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1999

Tan, C. M., Linggajaya, K., Er, E., & Chai, V. S. H. (1999). Effect of BOE etching time on wire bonding quality. *IEEE Transactions on Components and Packaging Technology*, 22(4), 551-557.

<https://hdl.handle.net/10356/91600>

<https://doi.org/10.1109/6144.814971>

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Effect of BOE Etching Time on Wire Bonding Quality

Cher Ming Tan, *Member, IEEE*, Kaufik Linggajaya, Eddie Er, and Vincent Siew-Heong Chai

Abstract—The dependence of wire bond-pull strength on the morphology of the underlying polycrystalline silicon (poly-Si) beneath the bondpad metal is studied using atomic force microscopy (AFM). Statistical analysis shows that the roughness of the poly-Si is correlated with the wire bond-pull strength. The correlation is believed to be due to the effectiveness of thermal dissipation through poly-Si during the wire bonding process. Statistical analysis also shows that the roughness of the poly-Si is correlated to the buffered oxide etch (BOE) etching time before the bondpad metal deposition. In this work, it is concluded that the BOE etching time has a significant effect on the wire bonding quality. The roughness parameter that links the BOE etching time to the wire bond-pull strength is found to be the localization factor.

Index Terms—AFM, bondpad, quality, statistical analysis, surface roughness study, wire bonding.

I. INTRODUCTION

BONDPADS are the key elements in an integrated circuit since they make the communication possible between an integrated circuit and the external world. The common failure modes related to bondpads are the formation of inter-metallics due to gold-aluminum interdiffusion at the bond wire to bondpad interface, whisker growth or dendrite growth at the bondpad in order to equalize compressive stress, and bondpad metal corrosion [1]. The first failure mode is assembly related, the second failure mode is wafer fabrication related, and the third failure mode is package related.

Recently, another wafer fabrication related failure mode for bondpad is found. The failure mechanisms are found to be either the surface morphology of the poly silicon underneath the bondpad metal or the extra metal layer on top of the poly silicon [2]. While the presence of extra metal layer can be eliminated by tight process control, it is found that the surface morphology of polycrystalline silicon (poly-silicon) depends on the buffered oxide etch (BOE) etch time before the bondpad metal deposition [2]. Hence, it is believed that BOE etch time will have an effect on wire bonding quality.

It is understood that when two solid surfaces are placed in contact, the actual contact takes place over only a very

small area, the tips of the asperities or surface irregularity [3]. These contact areas might directly affect the wire bonding quality as it can either affect the bondpad metal adhesion to the underlying poly-silicon or the heat dissipation during bonding process. Therefore, in this work, the effect of BOE etch time on the surface roughness of the poly silicon will be examined, and the effect of the roughness parameters of the surface on the bonding process will also be established.

Four roughness parameters are used in the work. They are the average roughness, RMS roughness, maximum roughness and localization factor. Although the RMS roughness has now almost gone out of practical usage [4], we include the parameter as the atomic force microscopy (AFM) measurement provides this parameter value, as well as it tends to be more sensitive than the average roughness to large deviation from the mean line [4]. Localization factor was introduced by the previous work [2], and its physical significant is the degree of localization of the high roughness peaks. The definitions of these parameters can be defined as [2], [4], [5]

Average roughness

$$R_a = \frac{1}{L} \int_0^L |z| dx \text{ over 2-20 consecutive sampling lengths}$$

$$\text{RMS roughness } R_q = \sqrt{\frac{1}{L} \int_0^L z^2 dx}$$

Maximum roughness

$$R_{\max} = \text{largest single peak-valley height in 5 adjoining sampling lengths}$$

$$\text{Localization factor } L.F. = R_{\max}/R_a$$

where z is the height of the surface measured from the mean line, and L is the profile sample length in the x -direction (Fig. 1).

II. EXPERIMENTS

Eight wafers are subjected to the identical processes as shown in Fig. 2 with the exception of the BOE etching time. The BOE etching time for each wafer is shown in Table I. Six bondpads are selected from each wafer as illustrated in Fig. 3, and their center areas are measured with digital atomic force microscope (AFM) with the scan area of $8 \mu\text{m} \times 8 \mu\text{m}$. The results of the roughness from AFM are summarized in Table II.

Manuscript received February 19, 1999; revised September 27, 1999. This paper was recommended for publication by Associate Editor D. N. Donahoe upon evaluation of the reviewers' comments. This work was supported in part by an Undergraduate Research Opportunity Program Project, Nanyang Technological University, Singapore.

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Publisher Item Identifier S 1521-3331(99)10270-8.

Fig. 1. Definition for some roughness parameters.

Fig. 2. Process flow chart for the experimental wafers. LDD means lightly doped drain; BPSG means boron-phospho-silicate glass.

