Nanoscale Modeling of Crack Coalescence During the Smart-Cut Process

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Abstract

Pressurized penny-shaped crack coalescence is the key mechanism responsible for controlled silicon fracture in the Smart-Cut process used for silicon-on-insulator (SOI) wafer fabrication. This study presents a three-dimensional numerical investigation of multiple crack propagation and coalescence using the eXtended Finite Element Method (X-FEM). The method combines level-set functions and enrichment techniques to accurately model crack evolution within a linear elastic fracture mechanics framework. To reduce computational cost, a multiscale adaptive 3D fractal mesh was developed, achieving nearly 90% savings in computation time compared with structured meshes. Internal pressure generated by hydrogen implantation and annealing is modeled through Neumann boundary conditions applied on crack surfaces. The study also addresses the evaluation of three-dimensional stress intensity factors (SIFs) for pressurized cracks. Numerical results for mode-I SIFs (KI) show excellent agreement with analytical solutions for isolated penny-shaped cracks, with errors below 1%. Crack propagation follows Griffith's brittle fracture criterion. Crack coalescence is simulated through dynamic updates of level-set functions and enrichment regions. The model successfully reproduces experimentally observed crack evolution and provides insight into local instabilities related to crack size and geometry in the Smart-Cut process.