COMPARISON OF THE PROPERTIES OF THERMAL AND ION BEAM OXIDES***

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*** Work supported in part by ARO through a contract with Battelle on Delivery Order 2441.

ABSTRACT

A comparison of the current-voltage (I-V) and the capacitance-voltage (C-V) characteristics of thermal and low temperature ion beam grown films of silicon oxide was made. The oxides were in the thickness range between 5 nm and 10 nm. The ion beam oxides were grown at room temperature. The bulk resistivities of the thermal oxides were about 10^{17} ohm cm and were about 5 orders of magnitude lower for the ion beam oxides. The interface charge densities at the Si-SiO_2 interface were about an order of magnitude higher in the case of the ion beam oxides. The oxide properties were also measured after current stressing at constant voltages. The thermal oxides showed an increase in the interface trap density at the Si-$Si0_2$ interface after stressing with a distinct trap appearing above mid-gap. The ion beam oxides showed very little increase in the interface trap density after stressing. The higher conductivity of the ion beam oxides may have lead to discharging of the interface traps generated during stressing.

INTRODUCTION

Modern high density integrated circuits have required limited thermal processing to maintain the fine dimensions of the individual devices.(1) The thermal growth of the gate oxide has always contributed to the total IC thermal budget. Recently, MOS transistors fabricated using ion beam oxides grown at room temperature were reported. (2) A project was undertaken to compare the properties of thermal oxides with ion beam oxides. Both thermal and ion beam oxides were fabricated into aluminum gate MOS capacitors with oxide thicknesses between 5 and 10 nm thick. The properties of the oxides were measured before and after stressing. The stress was provided by the passage of tunneling currents through the oxide.

EXPERIMENTAL

The test capacitors were fabricated on (100), 5 to 10 ohm cm, p-type silicon substrates. After chemical cleaning and growth and removal of a sacrificial 500 nm thick oxide, a 500 nm thick field oxide was thermally grown on the wafers. Capacitor windows were patterned and the thin gate oxides were grown. The thermal oxides were grown in dry oxygen at 900°C for 5 to 8 min followed by an in-situ nitrogen anneal for 30 min. The ion beam oxides were grown at room temperature using previously described techniques.(2) Aluminum was evaporated and defined and the capacitors were annealed in N_2-H_2 at 400°C for 15 min. The back side of the wafers were cleaned and metalized. Oxide thicknesses ranged from 5 to 10 nm, and the capacitor areas were either $4.1 * 10^{-4}$ cm^2 or $9.3 * 10^{-4}$ cm^2. Oxides selected for analysis in this report are described in Table I.

The test measurements were divided into two major parts. The first part was a measurement sequence that ensured that the capacitors were uniform. The I-V characteristics in surface accumulation and the C-V characteristics of 5 large area and 5 small area capacitors on each wafer were measured to ensure that the device properties were area independent and that no perimeter effects were present. After it was assured that the capacitors were uniform, detailed measurements before and after stress were made. Quasi-static C-V data was taken on the thermal oxides and high frequency C-V data was taken on the ion beam oxides. The low resistivity of the ion beam oxides made interpretation of quasi-static C-V data difficult. The capacitors were stressed by passage of tunneling current through the oxide at various constant voltages. The device characteristics were measured after every stress level. The individual devices were stressed, tested, stressed at higher stress levels, retested, etc until the capacitor failed through breakdown of the oxide.

THERMAL OXIDES				
Thickness	9nm	8nm	7.1nm	5.2nm
Wafer number	J3	J5	8B	5PB
ION BEAM OXIDES				
Thickness	9.1nm	8.6nm	5.5nm	
Wafer number	610B	524A	35A	

TABLE I THERMAL AND ION BEAM OXIDES THICKNESSES

RESULTS ON THE THERMAL OXIDES

A synopsis of typical I-V characteristics of the thermal oxides prior to stressing is presented in Figure 1. The oxides had uniformly low currents prior to the onset of tunneling. The breakdown fields were all of the order of 10^7v/cm. The tunneling current and the breakdown voltages scaled with oxide thickness as expected. Data from other oxides has been included in Figure 1 to show the spread in I-V characteristics that was typical of the thermal oxides. The quasi-static C-V characteristics of the 7.1 nm thick oxide are shown in Figure 2 before and after stressing. The traps generated by the passage of tunneling current through the oxide caused an increase in the capacitance in both the depletion and inversion regions. The positive trapped charge shifted the flat band voltage negatively as much as 0.3v at the highest stress levels. At stress levels above 10^{-2} coul/cm^2 the influence of the generated interface traps was evident in the I-V characteristics as shown in Figure 3. At stress levels of .9 coul/cm^2 the discharging of the interface traps caused a negative differential region in the I-V characteristics and an increased current in the oxide quality region. The effect of interface trapped charge on the I-V

