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Strength evaluation of a selected interface in multi-layered nano-material

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ABSTRACT

A novel notched nano-cantilever specimen consisting of a 1000-nm-thick SiN layer and a 200-nm-thick Cu layer on a Si substrate is proposed to evaluate the strength of a selected interface in multi-layered nano-materials. By introducing a nano-notch near the selected interface, a stress concentration is applied to the interface. The crack is successfully initiated at the Cu/SiN interface by the developed method. Detailed critical stress fields near the edge of Cu/SiN interface for cracking are analyzed by the finite element method, which reveals maximum normal stresses for cracking show good agreement. This indicates the normal stress at concentrated field governs the crack initiation at Cu/SiN interface.

1. Introduction

Micro- and nano-mechanical systems and electronic devices consist of dissimilar components, of which size is on the nanometer scale. Because intrinsic bi-material interfaces are inevitably introduced into these devices, deformation mismatch between the dissimilar materials induces a stress concentration at the interface. Thus, the interface is one of the potential sites of fracture [1–4]. Since the stress concentration region is proportionally scaled down for the shrinkage of component size, the stress concentration region at the interface edge is confined to the nanoscale in advanced devices [5–7]. The strength for the interface cracking in nano-scale is important in terms of assurance of integrity and reliability.

There are evaluation methods of interface strength in multilayered nano-materials [8] and the isolated grain boundary in polycrystalline materials [9,10]. In the application to a multilayered material, the weakest interface can be evaluated. Because the material combination, their shape, loading condition bring complex stress field in a real device, it is necessary to know the strength of all interfaces for the precise design. However, as it is difficult to make a fracture along a stronger interface in the multilayered material, there is no appropriate method to evaluate a selected interface in a multilayered nano-component. For example, a nano-cantilever bending specimen with the multi-layered material of silicon/copper/silicon nitride (Si/Cu/Si_3N_4) is developed to investigate the crack initiation at the edge of Cu/Si interface due to nanoscale stress concentration [11–15]. The crack was always initiated at the edge of Cu/Si interface because of weaker strength compared with another interface, Cu/Si_3N_4.

In this study, we develop a notched nano-cantilever method, which can control the location of stress concentration. Using the specimen, we will show that we can evaluate the strength of stronger interface.

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Nomenclature

C_{11}, C_{12}, C_{44}	elastic constants of the orthotropic Si substrate
P	applied load
P_C	critical load for crack initiation
t	loading time
ε	von Mises strain
σ	von Mises stress
σ_y	yield stress
FEM	finite element method
FIB	focused ion beam
SEM	scanning electron microscopy
TEM	transmission electron microscopy

2. Experimental procedures

2.1. Material

The specimen is manufactured from a multi-layered material, i.e., silicon/copper/silicon nitride ($Si/Cu/Si_3N_4$). A Si (100) wafer surface is cleaned by inverse sputtering, and then a Cu layer is deposited up to a thickness of 200 nm by radio-frequency magnetron sputtering. A Si_3N_4 (abbreviated as SiN in follows) layer is subsequently deposited up to a thickness of 1000 nm with the same method without breaking the vacuum.

2.2. Notched nano-cantilever specimen

Fig. 1 shows a nano-cantilever specimen that has been adopted to investigate crack initiation at the edge of Cu/Si interface in previous studies [11–15], where the cantilever part of specimen was made without any notch or defect. Since the interface between Cu layer and Si substrate possesses the weakest strength, the crack was always initiated at the upper edge of Cu/Si interface.

Fig. 2 shows the schematic illustration of the notched nano-cantilever specimen used to investigate the crack initiation at a particular interface in multi-layered materials, such as the Cu/SiN interface in this study. As shown in Fig. 2(a), a notch on the nanoscale is introduced in the SiN layer near Cu/SiN interface by focused ion beam (FIB). As its tip locates near the Cu/SiN interface, a concentrated stress field appears there. Three specimens with different size and shape of notch are prepared and their scales are summarized in the table of Fig. 2.

Fig. 3 schematically illustrates the fabrication procedure for the notched nano-cantilever specimen. Prior to the sample fabrication, passivation layers of gold (Au) and carbon (C) are deposited on the SiN layer to prevent the specimen from damage during processing. A cubic block with the side length of about 10 μm is cut from the multi-layered material by a focused ion beam (FIB) (Hitachi, FB2200) (Fig. 3(a)), and then it is picked up by attaching a manipulator of a micro-sampling system embedded in the FIB (Fig. 3(b)) with the block by carbon deposition. After gluing the block to the flat top of a gold (Au) wire with a diameter of 0.25 mm (Fig. 3(c)) by using carbon deposition, the cantilever part of specimen is made by the

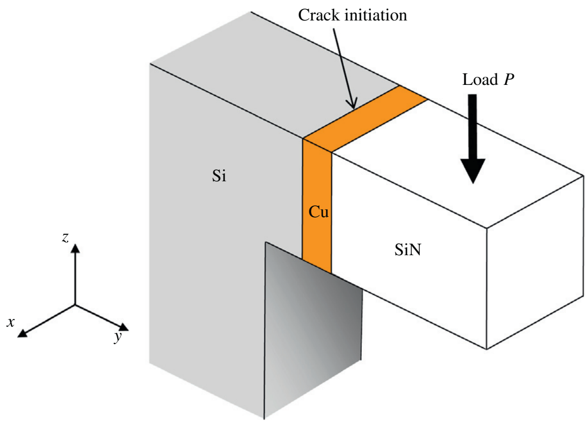

Fig. 1. Schematic illustration of a perfect nano-cantilever specimen for crack initiation at Cu/Si interface edge used in previous studies [11–15].