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SELECTIVE REACTIVE ION ETCHING OF PECVD SILICON NITRIDE OVER AMORPHOUS SILICON IN CF_4/H_2 AND NITROGEN CONTAINING CF_4/H_2 PLASMA GAS MIXTURES

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Abstract—In this paper, we report a highly selective dry etching process for plasma chemical vapour deposited silicon nitride over undoped and n^+-doped amorphous silicon. Dry etching is carried out in both CF_4/H_2 and nitrogen containing CF_4/H_2 plasma gas mixtures. The effect of pressure, H_2 and N_2 concentration on etch behaviour and selectivity is investigated. We report selectivities in the range of 2–40 for the differential etching of silicon nitride over doped/undoped amorphous silicon by using CF_4/H_2 plasma gas combination. Higher etch rates with nitrogen containing CF_4/H_2 are observed.

1. INTRODUCTION

In liquid crystal display applications using active matrix hydrogenated a-Si:H thin film transistors, it is frequently required to provide patterned thin films of amorphous silicon and silicon nitride. In advanced miniaturization of thin film based devices and integrated circuits it is imperative that for pattern transfer with dimensions below about $4\,\mu m$, wet chemical etching has to be replaced by dry etching[1,2]. Wet etching techniques based on KOH and HF are very commonly used to selectively etch a-Si:H and silicon nitride. However, wet etching is complicated and indirect. It uses corrosive liquids and results in toxic waste products. More importantly, dry etching is preferred over wet process for the possibility of a vertical etch rate that greatly exceeds the horizontal rate, called anisotropic etching.

One of the important figures of merit in dry etch is selectivity between two material layers. This selectivity assumes even more importance when the film that is being patterned overlays a thin material layer. In PECVD (plasma chemical vapour deposition) based thin film transistor fabrication, it is essential to have a good selectivity between silicon nitride and amorphous silicon. The cross-section of a typical inverted-staggered thin film transistor is shown in Fig. 1. To pattern the second silicon nitride layer (N_2), the etch process should be highly selective so as to minimize the etching of underlying a-Si:H. Selectivity again plays an important role while opening contact windows in the top masking silicon nitride (N_3). Since the underlying n^+ a-Si:H is usually very thin (≈ 500 Å), unless there is a good selectivity between Si_3N_4 and n^+ a-Si:H, there is a possibility of etching away the n^+ a-Si:H layer over which metal contact is made.

There have been several studies in literature for dry etching of plasma chemical vapour deposited silicon containing films[3–7]. Since Si_3N_4 film is widely used as a mask material for the local oxidation of silicon, LOCOS[8], in VLSI manufacturing, its dry etching behaviour and selective etching over SiO_2 have been the subject of several studies[9–15]. In most of the above studies, gases such as CF_4, C_2F_6, CHF_3, CF_3Cl, CF_2Cl_2 or CF_4/O_2 are commonly used to etch the silicon containing amorphous layers. Unfortunately, reports on differential etching between PECVD materials are very few. In one of the studies[7], the etch ratio of PECVD Si_3N_4 to a-Si:H has been investigated in CF_4, C_2F_6, CHF_3. It has also been reported recently[16] that a-Si:H can be selectively etched over Si_3N_4 using a $CF_4/SiCl_4$ RIE process. However, an interesting question which so far has received no serious attention is the etch selectivity of Si_3N_4 over doped/undoped amorphous silicon in CF_4/H_2 and nitrogen containing CF_4/H_2 plasma gas mixtures. As discussed above, this selectivity is a very useful process requirement in the fabrication of TFTs. Since CF_4[17,18] is very commonly used in reactive ion etching, it is useful to know if this gas can be used in combination with H_2 and N_2 to selectively etch Si_3N_4.

