Plasma Etching of Aluminium Using BCl_3 - Cl_2 Mixtures.

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Abstract

Reactive Ion Etching of evaporated and sputtered aluminium with BCl_3 - Cl_2 gas mixtures was studied. The aluminium oxide breakthrough time was mainly dependent on pressure and not as much on BCl_3 flow, what indicates that the ion bombardment is the most important process to remove the aluminium oxide. On the other hand, the aluminium etch rate was not dependent on ion bombardment but rather on the density of reactive species in the plasma. We found that the etch rate decreases in time, when a standard lithography process was used. We propose that during the etching, a polymer is formed which decreases the etch rate.

When using a standard lithography process, vertical side walls were obtained. However, in this case, the resist suffered very much from the etching and was removed in the centre of the lines, while "mouse bites" were formed at the border. Using a three level resist process, the resist remained relatively undamaged, but a lateral etching occurred. We attribute this behaviour to the fact that much less carbon is present in the plasma in this case, so less side wall protecting polymer is formed.

To obtain vertical aluminium side walls, together with the reproducible removal of the aluminium oxide, a process was successfully developed which uses initially a BCl_3 - Cl_2 mixture, followed by an etching step with a CCl_4 - N_2 mixture.

Introduction

Aluminium remains the main interconnect material in integrated circuit fabrication, despite increasing interest in alternative materials. The possibility of dry etching of aluminium by chlorine containing gases is one of the big advantages over other materials such as copper.

BCl_3- Cl_2 mixtures are commonly used to etch aluminium [1-3] The main goal of using BCl_3 is to remove fastly and reproducibly the aluminium oxide layer, while the Cl_2 enhances the etch rate of the aluminium. The addition of a carbon containing gas enhances the anisotropy of the etching [3].

Before starting the etching of the aluminium itself, a thin but very hard aluminium oxide layer have to be removed. The time to remove this aluminium oxide layer - the aluminium oxide breakthrough time - must be determined in order to be able to determine the aluminium etch rate. Both etch rate and breakthrough time can be determined by several different methods.

A first method is to etch aluminium films with the same process with 2 (or more) different etching times.

It is possible to determine the etch rate and breakthrough times with formulas (1) and (2) :

$$r = (h_1 - h_2)/(t_1 - t_2) \tag{1}$$

$$t_b = t_1 - h_1/r = t_2 - h_2/r \tag{2}$$

where :

h is the step height in the aluminium (indices 1 and 2 indicate wafer 1 and wafer 2)

t is the etching time (indices 1 and 2 indicate wafer 1 and wafer 2)

r is the aluminium etch rate

t_b is the aluminium oxide breakthrough time.

This method supposes that the etch rate is constant in time and that both etch rate and breakthrough time are equal for both wafers.

Another way is to determine the breakthrough time, by measuring a plasma parameter, e.g. the DC self bias voltage or the intensity of a spectral line, and determine the etch rate through formula (3) :

$$r = h/(t-t_b) \tag{3}$$

In this paper, the influence of BCl_3 and Cl_2 flow, pressure, etch time and resist type on aluminium oxide breakthrough time, aluminium etch rate and side wall profile is studied.

Experimental

The plasma etching processes are performed in a home built RIE single wafer reactor, with load-lock. Power is applied to the lower, 6 inch diameter aluminium electrode. The DC self bias voltage is measured by the power generator module (Advanced Energies, RFX 600). The system is described in more detail in [4].

Three inch, p type wafers in the 10 - 20 Ohm.cm range were thermally oxidised. Aluminium was deposited by thermal evaporation or sputtering, with thicknesses in the range of 600 - 800 nm. The wafers were patterned with a conventional lithography process, using AZ1350J resist or with a special three-level resist process, which is described in [5]. After etching the resist was removed in fuming nitric acid.

The selectivity tests were performed on wafers which were dry oxidised at 1150 °C during 2 hours, resulting in an oxide thickness of approximately 220 nm.

For these tests, the BCl_3 and Cl_2 flows were varied in the 10 -15 sccm range, pressure in the 50 - 100 mTorr range, and power was kept constant at 150 W. Etching times were varied, to obtain the data necessary to apply equations (1) and (2) and to verify if the etch rates remain constant in time.