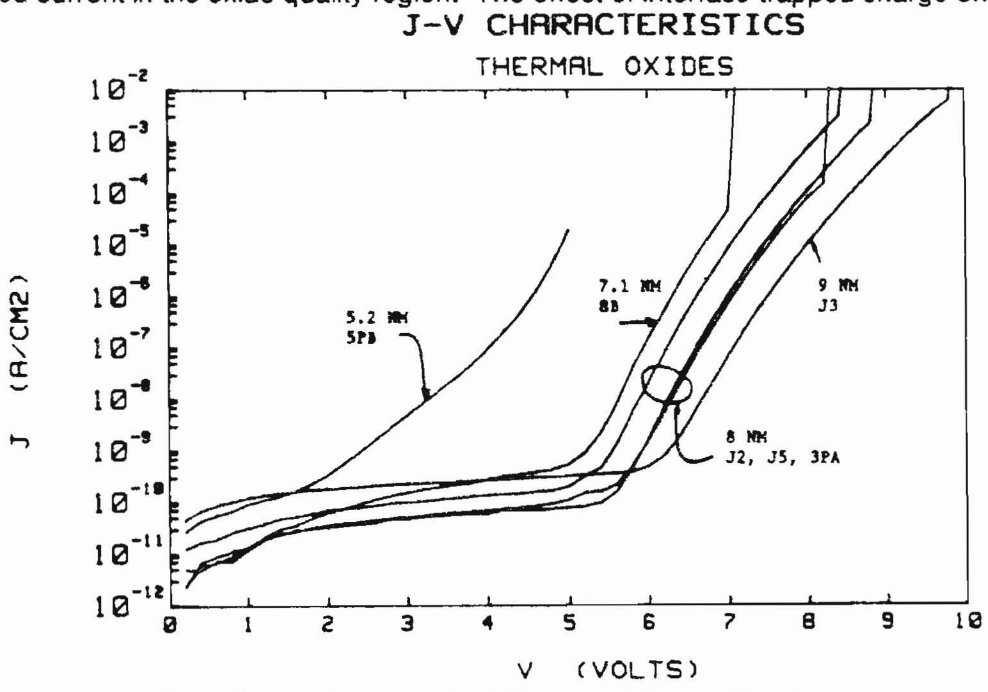

Figure 1 Representative I-V characteristics on thermal oxide capacitors

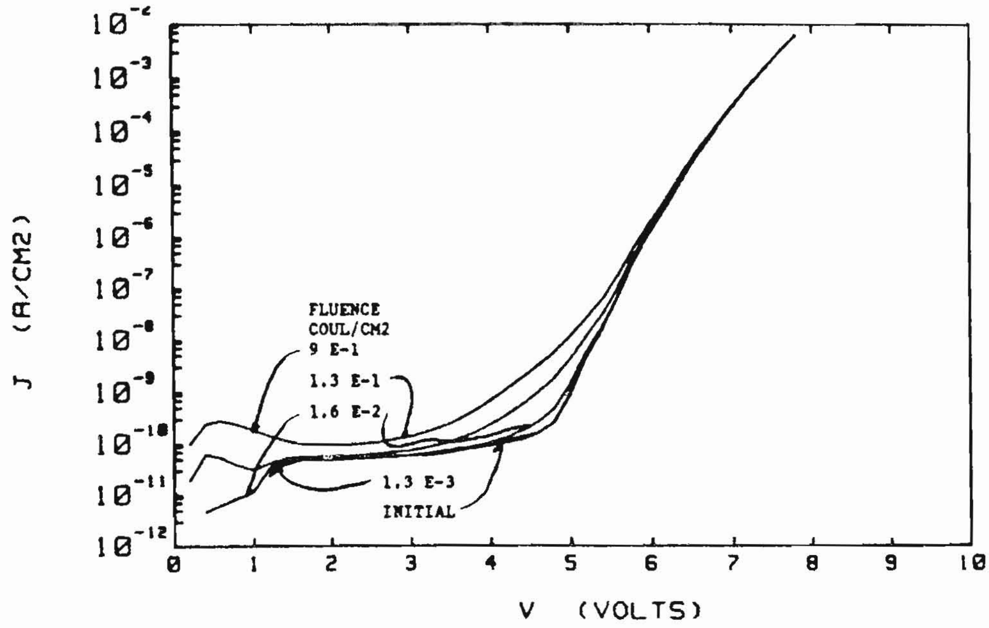

Figure 2 I-V characteristics for a 7.1 nm thermal oxide

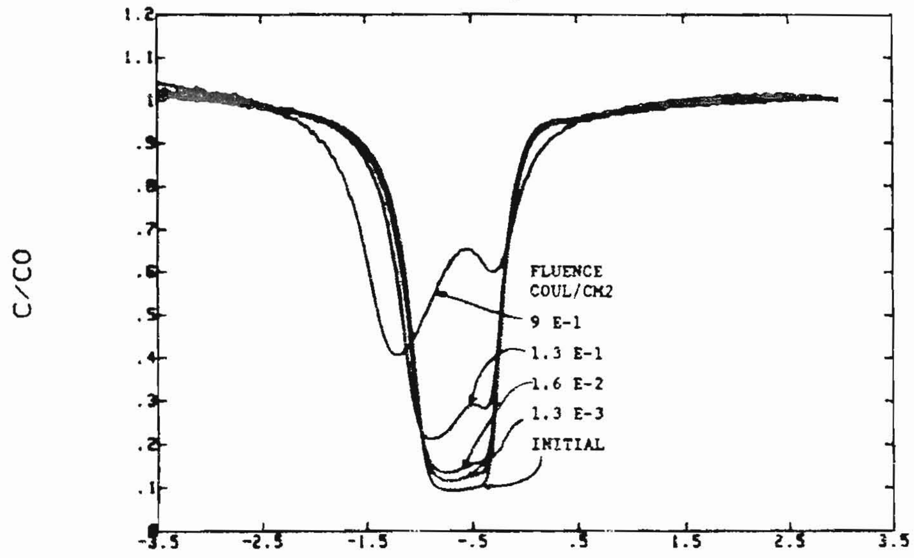

Figure 3 C-V characteristics for a 7.1 nm thermal oxide

characteristics of thermal oxides has been previously described.(3) The low level tunneling current also increased due to changes in the shape of the oxide barrier. Plots of the interface trap density vs. energy as a function of stress are shown in Figure 4 and indicate both a general increase in the trap levels and a specific trap being introduced slightly above mid-gap. Since the polarity of the gate during the stress was negative (the surface was in accumulation) the specific trap may be due to hydrogen leaving the Si-SiO_2 interface. All of the thermal oxides showed qualitatively similar changes in the I-V and C-V characteristics as described above due to stress.

RESULTS ON THE ION BEAM OXIDES

The I-V characteristics of the ion beam oxides prior to stressing are shown in Figure 5. The current levels were all higher than those measured for the thermal oxides. The thicker oxides showed distinct breakdowns at fields in the mid-10^6v/cm range. As in the case of the thermal oxides, the 5nm thick oxides had very high tunneling currents and no distinct breakdown was observed. The high conductivity of the ion beam oxides made measurement of the quasi-static C-V characteristics difficult. A typical high frequency C-V characteristic for a 9.1nm thick ion beam oxide before and after stressing is shown in Figure 6. No shift in the C-V characteristic was observed until stress levels greater than 5 coul/cm^2 were used. Since these oxides already had high surface state densities, it took a large amount of stress to introduce significantly larger interface trap densities.

