Bauschinger effect in thin metal films on compliant substrates

Citation for published version (APA):

Hoefnagels, J. P. M., & Vlassak, J. J. (2007). Bauschinger effect in thin metal films on compliant substrates. In E. E. Gdoutos (Ed.), *Experimental Analysis of Nano and Engineering Materials and Structures* (pp. 63-64). https://doi.org/10.1007/978-1-4020-6239-1_30

DOI:

[10.1007/978-1-4020-6239-1_30](https://doi.org/10.1007/978-1-4020-6239-1_30)

Document status and date:

Published: 01/01/2007

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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BAUSCHINGER EFFECT IN THIN METAL FILMS ON COMPLIANT SUBSTRATES

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Summary

Flexible electronic devices such as flexible displays and solar cells draw more and more attention from the industry. In these devices, the functionality is delivered by small-scale structures consisting of thin metal lines and other materials that are integrated on a compliant (e.g. polymer) substrate to make the device flexible. A major concern is reliability, since the small-scale structures with features on the order of micrometers or below are highly fragile, however, they are subjected to large thermo-mechanical loads during manufacturing and use. Although a growing literature exists on rupture and buckling of thin metal films on polymer substrates, see for instance Hutchinson and Suo [1], many mechanical issues of flexible electronics have not been studied in depth. In this project, one such issue, the Bauschinger effect of thin metal films bonded to a compliant substrate, will be studied in more detail, because the Bauschinger effect appears to be a particularly important issue in flexible electronics applications where the device is subjected to multiple strain cycles.

FIGURE 1. (a) Schematic of the plane-strain bulge test to determine the stress-strain curves of thin membrane, where the membrane may be a single material layer or a stack of multiple material layers. (b) Stress-strain curves of a freestanding $0.6\ \mu\text{m}$ Cu film and the same Cu film passivated by a hard SiN film. Both figures taken from Ref. [2].

We will study the effect of weak interfaces experimentally by means of the plane-strain bulge test technique, which was developed within the Vlassak group at Harvard University, see e.g. Ref. [3]. In this technique, rectangular micromachined membranes fabricated out of the material

of interest are deflected by applying a pressure to the membrane, see Fig. 1(a). The stress-strain curve of the membrane material is readily determined from the deflection, h , of the membrane. Previously, this technique has been used to measure stress-strain curves of metal films as thin as 100 nm [4]. It should be noted that the membrane does not need to be a single material layer, but can in fact be any multi-layer stack of thin material films.

Xiang and Vlassak used a double-layer stack consisting of a sputter deposited Cu thin film adhered on a hard SiN film to alternately drive the Cu film in tension and compression [2], see Fig 1(b). They observed that the Cu film exhibit an unusual Bauschinger effect with reverse flow already occurring on unloading. This behavior was explained by the built-up of a dislocation density at the Cu-SiN interface that was assumed to be impenetrable to dislocation movement, i.e. the interface was said to be ‘fully passivated’. On the other hand, the freestanding Cu thin film, showed little or no reverse flows when the film is fully unloaded, see Fig. 1(b).

While the effect on plasticity in metallic films with a free surface versus films with a strong interface on a hard and stiff substrate may be understood, it is unclear what is the effect of a weak interface or an interface with a soft layer, as is often the case in flexible electronics. For instance, plastic deformation in the thin film may trigger debonding of the interface, thereby allowing strain localization. Moreover, most free metal surfaces develop a native oxide which may also prevent dislocation movement to a certain degree, therefore, a highly compliant interface may reveal mechanical behavior closer to a truly unpassivated surface than a free metal surface with native oxide.

To test these hypotheses, in the present research, a range of three-layer membranes consisting of SiN/polymer/Cu and SiN/Cu/polymer stacks have been manufactured for testing in the bulge test apparatus. The SiN layer is always present in the stack to be able to drive the Cu layer into compression, while a range of polymer films with different hardness applied by a spin coating process is added to create a set of Cu interfaces with varying compliance. Particular care has been taken to assure that the Cu film at the Cu-polymer interface is not oxidized. The bulge tests are scheduled to be executed in the upcoming months and the resulting stress-strain curves of a Cu film adhered to compliant substrates will be compared to the stress-strain curves of (the same) Cu film in a freestanding and fully-passivated configuration. Emphasis will be on differences in the Bauschinger effect and in the flow stress [see Fig. 1(b)], while the evolution of the microstructure may be measured with transmission electron microscopy. The results promise to yield new and detailed insight into the plasticity of thin metal films found in flexible electronics applications and will be used to formulate an (extended) model of the dislocation dynamics at (weak) interfaces.

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