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Size dependent fracture strength and cracking mechanisms in freestanding polycrystalline silicon films with nanoscale thickness

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ABSTRACT

The size dependent fracture strength and fracture mechanisms of polycrystalline silicon films are investigated by analyzing a wide range of specimen lengths and widths with thicknesses equal to 240 and 40 nm. An on-chip method is used to deform the films and to determine the strength. The strength increases with decreasing external surface area. The thinnest films exhibit the lowest strength and a weaker size effect. The crack path changes from transgranular to intergranular with decreasing thickness. These results are related to differences in microstructure and surface roughness characteristics of the films as controlled by the fabrication process and thickness.

1. Introduction

Polycrystalline silicon (poly-Si) thin films constitute a key structural component for various applications such as displays and microelectronics devices [1], nano- and microelectromechanical systems [2] as well as pressure [3,4], infrared [5] and biological sensors [6]. Poly-Si can be deposited and patterned over a wide variety of substrates and has the advantage of low production costs. A range of electrical properties can be targeted by varying the doping level and implanted species [1,2]. The good mechanical properties make poly-Si versatile in terms of the combination of functional and structural performances [1,2]. As for any structural element, mechanical failure of thin poly-Si components compromises device operation. The understanding of the fracture mechanisms occurring in poly-Si films as well as the characterization of the fracture properties are critical concerns for supporting the design, development and fabrication of efficient and reliable applications.

At room temperature, poly-Si thin films fail in a brittle manner by cleavage [7]. The fracture typically initiates from critical defects present on external surfaces [7–13]. The fracture is reported to be transgranular, with the crack propagating quasi-instantaneously along the compact crystal planes [7,9,12,14]. The intrinsic toughening mechanisms due to local grain orientation changes and grain boundary (GB) toughening are not very effective [14]. The fracture strength of poly-Si films is

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Nomenclature

a	crack length
E	Young's modulus of the specimen material
E_a	Young's modulus of the actuator material
K_{Ic}	fracture toughness
L	specimen beam length
L_a	actuator beam length
Ra	arithmetic average of absolute values of the profile height deviations from the mean line
Rms	root mean square of the absolute values of the profile height deviations from the mean line
S	section of the specimen beam after the release step
S_a	section of the actuator beam after the release step
u	displacement of the specimen beam
u_a	displacement of the actuator beam
t	thickness of the specimen beam after the release step
Y	non-dimensional geometrical factor
ε^{mech}	mechanical strain of the specimen beam
ε_a^{mech}	mechanical strain of the actuator beam
ε^{mis}	mismatch strain of the specimen beam
ε_a^{mis}	mismatch strain of the actuator beam
σ	stress in the specimen beam
σ_a	stress in the actuator beam
σ_f	fracture strength
ACOM-TEM	automatic crystallographic orientation mapping in a transmission electron microscope
AFM	atomic force microscopy
c	crystallite
CSLB	coincidence site lattice boundary
ED	electron diffraction
FIB	focused ion beam
g	grain
GB	grain boundary
HAGB	high angle grain boundary
HF	hydrofluoric acid
Mono-Si	monocrystalline silicon
LAGB	low angle grain boundary
LPCVD	low pressure chemical vapor deposition
Poly-Si	polycrystalline silicon
RIE	reactive ion etching
SEM	scanning electron microscope
SiN	silicon nitride
TEM	transmission electron microscope

governed by the size of the most critical defects which act as a collection of small precracks. The defect with the highest stress intensity factor initiates the fracture and dictates the overall fracture strength [8,11]. The nature, location and spatial distribution of the critical defects depend on the processing conditions and on the film thickness as the microstructure [1,2] and surface roughness [15] are governed by both of them.

Poly-Si films can be produced by various techniques [1], the most common being low pressure chemical vapor deposition (LPCVD). As-deposited LPCVD silicon films can be amorphous or polycrystalline [1]. Amorphous films are smoother due to the absence of large defects such as GBs, but still exhibit lower tensile strengths than polycrystalline counterparts [10]. Amorphous silicon contains a significant concentration of hydrogen and has a lower density which both participate to the creation of large surface defects when etching the sacrificial layer to release the films. For polycrystalline films, the grain size and surface roughness increase with increasing film thickness [1,15]. The effect of deposition temperature on the grain size and roughness is not easy to determine because these parameters are also influenced by deposition pressure [1,15–17]. From our knowledge, no information is available in the literature about the evolution of the tensile strength of as-deposited poly-Si films as a function of the deposition conditions and film thickness. Amorphous films crystallise during an additional annealing step. A rapid thermal annealing allows controlling the grain size over a wide range of dimensions [1,10]. The higher the annealing temperature, the larger the nucleation rate, the smaller the grain size. Tsuchiya [10] showed that

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