Materials Letters 222 (2018) 54–57

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/mlblue

Featured Letter

Control of the residual stress gradients in copper films by inert ion implantation

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ARTICLE INFO

Article history:
Received 23 January 2018
Received in revised form 7 March 2018
Accepted 26 March 2018
Available online 28 March 2018

Keywords:
Micro-cantilever
Ion implantation
Residual stress gradient
Copper film

ABSTRACT

In this work, we studied the effect of inert ion implantation using helium and xenon ions on residual stress gradients in copper films. A copper microcantilever beam array was fabricated on a (1 0 0) silicon wafer by conventional bulk micromachining. The as-fabricated copper microcantilevers showed upward bending deformation as a result of positive residual stress gradient in films. Helium and xenon ions were implanted at various doses and energies into microcantilevers before releasing them from substrates. The magnitudes and signs of residual stress gradients were effectively controlled by both helium and xenon ion implantation and depended on implantation energy and ionic dosages. The mechanism of residual stress control appeared to involve counterbalancing residual stress gradients with compressive residual stresses induced by volume expansions of implanted regions and the direct effect of surface modification by ion bombardment.

1. Introduction

Freestanding microstructures deform as a result of residual stress gradients in films when they are released from substrates, exhibiting upward or downward bending deflections depending on stress gradient sign. The effects of residual stress gradients on deformation become particularly acute when film thickness is reduced [1], and such deformations might eventually lead to fabrication failure and diminish device performance [2,3].

Copper (Cu) films are widely used as electric and mechanical materials in micromachined devices, however, residual stress gradients in Cu films obstruct reliable fabrication of freestanding Cu microstructures [4–6]. Although high-temperature thermal annealing has been used to relieve residual stresses in thin films [7–10], it is not possible to treat Cu films thermally due to the low eutectic and melting points of Cu. Thus, a low-thermal-budget process is required that effectively controls residual stress gradients in Cu films.

Ion implantation has been widely used as a highly effective post-treatment because of its ability to modify material properties [11–13]. The technique is also practical from the perspective of micromachining because it is highly controllable and reproducible. In this work, we studied the effect of ion implantation treatment on residual stress gradients in Cu films. Helium (He) or xenon (Xe) ions were chosen to minimize unwanted chemical reactions and were implanted at various doses and energies into films. The reason for the observed residual stress control is discussed based on Monte Carlo simulation results regarding the penetration depth of ions in Cu films.

2. Experimental and results

2.1. Fabrication of Cu microcantilevers

A Cu microcantilever beam array was fabricated by conventional bulk micromachining to investigate residual stress gradients in Cu films. The microcantilever fabrication process and the experimental procedure are described in supplementary information Fig. S1.

2.2. Residual stress gradient in Cu film

Fig. 1 shows scanning electron microscope (SEM) images of the fabricated Cu microcantilever arrays. The inset shows an enlarged image of an array. Lengths of microcantilevers ranged from 40 to 240 μm but width and thickness were fixed at 40 and 0.5 μm, respectively. Film thickness was measured by profilometry (Alpha-step 200, Tensor Instruments) and tip deflections of specimens were measured using a non-contact laser profiler. As shown in Fig. 2, the as-fabricated microcantilevers exhibited positive bending deflection and this deflection increased with beam length.

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https://doi.org/10.1016/j.matlet.2018.03.171
0167-577X/

