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The effect of aspect ratio scaling on hydrostatic stress in passivated interconnects

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Abstract

In this study, numerical work using ANSYS and analytical work based on Eshelby models were performed to examine the effect of aspect ratio scaling on the hydrostatic stress in passivated metal interconnects. Aluminium and copper interconnects passivated with phosphosilicate glass (PSG) with aspect ratios ranging from 1×10^{-4} to 100 were studied. Copper interconnects in damascene structure were also studied. The results from analytical models agreed well with numerical results and relevant experimental results. The results showed a decreasing trend of hydrostatic stress with aspect ratio for narrow interconnects, and increasing trend of hydrostatic stress for wide interconnects, with a maximum hydrostatic stress at an aspect ratio of 1. It was observed that there is a large scaling effect. For example, in the case of aluminium interconnect, stress values vary between 50 MPa and 463 MPa. It was also observed from the hydrostatic stress contours that the regions of highest stress do not correspond to the void locations seen experimentally. This implies that it is insufficient to look only at hydrostatic stress for determination of failure sites. Another factor that should be examined is the stress gradient.

Keywords: Microelectronic reliability; Scaling effects; Stress voiding; Finite element method

1. Introduction

Stress-induced voiding was discovered in aluminium interconnects on semiconductor devices back in 1981 [1]. It is a failure mechanism in which voids grow in the absence of applied voltage or imposed thermal gradient. It was found that there is an inherent tendency for voids to form in the aluminium interconnect because of the large difference in thermal expansion between aluminium and its more rigid passivation. As interconnect dimensions continue to scale down into deep submicron regime, voids resulting from thermal stresses have become a major reliability issue. It was first calculated by Jones et al. that, for narrow interconnects, the tensile stresses in the interconnects can be several times the yield strength [2]. Since then, numerous work on finite element modeling of stresses in passivated metal interconnects have been done [3–10].

The present work focused on the analytical and numerical study of the effect of aspect ratio scaling on hydrostatic stress in passivated interconnect. In an earlier study [11], the

absolute value of the width was chosen. In the present study, the geometrical aspect ratio (height/width) was used. The interconnect was assumed to behave in an elastic-perfectly plastic manner. The Eshelby inclusion model [12] and Eshelby inhomogeneity model [13] were used in the analytical study, whereas numerical results were obtained from a commercial finite element software, ANSYS. In the Eshelby models, interconnects are modeled as ellipsoidal inclusions of infinite extent in the axial direction, embedded in a passivating matrix. In the Eshelby inclusion (EIC) model, the material properties (elastic modulus and Poisson's ratio) of the matrix are taken to be the same as that of the interconnect. In the Eshelby inhomogeneity (EIH) model, the matrix assumes its own material properties. Aluminium and copper interconnects were studied, with aspect ratio ranging from 1×10^{-4} to 100, and the height of the interconnects throughout assumed to be 1 μm . The passivation layer (matrix) chosen for this analysis is phosphosilicate glass (PSG). Copper interconnects in damascene structure were also studied.

2. Finite element model

The finite element model as shown in Fig. 1, consists of a 1 μm thick aluminium or copper interconnect on a 1 μm thick layer of borophosphosilicate glass (BPSG) on a 2 μm thick silicon (Si) substrate, with the interconnect passivated with a 1 μm thick PSG. Fig. 2 shows the geometric model of the copper damascene structure. It consists of a tantalum (Ta) barrier layer of thickness 20 nm for the bottom and 10 nm for the sidewall, and an etch stop layer (SiN) of thickness 50 nm. These thicknesses were held constant during the course of examining the effect of aspect ratio scaling. In this work, the directions along the line-width, along interconnect thickness, and along interconnect length are denoted by the x , y and z directions.

The interconnect was assumed to be very long and has both ends connected to other structures. Hence it experiences no strain in the z direction. Thus, a plane strain condition was used. It was also assumed that the interconnect is sufficiently isolated from its neighbours that no interaction occurs. Due to symmetry, only one half of the model was simulated. The boundary condition on the yz symmetry plane is zero x displacement. The Si substrate is also constrained at its base, i.e. no y displacement. The rest of the edges of the model are unconstrained. The whole assembly was cooled from a stress-free state at 400 $^{\circ}\text{C}$ to 25 $^{\circ}\text{C}$.

In this study, BPSG, PSG, SiO_2 , SiN, Ta and Si were modeled as temperature-dependent elastic materials while Al and Cu were modeled as temperature-dependent, elastic-plastic materials. Materials properties as shown in Table 1 were taken from Refs. [2,6,14,15]. The ANSYS finite element software was used to calculate the stresses. The hydrostatic stress referred to in the next section is the stress at the centre of the interconnect. The hydrostatic stress is defined as the average of x , y and z stresses.

