

## Application Note #1520

# Indentation-Induced Structural Changes Probed by Raman Spectroscopy

In the pharmaceutical industry, detection of different polymorphs of drug materials is critical, as any changes in the composition or structure may lead to a different clinical response. This application note discusses mechanical anisotropy and stress induced structural changes in single-crystal  $\beta$ -form piroxicam (anti-inflammatory drug). The variation of mechanical properties in the (0 $\bar{1}$ 1) and (011) crystallographic planes and the associated chemical changes under indentation were studied in detail.

Anisotropy in mechanical behavior was observed along (011) and (011) crystallographic planes utilizing a Hysitron® TI 980 TriboIndenter® for mechanical characterization, and a custom-built indentation device for in-situ Raman (Figure 1).

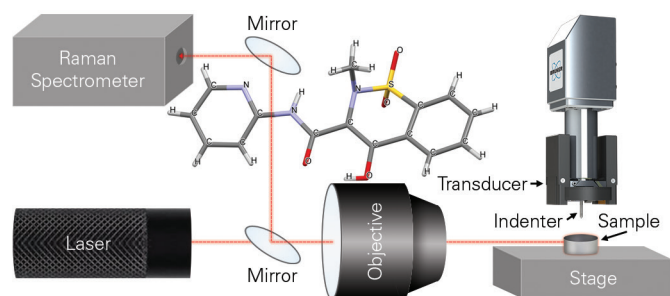


Figure 1. In-situ experimental configuration and piroxicam structure.

### In-Situ Indentation and Raman for Pharmaceuticals

Raman spectroscopy is a widely-used nondestructive chemical analysis method that can detect changes in the stress state, molecular orientation, crystallinity, and phase transformations in materials. Combining Bruker's nanomechanical test instruments with Raman spectroscopy enables in-situ analysis of mechanical properties and corresponding physiochemical changes.

In-situ Raman spectra recorded from the contact region detected changes in the chemical bonding. The main building block of the piroxicam crystal is centrosymmetric dimer of piroxicam molecules connected by two N–H...O (3.055 Å) hydrogen bonds. Each molecule in the dimer interacts with neighboring dimers via six C–H...O hydrogen bonds to form infinite corrugated two-dimensional layers that are parallel to the (010) plane. The interactions between separate two-dimensional layers comes from one C–H...O hydrogen bond and one  $\pi$ ... $\pi$  stacking interaction. Thus, the principal slip planes are along the (010) planes, which was reflected by lower hardness on (011) surface (Figure 2) during indentation.

In-situ Raman spectra recorded during indentation on ( $\bar{0}\bar{1}1$ ) face showed a shift in the  $1334\text{ cm}^{-1}$  band, corresponding to  $\text{SO}_2$  asymmetric stretching, over a normal load variation from  $3\text{ mN}$  to  $20\text{ mN}$  (Figure 3). In the case of the ( $011$ ) face, the in-situ Raman spectra did not show a shift in  $\text{SO}_2$  stretching modes; instead a small peak shift was observed at  $990\text{ cm}^{-1}$  which corresponds to C-O stretching (Figure 4). At higher loads ( $15\text{ mN}$ ,  $20\text{ mN}$ ) the  $990\text{ cm}^{-1}$  band shifted to  $995\text{ cm}^{-1}$ . This red shift in the C-O stretching vibration indicates a break in O-H...O intermolecular interaction during indentation. It is reasonable to conclude that the deformation resulted in a different bonding re-arrangement for ( $\bar{0}\bar{1}1$ ) and ( $011$ ) since an intra-layer interaction modification (C-H...O interactions) was observed for ( $011$ ), as compared to the interlayer interaction modification seen in case of ( $\bar{0}\bar{1}1$ ). Furthermore, the observed mechanical anisotropy is not solely related to the alignment of crystal planes, as the interlayer chemical interactions also contribute to the enhanced hardness of the ( $\bar{0}\bar{1}1$ ) surface. The results demonstrate the capability of the in-situ Raman indenter to collect the chemical as well as the mechanical information in real time, which can be correlated to gain deeper understanding of material behavior.

