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Research paper

Fabrication of top-down gold nanostructures using a damascene process

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ABSTRACT

In this work, we propose a damascene process to fabricate embedded gold micro- and nano-structures at the same time. We present a systematic study of the material removal rate (MRR) and the selectivity on both gold and silicon dioxide. The embedded microstructures are 2 µm wide and 60 nm deep, while the nanostructures widths vary from 70 nm to 500 nm for a 50 nm depth. Moreover, we highlight the contribution of the CMP in polishing the surfaces of gold films. Morphological characterizations are performed using mechanical profilometry, Atomic Force Microscopy (AFM), and Scanning Electron Microscopy (SEM). MRR and selectivity are evaluated as a function of time, applied pressure, platen rotation speed, and slurry flow.

1. Introduction

Gold main properties are its very low resistivity, its good chemical stability, its high melting point, and its resistance to electromigration [1]. For all these reasons, gold has been used in a variety of applications such as: interconnects for ultrahigh-speed devices on Si [2], self-assembled monolayer (SAM) [3], Ohmic contacts for semiconductor technologies [4], optoelectronics [5], catalyst for nanowires vapor-liquid-solid (VLS) growth [6], or imaging in x-ray optical microscopes [7]. Gold plasma etching still faces difficulties due to the high material chemical stability, while wet etching solutions provide less critical dimension control and are not compatible with CMOS industrial processes. Damascene processes using chemical mechanical planarization (CMP) alongside etching processes have proven to be an effective approach controlling metal thickness in micro- and nano-structures fabrication platforms [8]. Moreover, CMP is a pivotal operation widely used in microelectronics manufacturing: from metal gate integration in advanced CMOS transistors [9] to devices and interconnects resolution in the back-end of line (BEOL) [10]. It has also been used as a tool to reduce roughness and smoothing metal surfaces [3]. Few studies have elaborated gold microtrenches fabrication. Karbasian et al. [11] have realized gold CMP on wide trenches (10 µm for lines and 150 µm for pads). They have studied the effect of the slurry composition on the material removal rate (MRR), and realized microstructures planarization. To our knowledge, no research results on gold nanostructures fabricated using a damascene technology have been reported.

This paper presents a detailed study of the material removal rate (MRR), extracted from the polishing of blanket films as a function of CMP parameters for both gold (Au) and silicon dioxide (SiO_2). MRR and selectivity have been studied as function of the applied pressure platen rotation speed, and slurry flow. The effect of CMP on gold surface roughness has been also established. Using the evaluated MRR and related selectivity, 2 µm wide and 60 nm deep gold microstructures and 70 to 500 nm wide and 50 nm deep nanostructures are fabricated at the same time. Different morphological characterizations are performed in order to evaluate the final structures planarity and roughness.

2. Methodology and experimental results

2.1. Methodology

An ALPSITEC E460 CMP system with a 10×10 mm^2 sample holder has been used. The pad was an IC1000 polyurethane pad which surface was prepared with a diamond block before every polishing or planarization. A commercial Ultra-Sol A20 alumina based slurry with added potassium iodide, at pH = 4 was chosen. The mean abrasive nanoparticle size within the slurry is 240 nm. The CMP experiments have been carried out on 10×10 mm^2 Si samples with either a thermally grown oxide, or a 100 nm evaporated Au film on 5 nm titanium

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adhesion layer on top of SiO_2. The slurry solution is a mixture of surfactants (2.07 g of SDS with 1.75 ml of Tween 80) added to 600 ml of Ultra Sol A20:H_2O_2 in 1:1 volume ratio [11]. The SiO_2 thickness has been measured before and after CMP using ellipsometry, while the Au thickness was evaluated with SEM cross-section measurements.

2.2. Material removal rate and selectivity

We first investigated the effect of different CMP parameters on the material removal rate (MRR) and selectivity. The latter represents the ratio in removal rate of one material as compared to another in a particular slurry. Selectivity is a very important criterion in order to control planarization [12].

Fig. 1 presents gold and silicon dioxide MRR with selectivity as a function of the applied pressure, with fixed velocity at 30 rpm and slurry flow at 25 ml/min. The pad and the sample holder rotate in the same direction with close velocity values, for all used recipes. The error bars on the measurements of the Au MRR are related to the method used to extract the Au remaining thickness after CMP and do not reflect a non-homogenous polishing across the samples. The Au thickness has been averaged from 15 thicknesses cross section SEM measurements after CMP on each sample. The error bars represent the deviation around the mean MRR.

Both materials show a linear progression of their MRR which is in accordance with Preston law (RR = Kp P v; with Kp: Preston coefficient, P: applied pressure, and v: related velocity), but gold MRR increases faster than SiO_2. This phenomenon is due to the fact that mechanical forces have a higher impact on gold removal rate which is a softer material than silicon oxide.

The effect of the platen rotation speed on the MRR and the selectivity with fixed pressure (P = 300 g/cm^2) and slurry flow (D = 25 ml/min) is shown in Fig. 2.