Results and discussion

1. Aluminium oxide breakthrough times and aluminium etch rates.

Tables I and II show the results of several etching processes. From these tables, one can conclude that the etch rate of the aluminium is always higher at the border of the wafer than in the centre. A bull's eye effect occurs for all the processes.
Furthermore, one can see that the breakthrough time increases with pressure. This increase can be explained by the decreasing ion bombardment, as the (absolute value) of the DC self bias voltage decreases with pressure. The ion bombardment is a very important factor in the removal of the aluminium oxide.

Table I - Breakthrough times, step heights and average etch rates, calculated with formula (3), for aluminium deposited by evaporation, for several $BCl_3 + Cl_2$ processes.

Evaporation	etching time (s)			Al step height(A)			etch rate (nm/min)		
10sccm BCl3/15sccm Cl2	total	tq	Al	border	centre	border	border	centre	border
	30	8	22	1979	1761	2119	540	480	578
50 mTorr	50	8	42	3725	2810	3327	532	401	475
	29	9	20	2873	2204	2507	862	661	752
100 mTorr	54	12	42	5211	4576	5590	744	654	799
Evaporation	etching time (s)			Al step height(A)			etch rate (nm/min)		
15sccm BCl3/10sccm Cl2	total	tq	Al	border	centre	border	border	centre	border
	29	8	21	1705	1334	1737	487	381	496
50 mTorr	49	8	41	3115	2872	3197	456	420	468
	29	12	17	1974	1878	2146	697	663	757
100 mTorr	50	10	40	3527	3023	3253	529	453	488

Table II - Breakthrough times, step heights and average etch rates, calculated with formula (3), for aluminium deposited by sputtering, for several $BCl_3 + Cl_2$ processes.

Sputtering	etching time (s)			step height (A)			etch rate (nm/min)		
10sccm BCl3/15sccm Cl2	total	tb	Al	border	centre	border	border	centre	border
	30	4	26	2676	2445	2595	617	564	599
50 mTorr	41	4	37	3686	3617	3580	598	586	580
	30	5	25	3930	3143	3394	943	754	815
100 mTorr	40	5	35	5003	4031	4688	858	691	804
Sputtering	etching time (s)			step height (A)			etch rate (nm/min)		
15sccm BCl3/10sccm Cl2	total	tb	Al	border	centre	border	border	centre	border
	21	3	18	1894	1647	1928	631	549	643
50 mTorr	41	3	38	3608	3317	3744	570	524	591
	30	3	27	3240	2928	3309	720	651	735
100 mTorr	41	4	37	4895	3698	4554	794	600	738

The BCl_3 and Cl_2 flows do not influence very much the breakthrough time. For the sputtered samples, there is a slight decrease in breakthrough time with increasing BCl_3 flow. This is expected, as the B atoms of this molecule have a reducing effect on the aluminium oxide.
There is a huge difference between the breakthrough times of the evaporated aluminium and of the sputtered aluminium. In the case of the evaporation, the wafers are warmed up by the radiation of he filament. Although there are a few minutes between evaporation and the breaking of the vacuum, in our case we use ambient air, it is possible that a somewhat thicker

aluminium oxide is formed when the still warm aluminium surface enters in contact with the air. In the case of the sputtering, the wafers remain cool and the vacuum is broken with nitrogen gas. Therefore, it is our opinion that the difference in breakthrough time is not an etching effect but due to a difference in aluminium oxide thickness between the two wafer types.

For all processes, the reproducibility of the breakthrough time is relatively good and certainly much better than with $CCl_4 + N_2$ processes, as reported in [4,6]

Both tables show that when the pressure increases, the aluminium etch rate increases. For these processes, the concentration of active species determines the etch rate. The DC self bias voltage decreases with pressure. Therefore one may conclude that the aluminium etching is much more determined by the concentration of reactive particles than by the ion bombardment.

If one compares the processes with different flows, one can observe that the etch rate is in general higher for the process with the highest Cl_2 flow. Cl_2 is much more reactive than BCl_3 : it is known that Cl_2 in molecular form etches aluminium, while BCl_3 has not this characteristic [1]. Therefore, the density of reactive particles will be higher for processes with a higher Cl_2 flow. And once again, this effect will increase the aluminium etch rate.

