ADVANTAGES OF DUAL FREQUENCY PECVD

FOR DEPOSITION OF ILD AND PASSIVATION FILMS

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ABSTRACT

Dual frequency PECVD has been explored in R&D for several years. Recently it has been incorporated into production equipment for deposition of silicon nitride, oxynitride and TEOS oxides. The combination of high (13.56 MHz) and low (300-400 KHz) frequency RF provides control of film stress and can improve step coverage, film density, chemical composition and film stability. Optimization of these film properties is possible by controlling deposition pressure and the ratio of high and low frequency RF power.

INTRODUCTION

Plasma Enhanced Chemical Vapor Deposition has been widely used in the semiconductor industry for the deposition of silicon nitride, oxynitride and oxide films [1][2]. Over the last few years, the increasing complexity of advanced multilevel metal technologies has greatly challenged the deposition methods and processes in order to achieve enhanced film quality [3]. The decrease in metallization thicknesses, channel lengths and design linewidths has exacerbated problems such as stress cracking, stress induced metal voiding [4] and short-channel hot-electron device degradation [5]. The film requirements have therefore become more stringent and flexibility of process control and integration is being emphasized. One approach to improve film quality and process flexibility has been the introduction of dual frequency in PECVD. The benefits of this were first reported by Fujitsu for deposition of silicon nitride [6] and later more elaborated on by Novellus [7] and ASM [8].

In this paper, we discuss the advantages of dual frequency for the deposition of silicon nitride, oxynitrides and TEOS oxide films and propose a mechanism explaining the effects on step coverage, film stress, chemical composition and film density and stability.

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DUAL FREQUENCY HARDWARE DESCRIPTION

The PECVD reactor used in this study is described in detail elsewhere [9]. We focus here on the dual frequency configuration. Early work in the use of dual frequency for plasma deposition compared different RF configurations, i.e., high and low frequencies on the same electrode, separate electrodes and in a triode configuration. Using separate electrodes yields better results and allows better control. Figure 1 shows the RF configuration used in this work. The bottom electrode is a heated susceptor connected to a 300 KHz power supply. A matching transformer and a low pass filter ensure maximum efficiency for the RF power input and shunts high frequency to ground. The matching transformer is used since at low frequency the plasma is almost exclusively resistive. The top electrode, in a similar fashion, is connected to a 13.56 MHz RF generator through a high pass filter and a matching network. In the parallel plate configuration used, the electrode spacing is fixed and high and low frequency power can be controlled independently. Deposition at high frequency only, low frequency only or a mixture of both is possible.

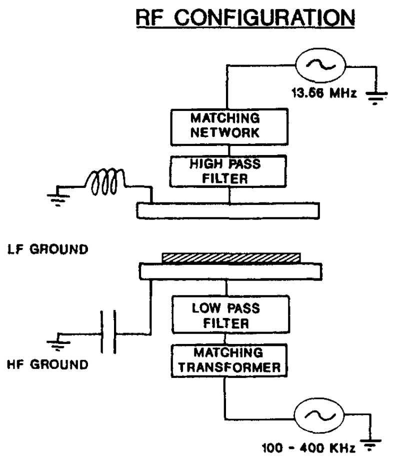

Figure 1. Dual Frequency RF Configuration

DUAL FREQUENCY AND ION BOMBARDMENT: MECHANISM

At high frequency (13.56 MHz) only the electrons are able to follow the RF field while the ions are "frozen" in place by their heavier mass and inertia. The cross-over frequency at which the ions start following the electric field is between 1 and 5 MHz depending upon the mass of the ions. Consequently, below 1 MHz, the ion bombardment is significantly higher. This has effectively been used in PECVD to obtain high quality films. The ion bombardment not only enhances chemical reactions but also causes a low energy ion implantation which densifies the film and provides an intrinsic compressive stress. However, in a low frequency system control of the ion bombardment is difficult. The only parameter which has some impact in is the deposition pressure. Unfortunately, changes in pressure also affect the deposition rate, uniformity, etc. Another limitation of most low frequency systems is the sensitivity to substrate resistivity causing deposition rate variations [10].