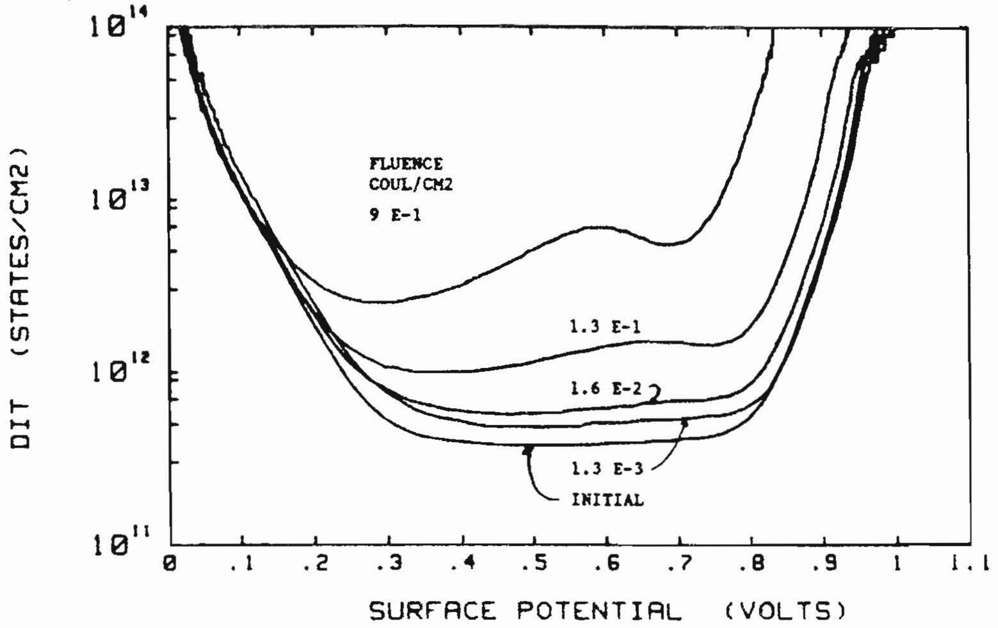

Figure 4 Introduction of interface traps into a 7.1 nm thermal oxide as a function of stress

