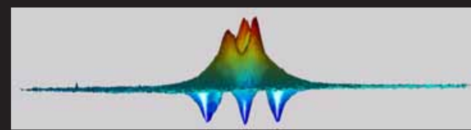
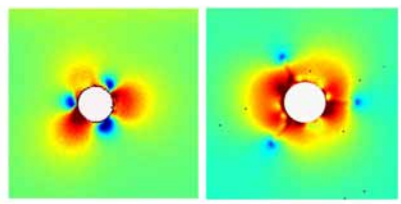
Nanoscale Stress Measurements and Standards

Objective

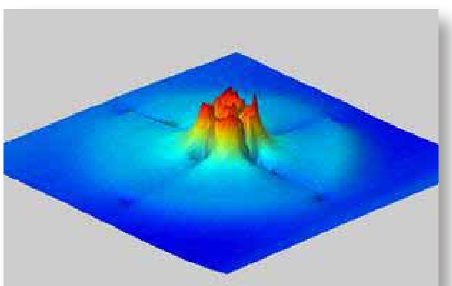
Our objective is to develop accurate measurement methods for the nanoscale stress distributions and surface defects that control device performance and reliability (performance over service life) in microelectronic and micro and nanoelectromechanical systems (MEMS and NEMS). Such methods will enable manufacturing processes to be optimized for device performance and lifetime, and address a critical measurement need in the MEMS industry, *i.e.*, 90 % of MEMS customers require a demonstration of device reliability, but only 50 % of vendors provide one.



Impact and Customers

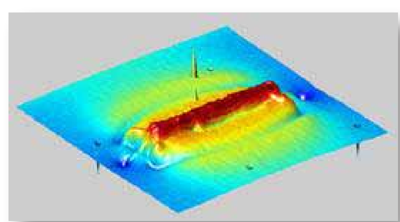


- The semiconductor microelectronics industry is a $250B worldwide market with 9% cumulative annual growth rate (CAGR) and 46 % US market share. The MEMS industry is a $50B worldwide market with 12 % CAGR and 41 % US share.
- Measurement of stress distributions around transistors in semiconductor devices will enable optimized processing of nano-scale engineered "stressors," which increase carrier mobility and thus device speed.



- Stress field measurements in MEMS and NEMS devices will enable lifetime-limiting defects to be identified and hence processing to be optimized to increase device reliability.
- NIST is working with semiconductor and MEMS manufacturers (*e.g.*, Intel, Qualcomm), and deposition and measurement tool vendors (*e.g.*, Novellus, Ultratech) to develop measurement methods and standards for nano-scale stress measurement.

Approach

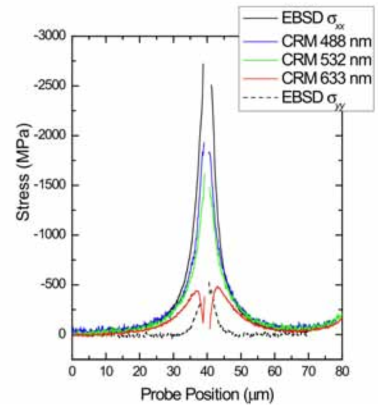


We will develop piezospectroscopic- and diffraction-based methods that accurately map nano-scale stress distributions in Si and other materials. Method development will focus on the use of super-resolution confocal Raman microscopy (CRM), electron back scattered diffraction (EBSD), and high-resolution X-ray diffraction (XRD) to identify and measure the stress distributions of structures and defects that control electrical and mechanical performance and reliability. Calibration of the Raman piezospectroscopic coefficients will be performed using the known stress fields of special test structures, indentations, and cracks. Polarized CRM methods will be developed in concert with special test structures to enable the entire stress tensor to be determined. The CRM measurements will be correlated with EBSD measurements on small-scale test structures and with XRD and curvature measurements on large-scale thin-film on substrate systems. A large-sample measurement system will be developed so that stress maps of 200 mm wafers can be generated for comparison with commercial wafer curvature tool measurements. Broadly-applicable standard reference materials for stress measurement will be developed.

