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Technical Note

Analysis of surface cracks in multi-crystalline thin silicon wafers

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ABSTRACT

Surface cracks are the most common defects in solar silicon wafers. The stress intensity factors (SIFs) calculated by the semi-analytical equation derived by Newman and Raju have been compared with results of 3D finite element analysis for a wide range of semi-elliptical surface crack configurations in thin silicon wafer subjected to bending. It has been shown that the geometrical nonlinearity of silicon wafers significantly influences the SIF values. The discrepancy between nonlinear and linear models is 19% for a surface crack with 20 μm depth and 1 mm length, while it is 74% for a surface crack with 160 μm depth and 100 mm length. Furthermore, the results show that for long surface cracks ($a/c \leqslant 0.01$) finite element models should be used to calculate the SIF and the existing semi-analytical solution is not reliable.

1. Introduction

Surface cracks are among the most common defects in solar silicon wafers. Stress analysis of these surface-cracked wafers is needed for reliable prediction of their fracture strength. This is particularly relevant during manufacturing and transport, where the wafers are subjected to global bending. Investigators have developed approximate analytical equations, experimental methods, or engineering estimates to obtain the SIFs. Few exact solutions for three-dimensional cracked bodies are available in the literature. One of these, an elliptical crack in an infinite solid subjected to uniform tension, was derived by Irwin [1] using an exact stress analysis by Green and Sneddon [2]. Irwin also estimated the SIF for a semi-elliptical surface crack in a finite-thickness plate. His analysis is thought to be reasonably accurate for crack depths less than one-half of the plate thickness, and for small-scale yielding. Kassir and Sih [3], Shah and Kobayashi [4], and Vijayakumar and Atluri [5] obtained closed-form solutions for an elliptical crack in an infinite solid subjected to non-uniform loadings. Many authors have developed methods accounting for effects of free surfaces and plastic deformation near the crack tip on the fracture behavior of surface-cracked specimens. Some of these authors have obtained the effects of the free surfaces on stress intensity magnification factors from experimental fracture data. Hence, the magnification factors obtained are generally applicable only to the material tested. A failure criterion which is independent of crack size and specimen configuration would require detailed knowledge of the stress state near the crack tip. Smith et al. [6] and Kobayashi [7], respectively, used the alternating method to obtain SIFs along the crack front for a semi-circular surface crack in a semi-infinite solid and a semi-elliptical surface crack in a plate of finite thickness. These studies have been extended by other researchers, applying the Finite Element method (FEM) to establish more detailed knowledge of the stress state near the crack tip. Newman and

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Nomenclature

a	depth of surface crack, mm
b	half-length of plate, mm
c	half-length of surface crack, mm
F	stress-intensity boundary-correction factor
J_{IC}	critical J-integral, N/mm
K_I	mode I stress-intensity factor, $MPa\sqrt{m}$
K_{IC}	elastic fracture toughness
M	applied bending moment
Q	shape factor for an elliptical crack
t	plate thickness, mm
W	half-width of plate, mm
σ_b	remote bending stress, Pa
σ_m	remote uniform tension stress, Pa
φ	parametric angle of the ellipse

Raju [8,9], Nishioka and Atluri [10] used the FEM; Heliot et al. [11] used the boundary-integral equation method and the FE alternating method to determine the SIF for embedded cracks in a finite solid.

All previous studies have concentrated on regular component shapes and not on components with a very small dimension in one direction compared to the others (e.g. very thin wafers). For ease of computation, however, results expressed in the form of equations are preferable. It is important to understand the validity of these equations when applied to the thin wafers.

This paper compares the SIF calculated from semi-analytical equation and the SIF determined from J-integral obtained by 3D-finite element analysis for different size (shallow and deep) of semi-elliptical surface cracks in finite elastic wafers subjected to bending. A meshing technique is also proposed for long surface cracks in ultra-thin silicon wafers (≈0.2 mm thickness). This paper covers a wide range of configuration parameters. The ratio of crack depth to wafer thickness (a/t) varies from 0.025 to 0.8; the ratio of crack depth to crack length (a/c) changes from 0.001 to 0.8. The paper is organized as follows: material properties, analytical and numerical models for thin wafers are presented in Section 2 and 3. The parametric study, results and discussion are presented in Section 4. Some concluding remarks are given at the end of paper.

2. Fracture toughness and semi-analytic approach

The SIF, K_I, is a parameter which is commonly utilized in fracture mechanics to predict the stress state ("stress intensity") near the tip of a crack caused by a remote load or residual stresses [12]. It is a theoretical construction usually applied to a homogeneous, linear elastic material and is useful to provide a failure criterion for brittle materials. The concept can also be applied to materials that exhibit small-scale yielding at a crack tip. The magnitude of K_I depends on sample geometry, the size and location of the crack, and the magnitude and the modal distribution of loads. The SIF for a semi-elliptical surface crack in a flat plate can be expressed [8,9]:

$$K_I = (\sigma_m + H\sigma_b)\sqrt{\frac{\pi a}{Q}}F\left(\frac{a}{t},\frac{a}{c},\frac{c}{W},\varphi\right) \tag{1}$$

for $0 < a/c \leqslant 1$, $0 \leqslant a/t < 1$, and $c/W < 0.5$. Here H, Q and F are the boundary- correction factors.

A crack begins to propagate when the SIF reaches a critical value. The critical value is a material dependent parameter and is called fracture toughness (K_{IC}). The $K_{IC} = 0.75 \pm 0.06\ MPa \times \sqrt{\mathrm{m}}$ is employed as fracture toughness for multi-crystalline silicon material in this study [13]. Numerically, SIFs were obtained via the J-integral calculated from FEM, using $J = K_I^2/E^*$, where E^* is the elastic modulus in plane strain condition.

3. Model geometry, load and boundary condition

The dimensions of the silicon wafers modeled in the present study are $156 \times 156 \times 0.2\ \mathrm{mm}^3$. A 3D finite element analysis was used to calculate the J-integral variations along the crack front for a surface crack in a thin silicon wafer. The wafer was subjected to a bending load shown in Fig. 1. The nominal outer-layer bending stress is calculated from the applied bending moment M. The mode I SIF, K_I, is calculated for any point along the surface crack front by both the semi-analytical equation and finite element analysis. The bending stress which is used to calculate K_I from semi-analytical equation is the same as the one obtained from FEM considering geometrical nonlinearity. Due to symmetry of the wafer geometry, boundary and load conditions, only one quarter of the overall model is built to minimize computational time. The external load is applied as a moment, and the J-integral is extracted from the simulations in each load increment. Two types of finite element meshing are used in this study. Semi elliptic shape is used for $a/c \geqslant 0.25$ which is denoted as model A. A combination of a quarter