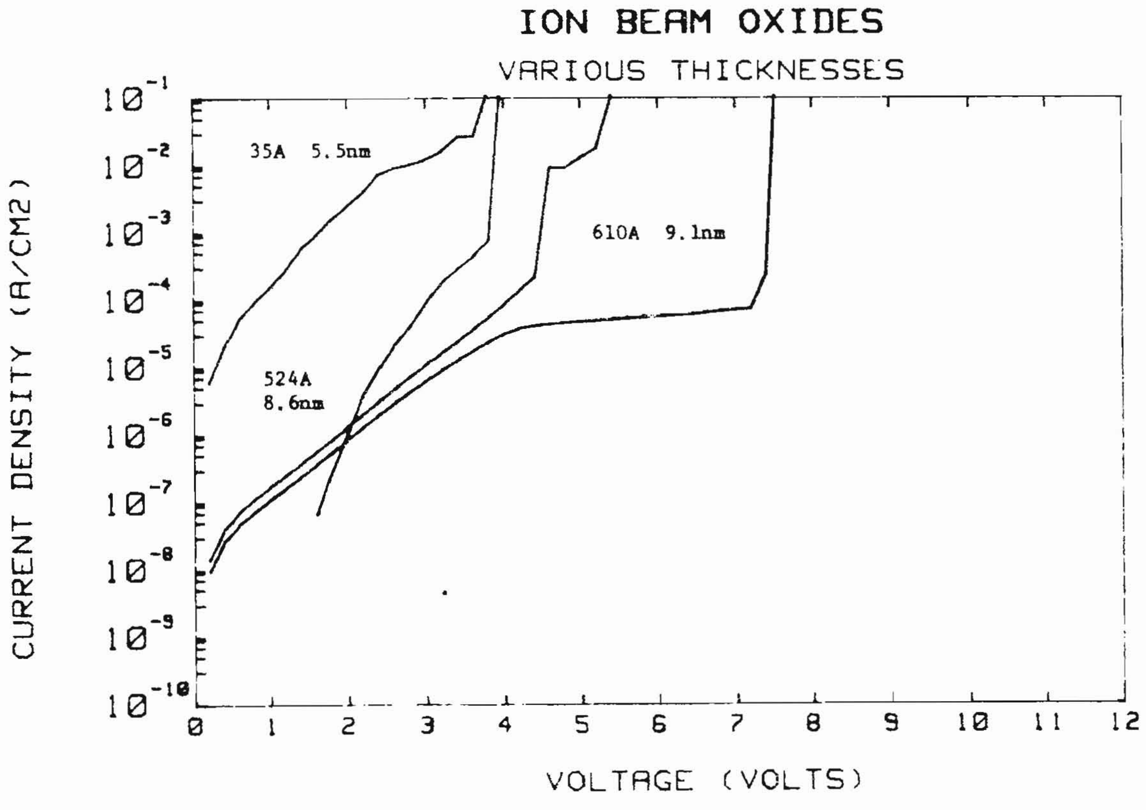

Figure 5 Current-Voltage Characteristics of Ion-Beam Oxides

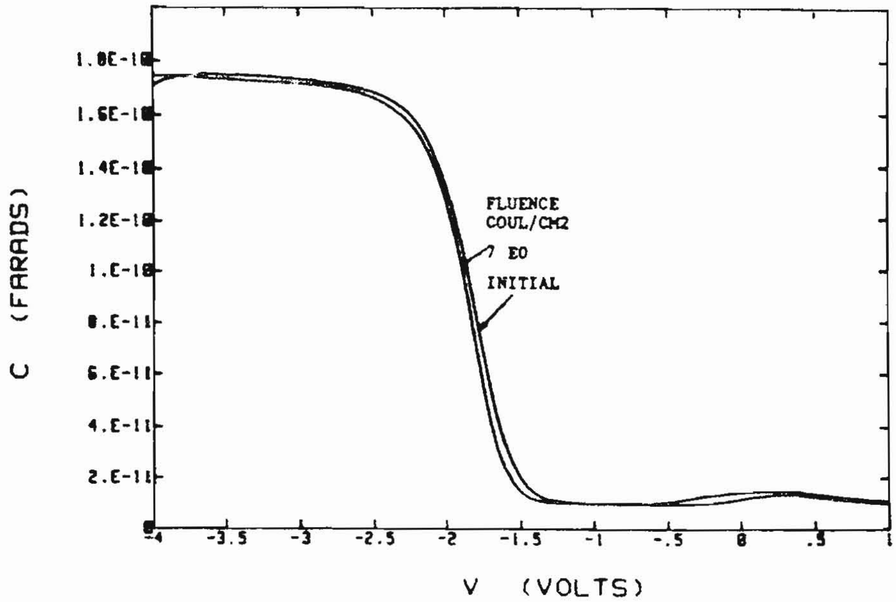

Figure 6 Effect of stress on the high frequency C-V characteristics of a 9.1 nm ion beam oxide

DISCUSSION OF RESULTS

The thermal oxides measured in this experiment were typical of high quality oxides that had been previously measured. The low level I-V characteristics measured prior to stressing indicated oxide resistivities of the order of 10^{17} ohm cm which is typical of high quality oxides (4). The response of the capacitor to pulsed dc voltages produced currents with time constants consistent with resistivities of the order of 10^{17} ohm cm. The flatband voltage of -1.4v for the 7 and 8 nm thick thermal oxides indicated a surface state density of about 10^{12} states/cm^2 which is on the high side for thermal oxides. The low growth temperature used for production of these oxides probably accounted for most of this high surface state density. The breakdown fields in the 10^7 v/cm range indicated relatively high quality oxides. The generation of interface traps at fluences in the 10^{-3} coul/cm^2 range is consistent with trap generation observed in other high quality thermal oxides. The lowest fluences caused no observable changes in the low level I-V characteristics, however, fluences an order of magnitude higher caused the current to increase in the trap generation region of the and to increase in the oxide quality region. Thus, it is suspected that wearout of the oxide was already occuring, but was unobservable due to instrumentation limits. At the high stress levels interface traps were introduced at a rate of 10^{13} states/coul. This rate seemed to increase at lower stress levels, however, the data was not so accurate at the lower stress levels. The rate of 10^{13} states/coul corresponds to a level of about 1 state per 10^6 electrons passing through the oxide.