The aim of this study is therefore to find a dry etch process using CF_4/H_2 and nitrogen containing CF_4/H_2 which will give a good selectivity while

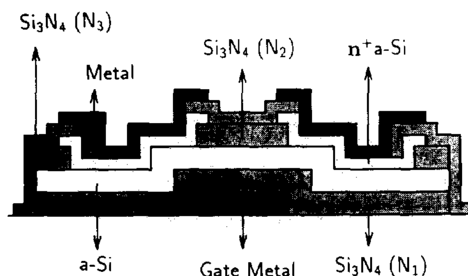

Fig. 1. Schematic cross-section of an inverted-staggered TFT structure.

providing a reasonable etch rate for the layer being etched. PECVD deposited a-Si:H, n^+ a-Si:H and Si_3N_4 are reactive ion etched by varying the etch process parameters such as the pressure, H_2 and N_2 concentration in CF_4/H_2 and its effect on selectivity and individual layer etch rates are reported.

2. EXPERIMENTAL

We have used 3 in. dia Corning 7059 glass substrates for the deposition of a-Si:H and n^+ a-Si:H. Silicon nitride layers are deposited on 3 in. dia silicon substrates. Before the deposition, all the wafers are cleaned in RCA solution and dried in nitrogen. The deposition of layers is done in a Plasma-Therm PECVD system (790 Series) using the following deposition conditions—for a-Si:H, the power is maintained at 10 mW/cm^2 and the flow rate of 100% SiH_4 is 50 sccm. For the deposition of n^+ a-Si:H, the power is again maintained at 10 mW/cm^2 and the flow rate of 1% PH_3/SiH_4 is 10 sccm. In the case of Si_3N_4 deposition, the power is set at 100 mW/cm^2 and the gas flow rates are 100 sccm of 50% NH_3/N_2 and 5 sccm of 100% SiH_4. The deposition rates for a-Si:H, n^+ a-Si:H and Si_3N_4 are 120, 64 and 120 Å/min respectively. The deposited layer thickness is approx. 1000 nm. After the deposition, following a photolithographic step using positive photoresist, patterns are transferred on to the photoresist on the sample from a line-and-space test mask. No post-baking is done on the wafers. We have cut these wafers into approx. 1 in. square pieces for the dry etching experiments and divided them into several sets—each set having one each of a-Si:H, n^+ a-Si:H and Si_3N_4 samples. Reactive ion etching is carried out on a given set of samples simultaneously in a given plasma gas combination. By simultaneously etching this way, it is expected that etching will be uniform on all the pieces and will minimize any errors in the etch rate measurements. Photoresist is stripped after reactive ion etching and the average etch rates are obtained by dividing the step heights, obtained with Sloan's "Dek Tak" profilometer, by the etch time. In all cases, the etching process is performed in about 3 min.

All the dry etching experiments are carried out using an MRC, RIE-51 reactor. This reactor has a cathode of 6 in. dia and is equipped with mass flow controllers to introduce the process gases into the chamber in controlled amounts. We have used semiconductor grade Matheson supplied CF_4, $H_2$40%/He60% and ultra high pure nitrogen. In all our experiments, we have set the RF power at 100 W. This moderate RF power is chosen to keep the etching rate compatible with the layer thicknesses involved in the TFT fabrication. Since etching rate increases monotonically with applied power[19], at RF powers greater than 100 W, it becomes very difficult to control the etching of thin layers of the order of 500–5000 Å commonly used in TFTs. Also higher RF powers result in excessive ion bombardment and lower selectivity, photoresist degradation, and an aggravation of the loading effect and lead to etching non-uniformities[20].

To study the effect of H_2 concentration on the etch rate of a-Si:H, n^+ a-Si:H and Si_3N_4 at a given pressure, we have varied the H_2 concentration from 0 to 50% in CF_4/H_2 gas mixture† while the chamber pressure is maintained at 25 mtorr. Similarly, to investigate the effect of pressure on etch rate and selectivity, we have varied the chamber pressure from 10 to 50 mtorr for a given H_2 percentage (20%) in CF_4/H_2 gas mixture. The effect of N_2 addition to the CF_4/H_2 gas mixture is studied (i) by varying the N_2 percentage for a given pressure and (ii) by varying the pressure for a given N_2 percentage in CF_4/H_2 gas mixture. In all our experiments, the total flow of CF_4 is fixed at 20 sccm and for a given gas flow rate, the pressure is controlled by adjusting the pump speed.

†It may be noted that in all cases, the percentage of H_2 is relative to CF_4/H_2 and that H_2 is diluted with He i.e., H_2(40%)/He(60%).