3. Results and observations

3.1. Effect of aspect ratio

Figs. 3 and 4 show the plots for aluminium and copper interconnects, respectively, of the hydrostatic stress at the centre of the interconnect against aspect ratio for the case where the interconnect is assumed to behave in an elastic-perfectly plastic manner. These figures are replotted from Ang and Ramanujan [11] using aspect ratio as the variable instead of line-width. The results show a decreasing trend of hydrostatic stress with aspect ratio for narrow interconnects, and increasing trend of hydrostatic stress for wide interconnects, with a maximum hydrostatic stress at an aspect ratio of 1, which is what was observed in Refs. [6,7,16,17]. The existence of the maximum point is due to the larger stress relaxation experienced by interconnects with aspect ratios other than 1 [11].

The calculated maximum hydrostatic stresses are 463 MPa and 534 MPa for aluminium and copper interconnects, respectively. The hydrostatic stress in copper interconnects for all aspect ratios is larger than that in aluminium interconnects due to copper being a stiffer material than aluminium. It was also observed that there is a large scaling effect. For example in the case of aluminium interconnects, stress values vary between 50 MPa and 463 MPa.

Experimental results were taken from Refs. [6,10]. Marieb [6] studied 1 μm wide and 0.7 μm thick copper interconnects, with 0.1 μm thick SiN and 0.8 μm thick SiO₂ passivation. Rhee [10] studied 0.25–1 μm wide and 0.6 μm thick copper interconnects, with 0.4 μm thick SiO₂ passivation. In both cases, the passivated interconnects were cooled from 400 °C to room temperature. Fig. 5 shows the numerical results obtained using the damascene structure, together with experimental results from Marieb and Rhee. It was observed that there is good agreement between the numerical and experimental results. It was also observed that Rhee's results did not show a maximum at aspect ratio 1.

Instead it showed that the hydrostatic stress increases with increasing aspect ratio. This discrepancy is due to the periodic parallel interconnect test structures used in Rhee's study. Shen [7] in his study of periodic interconnects had also concluded that maximum stresses in periodically arranged aluminium interconnects do not occur for aspect ratio = 1.

3.2. Hydrostatic stress contours

Figs. 6–8 show the hydrostatic stress contours for copper interconnects of aspect ratios 0.1, 1 and 10, respectively. It can be seen that for interconnect of aspect ratio 0.1, the highest stress regions are at the left and right interfaces. For interconnect of aspect ratio 1, the highest stress region is at the centre of the interconnect. For interconnect of aspect ratio 10, the top and bottom interfaces experience the highest stress. The locations of these regions can be understood if we liken the narrow and wide interconnects to cracks. It is well known that regions around the crack tip experience the highest stress, which is analogous to what was observed here.

It has been reported that regions of high tensile stress coincide with void locations. However, from a literature survey of void locations covering both aluminium [18–22] and copper [23,24] interconnects with aspect ratios ranging from 0.1 to 5, it was found

that voids appeared at the corners of the interconnects. However, our modeling work shows that the maximum hydrostatic stress does not necessarily occur at the corners. There are two possibilities of why our models fail to predict the void locations. First, our model may be too simplified as in plane strain condition was used instead of generalized plane strain. It was shown that model using generalized plane strain condition gives a more accurate result than model using plain strain condition [25]. Second, the coupling between neighbouring interconnects may also have to be considered. Shen [7] has shown that the spacing between interconnects has a significant effect on the stress state.

On the other hand, there may be criterion other than maximum hydrostatic stress that could be used to predict a void location. Criterion based on hydrostatic stress gradients should be examined, as voiding could be a diffusional process. The stress gradients will determine the direction of maximum flux of vacancies and thus the growth rate of the voids. Our preliminary modeling results support this hypothesis, and the maximum stress gradients are indeed located at interconnect corners (Fig. 9).

4. Conclusions

In this study, numerical work using ANSYS and analytical work based on Eshelby models were performed to examine the effect of aspect ratio scaling on the hydrostatic stress in passivated metal interconnects. Aluminium and copper interconnects of aspect ratios ranging from 1×10^{-4} to 100 were studied. Theoretical results show that maximum hydrostatic stress occurs at aspect ratio of 1. The calculated maximum hydrostatic stresses are 463 MPa and 534 MPa for aluminium and copper interconnects, respectively. The hydrostatic stress in copper interconnects for all aspect ratios is larger than that in aluminium interconnects due to copper being a stiffer material than aluminium. It was also observed that there is a large scaling effect. For example, in the case of aluminium interconnect, stress values vary between 50 MPa and 463 MPa.

Importantly, it was observed from the hydrostatic stress contours that the regions of highest tensile stress do not correspond to the void locations seen experimentally. This implies that it is insufficient to look only at hydrostatic stress for the determination of failure sites. Another factor that should be examined is the stress gradient.

