Temporal Evolution of 3D Dislocation Structures in Silicon by Correlative X-ray Diffraction Imaging

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To track the temporal evolution and 3D behavior of individual dislocations in bulk semiconductor wafers under semiconductor-processing-relevant conditions, we bring together X-ray white-beam topography, X-ray diffraction laminography (XDL) [1], and controlled sample annealing environments. In addition to recent developments in 3D XDL methodology, we recently developed and simulated a compact induction heating system with integrated infrared thermography for real-time and quasi in situ synchrotron experiments [2].

In the presented study, this correlative approach is applied to silicon (Si), which remains one of the most important semiconductor materials for modern micro- and nanoelectronic technologies. Thermally activated dislocation slip during wafer processing can critically influence fabrication yield and device performance, particularly with the ongoing miniaturization of electronic devices toward nanometer dimensions.

Here, mechanically damaged Si wafers were subjected to repeated thermal annealing cycles above the brittle-to-ductile transition temperature while the spatio-temporal temperature distribution was monitored by infrared thermography. Between successive annealing stages, quasi in situ 3D X-ray diffraction laminography (XDL) measurements were performed to follow the temporal evolution of thermally activated dislocation structures within the same crystal volume. Complementary X-ray white-beam topography (XWBT) measurements further enabled Burgers vector identification of the evolving dislocation structures.

In this study, more than 100 individual dislocations were identified, labeled, traced across successive annealing stages, and correlated with their corresponding Burgers vectors, enabling quantitative 3D analysis of dislocation propagation during thermal annealing. Furthermore, complex mechanisms including cross-slip, interaction of dislocations, and the early formation of single-ended Frank–Read-like multiplication sources were directly observed in 3D. Correlation of the experimentally observed dislocation propagation, distributions among different {111}⟨110⟩ glide systems, and multiplication mechanisms with resolved shear stress distributions provides new insight into the interplay between thermally driven dislocation dynamics and crystallographic glide behavior in Si wafers.

References

[1] D. Hänschke et al., Physics review Letters, 119, 215504 (2017)
[2] M. Kabukcuoglu et al., J. Synchrot. Rad., in press (2026)