A combination of high and low frequency (13.56 and 50-400 KHz respectively) provides a solution to the above problems. The high frequency gives a stable discharge, generates part of the reactive species and assures effective coupling to the substrate (Figure 2). The low frequency provides the ion bombardment/implantation. Accurate and independent control is possible using a constant total RF power and changing the low frequency percentage. Under this condition, the deposition rate, uniformity and other process parameters are hardly affected. The independent control allows optimization and provides process flexibility as discussed further on.

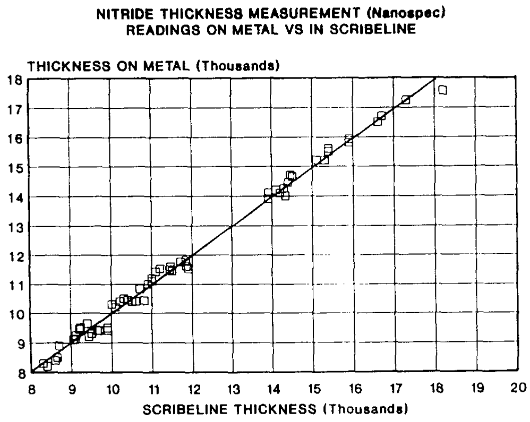

Figure 2. Comparison of thickness of dual frequency SiN in scribeline and on metal interconnect.

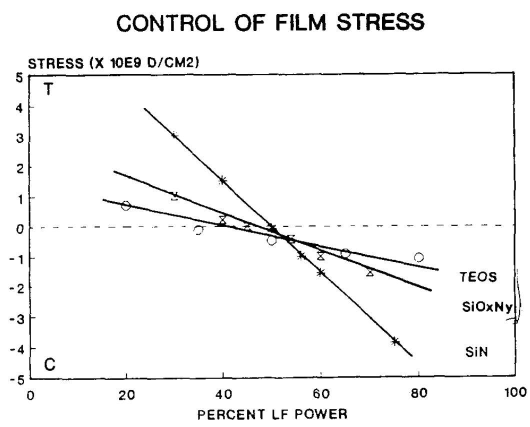

Figure 3. Film stress as a function of percent LF power. The total (HF and LF) power density in this and following figures was kept constant at 0.4 W/cm^2.

STRESS CONTROL

Dual frequency can be used to control the film stress (Figure 3). Increasing the amount of LF power increases the ion bombardment to which the growing film is subjected. The effect is a low energy (< 300 eV) implantation or "stuffing" of the film with Si, O or N. This stuffing causes a change in the intrinsic film stress from tensile to compressive and increases the film density. As shown in Figure 3, the change is gradual and easy to control. The different slopes between SiN, SiO_xN_y and SiO_2 are the result of differences in atomic distance -- the shorter the distance between the atoms in the amorphous material, the larger the effect of the low energy implantation. Changes in total RF power, deposition pressure or deposition rate do not affect the slope, only the position of the line. Higher deposition rates shift the line to the right, lower rates to the left.

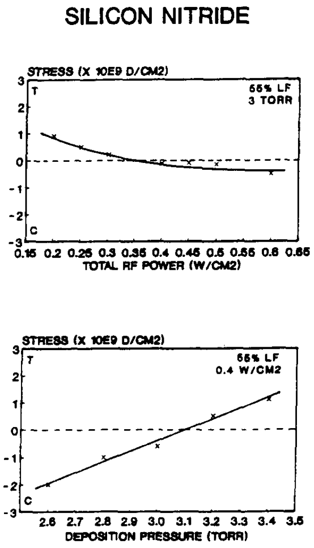

Figure 4. Dependence of SiN stress on RF power density and deposition pressure.

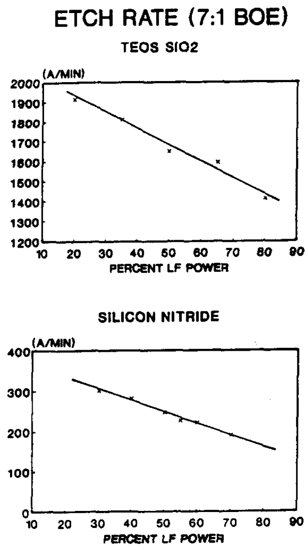

Figure 5. Wet etch rate of TEOS SiO_2 and SiN as a function of percent LF power.

