Interaction of rapidly moving crack front with propagating waves

M. WANG, M. FOURMEAU, D. NELIAS[a]
a. Univ Lyon, INSA-Lyon, CNRS UMR5259, LaMCoS, F-69621, France,
daniel.nelias@insa-lyon.fr

Abstract :

Crack propagating direction and front shape can be significantly affected when encountering stress wave perturbations, which changes fracture paths and fracture surface roughness. Here, we study the dynamic cleavage behavior of (001) silicon single crystal wafers under bending tests. We show that the crack propagates preferentially along the (110) cleavage plane under pure bending load regardless of the crack propagating velocity. However, when fracturing under bending load with contact perturbations, shear waves emit from the line-contact and deflects the crack front onto the (111) cleavage plane upon interaction which generates secondary Wallner lines. Yet, the crack propagation along (111) plane is not permanent as it recovers to the (110) plane after a certain length relating to the crack velocity, which reveals that the cleavage along (110) plane is energetically favorable and conforms to the principle of minimum energy dissipation even in high-speed fracture process. In addition, it is found that, during the crack growth on the (110) cleavage plane, the fracture surface is mirror-like and crack front shape can be approximated with a quarter-ellipse at the crack velocity lower than 2600 m/s. Above this velocity, the crack front shape involves a local curvature jump which is velocity-dependent. We highlight that special elastic waves occur from the curvature jump position, and we suggest that they are front wave resulting from a local fracture energy fluctuation. These waves contain the out-of-plane component that kinks the crack front to leave special surface undulations, which obviously alter the surface roughness.

Mots clefs : Brittle fracture, single crystalline silicon, moving crack front, elastic waves, crack deflection.

1 Introduction

Crystalline silicon has attracted substantial attention of research for decades because of its large applications in solar cells and microelectromechanical systems (MEMS) [1]. The high brittleness of silicon raises wide concerns, since the failure of this semiconductor material significantly increases the cost of fabrication and decreases the efficiency of the utilization of silicon components [2]. Therefore, understanding the fracture mechanism of silicon is of paramount importance to improve the reliability and durability of Si-based devices for both industrial and scientific practitioners.
Like mechanical properties, the fracture behavior of silicon single crystal highly depends on crystallographic orientations. According to the Griffith criterion [3], the crack grows in single crystalline silicon preferentially along the {111} or {110} cleavage planes, which contain lower fracture toughnesses than other planes [4]. Moreover, the fracture is in-planar anisotropic on {110} planes. The crack can stably propagate on the (110) plane along the [1-10] direction (abbreviated to (110)[1-10]), while systematical crack deflection from the (110)[001] onto (111)[11-2] has been observed in tensile

tests. This deflection scenario is explained by discontinuities of atomic bond breaking which involves in a large lattice trapping effect revealed by quantum mechanical calculations [5] and is reproduced latterly by molecular dynamics simulation [6]. Due to these rich anisotropies in fracture behavior, the understanding of the crack path selection of silicon remains challenging.

The moving crack is stable under pure tension loading when the crack propagation velocity *v*, is low. Translational symmetry of the crack tip breaks and micro-cracks branch out from the main crack at *v*~30% - 40% of the Rayleigh wave speed, generating the so-called micro-branching instabilities [7]. The straight crack becomes oscillatory related to near-crack nonlinear elastic fields at ultrahigh-speed cracks (*v*~90% of the shear wave speed) on suppressing the micro-branching event and undergoing oscillatory instabilities [8]. Moreover, it has been shown that the crack is locally destabilized when continuously encounters transverse waves emitted from material defects or artificial transducers [9], which leaves typical fracture surface marks, i.e., the Wallner lines [10]. Similar marks have been revealed generated by nonlinear elastic waves [11], called crack front waves, although the origin of these marks led to severe polemics [9].

