $1\text{MA/cm}^2$ and temperature of $200\,^\circ\text{C}$ have been used for input. The current is forced from the anode side flowing through contacts at cathode (grounded zero resistance) out the line. In this study, we only focus on the stress build-up (tensile stress) at cathode end, where the voids will be formed.

3. Results and Discussion

The Reservoir Area Effect
To illustrate the reservoir effect, the simulation results of the layout with different reservoir areas as shown in figure 1a, 1b, 1c and 1d were selected for comparing. The stress build-up at the right edge of the contact, which is the location with the highest stress, is shown in figure 2. It is seen in figure 2 that an increase in the reservoir area leads to a decrease in stress build-up. Increasing the reservoir area in the horizontal or vertical direction (compare 1c+d) give the same result. This result can be briefly explained that if there is more reservoir area, there is more material to provide metal atoms for locations around contacts. If there are more atoms providing, then the tensile stress will rise less fast. We see that the difference in stress build-up is already apparent in the beginning of electromigration process for these cases. The experimental data that already reported in [2,3,5] have the same conclusion as this work. In literature [3,5], they clearly showed the lifetime prolongation due to the increase the length of reservoirs (or reservoir area). The work from Atakov [2] showed that the reservoirs in various directions gave almost the same the lifetime.

Fig. 2: Evolution in time of the maximum stress taken at the right edge of the contact. a,b,c,d denote the different reservoir configurations (see figure 1)

Multiple-Via/Contacts Effect
Figure 3 shows the maximum stress build-up at the right edge of the contact (the contact number 2 in case of figure 1f) obtained from simulation structures of 1a, 1e and 1f. It is clearly shown that the stress build-up in time of a structure with single contact (figure 1a) is higher than that with two contacts. That means the lifetime of the structures with two contacts is longer comparing to the structures with single contact. It is easy to see that, the structures with two contacts have a larger reservoir area comparing to the structure with single contact. As mentioned above, when the reservoir area is increased, the lifetime is prolonged. Experimental data from literature [2,4] show comparable results. However, the question needs to be answered whether the lifetime is increased due to the increase the reservoir area or the increase the number of contacts. Therefore we have selected the simulation results of structures as show in figure 1c, 1e and 1f, in which the reservoir area was kept the same and there is one more contact in reservoir areas in vertical as well as horizontal direction. Their maximum stress build-up at the right edge of contacts (the contact number 2 in case of two contact in horizontal) are shown in figure 4. We found that there is no difference in stress build-up for those structures. Adding more contacts in a reservoir area has no effect on the lifetime. This result also indicates that the current sharing is much less important than the reservoir area.

Fig. 3: Stress build up taken at the right edge of the contact for constant overlap configurations seen in figures 1a, 1e and 1f.

Fig. 4: Stress build-up at the right edge of the contact (nr. 2) for a constant reservoir area with the via configurations of figures 1d, 1e, 1c, 1f.

To explain, we looked at the current distributions in those cases. The simulated results of current distribution for the
cases of single and two contacts in horizontal direction illustrated, that they are very similar at the right-most of contact (contact number 2 in case of figure 1f) (see figure 5).

**Fig. 5:** The current distribution in case of structure with single and 2 contacts in horizontal.

![Current Distribution Image](image1)

**Fig. 6:** The current density at right edge of contact/via from simulated structures of 1e and 1f.

![Current Density Image](image2)

**Fig. 7:** The stress distribution after 2000 hour of electrical current stress.

![Stress Distribution Image](image3)