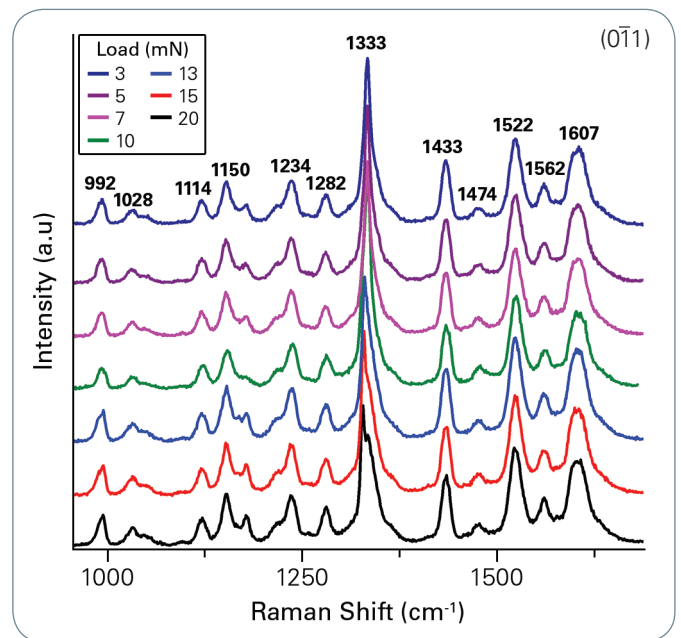


Figure 3. In-situ Raman spectra on ( $\bar{0}\bar{1}1$ ) face during indentation showing a shift in  $1334\text{ cm}^{-1}$  band, corresponding to  $\text{SO}_2$  asymmetric stretching, at various normal loads.

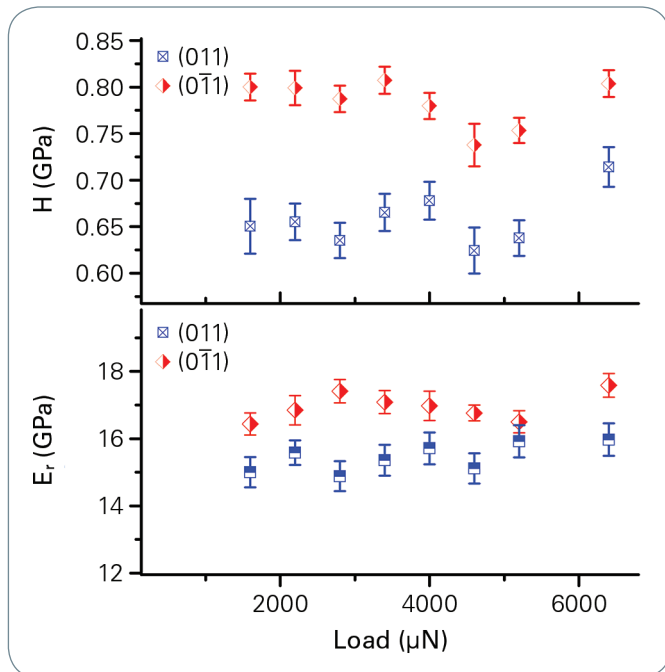


Figure 2. Hardness and modulus from indentation tests at varying loads on the ( $011$ ) face and ( $\bar{0}\bar{1}1$ ) face.

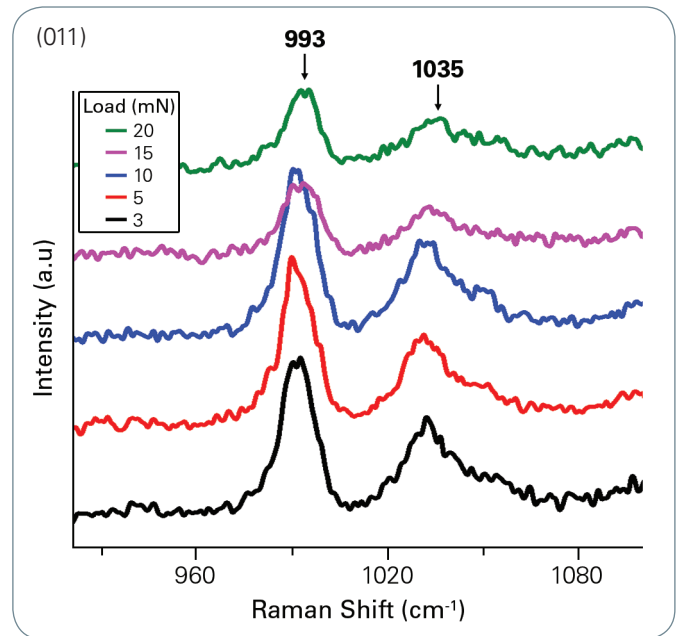


Figure 4. In-situ Raman spectra on ( $011$ ) face during indentation showing a small peak at  $990\text{ cm}^{-1}$  band, corresponding to C-O stretching.

