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PLASMA ANODISATION OF SILICON FOR ADVANCED VLSI

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Abstract - Inductively coupled, RF stimulated plasma anodisation of silicon is discussed in terms of both MOS electrical properties and the oxidation of Si$_3$N$_4$/SiO$_2$/Si materials systems. The electrical properties of the plasma oxides grown at 400°C are comparable to those of thermal oxides grown at 1000°C. Preliminary results based on transmission electron microscopy observations prior to and after plasma anodisation indicate that Si$_3$N$_4$/SiO$_2$ strips on silicon exhibit interesting lateral oxidation behaviour and therefore Si$_3$N$_4$ may be a potential mask against plasma anodisation for advanced VLSI.

1- INTRODUCTION

Plasma anodisation is an attractive technique for the oxidation of silicon due to the rapid oxidation rates observed at low temperatures /1/. Prolonged oxidation at high temperatures can generate defects in the silicon and these defects lead to degradation in both yield and performance of small geometry devices. An additional disadvantage of thermal oxidation is the so called "bird's beak" effect: lateral oxidation occurs underneath a masked area, thus limiting the minimum device separation which can be achieved. Although plasma anodisation has been widely investigated (see /1/ and references therein), previous studies have highlighted the severe difficulty of producing effective masks for this process /2/; most of the established masks against thermal oxidation appear to be consumed during plasma oxidation. Therefore an important issue with regard to plasma anodisation is to find materials systems in which the vertical oxidation rate of the mask is low compared to silicon and the lateral oxidation of both the mask and the silicon substrate under the mask are minimal. The present summary addresses this issue in the limited context of Si$_3$N$_4$/SiO$_2$ strips on Si and includes data which show that the electrical properties of plasma grown oxides at 400°C are acceptable for advanced VLSI applications.

2- EXPERIMENTAL

The experimental apparatus used for the anodisation has been described elsewhere in some detail /3/. The anodisation chamber consists of a quartz tube containing oxygen at a pressure of approximately 150 mTorr. The plasma is initiated using an inductively coupled RF generator operating at 27 MHz and 1 kW. The sample to be oxidised is positioned on a heated metal pedestal 5-6 cm from the plasma discharge centre and forms the anode in an external d.c. circuit. Silicon wafers of up to 100 mm in diameter can be uniformly oxidised.

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The response of several materials systems to plasma anodisation is being investigated by cross-sectional transmission electron microscopy (x-TEM). The materials systems include strip structures (~3μm wide) of silicon nitride/thermal oxide and silicon nitride/thermal oxide/polysilicon on (100) n-type silicon substrates. Both the silicon nitride and polysilicon structures were grown by CVD deposition. Specimens for TEM were prepared from the initial structures and from structures after oxidation by mechanical polishing to a thickness of ~30 μm, followed by ion-beam milling to perforation using 4 kV Ar ions. The x-TEM observations were carried out at 200 kV and all structures were imaged edge-on along the strip (i.e. [011]) under zone-axis, bright-field conditions.

3 - RESULTS

As shown in previous work /4/, the electrical properties of plasma oxides grown at 400°C are comparable to thermal oxides grown at 1000°C and the electrical breakdown strength of the plasma oxides exceeds that which is required for isolation of VLSI structures. A typical histogram of electrical breakdown data is presented in Fig. 1. The mean electrical breakdown strength is 9.5 MV/cm over 90% of the probed area with a complete absence of low-field breakdown. In addition MOS capacitors fabricated using plasma oxides have electrical integrity similar to that attainable using thermal oxides. Figure 2 shows a comparison between a typical I-V curve for MOS capacitors with plasma- and thermally-oxidised dielectric layers. Conduction through the oxide in the high-field region prior to breakdown is thought to occur by Fowler-Nordheim tunneling. The differences in the curves are attributed to a higher level of positive charge either near to the interface or within the oxide. At the present time these positively charged traps can only be removed by higher temperature anneals. The slight inflection, or ledge, in the plasma grown case is probable associated with electron traps which are filled by the Fowler-Nordheim tunneling current.

![Histogram showing the field strength of 25 MOS capacitors of diameter 0.38 mm: the plasma oxide was grown at 400°C and the oxide thickness was ~0.1 μm.](image)

The structural features of Si₃N₄/SiO₂ strips on silicon before and after plasma anodisation at 400°C are illustrated by the x-TEM micrographs in Fig. 3. Figure 3a is before plasma anodisation and Figs. 3b and 3c are after plasma oxides of ~0.17μm and ~0.45μm thickness were grown, respectively. It can be seen from this sequence of micrographs that the silicon substrate was masked from plasma oxidation at the expense of the Si₃N₄ strip, the surface of which has been partially converted into an oxynitride layer. Other important features which are apparent from Fig. 3c include a marked reduction of the "bird’s beak" effect usually produced during conventional LOCOS isolation, as well as the potential to achieve substantial improvements in the lateral encroachment of a vertical edge, produced by thermal oxidation (e.g., as illustrated in Fig. 3d). This important phenomenon is presently under investigation. Lastly, an electrical field
Fig. 2 - Current-voltage characteristics of plasma and thermal oxides showing comparable electrical integrity: plasma oxide was 420 nm thick and the thermal oxide was 460 nm thick.

induced variation in the oxide surface topography above the terminating edge of the silicon nitride strip is observed (Fig. 3c). This effect can be visualised quite dramatically from the low-

Fig. 3 - Cross-sectional electron micrographs showing similar portions of Si₃N₄/SiO₂ strips on crystalline silicon (a-c) and polysilicon (d): a) is before plasma anodisation; b) and c) are after plasma anodisation at 500°C; and d) is after thermal oxidation at 1000°C.
Fig. 4 - Cross-sectional electron micrographs showing the entire length of the Si₃N₄/SiO₂ strips on Si which appear in Figs. 3b and 3c. The terminations of the Si₃N₄ strip in 4a (downward arrowheads) map onto the inflections at the upper SiO₂ surface in 4b (upward arrowheads).

magnification micrographs shown in Figs. 4a and 4b which correspond, respectively, to the structures shown in Figs. 3a and 3b. It is quite clear from these observations that the end terminations of the Si₃N₄ strip in Fig. 4a map directly onto the inflections at surface of the plasma oxide in Fig. 4b. This result is taken as an indication that both the lateral and vertical oxide-field strengths are modified by the terminations of the Si₃N₄ strip. The fact that there is an anisotropy in the plasma-oxidation field strength is further supported by the observation that a SiO₂ thickness of ~0.45μm can be achieved at the expense of ~0.06μm of Si₃N₄ vertically and ~0.15μm of Si₃N₄ laterally. The net result of the lateral Si₃N₄ movement is to define the vertical limits of the underlying SiO₂/silicon interface (i.e. minimal bird's beak effect).

4 - CONCLUDING REMARKS

The present structural results are taken as an indication that the lateral shift of a Si₃N₄ mask under a given plasma anodisation process will depend strongly on the geometry of the Si₃N₄ strip. Furthermore the realization of large anisotropic electric-field effects for different materials systems and varying geometries of a particular materials system may open the way for nanometre-scale structural engineering in the field of plasma anodisation.

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