References

- [1] P.A. Totta, in: C.Y. Li, P. Totta, P. Ho (Eds.), *Stress-Induced Phenomena in Metallization*, First International Workshop, 1991, p. 1.
- [2] R.E. Jones Jr., M.L. Basehore, *Appl. Phys. Lett.* 50 (1987) 725.
- [3] B. Greenebaum, A.I. Sauter, P.A. Flinn, W.D. Nix, *Appl. Phys. Lett.* 58 (17) (1991) 1845.
- [4] A.I. Sauter, W.D. Nix, *IEEE Trans. Compon., Hybrids, Manuf. Technol.* 15 (1992) 594.
- [5] U. Burges, I. Eppler, W. Schilling, H. Schroeder, H. Trinkaus, in: Paul S. Ho, J. Bravmen, C.Y. Li (Eds.), *Stress-Induced Phenomena in Metallization*, Third International Workshop, 1995, p. 3.
- [6] T. Marieb, A.S. Mack, N. Cox, D. Gardner, X.C. Mu, *Materials Research Society Symposium Proceedings*, vol. 403, 1996, p. 639.
- [7] Y.L. Shen, *J. Appl. Phys.* 82 (4) (1997) 1578.
- [8] A. Gouldstone, Y.L. Shen, S. Suresh, C.V. Thompson, *J. Mater. Res.* 13 (7) (1998) 1956.
- [9] A. Wikström, P. Gudmundson, S. Suresh, *J. Appl. Phys.* 86 (11) (1999) 6088.
- [10] S.H. Rhee, Y. Du, P.S. Ho, *J. Appl. Phys.* 93 (7) (2003) 3926.
- [11] D. Ang, R.V. Ramanujan, in: A. Khor, R.V. Ramanujan, C.P. Ooi, J. Zhao (Eds.), *3rd International Conference on Materials Processing for Properties and Performance*, Singapore, November 24–26, 2004, *Materials Processing for Properties and Performance*, vol. 3, 2004, p. 450.
- [12] H. Niwa, H. Yagi, H. Tsuchikawa, *J. Appl. Phys.* 68 (1) (1990) 328.
- [13] M.A. Korhonen, R.D. Black, Che-Yu Li, *J. Appl. Phys.* 69 (3) (1991) 1748.
- [14] J.A. King, *Materials Handbook for Hybrid Microelectronics*, Artech House, 1988, p. 39.
- [15] J.M. Paik, H. Park, Y.C. Joo, *Microelectron. Eng.* 71 (2004) 348.
- [16] A. Tezaki, T. Mineta, H. Egawa, *International Reliability Physics Symposium*, 1990, p. 221.
- [17] I.S. Yeo, S.G.H. Anderson, P.S. Ho, C.K. Hu, *J. Appl. Phys.* 78 (2) (1995) 953.
- [18] M. Hasunuma, H. Kaneko, A. Sawabe, T. Kawanoue, Y. Kohanawa, S. Komatsu, M. Miyauchi, *International Electron Devices Meeting*, 1989, p. 677.
- [19] S. Kordic, R.A.M. Wolters, K.Z. Troost, *J. Appl. Phys.* 74 (9) (1993) 5391.
- [20] I.S. Yeo, P.S. Ho, *International Reliability Physics Symposium*, 1996, p. 131.
- [21] J.P. Lokker, G.C.A.M. Janssen, S. Radelaar, *Microelectron. Eng.* 50 (2000) 257.
- [22] D. Jawarani, H. Kawasaki, I.S. Yeo, L. Rabenberg, J.P. Stark, P.S. Ho, *J. Appl. Phys.* 82 (4) (1997) 1563.
- [23] P. Borgesen, J.K. Lee, R. Gleixner, C.Y. Li, *Appl. Phys. Lett.* 60 (14) (1992) 1706.
- [24] A. Sekiguchi, J. Koike, K. Maruyama, *Mater. Trans.* 43 (7) (2002) 1633.
- [25] Y.L. Shen, S. Suresh, I.A. Blech, *J. Appl. Phys.* 80 (3) (1996) 1388.

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Property	$T(^{\circ}\text{C})$ for Al, Si, BPSG and PSG							
Material	20	100	149	204	260	316	371	450
E (GPa)	$T(^{\circ}\text{C})$ for Cu							
Al	69	68	66	62	55	49	42	39
Cu	—		137	132	128	123	119	114
Si	130							
BPSG	120							
PSG	79							
SiO ₂	59							
SiN	220.8							
Ta	185.7							
σ_Y (MPa)	$T(^{\circ}\text{C})$ for Cu							
Al	104	104	93	72	41	31	21	15
Cu	—			455	289	163	77	32
α ($10^{-6}/\text{K}$)	$T(^{\circ}\text{C})$ for Cu							
Al	22.5	24.2	25.3	26.5	27.7	28.9	30.0	30.7
Si	2.3	2.9	3.2	3.4	3.6	3.8	4.0	4.1
BPSG/PSG	1.1	1.7	2.0	2.2	2.4	2.6	2.8	2.9
Cu	—			16.5	17.6	18.3	18.9	19.5
SiO ₂	1							
SiN	3.2							
Ta	6.5							
ν								
Al/Cu	0.33							
Si	0.28							
BPSG/PSG	0.20							
SiO ₂	0.16							
SiN	0.27							
Ta	0.342							

Table 1

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9