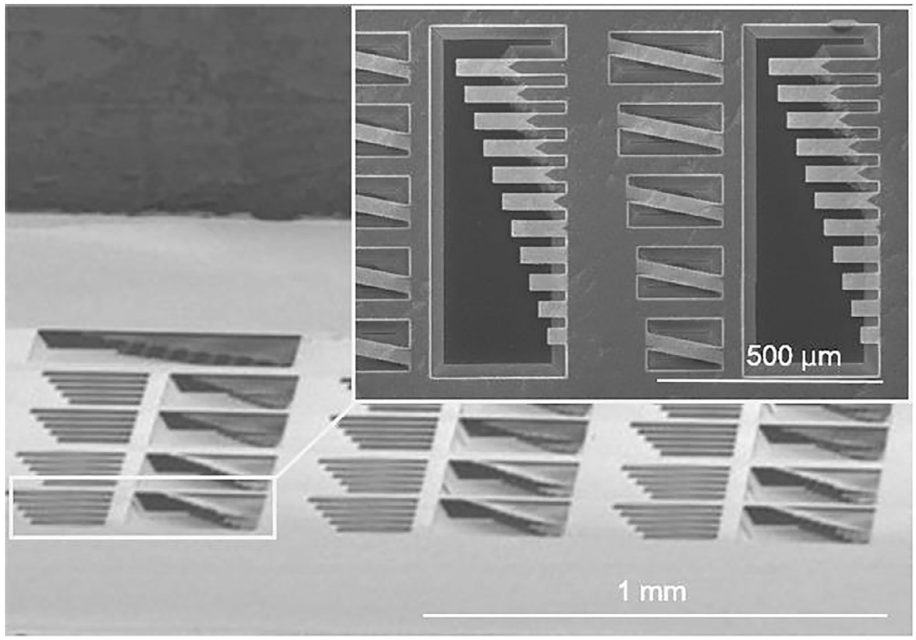

Fig. 1. SEM images of the fabricated Cu microcantilever beam array.

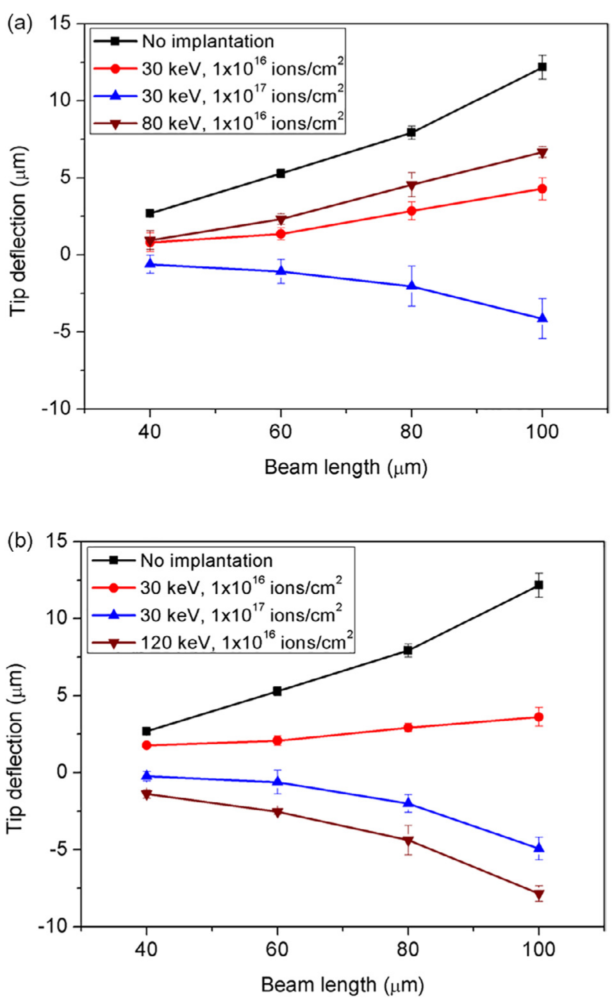

Fig. 2. Tip deflection changes of Cu microcantilevers after (a) He and (b) Xe ion implantation treatments, respectively.

Generally, when a cantilever beam with a positive residual stress gradient is released from a substrate, residual tensile stress in its upper surface is relieved by contraction, that is, by decreasing interatomic distances, whereas compressive residual stress in its lower surface is relieved by extension [14]. Consequently, a Cu microcantilever bends upwards due to the presence of a positive residual stress gradient.

2.3. Ion implantation effects on residual stress gradients

He and Xe ion implantations were used to relieve residual stress gradients in Cu microcantilevers. The experimental conditions are summarized in Table 1. In order to minimize chemical effects, ions of inert gases were used and the experiments were conducted at low pressure and room temperature. Specimens were secured with a chuck, which rotated during ion implantation to ensure uniform surface treatment. After ion implantation treatment, tip deflections of microcantilevers were measured and compared (Fig. 2). The results confirmed both He and Xe ion implantation treatments significantly changed residual stress gradients in Cu films in an ion energy and dose dependent manner. In the case of He ion implantation (Fig. 2(a)), the positive residual stress gradient of as-fabricated microcantilevers was relaxed at an implantation energy of 30 keV and an ion dose of 1×10^{16} ions/cm^2. An ion dose increase from 1×10^{16} to 1×10^{17} ions/cm^2 resulted in a negative residual stress gradient, and ion implantation at 80 keV and 1×10^{16} ions/cm^2 resulted in less relaxation than at 30 keV. Thus, implantation energy and dose were found to modify residual stress

Table 1
Ion implantation conditions.

Ion	Energy (keV)	Dose (ions/cm^2)	Condition
He	30	1×10^{16}	10^{-6} Torr, 25 °C with rotation
	30	1×10^{17}	
	80	1×10^{16}	
Xe	30	1×10^{16}	
	30	1×10^{17}	
	120	1×10^{16}	