The present work investigates the fracture behavior of (100) single crystalline silicon wafers under bending solicitation. Both crack propagations under pure bending in four-line bending tests and line-contact in three-line bending tests are studied. The crack propagating velocity *v* is measured by the high-speed imaging technique and the local crack behavior is analyzed by the quantitative fractographic method. It is found that the crack solely propagates on the (110) cleavage plane under pure bending loading, while it deflects from the (110) plane to the (111) plane with the presence of line-contact perturbation. The (110)-(111) crack deflection is found to evolve along the secondary Wallner lines, which reveals that shear waves dominate the crack deflection. Furthermore, crack front shape at high crack velocity is addressed that containing a local curvature jump. Jointly, special surface undulations differing from the Wallner lines raise at the curvature jump spot. These special traces extend with the moving crack front and we propose that they are front waves traces that generated by local fracture toughness variation.

2 Experimental method

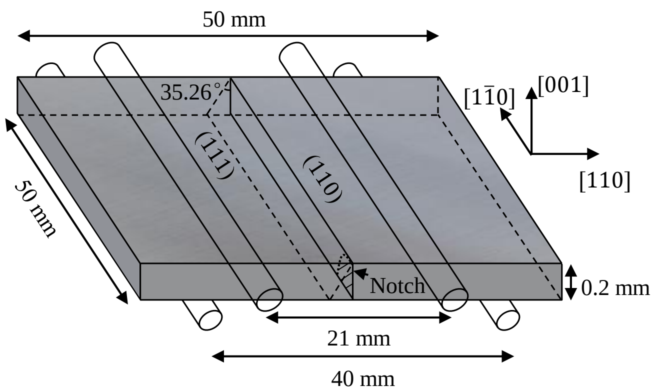

Figure 1 Four-line bending geometry of (100) single crystal silicon wafer.

The wire-cut (100) single crystalline silicon wafer with the dimension of 50 x 50 x 0.2mm^3 was used. The specimens were fractured in quasi-static loading under three-line bending and four-line bending tests. The example of the four-line bending configuration and the crystallographic orientation are illustrated in Fig.1. The wafer is loaded along the <110> direction so that the (110) plane coincides the maximum tensile loading which becomes the most energetically preferential fracture plane. Note that the effective fracture energy of the (111) plane is higher than the (110) plane due to the 35.26° tilt angle relative to the loading direction. In order to control a single propagating crack, an edge notch was produced in the middle of one edge. Thanks to various sizes of the edge notch, the mean crack propagation velocity v_s varies from 840 m/s to 3700 m/s measured by a high-speed camera in our tests, more information about the measurement technique can be found in [12]. The crack behavior was then investigated by the 2D fractography or 3D topography of the post-fracture surface using a digital microscope, a laser scanning profilometer and AFM measurement.

2 Results

2.1 Secondary Wallner lines and crack deflection

The cleavage plane was examined and correlated to the mean crack propagating velocity v_s. Figs.2 shows fracture surface morphologies at v_s = 3600 m/s under four-line bending load (Fig.2a) and three-line bending load (Fig.2b). Due to the stress gradient under bending, the crack initiates on the (110) plane from the bottom surface of the wafer and then gradually grows to the upper surface with propagating from left to right. This phenomenon is revealed by the shape evolution of primary Wallner lines, as highlighted by the red dotted line in Fig.2a. When focusing on the cleavage plane, it can be found that the crack propagates on the (110) plane under pure bending (Fig.2a) while it deflects from