SEMICONDUCTORS

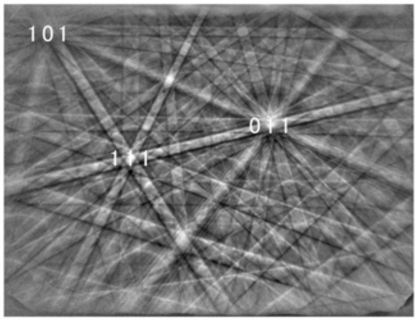
Accomplishments

Stress measurement by Raman scattering is based on measuring the shift of Raman phonon bands in materials under stress. A CRM scattering system has been developed with state-of-the-art stress and spatial resolution. Automated peak fitting routines enable shifts in the 522 cm^{-1} Raman peak in Si to be measured with approximately 0.02 cm^{-1} uncertainty, corresponding to measurement-limited stress precision of about 10 MPa (strains of about 10^{-4}). Scans consisting of 128 x 128 hyperspectral arrays range from wide area, 150 μm x 150 μm, to small area, 5 μm x 5 μm, the latter giving rise to a pixel spacing of 40 nm. Each spectrum takes about 1 second, enabling a high resolution stress map to be generated in about 4 hr. Measurement development has focused principally on three aspects (using single-crystal Si test vehicles): (i) identification and quantification of the stress "signatures" of controlled, contact-induced defects in Si using micro- and nano-indentation techniques; (ii) verification of the scalar (tensor-averaged) piezospectroscopic coefficients through comparison with EBSD measurements, using the known stress distributions of indentation flaws and their associated cracks; and (iii) determination of the limits of the technique for measuring stress variations in engineered structures. Examples of (i) are shown in the figures on the previous page, which show rendered stress maps of a three-sided Berkovich nanoindentation on a Si(111) surface, spherical nanoindentations on Si(111), a four-sided Vickers microindentation on Si(001), and a linear wedge nanoindentation on Si(001) (top to bottom on the page, respectively). Red and blue indicate compressive and tensile stress, respectively, and the different signatures of the fracture and deformation patterns for the various defects are obvious: such information can be used to predict the behavior of the defects under subsequent loading.



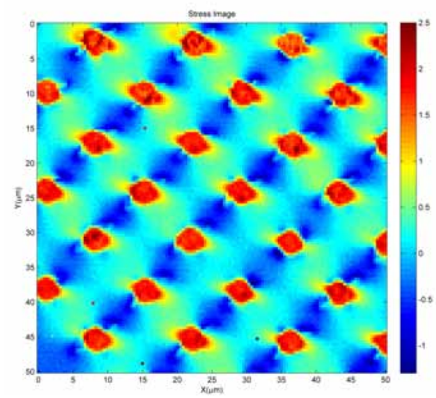
CRM and EBSD stress profiles across a wedge indentation in Si

Progress in (ii) has been marked by the quantitative agreement obtained between CRM and EBSD measurements, largely through the ability to probe different depths beneath a sample surface using different Raman excitation light, as shown in the stress profile figure for the wedge indentation. Stress measurement by EBSD is based on distortion of the diffraction pattern by strain in the crystalline lattice. A cross-correlation method has been developed that compares high-quality diffraction patterns (such as in the example figure) obtained from scanning electron microscope scans and produces stress maps with stress and spatial resolution comparable to those obtained with CRM. Agreement between the two methods was shown to be exact when surface-localized blue excitation was used for the CRM measurement.



EBSD pattern used for strain mapping of Si

Arrays of indentations aligned along different crystallographic directions were used in (iii) and an example is shown in the next figure. Clear differences in the local stress fields of the spherical indentations are visible.



Raman stress map of a stress-engineered Si surface

Learn More

Stephan Stranick (CSTL)
Ryan Koseski
Yvonne Gerbig
Mark Vaudin

Robert F. Cook
(Ceramics Division)
(301) 975-3207
robert.cook@nist.gov
www.nist.gov/ceramics

Publications

Vaudin MD, Gerbig YB, Stranick SJ and Cook RF *Comparison of Nanoscale Measurements of Strain and Stress using Electron Back Scattered Diffraction and Confocal Raman Microscopy* Appl. Phys. Letters, 93: 193116 (2008)

Gerbig YB, Stranick SJ, Vaudin MD, Morris, DJ and Cook RF *Effect of Crystallographic Orientation on Phase Transformations During Indentation of Silicon* J. Mater. Res., 24: 1172 (2009)

Cook RF *Strength and Sharp Contact Fracture of Si* J. Mater. Sci., 41: 841 (2006)

Beversluis M, Novotny L and Stranick S *Programmable Vector Point-Spread Function Engineering* Optics Express, 14: 2650 (2006)