This means that in structure 1f almost all current flows through the contact number 2. Comparing the current distributions in cases of two contacts in horizontal and vertical configuration as shown figure 6, we found that the maximum current density points have almost the same value. This behaviour of current distribution with the same maximum current density explains that the maximum stress build-up at right edge of contacts (highest stress location) have the same value for horizontal and vertical contact placement. Therefore, the estimated lifetime based on the critical stress will be the same. Similarly, when more contacts are added in the same reservoir, the lifetime does not increase. Our simulation data corresponds with experimental data from Dion [11]. He also showed that in case of adding more contacts in the same reservoir area, the lifetime is almost the same. In cases of two contacts in vertical and horizontal direction with the same reservoir area, the experimental data from Atakov [2] show that they have the same electromigration lifetime. Another interesting result obtained from our simulation is that the mechanical stress in the reservoir area is homogenous for a long time of electrical current stress as shown in figure 7. Hence voids can appear anywhere in the reservoir area. In reference [11], Dion has shown a lot of FIB pictures in which the voids appeared anywhere in the reservoir area. This correlates well our simulation results.

**The Current Sharing Effect**

Some experimental studies reported that multiple contacts would prolong the electromigration lifetime of multilevel metallization [4,6]. In reference [4], the test structures were designed with very large second metal layers to force or sense current, and in [6] the test structures are designed with a very large metal layer and another layer with multiple branches of reservoir area. It recognises that in these test structures, the structures with multiple contacts will carry a lower current density comparing to one with single contact. For instance, if there is a current density (J) through the line of each structure, this current density will be divided among the contacts such that the approximate current density through the contacts are much lower at J/n for multiple contacts. Where n is the number of contacts. We have simulated this situation by adjusting the current density going through each contact at the cathode site in structure 1f to J/2. The results are shown in figure 8. In this situation, we found that the right edge of contact number 1 sustains the highest stress instead of the right edge of contact number 2 as mentioned above. To illustrate, the distribution of stress build-up in the reservoir area after 1000 hours electrical current stress for this situation and case of almost all the current flowing through contact number 2 are shown in figure 9. Although a current density of J/2 was forced through the contacts, the stress build-up is not much different comparing to single contact. It is our hypothesis is that the effect of the reservoir area is more important then that of the sharing of current density because the contacts/vias are much smaller than the reservoir area. This assumption can be checked by simulating 1c and 1f with larger vias. The via size is 3.2µm×3.2µm, the overlap and the end-cap is 0.4µm and the line width is 3.2µm as shown.
in figure 10. It is obvious that now the via is only slightly smaller than the reservoir area. The maximum stress build-up in at the right edge of contact (contact number 1 in case of two contacts) reservoir area is shown in figure 11. We found that the stress build-up is much larger in case of one contact then in case of two contacts. That means the lifetime is much longer when the multiple contact is used, which proven the hypothesis that the relative size of reservoir with respect to via size plays important rule.

Validation using experimental data of literatures
To compare this work with experimental data from literature, the normalized lifetime, $t_{50}/t_{50}^0$ is plotted against the normalized reservoir area $S_r/S_{r0}$, where $t_{50}^0$ is the time to failure of structures with minimum reservoir area $S_{r0}$ or single contact (like figure 1a). In our study, the time to failure (TTF) was calculated by using the critical stress.

The overlaps are smaller comparing to 1c and 1f. It is obvious that now the via is only slightly smaller than the reservoir area. The maximum stress build-up in at the right edge of contact (contact number 1 in case of two contacts) reservoir area is shown in figure 11. We found that the stress build-up is much larger in case of one contact then in case of two contacts. That means the lifetime is much longer when the multiple contact is used, which proven the hypothesis that the relative size of reservoir with respect to via size plays important rule.

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data from one of the two groups literatures that can be
distinguished. The background of difference of the two
groups is not a topic for this paper. It is thinkable to be
related the literature works.

4. Conclusion
Our electromigration simulation shows that the lifetime
prolonging effect of reservoirs in aluminium metallization is
caused by the total amount of metal present as a reservoir.
The electromigration lifetime is independent of the
placement of multiple contacts. In multilevel interconnect,
the adding more contacts in a given reservoir area. A second
smaller effect is the division of current through the vias. If
the current flow equally through all vias, the lifetime is
increased. This effect is larger when overlap areas are
smaller.

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