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High cycle fatigue properties of Cu films

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ABSTRACT

In this study the mechanical fatigue behaviour of Cu metallization film stacks on rigid Si substrates, as well as on free standing copper bars was investigated in the high cycle fatigue (HCF) regime ($> 10^9$ cycles) at room temperature. Sputtering technique and electrochemical deposition under various process conditions were used to retrieve three different Cu films of different microstructure. The Cu stacks ($Si/SiO_2/TiW/Cu$) and 20 μm × 20 μm × 130 μm free standing copper bars were subjected to symmetrical tension–compression fatigue loading using ultrasonic resonance fatigue testing systems. Fatigue life of free standing Cu films was found to be mainly dependent on the grain size. The degree of surface deformation after fatigue loading of Cu films on Si substrates was dependent on the film thickness, grain size and texture, as well as adhesion strength of the film to the underlying substrate.

1. Introduction

Thin metallization film stacks are key components for internal and external electrical connections in microelectronic devices that cover a broad range of products from power semiconductors to micro-electro-mechanical systems (MEMS). The continuous demand to increase the performance by reducing the metal line resistance has led to a transition from aluminium to copper as material of choice in semiconductor components, due to the better electromigration resistance, and superior thermal- and electrical conductivity.

These components are subject to tensile and compressive stresses during their lifetime due to the difference in the coefficients of thermal expansion of the metal film and the underlying silicon substrate. Temperature fluctuations of several hundred degrees centigrade occur, due to the electric pulses during operation.

As copper has a high diffusivity into silicon and silicon oxide degrading their properties, a metallic barrier between the copper and the substrate is needed. Lots of effort has been spent on finding barrier materials that block diffusion but also show good adhesion to the copper and the underlying substrate.

While it is well established that mechanical behaviour of small scaled structures with dimensions in the nano- and micrometre range is significantly different to that of their bulk counterpart, there is still an ongoing discussion concerning the underlying mechanisms. Mechanical fatigue properties on copper thin films of different thickness and microstructure on a flexible polyimide substrate were studied by Zhang et al. [1]. They proposed a deformation mechanism map as a function of film thickness and grain size, splitting the map into bulk like-, small volume- and transition behaviour regimes. The deformation mechanisms are governed by ratio of thickness to grain size, splitting the map also in a film thickness- and grain size controlled area. Another study on the HCF behaviour on 1 μm Cu films on Si substrate, using a resonant bending set-up, by Burger et al. [2] found loosely arranged dislocation structures inside the grains leading to extrusion islands on the surface as well as short cracks between adjacent extrusions. They also indicated an influence of the adhesion on the fatigue response, stating that a weaker interface might constrain dislocation motion leading to a lesser degree of deformation. It was the goal of this study to investigate length scale influences such as film thickness and grain size, and the influence of the texture on the fatigue behaviour of Cu films on Si substrate for film thicknesses in the range from 5 μm to 20 μm as to our knowledge similar systematic studies have not been performed. For this purpose Cu film stacks on Si substrate as well as free standing Cu films with different microstructure were fabricated and subjected to fatigue loading.

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2. Experimental procedures

2.1. Sample preparation

Both the thin film Cu film stacks and the free standing copper bars were produced by depositing copper onto ⟨100⟩ oriented Si wafers. Two types of electro-deposited samples, using two different electrolyte compositions, hereinafter referred to as type A and type B respectively, each with a film thickness of 5 μm and 20 μm have been prepared. A third set of samples with a film thickness of 5 μm and 10 μm, type C, was produced by sputtering of the copper film. All copper films were annealed after deposition at 400 °C for 30 min under forming gas to ensure a stable grain size and microstructure.

Another series of samples of type A copper with a simpler layer structure and four different diffusion barriers were fabricated for investigations of the diffusion barrier and its adhesion strength on the fatigue response.

An overview of the sample stacks is given in Fig. 1.

Free standing copper bars (20 μm × 20 μm) with a gauge length of 130 μm of the type A and type B copper were fabricated in the same way. After the annealing step the backside layers were etched off leaving free standing films of the desired length and thickness. A detailed description of the etching process can be found in [3]. The microstructure and grain size of the initial copper specimens were characterised using a scanning electron microscope (SEM) attached with an electron backscatter diffraction (EBSD) detector.

2.2. Ultrasonic fatigue testing system

For HCF measurements on the Cu/Si stacks an ultrasonic (US) resonance fatigue testing system working at 36 kHz, consisting of the US transducer, the acoustic horn, and the sample was used (Fig. 2).

