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Structural features of nano-scale damascene copper lines after annealing in wide temperature range

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Abstract

Grain structure and texture evolved in damascene nano-scale copper lines after annealing in a wide temperature interval of 200-500^{o}C were analyzed. Electron backscatter diffraction (EBSD) technique was used for rigorous investigation of the overburden layer, upper and bottom parts of the lines. In all cases, the microstructures were found to stabilize after achieving the same level of total grain-boundary area per unit volume. The grain growth behavior was supposed to be governed by the pinning effect of second-phase particles entrapped during the electrodeposition process.

Introduction

The minimization of electronic devices is prompting a reduction of interconnects widths down to a nano-scale. For production of such interconnects, a copper damascene process is currently used. The problem is that resistivity of the narrow copper lines considerably increases in the nano-scale range [1-2]. This effect is usually attributed to electron scattering on sidewalls as well as on grain boundaries because grain size in such interconnects is expected to approach the mean electron free path (~40 nm at ambient temperature). One of the possible solutions of this problem is an appropriate annealing process which allows production of reasonably coarse-grained structures. In this regard, annealing behavior of the electrodeposited copper becomes of particular practical interest. Microstructural observations in the nano-scale wires are still limited. The previous works were typically performed in a limited range of annealing conditions (including only one or two annealing temperatures) and were based on scanty experimental statistics. More systematic research is needed in this field with the final aim being precise microstructural control of the copper interconnects. This work presents a detailed study of grain structure and texture evolution after annealing in a wide temperature range for better understanding of the annealing processes and grain growth mechanism in these materials.

Experimental

Damascene trenches (80 nm wide and 200 nm height) were patterned in SiO_2/Si dielectric films using electron beam lithography and reactive ion etching (Fig.1). An ultra-thin TaN/Ta (7.5 nm/7.5 nm) layer was first sputter-deposited on the trenches as a diffusion barrier and adhesion layer, followed by sputter deposition of a 50 nm copper seed layer to serve as the cathode for electroplating. To investigate the annealing behavior of the copper lines, the samples were annealed for 1 hour at 200-500^{o}C in vacuum immediately after completion of the electrodeposition process, and microstructural examinations at the trench heights of ~50 and 200 nm as well as in the overburden layer were performed by using EBSD technique preceded by chemical mechanical polishing (CMP); a Hitachi S-4300SE field emission gun scanning electron microscope equipped with a TSL OIM^{TM} EBSD system was employed.

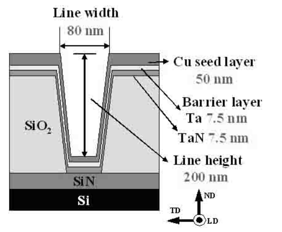

Fig. 1. Schematic representation of a cross-section of trench before electrodeposition

Results

Experimental observations showed that the microstructure of the overburden layer significantly coarsened during annealing at 200^{o}C. However, a heat treatment at higher temperatures did not led to substantial changes in grain structure either in the overburden layer or within the line. The textural observations revealed some evidences of downward penetration of the growing grains from the overburden layer as well as upward growth of the bottom grains. In both cases, however, the grain growth effect was relatively small.

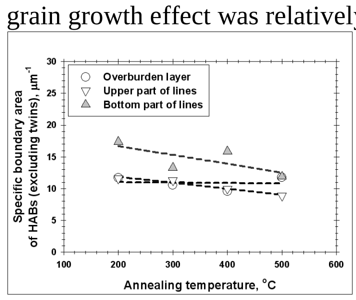

Fig. 2. Effect of annealing temperature on specific grain-boundary area of HABs without Σ3 twin boundaries in different parts of lines

Grain growth is commonly believed to be driven by a minimization of energy stored in grain boundaries and thus is directly related with grain-boundary area. In this work, specific grain boundary area was used which was equal the total grain-boundary length in an EBSD map divided by the area of the EBSD map. It was found that the relatively high thermal stability of the material within the lines may be attributed to the relatively low grain-boundary area in this region (Fig. 2). Due to the specific bamboo-morphology as well as the geometric restrictions of the lines, the microstructure here was characterized by the dominance of phase boundaries (between the copper and tantalum diffusion barrier), but not grain boundaries.

Conclusions

In this work structural features of nano-scale damascene copper lines after annealing at 200-500^{o}C and microstructural and textural changes were tracked in the overburden layer as well as in the upper and bottom parts of the lines. The main conclusions are as follows. The grain structure within the lines as well in the overburden layer was found to stabilize after achieving nearly the same grain boundary area. This observation was interpreted as indirect evidence that the grain growth in damascene copper lines was controlled by the pinning effect of second-phase particles which were presumably entrapped during the electrodeposition process.

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