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Room-temperature control of the residual stress gradient in titanium micro-cantilever beams by helium ion implantation

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ABSTRACT

Characterization and the reduction of residual stress and its gradient in thin films are important for improving the reliability of microelectromechanical systems (MEMS) devices. This study examined the room-temperature control of the residual stress gradient in sputtered titanium (Ti) films by helium (He) ion implantation. Ti micro-cantilever beam arrays were fabricated by surface micromachining and used to evaluate the residual stress gradient of the film by measuring the tip deflection of the cantilever beams. The as-fabricated Ti cantilever showed downward bending deformation as a result of the negative residual stress gradient in the film. To release the residual stress gradient, helium ions were implanted at various doses and energies into the Ti cantilever before releasing it from the substrate. The residual stress gradient could be controlled effectively by adjusting the implantation conditions. Almost straight Ti micro-cantilever beams with no residual stress gradient were achieved using the optimal implantation condition of He ions with a dose of 2.0×10^{15} at 80 KeV. The effects of He implantation on the surface properties, such as surface roughness and optical reflectance, were also investigated.

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1. Introduction

Titanium (Ti) is used widely in micromachined devices, especially operating under harsh conditions that require high fracture toughness and abrasion resistance, on account of its superior mechanical properties, such as a bulk modulus of 110 GPa and Vickers hardness of 970 MPa [1–4]. In addition, the techniques for titanium patterning, including the wet etching of titanium films using hydrofluoric-acid-based solutions and dry etching using metal anisotropic reactive ion etching with oxidation (MARIO) [5–7], have broadened the applicability of titanium to a wide range of MEMS devices. For example, the Ti micro-cantilever and its array have been used as structural members in microelectromechanical systems (MEMS) relay switches and comb drive actuators, respectively [2,5,8]. On the other hand, the use of titanium for freestanding MEMS devices has difficulties because of its high residual stress gradient [2,9–11]. Titanium structures released from a substrate normally deform undesirably as a result of the residual stress gradient, showing upward or downward bending deflections depending on the sign of the gradient. Undesirable deformation affects the mechanical and electrical behavior of the structure, which eventually leads to the failure of reliable fabrication and operation of the devices. Therefore, effective methods to release the residual stress gradient in titanium microstructures are needed, particularly for freestanding MEMS applications.

The residual stress and its gradient in a film is normally generated by the intrinsic growth of residual stresses through the thickness direction, or extrinsic thermal stresses due to a difference in the thermal expansion coefficient from that of the substrate [12–16]. A range of approaches has been developed for relaxing the residual stresses in a thin film. Among them, furnace annealing [17–19] and rapid thermal annealing (RTA) [20–22] are common methods for relaxing residual stresses. On the other hand, thermal annealing processes generally have high thermal budgets, and are limited in applications to integrated systems of electronic circuits made of metals. An alternative process for relaxing the residual stress of thin films of metals is the ion implantation technique, which is reproducible and accessible at room temperature [23–25].

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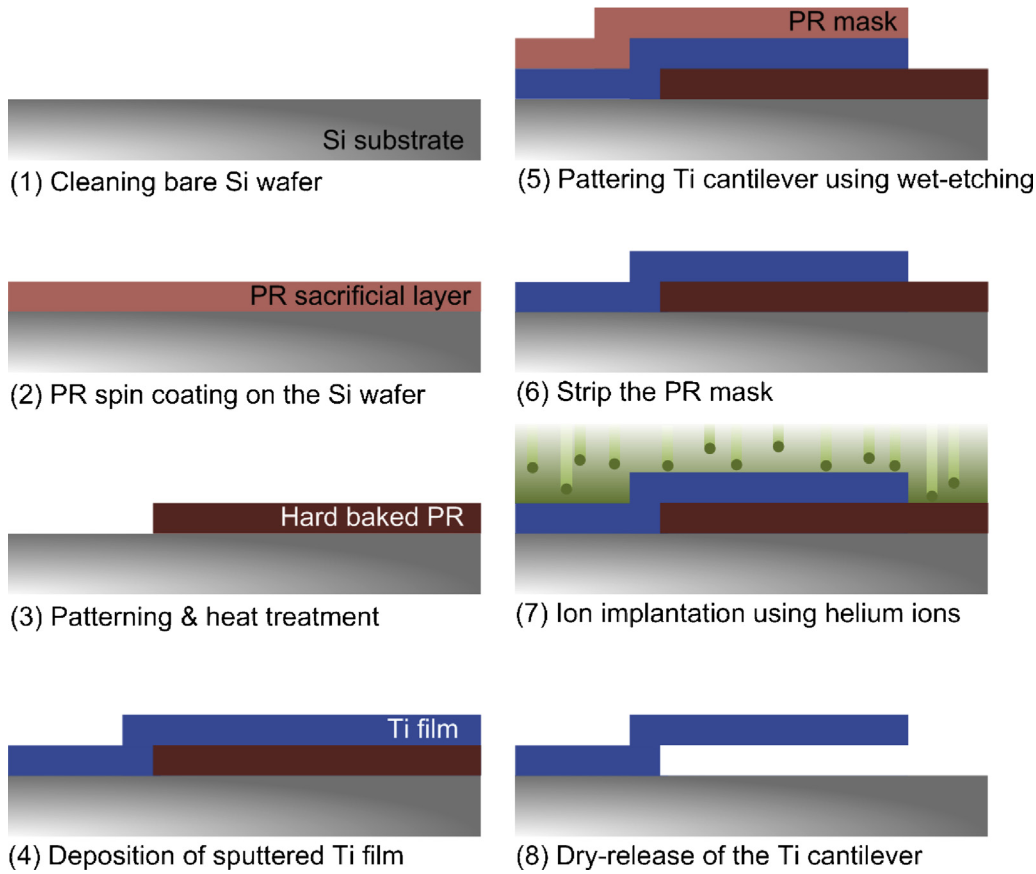