The higher dc currents measured in the ion beam oxides, the lack of well defined breakdown voltages and the absense of well defined tunneling currents were characteristics of all of the ion beam oxides. All of the above listed effects could be caused by reduced quality of the oxide due to either impurity incorporation into the oxide or the presense of traps and defects in the oxide. The high frequency C-V data showed an additional -1v flatband voltage shift as compared to the thermal oxides indicative of positive charge in the oxide. The oxide charge in the ion beam oxides was of the order of 1 to $3 * 10^{12}$ states/cm^2. The generation of interface traps in the ion beam oxides caused no observable changes in the I-V characteristics. Interface trap generation was observable as changes in the HF C-V data on the ion beam oxides at stress levels of 10 coul/cm^2, which was about an order of magnitude higher than observed in thermal oxides. Any shifts that would have occurred in the I-V characteristics of the ion beam oxides with increased stress were masked by the higher conduction current in these oxides.

CONCLUSIONS

The properties of both thermal and ion beam grown silicon oxide films were measured and compared. The ion beam oxides had higher conductivity than the thermal oxides. The ion beam oxides showed less effect of trap generation due to current stressing than did the thermal oxides. Even though the ion beam oxides had higher conductivity than the thermal oxides, these oxides have been of sufficiently high quality to be used for the fabrication of MOS transistors.

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