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Filling trenches on a SiO_2 substrate with Cu using a hot refractory anode vacuum arc

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ABSTRACT

First results of complete filling of 100 nm wide × 300 nm deep trenches with Cu using the expanding plasma plume from a hot refractory anode vacuum arc (HRAVA) plasma source are presented. The arc was ignited between a consumed water-cooled cylindrical Cu cathode (30 mm diameter) and a non-consumed W cylindrical anode (32 mm diameter, 30 mm height) that was heated by the arc. An arc current of 200 A was applied for periods of 180 s. The films were deposited on a Si substrate with a top SiO_2 layer. The substrates were exposed to the plasma plume for 120 s, while a shutter was open. The distance to the substrate from the electrode axis was varied over the range of about 74–122 mm. A pulsed bias voltage of −75 or −100 V, with a 60 kHz pulse repetition rate and a 50–80% duty cycle was applied to the substrate. The films were examined using a scanning electron microscope. The average film resistivity was measured with a four point probe. The deposition rate was as high as 425 nm/min, and the minimum average resistivity was 5.5 μΩ cm.

1. Introduction

One of the important steps in integrated circuit (IC) manufacturing is the production of metal connections between different parts of the circuit [1]. These connections are in the form of trenches or vias etched in dielectric material. It is required to completely fill them with metal.

Previously, Al was commonly used as an interconnect material, but recently Cu was introduced as a replacement, due to its lower resistivity and better electromigration reliability. Several processes have been demonstrated to deposit Cu into vias and trenches. CVD [2], with a typical deposition rate less than 100 nm/min, electrochemical plating [3] and electroless plating methods [4,5], with typical deposition rates of about 150 nm/min and physical vapor deposition (PVD), e.g. based on thermal evaporation and sputtering, which produce mostly neutral particles [1]. Another approach, ionized physical vapor deposition (I-PVD) [6] techniques, was developed from conventional sputtering and has a typical deposition rate of about 200 nm/min [7]. The main disadvantages of the PVD processes are relatively low deposition rate, and high sidewall and low bottom deposition, creating a void. The main disadvantage of the electrochemical and electroless processes is that plating baths must be disposed, posing both practical and environmental concerns.

Cathodic vacuum arcs generate highly ionized metallic plasma from cathode spots [8]. The main disadvantage of using arc plasma is the presence of droplets, known as macro-particles (MPs), which also generated from the cathode spot. Several techniques for eliminating or reducing the MP density in the coating are used [8–10], but generally have poor material utilization. A new high rate deposition method using a hot refractory anode vacuum arc (HRAVA) was recently developed [11]. The HRAVA operates with a consumable water-cooled metallic cathode and a non-consumable refractory anode. The discharge is started as a conventional vacuum arc with cathode spot emitted plasma, but quickly reaches a stage where the inter-electrode region contains cathodic metal vapor re-evaporated from the hot refractory anode. The re-evaporated cathode material forms a strongly ionized anodic plasma plume. The radially expanding anodic plasma in a HRAVA can be used to produce mostly MP-free metallic coatings with deposition rates of up to 2 μm/min [12,13]. However, the ability of the HRAVA to fill trenches and vias was not previously studied. The objective of this work was to evaluate trench filling using the HRAVA. A W anode that allows higher currents than possible with graphite and molybdenum anodes [11–13], was used.

2. Experimental setup and procedure

2.1. Cathode–anode assembly

The arcs were conducted in a stainless steel chamber of 530 mm length and 400 mm diameter. The chamber was water-cooled using U-shaped channels welded onto the chamber walls. The chamber was pumped down to a pressure of 0.67 mPa by a diffusion pump before arc initiation. The experimental system is shown

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schematically in Fig. 1. During the arc, the chamber pressure increased to approximately 13 mPa. An arc current of 200 A was applied for a period of 180 s between a 30 mm diameter cylindrical, water-cooled, Cu cathode and a W anode, 32 mm in diameter and 30 mm in length.

The arc was initiated by momentarily touching the cathode with a trigger electrode (not shown in Fig. 1), electrically attached to the anode through a current limiting resistor. The anode was supported on a thin W rod that also connected it to the electrical circuit. The cathode was surrounded by a molybdenum shield, 40 mm in diameter, placed flush with the cathode surface. The aim of the shield was to block any macro-particles originating in the cathode spots from reaching the substrate. The inter-electrode gap was approximately 10 mm.

2.2. Substrate preparation and mounting

The substrate was a silicon wafer with a top layer of 1.2 μm thick SiO_2, in which trenches of 300 nm depth and widths down to 100 nm were etched. The wafer was cut into samples with areas of approximately 10×10 mm^2. The substrates were mounted on a holder, which allowed orienting the substrate to perpendicularly face the plasma flux emanating from the inter-electrode gap in the anode region [13]. The substrates were located at a distance (d) from the electrode axis, which was varied from 74 to 122 mm.

