Enhanced Copper Electroplating Using High Frequency Acoustic Streaming

A. A. Busnaina, C. S. Tiwari and I. I. Suni
Clarkson University, Potsdam, NY
and
V. Reynolds, M. Nakoski, C. Neely, and T. Way
Reynolds Tech, Syracuse, NY

Introduction

As the size of the circuit line width approaches one tenth of a micron, the need for a fast and effective electroplating process for 0.12 micron and smaller interconnects becomes essential. It is therefore necessary to develop effective and high throughput process that meets the needs for the required sidewall step coverage and gapfill. This work investigates the effect of a non-contact physical mechanism (acoustic streaming) to enhance the convection of chemicals near the wafer and improve the gap fill characteristics for the copper electroplating process.

Megasonic cleaning at high frequencies near 1 MHZ has gained attention as an efficient, though poorly understood, Si surface cleaning technique. McQueen [1,2] recognized the importance of acoustic streaming in decreasing the boundary layer thickness, based upon his studies of removing small particles from surfaces. Megasonic cleaning applications were first described in detail by RCA engineers [3-5]. Kashkoush, Busnaina et. al. [6-10] studied ultrasonic and megasonic particle removal, focusing on the effects of acoustic streaming. Removal percentage increased with power.

The same removal mechanism responsible for removing particles will also convect chemicals or replenish them near the wafer surface. Gale and Busnaina showed that rinsing of chemicals from the wafer surface can by enhanced by an order of magnitude or more (depending on the frequency) when using high frequency acoustic streaming [11]. The removal and the convection are accomplished using acoustic streaming applied during the megasonic process. The tremendous enhancement in rinsing and particle removal relies on the reduction of the boundary thickness on the substrates and the three types of acoustic streaming in the tank; Eckart streaming, Schlichting streaming and microstreaming. Acoustic streaming has been shown by Gale and Busnaina [10] to be the particle removal mechanism in high frequency ultrasonics. The acoustic streaming velocity increases with increasing frequency and power, and decrease with increasing kinematic viscosity. Large velocity gradients exist in the boundary layer, causing high viscous stresses, which can aid in reaction acceleration and the removal of surface contaminants and chemicals [6]. Figure 1 shows that using megasonics is extremely effective in rinsing ionic contamination on the surface and in the bulk inside a trench. Acoustic streaming patterns have been visualized at the Microcontamination Research Laboratory at Clarkson University. Streaming velocities of up to about 20 cm/s have been measured and were found to be in reasonable agreement with theoretical predictions.

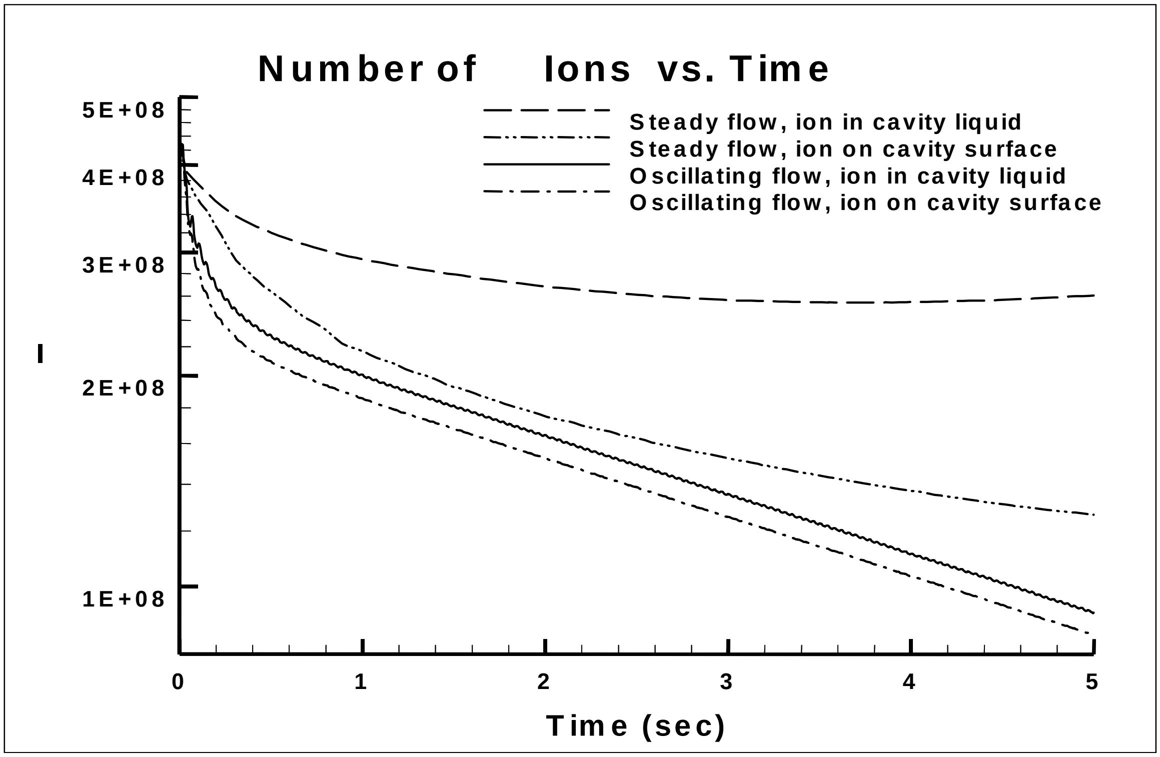

Figure 1. The number of ions in a trench rinsed using steady and oscillating flow.