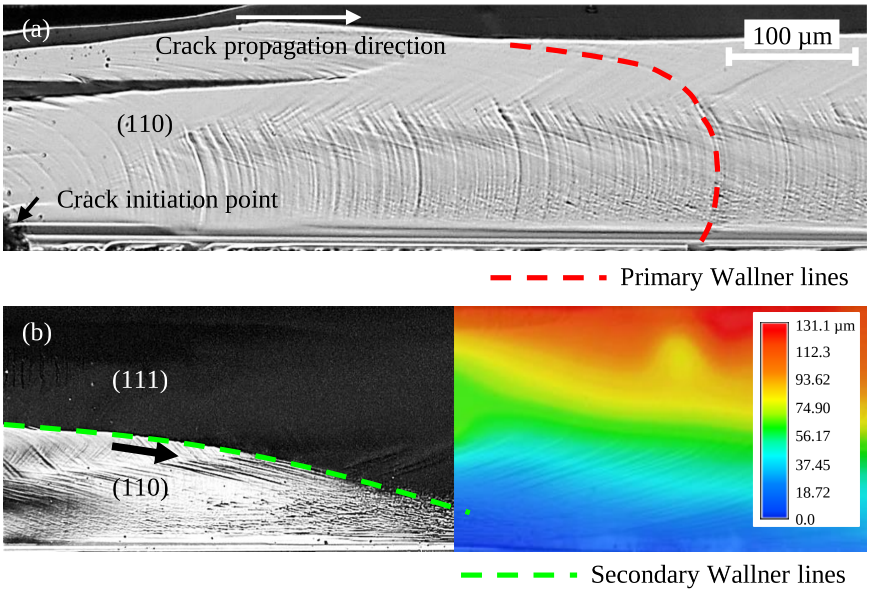

Figure 2 Fracture surface morphologies at crack initiation of (a) (110) cleavage plane under pure bending at vs = 3600 m/s and (b) (110)-(111) crack deflection under line-contact at vs = 3600 m/s.

the (110) plane to the (111) plane until propagating on the (111) plane in the line-contact case (see Fig.2b), where the bright part presents the (110) cleavage plane and the dark part presents the (111) plane owing to different light reflection. The variation of the fracture surface height in Fig.2b highlights the (111) cleavage plane. It can be noticed that the crack deflection is progressive which evolves along a specific surface mark (green dotted line in Fig.2b) with the crack propagation. The profile of the specific surface mark and its out-of-plane amplitude *A* as a function of the extending distance *r* are measured by the laser scanning profilometer and are shown in Figs.3. The generated surface profile and the linear decay of the amplitude on the logarithmic scale with a rate of $1/r^2$ indicate that the specific surface mark is hence the Secondary Wallner lines [9]. Since the Wallner lines are generated by the interaction of the moving crack front with shear waves, the dependence of the (110)-(111) crack deflection on the Wallner lines reveals that the former is induced by shear waves. Comparing with the sole (110) cleavage plane in the pure bending case, we propose that these shear waves are engendered by the sudden release of the contact stress upon crack initiation and deflect the crack front from the (110) plane to the (111) plane.

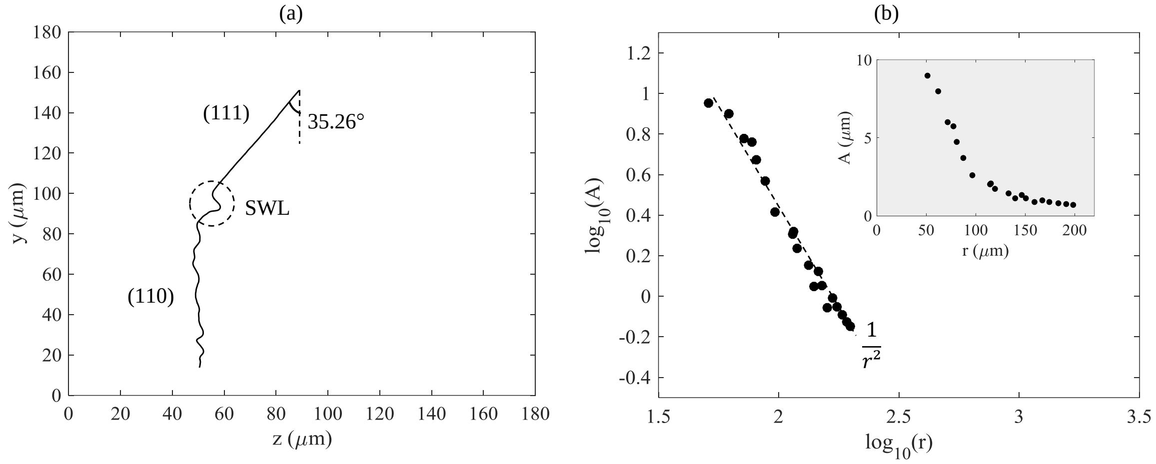

Figure 3 Characteristic of Secondary Wallner lines (SWL): (a) undulation shape of SWL measured along the wafer thickness and (b) undulation amplitude decay as a function of the extending distance.