Four other wafers are also subjected to the processes as in Fig. 2, with the BOE etching time as shown in Table III. But these four wafers go further to the deposition of bondpad metals, and wire bonding process. The diameter of the gold bonding wire used is 1.3 mil. Wire pull test (WPT) is performed on each bond, and the summary results are shown in Table IV. No bondpad peeling is observed in the experiment, and all the failure modes are break in wire span, i.e., either break at the neck or at the Au/Al intermetallic. The specification for WPT is 6 gm.

(a)

(b)

Fig. 3. Illustration of (a) the selection of dies on wafer and (b) bondpads on the selected die for AFM measurement.

TABLE I
BOE ETCHING TIME FOR DIFFERENT WAFER

Wafer Number	BOE Etching Time (seconds)
1 & 2	10
4 & 5	20
7 & 8	30
10 & 11	45

TABLE II
SUMMARY OF EXPERIMENTAL RESULTS OF AFM (unit is nm)

Wafer #	R_g		R_q		R_{max}		Computed $L.F$	
	μ	σ	μ	σ	μ	σ	μ	σ
1	13.48	0.93	17.87	1.12	107.1	6.50	7.96	0.34
2	13.42	0.78	17.51	0.67	99.74	2.63	7.45	0.45
4	14.03	1.06	18.61	1.30	119.7	29.9	8.51	1.75
5	13.98	0.76	18.30	0.66	106.1	10.1	7.63	1.04
7	13.64	0.72	18.04	0.85	113.3	14.4	8.28	0.62
8	14.43	1.20	18.83	1.65	116.9	12.0	8.10	0.48
10	12.83	1.78	17.51	1.62	112.6	9.91	8.94	1.67
11	14.24	0.55	18.82	0.91	112.6	4.28	7.91	0.27

Note: μ is the average value and σ is the standard deviation of a roughness parameter over the six bondpads/wafer

TABLE III
BOE ETCHING TIME FOR DIFFERENT WAFER

Wafer Number	BOE Etching Time (seconds)
3	10
6	20
9	30
12	45

III. ANALYSIS OF EXPERIMENTAL RESULTS

Software STATGRAPHICS Plus 3.1 is used to analyze the experimental data. The Box plots and Table of canonical correlation analysis for the four roughness parameters with respect to the BOE etch time are shown in Figs. 4–7 and

TABLE IV
WPT RESULTS (AVERAGE OVER 15 PADS, UNIT: gm)

Wafer #	Average	Minimum	Maximum	Std Dev
3	11.90	10.27	13.78	0.64
6	13.09	10.26	16.81	1.05
9	12.74	9.43	16.76	1.36
12	12.24	9.54	16.93	1.25

Fig. 4. Box plot of average roughness versus BOE etching time, and line plot for the average R_a versus BOE etching time (solid line with square symbols).

Fig. 5. Box plot of RMS roughness versus BOE etching time, and line plot for the average R_q versus BOE etching time (solid line with square symbols).

Table V. Canonical correlation analysis is used because it is a method of analysis for investigating the relationship between two groups of variables, surface roughness and BOE etching time in this case. Within each group of variable, there can be several variables, such as R_a , R_q , R_{max} and $L.F$ in the surface roughness group [6].

Correlation analysis shows that all the four parameters are statistically significant correlated at 95% confidence level since their P-value is less than 0.05 [7].

Fig. 4 shows that R_a increases with the BOE etching time until about 30 s, and then it decreases with the etching time. This can be explained by referring to the surface profile of the

Fig. 6. Box plot of maximum roughness versus BOE etching time, and line plot for the average R_{max} versus BOE etching time (solid line with square symbols).

Fig. 7. Box plot of localization factor versus BOE etching time, and line plot for the average $L.F.$ versus BOE etching time (solid line with square symbols).

poly-silicon illustrated in Fig. 8. Since the energy states at the valleys are usually high, acid preferentially reacts with these sites more rapidly than it reacts with other regions of the solid surface [3]. Hence, as etching progress, the valley will become deeper with respect to other regions of the surface, causing the z to increase with the etching time, and thus an increase in R_a . However, since BOE attacks only the silicon oxide, when all the oxide in the valleys are etched away, the etching stop for the valleys. On the other hand, since the etching rates at other regions are slower than that in the valley, residue oxide can still remain in these regions. Then, while etching has stopped in the valley, the etching continue at the other regions. This results in a decrease in z , and hence R_a decreases with the etching time.

Fig. 5 shows that R_q follows the similar trend as R_a with respect to the BOE etching time. This is expected since R_q is basically another way of representing the mean roughness.

After the valleys have stopped the BOE etching process, the next fastest BOE etch will occur at the peaks of the surface

TABLE V
CANONICAL CORRELATION ANALYSIS FOR ROUGHNESS PARAMETERS VERSUS BOE ETCHING TIME

Parameter	Eigenvalue	Canonical Correlation	Wilks Lambda	Chi-Square	D.F	P-value
R_a	0.242922	0.492871	0.757078	16.0016	1	0.0001
R_q	0.0866647	0.294389	0.913335	5.2125	1	0.0224
R_{max}	0.110459	0.332354	0.889541	6.73038	1	0.0095
$L.F$	0.396354	0.629567	0.603646	29.0242	1	0.0000

Fig. 8. Surface profile of poly-silicon of a bondpad as measured by AFM.

morphology since their energies are higher. Hence, as etching continues, the peaks' height reduces, and R_{max} reduces. This is shown in Fig. 6.