## Indentation-Induced Phase Transformation in Monocrystalline Silicon

Combining Bruker's Hysitron TI 950 or TI 980 system with Raman spectroscopy enables mechanical and chemical mapping of the sample of interest. Indentation-induced phase transformation in silicon is one of the most studied phenomena for the last few decades. Figure 5 demonstrates the capabilities of the integrated indentation and Raman system, where combined high-resolution SPM imaging and Raman mapping enables local topographical and chemical variation characterization. The Raman map in Figure 5 shows an indentation-induced phase transformation zone in monocrystalline silicon. A Raman line scan profile generated across the indent showed a variation in diamond cubic 520  $\text{cm}^{-1}$  band, where compressive stresses at the edges shifted the dc peak to higher wavenumbers. In the phase transformation zone corresponding to amorphous silicon, r8 and bc8 phases of silicon were observed.

### Conclusions

Bruker's Hysitron TI 980 combined with Raman spectroscopy enables chemical and quantitative ultra-high-speed nanomechanical property mapping in a single platform. Since Bruker preserves the concept of modularity with Raman instruments, almost any laser source and spectrometer can be used with this solution. Ultimately, Bruker's two-dimensional capacitive transducer technology enables friction and wear testing at the nanoscale, and can also be combined with Raman mapping to help researchers gain further insight on interfacial phenomena, enabling the development of new advanced coatings or materials.

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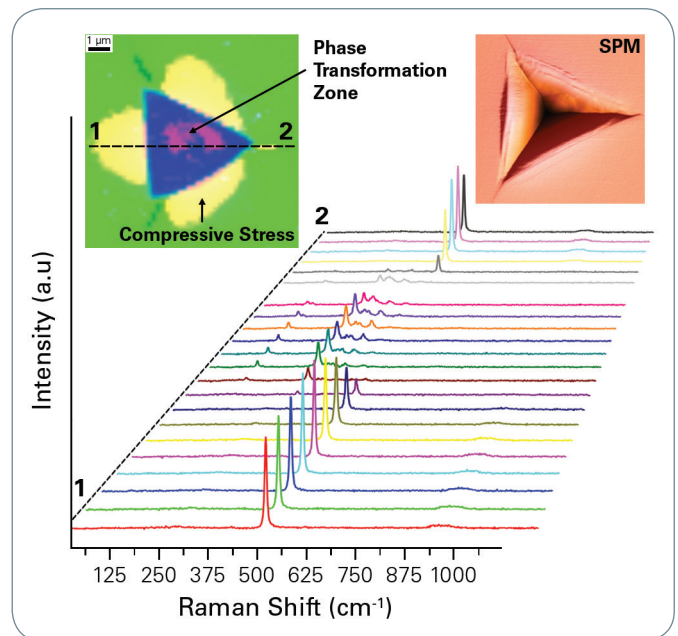


Figure 5. Raman spectral map on silicon indent showing the phase transformation zone and region of compressive residual stress.

### Other Applications

- Semiconductors: Residual stress measurements, impurity detection, and pressure-induced phase transformation
- Coatings and Thin Films: Failure analysis, residual stress measurements, detection of surface chemical and mechanical property modifications
- Advanced Nanomaterials: Identification of chemical heterogeneity, quantitative thickness, and strain measurements in 2D materials (mono- or multi-layered  $\text{MoS}_2$ ,  $\text{MoSe}_2$ ,  $\text{WS}_2$ ,  $\text{WSe}_2$ , and graphene)
- Polymers and Composites: Correlation of mechanical properties with chemical structure, bond arrangement and cross-linking, and physical state of the polymer (along with blends) including crystallinity
- Pharmaceuticals: Polymorphism, mechanical and chemical heterogeneity
- Biomaterials: Nondestructive chemical and mechanical characterization of tissues, bones, and implant materials
- High Temperature: Combining Bruker's xSol® high-temperature stage and Raman spectroscopy enables real-time detection of temperature-induced chemical and mechanical changes

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