3. RESULTS AND DISCUSSION

3.1. *Reactive ion etching in CF_4/H_2*

Figure 2 shows the etch rate of amorphous silicon and silicon nitride as a function of H_2 concentration in CF_4/H_2 gas mixture. Our etch rate measurements on a-Si:H and n^+ a-Si:H have shown that both the materials get etched at identical rates in CF_4/H_2. The etch rate for both amorphous silicon and Si_3N_4

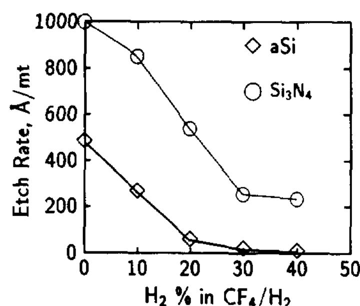

Fig. 2. Etch rates of amorphous silicon and silicon nitride as a function of H_2 concentration in CF_4/H_2 gas mixture.

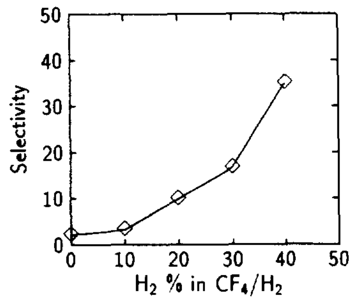

Fig. 3. Etch selectivity for Si_3N_4 (Si_3N_4 etch rate divided by amorphous silicon etch rate) as a function of H_2 concentration in CF_4.

decreases as the H_2 concentration increases. For the a-Si:H, the etch rate has fallen from about 500 Å at zero H_2 concentration to a negligible value at 40% H_2 concentration. For Si_3N_4, the fall is from about 1000 to 250 Å/min. The fall in etch rates for H_2 percentages greater than 40 is due to the extensive polymerization that occurs on all surfaces exposed to the reactive discharge. This etching behaviour is similar to that observed in the case of silicon dioxide and silicon for which a high selectivity ratio relative to silicon is situated directly before this point[21,22].

Figure 3 shows the etch selectivity for Si_3N_4 (Si_3N_4 etch rate divided by amorphous silicon etch rate) as a function of H_2 concentration in CF_4/H_2. It is interesting to note that the selectivity of Si_3N_4 over amorphous silicon increases from about 2 to 40 as the H_2 concentration is increased. A selectivity of 10–15 is considered reasonable because at higher selectivities, the etch rate of the layer being etched can become too small to be practical. We note from Fig. 3 that a selectivity of 10 between Si_3N_4 and amorphous silicon can be obtained when the H_2 concentration is 20%. At this H_2 percentage, the etch rate for Si_3N_4 is 550 Å/min and for amorphous silicon it is 55 Å/min. Since in a typical TFT, the thickness of Si_3N_4 is in the range of 2000–3000 Å, this etch rate allows us to etch Si_3N_4 in a reasonable time without affecting the underlying a-Si:H.

We have next investigated the effect of pressure on both selectivity and etch rate of a-Si:H, n^+ a-Si:H and Si_3N_4. For a fixed 20% H_2 concentration in

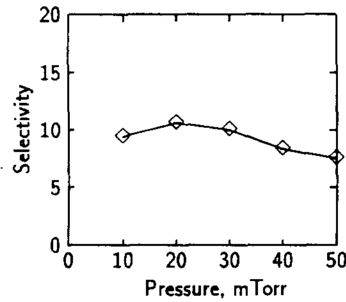

Fig. 5. Selectivity of Si_3N_4 over amorphous silicon as a function of pressure in CF_4/H_2 gas mixture.

CF_4/H_2, etching is carried out at different pressures. Figure 4 shows the etch rates of amorphous silicon and silicon nitride as a function pressure. Again, we have found no difference in the etch rates for doped or undoped a-Si:H for the pressures ranging from 10 to 50 mtorr. As can be noted from Fig. 4, the etch rate decreases as the pressure increases. For a given flow rate, at higher pressures, the residence time and particle collision rate will increase resulting in a reduced average electron energy[19]. The reduction in electron energy leads to a smaller generation rate of active species and hence we observe decreasing etch rates with increasing pressure.

