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Condensed matter physics in the 21st century: The legacy of Jacques Friedel

A versatile lab-on-chip test platform to characterize elementary deformation mechanisms and electromechanical couplings in nanoscopic objects

Plate-forme versatile d'essai sur puce pour la caractérisation des mécanismes élémentaires de déformation et des couplages électromécaniques dans les objets nanoscopiques

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A B S T R A C T

A nanomechanical on-chip test platform has recently been developed to deform under a variety of loading conditions freestanding thin films, ribbons and nanowires involving submicron dimensions. The lab-on-chip involves thousands of elementary test structures from which the elastic modulus, strength, strain hardening, fracture, creep properties can be extracted. The technique is amenable to in situ transmission electron microscopy (TEM) investigations to unravel the fundamental underlying deformation and fracture mechanisms that often lead to size-dependent effects in small-scale samples. The method allows addressing electrical and magnetic couplings as well in order to evaluate the impact of large mechanical stress levels on different solid-state physics phenomena. We had the chance to present this technique in details to Jacques Friedel in 2012 who, unsurprisingly, made a series of critical and very relevant suggestions. In the spirit of his legacy, the paper will address both mechanics of materials related phenomena and couplings with solids state physics issues.

R É S U M É

Une plate-forme d'essai nanomécanique sur puce a été récemment développée afin de déformer, sous des conditions de chargement variées, des films minces, rubans et nanofils libres impliquant des dimensions submicroniques. Le laboratoire sur puce comprend des

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milliers de structures d'essai élémentaires à partir desquelles peuvent être extraits le module d'élasticité et les propriétés de résistance, d'écrouissage, de rupture et de fluage. La technique est adaptée pour des études in situ par microscopie électronique en transmission pour élucider les mécanismes sous-jacents fondamentaux de déformation et de rupture qui, souvent, induisent des effets de dépendance de la taille des échantillons. La méthode permet d'investiguer les couplages électriques et magnétiques ainsi que d'évaluer l'impact de niveaux de contrainte mécanique élevés sur divers phénomènes de physique de l'état solide. Nous avons eu la chance de pouvoir présenter cette technique à Jacques Friedel en 2012, lequel a, sans surprise, émis une série de suggestions critiques et particulièrement pertinentes. En hommage à son héritage scientifique, cet article aborde aussi bien des phénomènes relatifs à la mécanique des matériaux que des questions liées à des couplages en physique de l'état solide.

1. Introduction

The playground of solid-state physics has been enlarged in recent years owing to the development of novel nanomechanical testing set-ups that allow deforming nano-sized material systems, under controlled mechanical loads with additional electrical, magnetic or environmental effects, sometimes involving in situ characterization capabilities, see, e.g., reviews [1–4]. The most widely used methods in nanomechanics involve (see the review papers [1–4] and references therein) the following techniques: (i) nanoindentation consists in penetrating a hard sharp tip inside the material with continuous measurement of the load and displacement allowing to probe the response of volume elements with a characteristic dimension typically larger than 20 nm; (ii) AFM and its variants are used to probe (visco-)elastic and adhesion properties, of soft to medium soft systems, at even smaller length scales; (iii) micro- or nano-pillars compression, for instance with a flat nanoindentor tip, allows testing freestanding submicron specimens up to large strains but with the difficulty to produce clean samples with sharp geometrical tolerances; (iv) "wafer curvature" methods for thin films and coatings deposited on perfectly flat substrates and loaded through thermal expansion mismatch are particularly simple to operate to address the small strain response, though under the constraint of the underlying substrate; (v) various "top-down" tensile testing set ups consist of miniaturized version of macroscopic machines with the difficulty to manipulate micrometer-sized samples and to apply and measure extremely small loads and displacements; (vi) testing methods based on micro- or nano-fabrication techniques are based on producing freestanding specimens directly integrated in a micro- or nano-testing platform processed by the same methods; (vii) several of the aforementioned methods have been combined in different ways, e.g. freestanding membranes or beams processed by lithography and etching methods (vi) are deflected by nanoindentor (i) or AFM (ii) or by a pressure (the so-called bulge test). In most cases, these methods have been adapted to work under different environmental conditions and range of temperatures with possible couplings to electrical or magnetic fields.

Some of the tested nano-sized systems can be produced with near-ideal defect-free microstructures or, alternatively, with extremely large densities of internal interfaces and defects. Among others, a number of elementary deformation mechanisms related to the nucleation, propagation, interactions and multiplication of defects can be experimentally revisited and quantitatively characterized through these new testing capabilities. Sometimes, unique mechanisms, related to unusual constraints associated to the small dimensions or to the nanocrystalline structure are unraveled, challenging the current state of knowledge, see, e.g., [5–10]. Furthermore, the level of stress and stress gradient that can be attained in some of these nanowire or thin-film-type systems being extremely large compared with bulk counterparts, due to the so-called "smaller is stronger" paradigm, significant distortion of the crystal lattice takes place, leading to strong modifications of the transport properties, involving for instance large piezoresistive, flexo-electric, or magnetostriction effects. The field of the so-called "strain engineering" in nano-objects reconciles and forces cross-fertilization between the mechanics of solids, materials science and solid-state physics communities in a way that perfectly corresponds to the legacy of Jacques Friedel, who always naturally conceived all these viewpoints within a unified approach. We had the opportunity to present and discuss with him a new concept for measuring experimentally the mechanical response of small-scale objects while allowing in situ defect characterization and transport measurements. The present contribution is an opportunity to explain the concept, to outline some recent extensions and results, and to indicate perspectives for its future development and expected contribution to the generation of new knowledge in this exciting field.

The outline of the paper is the following. The basic concept underlying the generic on-chip test method is presented in Section 2. Section 3 explains how the technique can be extended to address various loading, environmental and coupled effects, involving in situ capabilities. In Section 4, selected results obtained on Pd thin films over the last 4 years are revisited, involving interesting fundamental examples of dislocation and twin interaction mechanisms. Section 5 is devoted to the extraction of piezoresistance effects in silicon nanowires of different doping levels over a large range of deformations as an example of electrical–mechanical coupling analysis using this lab-on-chip test platform concept.