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Thermal stability of tantalum nitride diffusion barriers for Cu metallization formed using plasma immersion ion implantation

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Abstract

Plasma immersion ion implantation (PIII) technique was employed to form Tantalum nitride diffusion barrier films for copper metallization on silicon. Tantalum coated silicon wafers were implanted with nitrogen at two different doses. A copper layer was deposited on the samples to produce Cu/Ta(N)/Si structure. Samples were heated at various temperatures in nitrogen ambient. Effect of nitrogen dose on the properties of the barrier metal was investigated by sheet resistance, X-ray diffraction and scanning electron microscopy measurements. High dose nitrogen implanted tantalum layer was found to inhibit the diffusion of copper up to 700 °C.

Keywords: Diffusion barrier; Copper metallization; Plasma immersion ion implantation; Thermal stability; Tantalum; SEM; XRD

1. Introduction

Copper (Cu), because of its inherent low resistance and high electromigration resistance has become the metal of choice for interconnects in ultra-large-scale integration (ULSI) and giga-scale integration (GSI) era [1–4]. Low resistivity of Cu films as compared to aluminium films helps in reducing both resistance and capacitance part of RC delay. Higher resistance to electromigration makes it possible to carry higher currents in Cu-metallized microcircuits and to use narrower and thinner conductors and interconnections. In addition to its use in integrated circuit applications, Cu has also been

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found to be beneficial in photovoltaic applications [5].

The major problem posed by Cu metallization is its high diffusivity in silicon, silicon dioxides and other dielectrics used in integrated circuits. Diffusion of Cu even after annealing at temperatures as low as 200 °C causes line-to-line leakage and the device failure [6–8]. Therefore, there is a strong need to develop an effective diffusion barrier between Si and Cu to prevent the diffusion of Cu. In addition to providing efficient barrier to Cu diffusion, it must also be conformal, continuous and as thin as possible. Ideally, the diffusion barrier should be electronically transparent with negligibly small voltage drop across the barrier layer and should be atomically opaque by not allowing foreign atoms to pass across it [9,10].

Though a large number of diffusion barriers have been studied for Cu/Si system [11–15], refractory metals and their nitrides such as tungsten, titanium, tantalum, tantalum nitride, titanium nitride, titanium tungsten and tungsten nitride have been found to be very effective barrier materials. It has been found that the nitride of refractory metals exhibits better barrier properties than that of pure refractory metals. Conventionally nitride barrier layers are formed by annealing the refractory metal film in nitrogen ambient or directly sputtering from a composite target or by reactive sputtering. All these techniques are limited by the degree of nitridation achieved. Ion Implantation is a technique successfully adopted for transporting nitrogen for the nitridation of barrier metals [16]. Due to the small thickness of diffusion barrier films, ion implantation is to be carried out at very low energy (10–20 keV) to confine the implanted ions in the barrier layer. Conventional beam line ion implantation suffers from low dose rate at these small energies and thus cannot be used to achieve high degree of nitridation of thin barrier metal films.

Plasma immersion ion implantation (PIII) due to its high dose rate at low energies along with its other advantages such as high throughput, absence of beam/target manipulation, low cost and ability to handle large size wafers [17] has been employed for the formation of tantalum nitride film as diffusion barrier between silicon and copper in this study.

The similar studies have also been carried out by Weisner et al. [18] using AES and X-ray diffraction technique for characterization. In the present study, we have carried out electrical measurement like sheet resistance by four-probe method and also studied the surface morphology using SEM technique. At the end of paper, results of our experiments have been compared with the results of Weisner et al.

2. Experimental

A 100 nm thick Ta layer was deposited on *n*-type silicon wafer of (1 0 0) orientation and 1–10 Ω cm resistivity using RF magnetron sputtering system. A working pressure of 20 mTorr was maintained by controlling the gas flow. RF power of 200 W was applied to the target to carry out the deposition. The thickness of Ta film was measured by Dektek 3030ST profilometer. The Ta coated silicon wafers were implanted with nitrogen ions using PIII technique to form Ta(N)/Si structure [19,20]. The plasma chamber was evacuated to a base pressure of 0.01 mTorr and nitrogen gas was introduced into the chamber maintaining a working pressure of 1 mTorr by controlling the gas flow. Plasma was generated by applying 100 W capacitive coupled RF power to the chamber. A 20 kV negative voltage pulse was applied to the metallic holder on which samples were placed. Pulse voltage and ion current were measured using an oscilloscope. The samples were implanted at a frequency of 50 Hz and pulse width of 10 μs for a low dose of 10^{15} ions/cm^2 and at a frequency of 1 kHz and pulse width of 50 μs for a high dose of 10^{17} ions/cm^2. Total implantation time was 10 min for both the cases.

After implantation, Cu layer of 200 nm thickness was sputter deposited on Ta/Si, Ta(N)/Si and Si samples. Deposition was carried out at 20 mTorr working pressure and 300 W RF power. Annealing of samples was carried out in N_2 ambient at different temperatures for 30 min.

Scanning Electron Microscope JEM-1200 EX (JEOL) was used to study the surface morphology of the samples. For composition analysis by X-ray diffraction, Philips Model PW 1729 X-ray diffractometer with Cu target and nickel β-filter was used.