The influence of total RF power and deposition pressure are shown in Figure 4. The RF power has little effect even on silicon nitride deposition as an increase in ion bombardment is canceled out by a higher deposition rate. Deposition pressure, however, has a large influence as it changes the plasma potential and deposition rate in opposite directions.

FILM DENSITY AND STABILITY

The density of the as-deposited film is a strong function of the deposition temperature, amount of ion bombardment and the deposition rate. Whereas the density of thin films is difficult to determine accurately, wet etch rate and refractive index can be considered a reasonable representation of what is happening with the film, assuming no major changes in chemical composition [11]. Figure 5 shows the etch rate of TEOS SiO_2 and SiN in 7:1 BOE as function of low frequency power. Again a linear relationship is observed which correlates well with the change in stress and changes in refractive index.

The change in film density is particularly important for TEOS SiO_2. Low density tensile films tend to pick up water and form SiOH groups. This causes degradation of electrical and mechanical properties. The water adsorption can be determined by changes in film stress during exposure to water vapor and/or by FTIR analysis.

Typically, films deposited with an intrinsic compressive stress are stable and are even able to withstand boiling water without increasing the SiOH content or adsorbing water.

STEP COVERAGE IMPROVEMENT

PECVD TEOS oxide is gradually being introduced in ILD applications because of the superior step coverage [12]. Silicon nitride and oxynitrides have long been known to have acceptable step coverage [13]. In both cases the step coverage is the result of a low sticking coefficient of the precursors which enhances the surface mobility [14][15]. The effect of low energy ion bombardment on this is significant. The low energy ion flux, which is perpendicular to the substrate, increases the desorption rate and improves the surface mobility of the precursors on the horizontal surfaces. The result is a better sidewall step coverage.

Improvement in step coverage will only occur when the ions have a low energy. Higher energy ions have the exact opposite effect, breaking the precursors and increasing the reaction rate on surfaces perpendicular to the flux. The result: a higher deposition rate and a decrease in surface mobility on the horizontal surfaces leading to degradation of the sidewall step coverage.

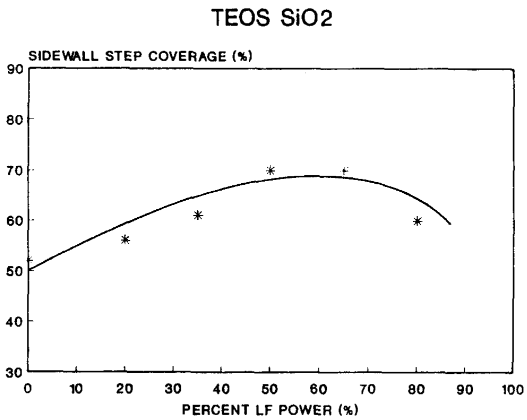

Figure 6. TEOS SiO_2 sidewall step coverage as a function of percent LF power. (Aspect ratio = 0.35)

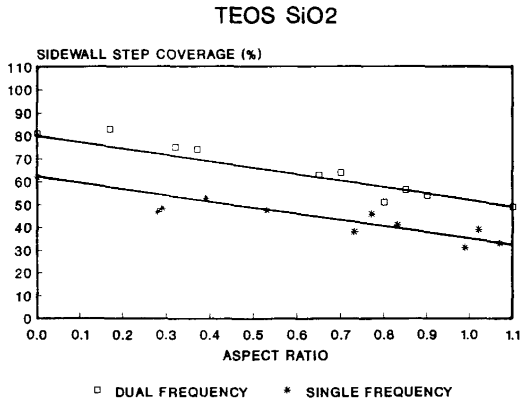

Figure 7. Sidewall step coverage for single and dual frequency deposited TEOS SiO_2 as a function of aspect ratio. (Metal height = 0.8 um).

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