Figure 1 shows the height of the step etched in the aluminium for 2 different etching times, and also the aluminium oxide breakthrough time as determined by the DC self bias voltage measurement. This figure shows clearly that the etch rate decreases with time. Tables I and II also show that for the longer etching times, the etch rates are (almost) always lower. It is our opinion that this etch rate decrease in time really occurs. A possible explanation is the increasing formation of polymers, which decrease the etch rate when increasing the etching time. Extra comments follow below.
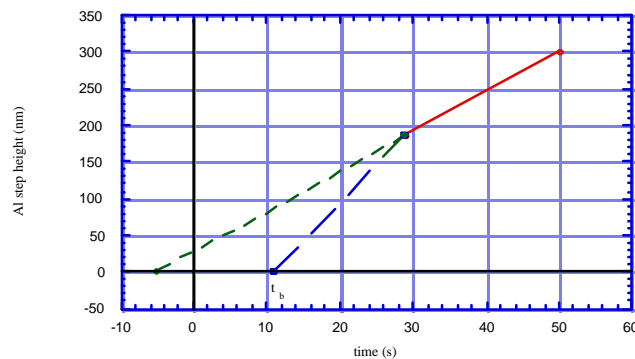

Figure 1 - Aluminium oxide breakthrough time and aluminium step height as a function of time for 15 sccm BCl_3/10 sccm Cl_2, 100 mTorr, 150 W processes, for evaporated films.

As the etch rate is not constant in time, it is impossible to determine the aluminium oxide breakthrough time using formula (2) : as shown in figure 1, a negative time would be obtained, which is impossible.

Therefore, the only way to accurately determine the oxide breakthrough time and the time average etch rates is by using the measurement of the DC self bias voltage together with formula (3).

The selectivities of the aluminium etching towards the thermal oxide, range between 8:1 and 10:1 for the 50 mTorr processes, between 13 and 15 for the 15 sccm BCl_3 - 10 sccm Cl_2 - 100 mTorr process and between 32 and 35 for the 10 sccm BCl_3 - 15 sccm Cl_2 - 100 mTorr process. These selectivities are high enough for whatever practical application.

The selectivities towards the lower three level resist layer are relatively low : they range from 0.7:1 to 1.3:1. When using a 2 micrometer thick resist layer, this is just sufficient for practical processes.

2. Aluminium wall profiles

The wall profiles of the different processes were investigated by SEM analysis.