The Cu/Si sample strip with a width of 10 mm and the corresponding resonance length of 105.7 mm was glued into the acoustic horn using a 2-component epoxy glue. The silicon sample was then excited to a push–pull vibration with completely reversed cyclic loading ($R = -1$), with the site of maximum strain exactly in the middle of the sample (Fig. 2). To release residual stresses in the multilayer samples, caused by the copper deposition, which could induce a parasitic transversal oscillation mode of the specimen, the copper film was partially removed leaving only a 5 mm copper strip in the middle of the specimen. The strain was determined by strain gauges that were glued on the backside of the sample at the site of maximum strain as well as by displacement measurements using a laser-Doppler vibrometer, which was also used to inspect the oscillation behaviour of the samples and to calculate the maximum strain. The tests were performed at room temperature with additional cooling of the bonding of the specimen. An infrared thermometer was used to measure the copper film temperature to ensure the constant temperature testing conditions.

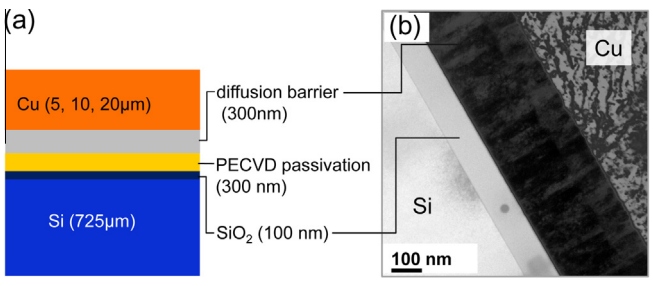

Fig. 1. (a) Schematic illustration of the Cu film stack, (b) SEM image of the cross section of the simpler Cu film stack for adhesion influence investigations.

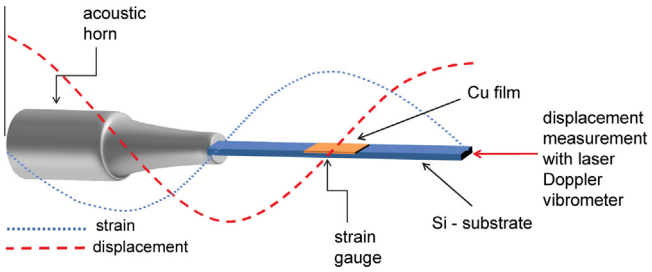

Fig. 2. Schematic overview of the US resonance principle (36 kHz set-up). Sinusoidal strain distribution in the sample, with maximum strain in the middle of the Cu/Si strip.

For the fatigue tests on the free standing copper bars an US system working at 20 kHz was used. The free standing copper bars were glued across a hole in the centre of a bar shaped titanium sample holder using a cyanide-acrylate adhesive. Analogue to the 36 kHz system described above this sample holder is part of the resonance testing system. A push–pull vibration ($R = -1$) is excited with the site of maximum strain, which was measured using strain gauges glued to the sample holder. The number of loading cycles (N_f) to failure was determined by evaluating optical microscope images that were recorded by a CCD camera attached with an optical microscope mounted above the sample.

2.3. Fatigue criterion

As films on a substrate do not fail fatally when cracking occurs a "deformation density", defined as the percentage of plastically deformed surface area to the total area was introduced as fatigue criterion. For this purpose optical microscope images were taken at certain intervals during the fatigue tests. The deformed areas are clearly visible in these images as dark reflections (Fig. 3). The number and area of these reflexes was analysed assisted by the image analysis software "ImageJ" [5]. The "deformation density" could then be plotted versus the loading cycles.

3. Results and discussion

3.1. Microstructure and morphology

SEM studies, using EBSD technique, of the samples revealed differences in grain size and microstructure of the different types of copper films of different thickness. For both electro-deposited copper films and both the thin 5 μm and the thick 20 μm samples a randomly orientated texture can be found. The type A copper has the smallest grain size of 2.4 μm (with an average grains per cross section (ζ) of 1–3), that does increase only slightly to 2.9 μm ($\zeta = 5$—10) when increasing the film thickness to 20 μm. The type B copper shows a similar grain size of about 4 μm ($\zeta = 1$—2) with the thin sample, but shows a significant grain size increase to 18.2 μm ($\zeta = 1$—2) in the thick film. The sputtered type C copper shows a strong preferential ⟨111⟩ out of plane orientation. The grain size of 2.6 μm in the thin sample increases also only slightly to 2.8 μm in the 10 μm thick sample. An overview of texture and grain size is presented in Fig. 4. Tension tests on the free standing copper bars of 20 μm thickness, performed by Wimmer et al. [7], revealed different mechanical properties of the type A (Ultimate tensile strength $UTS = 291$ MPa, Young's modulus $E = 100 \pm 15$ GPa) and type B ($UTS = 177$ MPa, $E = 70 \pm 20$ GPa) copper.

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