The substrate consisted of two main layers, a top SiO_2 layer facing the plasma flux and a bulk silicon layer to which bias voltage was connected. As the top SiO_2 layer was an insulator, applying a DC bias via the substrate does not affect the potential of the surface exposed to the plasma, and hence does not influence the energy of the incoming ions. Barnat et al. [14,15] studied the influence of pulsed bias to eliminate surface charging, in order to deliver an approximately mono-energetic ion flux while varying the pulse width. It was shown that for bias a voltage of −100 V, pulse frequencies between 0.1–1000 kHz and a duty cycle of 70–90%, the average surface potential of the insulating substrate was minimized to within about 1–5% in a frequency range of 50–90 kHz. In the present work, we studied Cu deposition with a HRAVA system using conditions close to the optimum found by Barnat et al. [14,15], specifically a bias voltage of −100 V a duty cycle of 80%, and pulse frequency of 60 kHz. In order to best utilize the HRAVA properties, the substrate was isolated from the particle flux by a shutter during the first 60 s after arc initiation in order to allow the HRAVA mode to be established [13], and thus producing MP-free plasma and the highest deposition rate.

2.3. Film examination

The deposited films were examined using a high resolution scanning electron microscope (HRSEM). The cross-section of the deposited substrates was examined after cleaving the substrate, to determine fill quality, film thickness and deposition rate. The sheet resistance was measured on the top surface of the coating using a Signatone S-301-6 manual four point probe, with a 62085TRS head. The resistivity was calculated based on the film thickness measured with HRSEM in flat regions, i.e. without trenches. An X-ray diffractometer equipped with Cu K_α radiation ($\lambda = 1.5406$ Å) in Bragg geometry was used to analyze the structure of the deposited films.

3. Experimental results

Figs. 2 and 3 show the cross-sectional microstructure of HRAVA-deposited films, showing a Cu deposited substrate with a row of successfully filled trenches using 80% duty cycle with −75 V and −100 V pulsed bias voltage respectively, and 2 min exposure time to the plasma. The narrowest trenches were 100 nm wide and 300 nm deep (aspect ratio of 3). It was found that the trenches were always completely filled using 80% duty cycle. With duty cycles about 50%, some of the trenches were filled and some were not. A typical top view of the samples is shown in Fig. 4. The observed films on the overlying flat surfaces and partially filled wide trenches had the same average grain size, 45 nm. Fig. 5 shows a typical XRD pattern, showing strong (111) texture – the intensity ratio between the (111) and (200) planes was 3.4.

The deposition rate and average surface resistivity dependencies on the distance d of the substrate from the arc axis are presented in Fig. 6. It can be seen that the deposition rate decreased and the average resistivity increased with d. The film thickness was in range of 350 to 850 nm. The maximum deposition rate was 425 nm/min, and the minimum average resistivity was 5.48 μΩ cm.

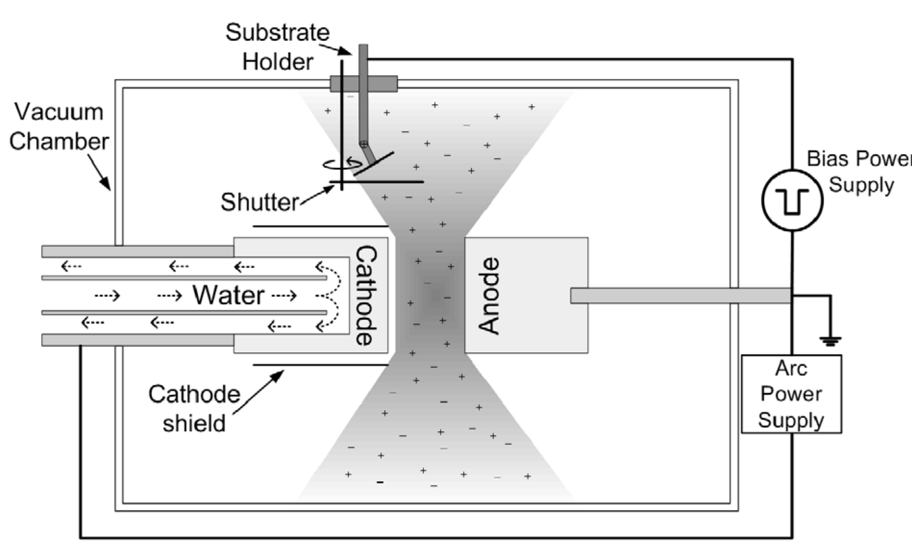

Fig. 1. Schematic drawing of the experimental HRAVA deposition system and the radial plasma expansion.