In the first place, the use of a conventional lithography process was investigated. If this process would result in a satisfactory profile, it would have the great advantage over the three level resist process that it is much easier to perform, with much less process steps and therefore at a much lower cost.
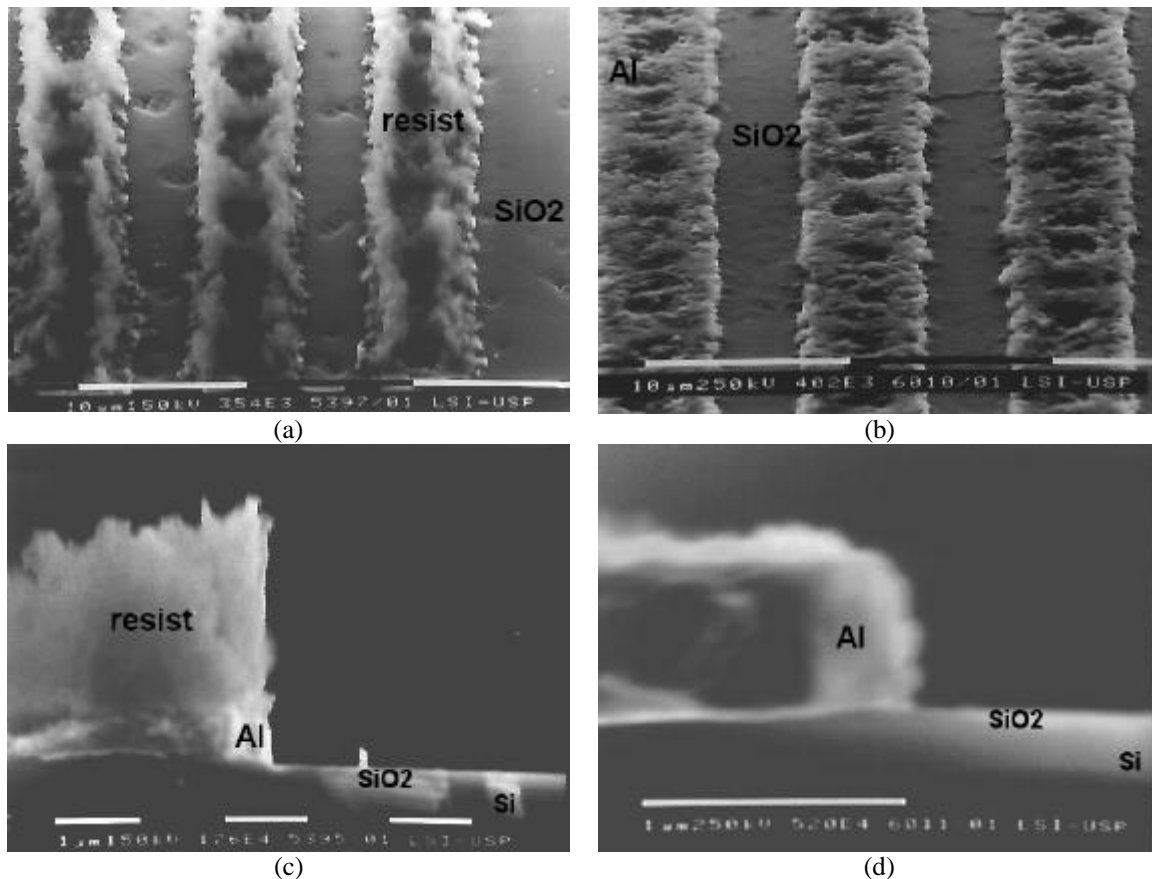

(a)

(b)

(c)

(d)

Figure 2 : Aluminium lines etched with a 10 sccm BCl_3 - 15 sccm Cl_2, 50 mTorr process, with a conventional lithography process, figures (b) and (d) after resist removal.

Figures 2 (a) to (d) show different aspects of the etched aluminium lines, before ((a) and (c)) and after ((b) and (d)) resist removal. For this case, the aluminium was deposited by evaporation and the 10 sccm BCl_3 - 15 sccm Cl_2, 50 mTorr process was used. Other processes yield similar results, for both evaporated and sputtered films.

Figures 2 (a) and 2 (b) show the accentuated erosion of the resist due to the aggressive attack of the chlorine containing species. In the centre of the lines, the resist was already removed

and the aluminium is partially etched. One also observes that the resist deformed during the etching, resulting in a pattern full of "mouse bites" at the border of the aluminium lines.

On the other hand, figures 2 (c) and (d) show that the resulting profile is relatively vertical. But figure 2 (c) also shows that the resist is completely deformed after the etching process.

The fact that the aluminium side wall is relatively vertical indicates that there is a lot of polymer formation. Therefore, it is possible that this polymer formation causes the decrease in etch rate with etching time, as commented above.

The fact that the aluminium is already partially removed in the centre of the lines and that there are lots of "mouse bites" turns these processes unacceptable.