SiO_2 and Au show a linear behavior in accordance with the Preston law. The mechanical forces in this system have also led to a higher gold polishing rate compared to the oxide removal rate. A selectivity around 2 is obtained at 50 rpm, which is very important for the planarization of Au nanostructures embedded in SiO_2 as shown hereafter.

The effect of the slurry flow rate is also shown in Fig. 3. Increasing the slurry flow promotes the removal rate on both materials. This is due to the increased number of abrasive particles that will flow between the sample and the pad.

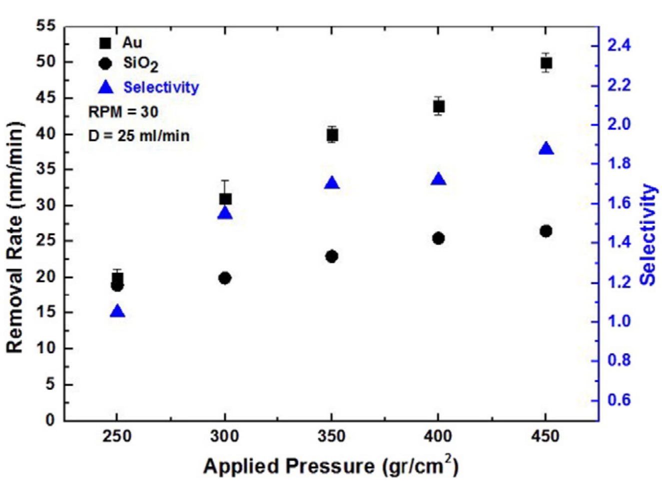

Fig. 1. Average gold and oxide removal rate and selectivity as a function of the applied pressure.

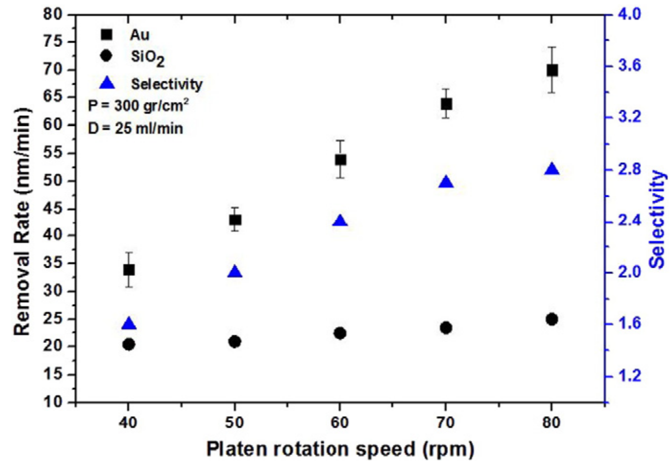

Fig. 2. Average gold and oxide removal rate and selectivity as a function of the platen rotation speed.

2.3. CMP polishing characterization

We have also studied the impact of CMP on the surface of gold film, prepared on 10 × 10 mm^2 silicon sample. Accordingly, we used the previous MRR study to remove ~35 nm of gold film in a 60 s CMP operation. Atomic Force Microscopy (AFM) measurements on 10 μm × 10 μm sampled surfaces for different geometric locations are realized before and after CMP. These observations have shown RMS roughness values ranging from 0.8 nm to 1.4 nm for both cases, as seen on Fig. 4. The CMP process did not deteriorate the surface topography although scratches (grooves or indentations) are detected on the planar gold films. These scratches tend to appear on a large surface, with a limited effect on the nanostructures.

The scratches can be related to the particle distribution within the slurry [13], or to the Au material removed from the edges of the samples that do scratch the sample surface. Using a silica based slurry after the alumina based planarization can be exploited as a way to alleviate these defections [3] [14].

2.4. Damascene process for micro- and nano-structures patterning

A simplified scheme of the damascene process used to fabricate both micro- and nano-structures in a single step is given in Fig. 5. First a 150 nm thick silicon dioxide is thermally grown on silicon substrates. Then 60 nm deep microstructures are patterned in the dielectric using photolithography and ICP reactive ion etching [15]. Afterwards, e-beam

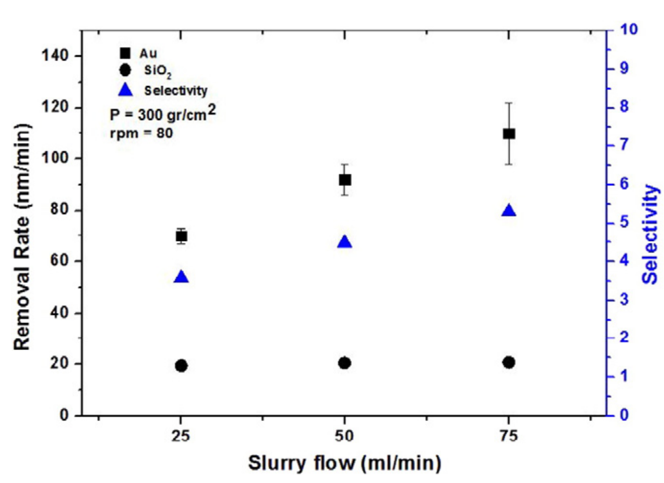

Fig. 3. Average gold and oxide removal rate and selectivity as a function of the slurry flow.