This paper will show the effect of high frequency acoustic streaming on the enhancement of copper electroplating as a function of process power, temperature and plating time. The effect of the enhancement on the Cu film properties such as sidewall step coverage, gap fill characteristics and resistivity will be investigated. Initially, the effects of key plating process parameters on the resulting copper film properties and performance on non-patterned wafers will be examined. Results demonstrating complete fill of 0.18-0.12 micron features with pure copper without the utilization of additives will be presented at the conference.

Theory

Electrodeposition of copper is carried out in $CuSO_4$ and H_2SO_4 bath. Sulfuric acid is used to increase the conductivity in the electroplating bath. The following reactions take place during deposition:

Dissociation of $CuSO_4$ in water:

$$CuSO_4 \longrightarrow Cu^{++} + SO_4^{--}$$

Reduction of Cu^{++} at cathode:

$$Cu^{++} + 2\,e \longrightarrow Cu$$

Oxidation of copper at anode (consumable Cu anode):

$$Cu \longrightarrow Cu^{++} + 2\,e$$

Experimental

A Cu seed layer of thickness 160 nm was deposited using a sputtering system (Magnetron Ionized Metal Physical Vapor Deposition) in n-type (100) silicon wafer. Before depositing the seed layer a Ta barrier layer of thickness 160 nm was deposited by the same system.

Electrodeposition parameters were kept the same for the two processes namely deposition without megasonics and deposition with megasonics. The electroplating bath composition was kept at 110 g/l $CuSO_4$ and 200 g/l H_2SO_4. The thickness and global roughness measurements were conducted using profilometer (Dektak). The topography of deposited films was analyzed using an atomic force microscope operated in contact mode (Burleigh Instruments). For a rough estimate of grain size, scanning electron microscope was used.

Results

Preliminary experiments were conducted using traditional copper electroplating chemistry. The electroplated films exhibited slightly different characteristics when using high megasonic frequency vibrations in the electroplating bath. Roughness slightly increased with megasonic power indicating a slightly larger grain size. The grain size can also be controlled by temperature and by the sulfuric acid concentration. The results obtained from profilometer and AFM images were analyzed and compared for two processes. The comparison shows the following:

1. Global roughness increases with increase in megasonic power. Roughness is approximately 30 nm without megasonic power, 60 nm with 1-% megasonic power, and 100 nm with 5% megasonic power.
2. Megasonic power has little effect on thickness. Thickness of film obtained without megasonic was 2.6μm. With megasonic power thickness decreased very slightly (around 100nm). This reduction in thickness may be contributed by etching due to convection resulting from acoustic streaming.
3. AFM images shown in figure 1 show an increase in local roughness (root-mean-square, Sq). The local roughness is 71.44 nm without megasonic, 97.29 nm with 1-% megasonic power, and 125.55 nm with 5% megasonic.

Conclusions

The results show that acoustic streaming does increase roughness slightly, however that can be controlled by the ionic strength, bath temperature and the current. The main effect of the megasonic energy is delivering fresh chemicals to the bottom of submicron trenches using the megasonic pressure mechanism.

(a) (b)

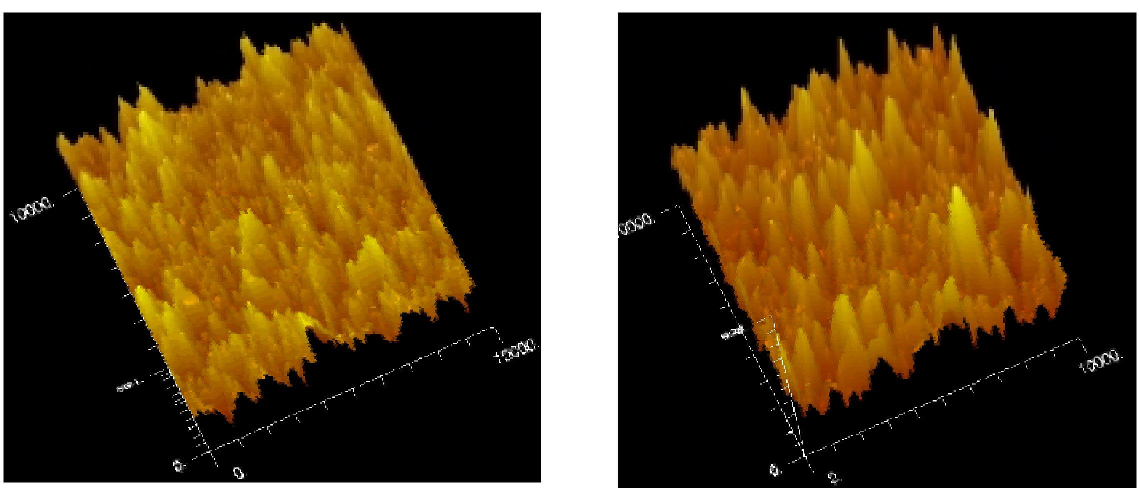

Figure 1. AFM images of electrodeposited copper films (a) without megasonic, and (b) with megasonic.

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Biography

Ahmed A. Busnaina, Ph.D. is a Professor and Director of the Microcontamination Research Laboratory, at Clarkson University. He specializes in wafer cleaning technology, chemical and particulate contamination in LPCVD and sputtering processes, fine particle adhesion, transport, deposition and removal in clean environments. He authored more than 200 papers in journals, proceedings and conferences. He is a Fellow of the American Society of Mechanical Engineers and R. L. Patrick Fellow of the Adhesion Society.
Chandra S Tiwari, is a graduatre student at the Chemical Engineering Department at Clarkson University.
Ian Suni, Ph.D. is an associate professor of Chemical Engineering. Professor Suni's research interests are in the area of interfacial phenomena, particularly the solid-liquid interface with applications to fields such as electrochemistry, electrodeposition, corrosion, and wet cleaning of semiconductors.