In the case of a conventional lithography process, the resist was post baked at 90°C. When applying the three level resist process, the first resist layer is baked at 190°C. Therefore, this resist layer will be much more resistant to the attack of the plasma. New tests were performed to evaluate the performance of these etching processes when the aluminium was masked by the three level resist process.
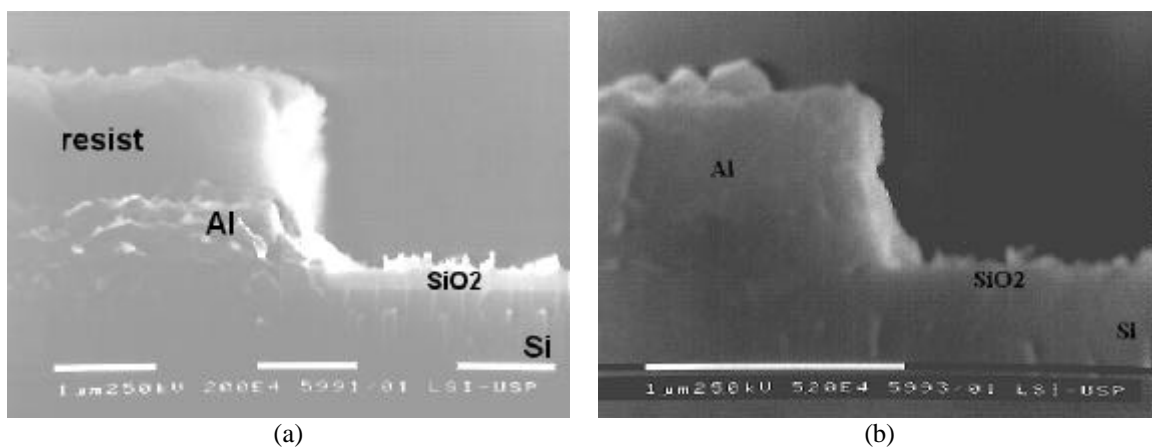

(a)   (b)

Figure 3 : Side wall profiles after etching with a a 15 sccm BCl_3 - 10 sccm Cl_2 100 mTorr process, using a three level resist process, figure (b) after resist removal.

Figure 3 shows the resulting wall profiles after etching with a 15 sccm BCl_3 - 10 sccm Cl_2 100 mTorr process, before (a) and after (b) resist removal. One can clearly observe that a lateral underetching occurred : the resulting side wall is much less vertical than in the case of the conventional resist process. In the case of the three level resist system, the resist masks the aluminium much better and will be etched away at a much lower rate. This means that for these processes, there will be a much lower concentration of carbon atoms in the plasma than in the case of the conventional resist process. Therefore, one may conclude that in this case, much less polymer will be formed and it is well known that it is exactly this polymer which forms the side wall protection and inhibits the lateral undercut. Taking all these factors into account, we propose that the undercut which occurred when using a three level resist process happens because there is not enough polymer formation in the plasma due to the low resist etch rate.

When a process is used with a CCl_4 containing plasma, the resist erosion rate has less influence on the polymer formation in the plasma, as CCl_4 already contains a carbon atom. The main problem with CCl_4 plasmas is their non-reproducibility, mainly of the breakthrough time. As reported in [6], we are able to obtain vertical wall profiles, using a CCl_4 + N_2 etching process. However, the reproducibility of these processes will be enhanced if the aluminium breakthrough time could be reduced and kept more reproducible. When using a

BCl_3 - Cl_2 process for this task and a CCl_4 - N_2 process for the etching of the aluminium, a good compromise can be obtained.

(a)　　　　　　　　　　　　　　　　　　(b)