Selectivity of Si_3N_4 over amorphous silicon as a function of pressure is shown in Fig. 5. We observe that selectivity between Si_3N_4 and a-Si:H remains around 10 when the pressure is between 10 and 30 mtorr. Pressure therefore can be adjusted to obtain a desired etching rate for Si_3N_4 between 400 and 800 Å/min while keeping the selectivity around 10.

This high selectivity for Si_3N_4 over amorphous silicon in CF_4/H_2 plasma gas mixture can be explained by the fact that there could be a formation of polymeric species or their precursors in fluorine-deficient fluorocarbon plasmas[18]. With the addition of H_2 to CF_4, hydrogen consumes atomic fluorine and alters the ratio of F to CF[23,24], and results in an enhanced deposition of a fluorocarbon film. X-ray photoelectron spectroscopy (XPS) shows this film to preferentially form on silicon surface rather than Si_3N_4[25], thus reducing the etch rate of Si_3N_4. This is similar to the high etch rate observed for SiO_2 over

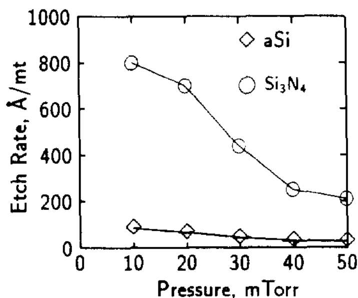

Fig. 4. Etch rates of amorphous silicon and silicon nitride as a function of pressure in CF_4/H_2 gas mixture.

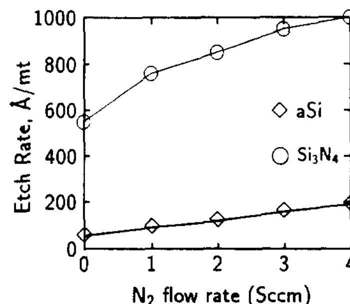

Fig. 6. Etch rates of amorphous silicon and silicon nitride as a function of N_2 flow rate in CF_4/H_2 gas mixture.

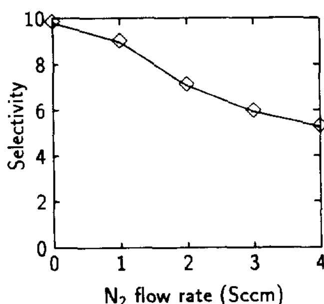

Fig. 7. Etch selectivity for Si_3N_4 (Si_3N_4 etch rate divided by amorphous silicon etch rate) as a function of N_2 flow rate in CF_4/H_2.

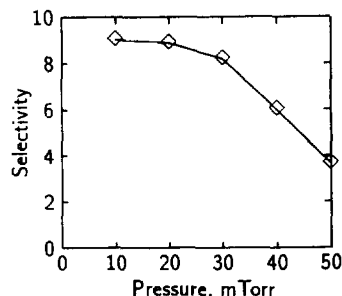

Fig. 9. Selectivity of Si_3N_4 over amorphous silicon as a function of pressure in nitrogen containing CF_4/H_2 gas mixture.

silicon by the addition of H_2[26,27] or C_2H_4[28,29] or by using CHF_3 rather than CF_4[30,31]. However, the decrease in the etch rate of Si_3N_4 at higher H_2 concentrations (Fig. 2) suggests that when the hydrogen content of the plasma is too high, it leads to a relative increase in the amount of polymerizing precursor species in the plasma thus diminishing the etch rate of Si_3N_4[32].

3.2. Reactive ion etching in nitrogen containing CF_4/H_2

Recently, it has been shown that by adding 1% of N_2 to CF_4/O_2 plasma, a three-fold increase in the etch rate of silicon can be obtained[33]. An overall increase in the atomic fluorine concentration is shown to be responsible for this enhancement[34]. There have been no studies on how this nitrogen addition to CF_4/H_2 plasma alters the etch rate of PECVD based a-Si:H and Si_3N_4. To investigate this effect, we have performed the reactive ion etching under the following conditions: (i) by adding 1–4 sccm nitrogen to CF_4/H_2 (CF_4 = 20 sccm with 20% H_2 added to it) at 25 mtorr pressure and (ii) by changing the pressure from 10 to 50 mtorr for 1 sccm N_2 added to CF_4/H_2. The RF power is fixed at 100 W.