2.2 Periodic surface undulation

Fig.4a presents the fractography of fracture surface under pure bending load at v_s = 1200 m/s and 3550 m/s. The crack front shape obtained by the retroactive kinetics of the Wallner lines [12] is highlighted by the black line. It can be noticed that the crack front shape is a quarter-ellipse at low velocity where

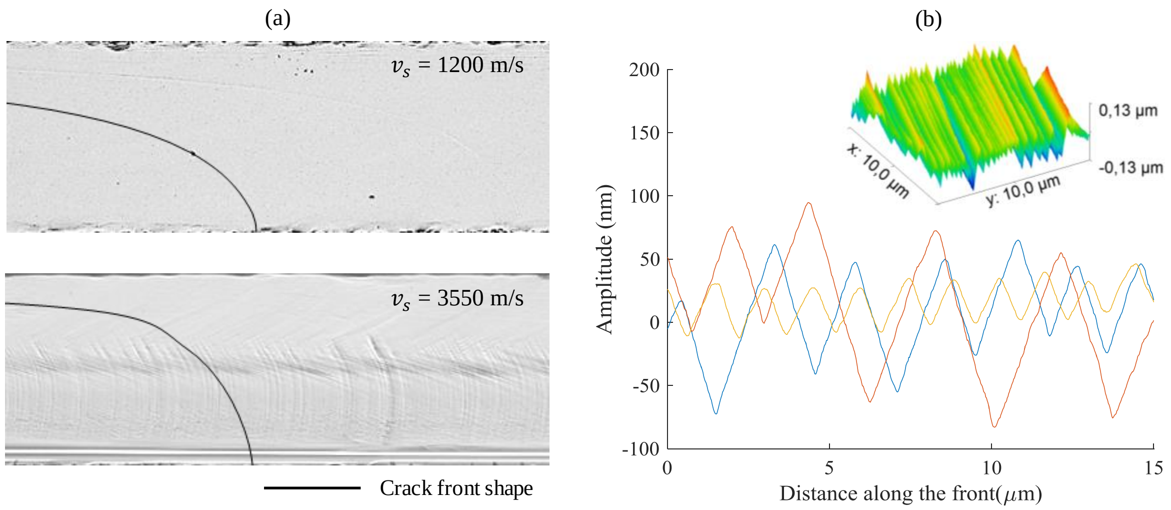

Figure 4 Surface morphologies at crack propagation zone. (a) Comparison between fractography at v_s = 1200 m/s and 3550 m/s. (b) Three examples of the periodic surface undulations measured along the crack front. Insert figure shows the topography of surface undulation.

the local crack velocity decreases monotonically along the front from top to up. However, the crack front shape becomes complex that containing a local curvature jump at high velocity, which induces a local fluctuation on the local crack velocity at about 2500 m/s [4]. Indeed, as the dynamic fracture toughness of silicon abruptly increases at about 2500 m/s [13], the local crack velocity decreases to compensate for this variation, which induces the curvature jump on the crack front. Moreover, except the primary Wallner lines, the crack surface at low velocity is mirror-like, while significant surface undulations can be observed at high crack speed raising in the middle of the crack surface. Fractographic examinations show that the occurrence of these surface undulations has a high dependence on the local velocity fluctuation [4]. Fig.4b shows the profiles of the surface undulation along the crack front measured by AFM. Differing from the Wallner line's shape as shown in Fig.3a, the profiles of the surface undulations are periodic. We propose that, in the absence of plasticity, the surface traces with well-defined profiles are generated by localized waves propagating along the crack front. Interestingly, it is found that, regardless of the spatial dimension of surface undulations, all periodic profiles have a unique characteristic shape, i.e., the ratio between wavelength and amplitude is constant, which conforms to the nonlinear characters of crack front waves [11]. Besides, since the local fracture toughness fluctuation excites the crack front waves [7], we suggest that the periodic surface undulation in high-speeding crack propagation are the front waves traces.

3 Conclusion

The fracture behavior of the (001) single crystal silicon wafer based on three-line and four-line bending tests has been studied using quantitative fractographic and topographic analysis. It is deduced that the anti-planar shear waves generated from the sudden release of the line-contact breaks down the pure mode I fracture by introducing a mode III fracture and leads to (110)-(111) crack deflection. Besides, nonlinear elastic waves generated by the dynamic fracture toughness jump at high crack velocity locally interact with the crack front and leave periodic and well-defined surface marks, and we suggest these waves are crack front waves.

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