(c)　　　　　　　　　　　　　　　　　　(d)
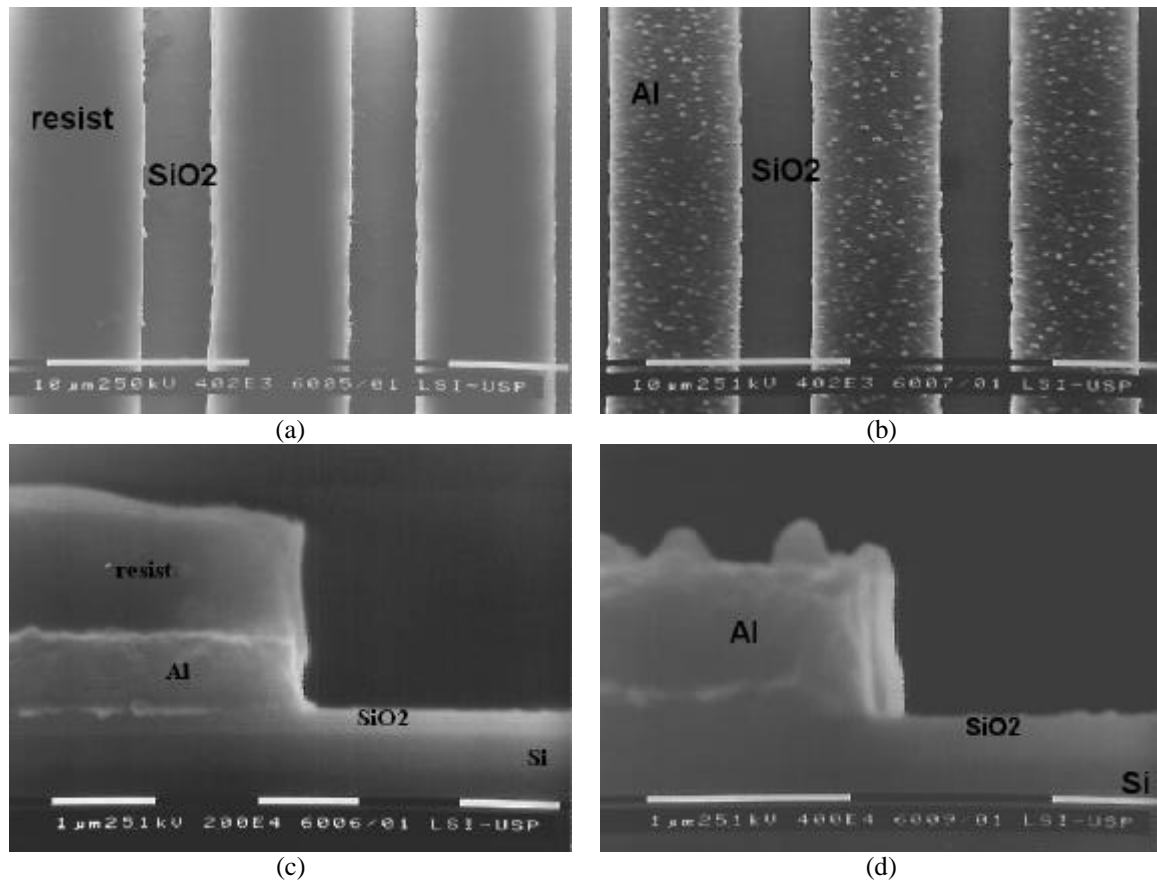
Figure 4 : Aluminium lines after a combined 15 sccm BCl_3 - 10 sccm Cl_2 100 mTorr 150 W and 13 sccm CCl_4 - 15 sccm N_2 100 mTorr 150 W etching process, using three level resist lithography, figures (b) and (d) after resist removal.

Wafers were etched during 5 seconds with a 15 sccm BCl_3 - 10 sccm Cl_2 - 100 mTorr - 150 W process, followed by a 13 sccm CCl_4 - 15 sccm N_2 - 100 mTorr - 150 W process until endpoint, followed by a 15% overetch time. The results are shown in figure 4. Figures 4 (a) and (b) show that the resist remains fairly intact after etching (a) and that no "mouse bites" occur (a-b). Figures 4 (c) and (d) show that the resulting aluminium wall profiles are vertical, with little or no undercut. Figure 4 (c) also shows the remaining resist, which shows no deformation at all. One may conclude that this combined process uses the best characteristics of both BCl_3 - Cl_2 and CCl_4 - N_2 processes.

Conclusions

Evaporated and sputtered aluminium films were etched in BCl_3 - Cl_2 plasmas. The aluminium breakthrough times increase with increasing pressure indicating a strong effect of the ion bombardment. The aluminium etch rates increase with pressure and increasing Cl_2 flows, indicating that for these processes, the concentration of reactive species determines the etch rate. Besides, the etch rate decrease with time, probably due to a polymer which is formed during the etching.

When using conventional lithography processes, it is possible to obtain vertical wall profiles, but the resist is excessively eroded, resulting in removal of some aluminium in the centre of

the lines and in "mouse bites" at the borders. When using a three level resist process, these problems did not occur, but the etching becomes less anisotropic.

Combining a BCl_3 - Cl_2 process to remove the aluminium oxide layer, with a CCl_4 - N_2 process to etch anisotropically the aluminium, it is possible to obtain aluminium lines with vertical side walls and without any "mouse bites".

This process can be successfully used for practical purposes.

References

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