From the above explanation, and it can also be seen from Figs. 4 and 6, that the increase in R_{max} is faster than R_a at etching time below 30 s, and the decrease in R_{max} is slower than R_a at etching time above 30 s. Hence, $L.F$ increases with the etching time continuously as shown in Fig. 7.

Therefore, one can see that BOE etching time has an effect on the morphology of the poly-silicon surface. Fig. 9 shows the SEM micrographs of the poly-silicon surface after BOE etching of 10 and 20 s, respectively, revealing the dependence of morphology of the poly-silicon surface on BOE etching time.

As we know that when two solid surfaces are placed in contact, the actual contact takes place over only a very small area [3], one expects that poly-silicon surface morphology can

also affect the wire bonding quality. This is because wire-bonding process is a thermo-compression process, and if the effective contact area between the bondpad metal and the underlying poly-silicon is small, heat dissipation will be less effective, and the effective temperature during bonding will be higher. This could cause purple plague to occur as it is evidenced that the purple plague will occur between gold wire bonded to Al if the temperature-time product is large enough [8]. As a result, the wire-pull strength will be decreased. The higher effective temperature during bonding could also cause the grains of gold in bonding wire to increase in size, rendering a lowering of the average pull strength [9]. In fact, the decrease on film cooling effectiveness due to the increase in surface roughness has been verified experimentally by Barlow and Kim [10].

Based on the above discussion, one can see that if the localization factor of the poly silicon is high, the effective

(a)

(b)

Fig. 9. SEM micrographs of poly-silicon surface subjected to different BOE etching time: (a) 10 s and (b) 20 s.

Fig. 10. Schematic illustration of the effect of localization factor on wire pull strength: (a) small contact area between metal and poly Si for large $L.F$ and (b) larger total effective contact area for small $L.F$.

contact areas will be small, and the wire pull strength will be small. This can be illustrated schematically in Fig. 10. In other word, WPT should be decreases with the localization

Fig. 11. Effect of localization factor on the WPT values.

Fig. 12. Relationship between WPT and BOE etching time.

factor. This is indeed the case as seen in Fig. 11. The lower WPT at the lowest $L.F$ value correspond to the short BOE etching time. For these samples, the oxide thickness on the poly-silicon is sufficient high to retard the heat conduction through silicon during the wire bonding process, making the WPT value to be low.

From the results of WPT versus $L.F$, it is evidenced that the effective contact area of the bonding metal on the underneath poly-silicon decreases as the $L.F$ increases. This indicates that metal peeling as observed in the previous work [2] is likely to be due to the large localization factor, together with the presence of the observed extra layer

Since localization factor is affected by the BOE etching time, the WPT values should be affected by the BOE etching time. This is shown in Fig. 12.

Figs. 13 and 14 show the WPT strength versus R_{max} and R_a , respectively. One can see a lack of correlation between them as expected from the discussion earlier on the relationship between surface morphology and WPT strength.

Fig. 15 compares the relationship between the $L.F$ and BOE etching time from the previous work [2] and the present

Fig. 13. Relationship between WPT and R_{max} .

Fig. 14. Relationship between WPT and R_a .

work. The relationship between the $L.F$ and BOE etching time can vary from batch to batch. This is believed to be due to the difference in the ratio of the NH_4F/HF and the original bare poly silicon surface morphology. The ratio is one of the causes as different ratio results in different etch rate as shown in Fig. 16 [11].

Since the relationship between the $L.F$ and BOE etching time varies from batch to batch, the use of BOE etching time as a process control parameter does not seem to be the good parameter, and instead $L.F$ should be the better control parameter in ensuring good wire bonding quality.

IV. CONCLUSION

The effect of BOE etching time on the surface morphology of the poly silicon before bondpad metallization is studied using AFM. It is found that the etching time has a significant effect on the poly silicon morphology.

The effect of surface morphology on the wire pull test strength is also studied. It is found that localization factor is the key parameter in determining the wire pull test strength.

Fig. 15. Relationship between localization factor and BOE etching time from different works. Solid line represents the present work, which is the same as in Fig. 7 with only the average values shown, and dashed line represents the previous work [2].

Fig. 16. Oxide etch rates in BOE.

Since localization factor is affected by the BOE etching time, the wire pull test strength is related to the BOE etching time.

The study of the effect of the localization factor on the wire pull test strength also suggests that the metal peeling as observed in the previous work [2] is due to the presence of extra layer and the large localization factor.

The relationship between BOE etching time and the localization factor is found to vary from batch to batch. Therefore, it is suggested that BOE etching time is not a good process control parameter in ensuring good wire bonding quality, but the localization factor can be a better parameter.

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