Fig. 1. Fabrication procedure for the Ti micro-cantilever beams.

This study examined the release of the residual stress gradient in thin titanium films using helium ion implantation. The effects of He implantation on the surface properties, such as the surface roughness and optical reflectance, were also investigated.

2. Experimental details

2.1. Fabrication of specimen

Sputter-deposited Ti thin films were used to make two types of specimens. One was a micro-cantilever beam array to examine the change in the residual stress gradient by measuring the beam deflections, and the other is a square-patterned specimen to examine the surface roughness and optical reflectance. Fig. 1 shows the fabrication procedure for the Ti micro-cantilever beams. A bare (1 0 0)-silicon (Si) wafer was cleaned to remove the organic contaminants and native oxide. The photoresist (PR, AZ1512), which is used as a sacrificial layer for a freestanding Ti structure, was spin-coated on the Si substrate at 4000 rpm for 35 s, and anchor holes and squares were patterned using a photolithography process. Heat treatment was performed to increase the thermal and chemical resistance of the PR layer at 120 °C for 10 min. The final average thickness of the PR layer was measured to be 1.12 μm using a surface profiler, which corresponds to the gap distance between the undeformed beam and substrate. The PR sacrificial layer is commonly used to fabricate freestanding MEMS devices because the layer thickness can be controlled precisely under spin-coating conditions and can be etched easily without damaging the devices using appropriate solvents, such as acetone and PR stripers. A Ti film with a thickness of 550 nm was deposited on the entire Si wafer with a patterned PR layer using a direct current (DC) magnetron sputtering system. Another PR layer was coated on the Ti thin films and patterned to make a mask for wet etching of the Ti thin films. The Ti film was wet-etched using a hydrofluoric (HF)-acid-based chemical etchant (200:1 volume percent of deionized water and 49% HF) to fabricate micro-cantilever and square patterns, and a mask PR layer was then removed with acetone. Two types of cantilever array specimens were fabricated: (1) 550-nm thick, 5-μm wide, and 10–100-μm long with 10-μm intervals, and (2) 550-nm thick, 20-μm wide, and 50–500-μm long with 50-μm intervals. The aim of this study was to develop an effective method to release the residual stress gradient in titanium microstructures. Therefore, Ti micro-cantilevers with various dimensions were examined to provide reliable results, but no attempt was made to optimize the geometry of the Ti structure for specific applications. To control the residual stress gradient in the Ti film, helium ions were implanted at various doses and energies onto the Ti cantilevers before releasing them from the Si substrate. Finally, the micro-cantilever beams were released by removing the sacrificial (PR) layer through oxygen plasma ashing.

2.2. Direct current magnetron sputtering for Ti film

Ti films were coated onto silicon substrate with the patterns of anchor holes and squares by direct current (DC) magnetron sputtering deposition with an argon flow rate of 40 sccm at 300 W. The deposition rate and thickness were monitored using a quartz crystal microbalance (QCM). During deposition, the substrate was rotated at a rate of 24 rpm to obtain a uniform Ti film coating. The deposition rate was kept constant at ∼20 nm/min, and the vacuum in the chamber was maintained below 4 mTorr. The deposition conditions used in magnetron sputtering in the present study were

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