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LASER-BASED DESTRUCTIVE AND NONDESTRUCTIVE TESTING OF MECHANICAL PROPERTIES OF SILICON

Peter Hess[1(*)], **Alexey M. Lomonosov**[1,2]
[1]Institute of Physical Chemistry, University of Heidelberg, D-69120 Heidelberg, Germany
[2]General Physics Institute, Russian Academy of Sciences, 119991 Moscow, Russian Federation
[(*)]*Email:* peter.hess@urz.uni-heidelberg.de

ABSTRACT

Strongly nonlinear surface acoustic waves (SAWs) developing steep shock fronts during propagation were employed to form partially closed cracks at single-crystal silicon surfaces. Calibration of the nonlinear SAW pulses allowed the determination of the fracture strength of silicon for defined crystallographic planes and directions and the comparison with *ab initio* calculations. The size, mean interfacial stiffness, and localization of these surface-breaking cracks were determined using the optical pump-probe setup with linear SAW pulses and laser-probe-beam deflection for measuring the surface velocity.

Keywords: impulsive load by shocks, fracture strength of silicon, surface-breaking partially closed cracks, nondestructive evaluation.

INTRODUCTION

Single-crystal silicon is one of the most important materials in current technology, e.g., in semiconductor and sensor industries. It is one of the purest materials with very low defect concentration. While its linear mechanical properties are well known, nonlinear mechanical properties are of increasing interest, since they are particularly sensitive to any defects and distortions of the ideal crystal lattice. *Ab initio* calculations of the critical fracture stress of silicon crystals are available for a few selected geometries of the anisotropic crystal. However, there is a lack of experimental data of the fracture strength for crystal geometries defined by the crystallographic plane and direction along this plane. Only those data can be compared directly with the theoretical values. Impulsive fracture of silicon with nonlinear SAW pulses, excited by the absorption-layer method and developing shocks during propagation, yields the fracture strength and allows a direct comparison with theory.

The surface-breaking partially closed cracks generated by the impulsive loading method with a transient nonlinear SAW pulse can be characterized by using linear SAW pulses. A very sensitive analysis is possible, when the center wavelength of the broadband SAW pulse is comparable to the depth of the crack, since then the partial waves with smaller wavelengths are essentially reflected and the components with longer wavelengths tend to be transmitted. From the reflection and transmission coefficients sizing of the crack is possible based on independent information. Analysis of the modified reflected pulse shape provides additional information on the mean interaction between the two touching crack faces. The observation of a tripolar pulse profile not only proves the interaction of the two crack faces during the reflection process but makes it possible to evaluate quantitatively the decrease of the stiffness in the crack region. Furthermore, the probe signal is strongly enhanced if the probe laser hits the crack position owing to changed boundary conditions. Therefore, scanning the probe laser allows the accurate localization of the crack (Lomonosov 2009).

RESULTS AND CONCLUSIONS

Measurements of the fracture strength of silicon were performed for SAW pulses propagating, for example, along the Si(111) plane in the [-1-12] direction. Calibration of the pulses yielded a critical tensile stress of 4.0 GPa for crack opening at the surface. This can be compared with the ideal fracture strength of 21 GPa obtained by *ab initio* theory. As expected, the crack extended along the {11-1} cleavage plane into the bulk with an angle of 19.5° to the surface normal. With respect to this cleavage plane the tensile opening stress was 3.6 GPa and the shear stress was -1.3 GPa.

The microcracks induced by impulsive stress loading had a size of approximately 50−100 µm determined by the SAW pulse length and the crack velocity, which may approach the Rayleigh velocity. The radius of the penny-shaped crack extracted from the reflection coefficient was 34 µm and from the time shift of the transmitted pulse 40 µm. Contrary to the bipolar incoming and transmitted SAWs the reflected SAW had a tripolar shape, as shown by the solid black line in Fig.1. By assuming that in the partially closed crack all stress components are reduced by the same amount ("reduced stress model") the tripolar pulse form and the corresponding stronger SAW transmission could be described (see grey lines in Fig. 1). This simple single-parameter model yields a reduction of the average crack stiffness to 8% of the intact crystal value. Note that for a completely open crack the reflected pulse is bipolar and transmission is much smaller than actually measured (see dashed lines in Fig.1.)

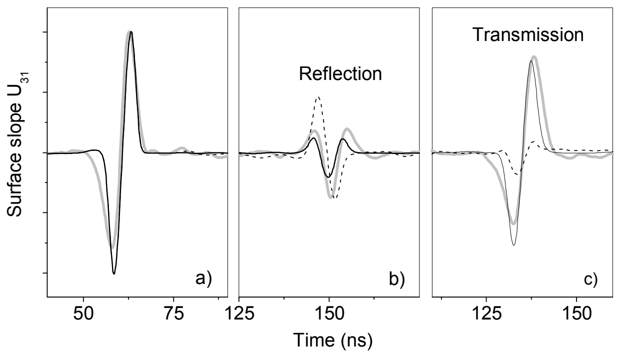

Fig. 1 - Comparison of SAW pulses; black solid lines: experiment, dashed lines: FD simulation with reduced stress parameter 0, grey lines: FD simulation with reduced stress parameter 0.08, a) incoming SAW, b) reflected SAW, c) transmitted SAW.

We conclude that with the developed laser technique that gives access to strongly nonlinear and linear SAW pulses the fracture strength of silicon can be determined and the generated cracks can be characterized. Crack closure can be recognized and the remaining average interfacial stiffness can be estimated by finite-difference (FD) simulations (Lomonosov 2013). Crack localization is achieved by scanning the probe laser through the crack position.

REFERENCES

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