Figure 6 shows the etch rate of amorphous silicon and silicon nitride as a function of N_2 concentration in CF_4/H_2 gas mixture. Our etch rate measurements on a-Si:H and n^+ a-Si:H have shown that both the materials get etched at identical rates in nitrogen containing CF_4/H_2. The etch rate for both amorphous silicon and Si_3N_4 increases as the N_2 concentration increases. For the a-Si:H, the etch rate has gone up from about 50 Å at zero N_2 flow to 200 Å at 4 sccm of N_2 in CF_4/H_2. For Si_3N_4, the increase is from about 550 to 1000 Å/min. Thus, we note that as in the case of nitrogen containing CF_4/O_2 gas mixtures, when N_2 is added to CF_4/H_2, the etching rate of both a-Si:H and Si_3N_4 increases. This could be because of an increase in fluorine concentration with increasing N_2 flow.

The selectivity of Si_3N_4 over a-Si:H is plotted in Fig. 7 as a function of N_2 flow in CF_4/H_2. At higher N_2 flow, the selectivity decreases to about half the value obtained with no nitrogen. This indicates that with increasing nitrogen concentration the increase in the etch rate of a-Si:H is faster than that of Si_3N_4. This may be because higher N_2 flow results in an overall increase of atomic fluorine concentration[34], thus enhancing the etch rate of a-Si:H.

We have next investigated the effect of pressure on both selectivity and etch rate of a-Si:H, n^+ a-Si:H and Si_3N_4 in nitrogen containing CF_4/H_2. We have added 1 sccm of nitrogen to CF_4/H_2 containing 20% of H_2 (CF_4 flow = 20 sccm) and etching is carried out at different pressures. Figure 8 shows the etch rates of amorphous silicon and silicon nitride as a function of pressure. Again, we have found no difference in the etch rates for doped or undoped a-Si:H for the pressures ranging from 10 to 50 mtorr. As can be noted from Fig. 8, the etch rate decreases as the pressure increases. However, when nitrogen containing CF_4/H_2 is used, we note that the etch rate remains relatively constant at pressures between 10 and 30 mtorr unlike in the case of CF_4/H_2 with no nitrogen, as can be seen from Fig. 4.

Selectivity of Si_3N_4 over amorphous silicon as a function of pressure is shown in Fig. 9. We observe that selectivity between Si_3N_4 and a-Si:H remains at around 8–9 when the pressure is between 10 and 30 mtorr. However, the selectivity decreases to about 4 when the pressure is raised to 50 mtorr.

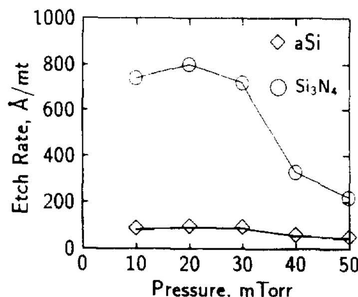

Fig. 8. Etch rates of amorphous silicon and silicon nitride as a function of pressure in nitrogen containing CF_4/H_2 gas mixture.

4. CONCLUSIONS

Detailed experiments are carried out to investigate the etch behaviour and selectivity of a-Si:H, n^+

a-Si:H and Si_3N_4 in CF_4/H_2 and nitrogen containing CF_4/H_2 plasma gas mixtures. Effect of pressure and concentration of H_2 and N_2 in CF_4/H_2 on the etching behaviour are studied. We report that Si_3N_4 can be etched with high selectivities ranging from 2 to 40 when etched in CF_4/H_2. We have not observed any difference in the etching behaviour of a-Si:H and n^+ a-Si:H in CF_4/H_2. Higher etch rates are obtained for amorphous silicon and Si_3N_4 when N_2 is added to CF_4/H_2 plasma gas mixtures but however, selectivity between layers is less than that can be obtained with CF_4/H_2 with no nitrogen added to it.

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