MODULATED REFLECTANCE MEASUREMENT OF REACTIVE-ION AND PLASMA ETCH DAMAGE IN SILICON WAFERS

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INTRODUCTION

Reactive ion etching (RIE) and plasma etching (PE) are vital processes for the attainment of densely-packed, micron-scaled structures for VLSI integrated circuits. However, it is widely recognized that undesirable modifications of semiconductor or insulator materials may accompany the use of these dry etch processes. For example, during the RIE process, samples are exposed to high energy ions, UV photons and x-rays, all of which can result in radiation damage [1] in the form of non-annealable structural defects in gate oxide or Si/SiO₂ interface regions, deep level traps or surface states. In terms of IC device performance, these effects cause transistor threshold voltage shifts, poor subthreshold performance, increased junction leakage or decreased capacitor charge retention time, degradation of minority carrier lifetime, barrier shifts in Schottky diodes and reduction of the integrity of trench isolation structures [2,3]. Contamination from sputtering of the chamber parts or of the oxide mask may add to these problems. In addition, polymer material that may be deposited from carbon-containing gases has been found to create oxygen-induced stacking faults [4]. All of the above can lead to significant yield reduction.

A number of techniques have been developed to study the effects of RIE or PE on single crystal silicon. MOS capacitors can be fabricated and capacitance-voltage plots generated to obtain threshold shifts or interface state densities [5]. Generation lifetimes can be measured. Deep level transient spectroscopy can be used to determine trap levels in silicon, but in this technique wafers are subjected to temperature extremes (100 - 300 °C) during the measurements [6]. Alternatively, a decorative, wet chemical etch such as a Seeco [7] or Wright [8] etch can be used to highlight dislocations in silicon. These etches are, however, destructive in nature. Channeling-mode Rutherford back scattering, reflected high energy electron diffraction, electron spin resonance and measurement of the current-voltage characteristics of Schottky diode structures [9] have also been employed to study radiation damage in silicon. Each of the above
methods is either destructive to the examined wafers or lacks the speed or ease of use necessary to constitute an effective, practical method for detecting RIE or PE damage during dry etch process development or during the integrated circuit manufacturing process.

Recently it has been shown that measurement of laser-induced modulated optical reflectance can nondestructively detect the radiation damage in Si due to RIE or PE with good sensitivity [10,11]. This method also measures etch uniformity over the wafer surface and can detect the presence of deposited polymer material on micron-scale device features on patterned wafers. In the present study, we have used this method to measure RIE damage at the bottom of 6-micron deep trench structures as a function of RIE process parameters such as dc bias and pressure. This parametric study allows the RIE process variables to be adjusted to minimize damage to the silicon surface.

**EXPERIMENTAL PROCEDURE**

**Sample Preparation**

The trench samples used are p-type <100> silicon substrates with n+ buried layer and n- epi silicon as illustrated in Fig. 1. The masking material for the silicon trench etch is 4% P-doped CVD oxide etched in a commercial oxide etcher. Trench openings are 1.2 microns wide, with one 10-micron wide trench surrounding the die. This wider trench is used for the modulated reflectance measurements. Prior to silicon etch, samples are cleaned in RCA solution and dipped in 10:1 HF.

Fig. 1: Diagram of the structure of the trench wafer samples. Also shown is the measurement laser beam focused on the wider trench bottom.

**Etch Apparatus and Process**

The main etch step is a low pressure, medium power process with which 80% of the trench is etched. As will be described below, two of the
parameters varied in the experiments to determine their effect on damage are the relative proportion of the constituent gases and the total flow in this etch step. A "clean up" etch step is incorporated to remove the damaged Si produced by the "main" step while completing the etch. As experimental parameters in this "clean up" step, the dc self-bias voltage is varied between -60 and -250 volts and the pressure between 15 and 100 mTorr to determine their effect on silicon damage.

Evaluation Technique

The apparatus employed is the commercial Therma-Probe inspection system (TheraWave, Inc., Fremont, CA), which is described in the article by Smith, Hahn and Arst in these proceedings [12]. In this apparatus, thermal waves are generated and detected by two low-power laser beams auto-focused to a 1-micron spot diameter on the wafer surface. Absorption of light from an acousto-optically modulated (1 MHz) Ar-ion "pump" laser generates thermal and plasma waves within the surface region of the silicon down to an effective depth of about three microns. These waves are then detected by the HeNe "probe" laser through the pump-induced, 1 MHz modulation of the sample reflectivity at the wavelength of the probe laser. As described in [13-16], the effects of the thermal and plasma waves on the reflectivity of silicon result in a net modulated reflectivity signal that is very sensitive to the presence of disorder or defects in the surface region of the wafer. The measurement method is similar to that employed for ion implant monitoring [17,18] and polishing damage characterization [12] in which damage to the silicon is detected by the Therma-Probe system. Significant characteristics of this method are the use of low-power laser beams for noncontact, nondestructive measurements, the use of a 1-micron probe spot allowing measurements to be made on patterned, product wafers as well as test wafers, the speed of the measurements (3-7 minutes) and the high sensitivity allowing extremely low levels of damage to be measured.

For all the measurements presented in the next section, a Therma-Probe scan of 50-micron length is made along the bottom of a wide trench (Fig. 1) on each sample wafer. The average value of the modulated reflectance, $AR/R$, signal from each wafer is displayed on the following graphs. Longer (diameter) scans and whole-wafer contour maps are also available in this method.

RESULTS AND DISCUSSION

Dependence on Bias Voltage

Figure 2 illustrates the results of varying the dc self-bias voltage from -60 to -250 V in the "clean up" step of the silicon etch process. The purpose of this step is to remove the first few hundred Angstroms of silicon, damaged by the previous high-bias main etching step, from the bottom of the trench while rounding out the trench bottom corners by operating at a slightly higher pressure. The results, in general agreement with previous work by Pang et al. [19], show that the level of RIE damage as measured by the modulated reflectance technique increases markedly with increasing bias voltage above a certain threshold bias voltage, in this case about -120 volts. The data points in Fig. 2, the light and dark dot symbols representing measurements on two separate runs in the same etcher but several weeks apart, illustrate the reproducibility of the damage produced by the etch process and measured by the Therma-Probe system. Note that at low bias voltage, the measured $AR/R$ signals are very close to $30\pm3\times10^{-4}$, the value generally obtained on non-damaged silicon in other studies [12].
Dependence on Pressure

The effect of varying pressure in the "clean up" silicon etch step is shown in Fig. 3. As the pressure is increased under constant flow conditions, the mean free path of the reactive ions is shortened, and the mechanisms of etch become more chemical in nature, rather than physical (sputtering). Thus damage to the crystal lattice should lessen. This is reflected in our data, where the general trend shows a decrease in crystal damage with increasing pressure. The anomalous data point at a pressure of 15 mTorr may be due to an inadequate supply of reactant gas at such low operating pressure.

Fig. 2: Measured modulated reflectance signal, indicating the level of RIE-induced damage, versus bias voltage for the "clean up" step of a silicon etch process. The light and dark dot symbols denote data recorded on two separate runs weeks apart in time.

Fig. 3: Modulated reflectance signal versus pressure in the "clean up" step of a silicon etch process.
Dependence on Etch Chemical Composition

The effect of etch chemistry on crystal damage has also been investigated. Figure 4 shows the dependence of the $\Delta R/R$ signal on the percentage of BC$_3$, in a BC$_3$/Cl$_2$ mixture at two different values of total flow rate. The substantial variation of the indicated damage in these data is surprising and will be further investigated.

Fig. 4: Modulated reflectance signal versus percentage of BC$_3$ in a BC$_3$/Cl$_2$ mixture, at two values of total flow rate, in the "main step" of a silicon etch process.

Modulated Reflectance Signal vs. Process Step

The above results have illustrated the capability of modulated reflectance measurements to provide a quick, nondestructive means for optimizing the silicon etch process to minimize damage. Since device wafers can be used, another application of this technique is as a routine monitor of critical process steps that may contribute to lower yields. Figure 5 illustrates the $\Delta R/R$ signals obtained at eight process steps in the trench-formation sequence: starting material, after oxide etch, after pre-silicon-etch clean, etc. Any deviation from a standard set of $\Delta R/R$ signals can be immediately observed and the process problem rectified before device yields are impacted. For example, wafers can be reclined after oxide etch if not "in spec". Any drift in the equipment or process that affects the level of silicon damage can be identified immediately rather than later at the nonsalvageable stage of wafer probe.
CONCLUSIONS

In this work we demonstrate that RIE-induced damage to silicon wafers is readily detected and quantified using a modulated reflectance technique. This method is rapid, noncontact, nondestructive, and has 1-micron spatial resolution. No special patterns or devices need to be fabricated or test structures created; rather, actual device wafers can be used. Measuring along the bottom of 10-micron wide trenches, RIE damage versus etcher bias, pressure, flow and gas composition can be measured. These parametric results enable adjustment of process etch parameters to minimize damage. We also demonstrate the use of modulated reflectance measurements to monitor process and equipment stability at critical steps in the RIE trench etch sequence.
REFERENCES

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