Bulletin: The Role of Scanning Probe Microscopy in Nanophysics

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Abstract

At nanoscale, increasingly more various physical properties can be measured, analysed qualitatively, and even quantitatively. Scanning probe microscopy has been gradually widely adopted due to data derivation from its specific interaction between the tin of probe and super-surface of sample material. In this text, we identify the role of this technique in the area of nanophysics from the perspective of three aspects: atom-related or molecule-related visualisation, visualisation of nano-processes, and property characterization.

Keywords

Scanning Probe Microscopy; Nanoscale, Structure-Property Analysis; Visualisation of Particles; Manipulation; Dynamic Processes; Properties Measurement and Quantification.

1. Introduction

On a nanoscale, due to the interactions by various particles from 0.1 nm to 100 nm [1], plentiful new-born, unique performance can be discovered and detected in the process of characterization and fabrication. In order to fully excavate and deploy these properties of matter on the nanometre length scale, scanning probe microscopy (SPM) has been continuously developed and deemed as an efficient technique since its invention in 1981 [2]. Its core principle is to detect the interaction between the tip of a super-sharp probe and the surface morphology of a material. Based on this, a systematic series of probe-based, surface-sensitive techniques for high resolution scanning has been gradually formed, including scanning tunneling microscopy (STM), atomic force microscopy (AFM), and near-field scanning optic microscopy (NSOM) [3]. Specifically, SPM cannot only be operated to collect the images on atomic structure or distribution of state densities, but also to measure, identify, and even quantify structure-tailored properties of matter, like magnetic, thermal, mechanic, and photoelectric characteristics [4]. Hence, this powerful technique, which integrates observation, analysis, and nanolevel manipulation, firmly demonstrates its wide applicability and tremendous potential prospects.

In this review, we focus on the indispensable role of the integrated family of scanning probe microscopy and give an explicit interpretation regarding three different aspects: atom- or molecule-related visualisation, visualisation of nano-processes, and property characterization.

2. Atom- or Molecule-Related Visualisation

A prevalent but still fascinating application in the nanoworld is visualisation of atoms, molecules and assemblies. Via morphological imaging, topographic information (e.g. defects [5], surface reconstruction [6], surface adsorption [7], grain boundaries [8]) can be derived to display the alignment of atoms or the architecture of molecules. Its atomic resolution enables greater insights into the arrangement and organization of particles, ranging from single crystals [9] to assembled macromolecules based on superstructure [10] or bio-affinity [11], to actualise a specific function. In this context, a comprehensive structure-based analysis is usually conducted using well-patterned 2D SPM data compared with 3D crystal structure analysis by X-ray diffraction [12, 13]. Such behavior of organic functional materials can be clearly described by visualizing the images of molecular alignment.

3. Visualisation of Nanolevel Particulate Processes

Also, specific dynamic processes can be characterised as high-resolved SPM images. This technique provides the reliability to construct unique nanosized structures by precisely tunable manipulation of atoms or molecules [14]. Typically like surface diffusion [15], image-based atomic control contributes to the fine monitoring on different dynamic processes on the surface of materials. Also, the broad adaptability of SPM in different working conditions (e.g. in the normal temperature [16], in vacuum [17], in liquids [18]) gives access to its detection well-suited for various experimental environments, like multi-phase catalysis [19], superconducting conditions [20] and monitoring the renewal of electrode surface during the electrochemical reactions [21].

4. Nanoscale Property Characterisation

Finally, testing the properties of materials with high spatial resolution signifies the nanolevel structure-property connections, even on the scale of each single atom. For example, the measurement of mechanical properties can be implemented with the attractive or repulsive interaction between the tin of probe and sample [4, 22]. Each category of SPM monitors the strength of a specific interaction to reflect the surface properties of sample, like pulsed force microscopy AFM (PFM-AFM) [23] and dynamic scanning probe microscopy (DSPM) [24], and then image the relative information. Furthermore, for more accurate detection and reproducible force regulation, more exploration focuses on obtaining quantitative data of these properties. However, a drawback worth mentioning is inevitable time-consuming calibration during the acquisition of quantitative information. The reason for this is tip damage or plastic deformation on the soft surface of sample may occur regarding the changeable mechanisms in tin-surface approach [25].

Additionally, electrical behavior can also be under accurate measurement, like research on relations between internal structure and conductivity of carbon nanotubes (CNTs) [26] and quantum interference in single-molecule charge transport with STM-assisted methods [27].

5. Conclusion

Overall, based on single-atom- or single-molecule-dominated SPM techniques, the rapid development of chemical systems and devices on the nanoscale provides a broader platform for more precisely tuned structure-property-performance correlations.

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References

[1] Mckenna, K. P. Introduction to Nanoscale Materials in Chemsitry. Nanoscale materials in chemistry, second edition; Klabunde J. K., Richards M. R., EDs; John Wiley & Sons,Inc.: Hoboken, 2009; pp 4-8.

[2] Xiao, R.; Yang, X. September, 1981: the Invention of STM. Mod. Phys. 2010, 22(5), 68-69.

[3] Nečas, D.; Klapetek, P. Gwyddion: an Open-Source Software for SPM Data Analysis. Cent. Eur. J. Phys. 2012, 10(1), 181-188.

[4] Loos, J. The Art of SPM: Scanning Probe Microscopy in Materials Science. Adv. Mater. 2005, 17(15), 1821-1833.

[5] Wang, Q.; Lei, Y.; Zhu, Y.; Hong, J.; Feng, G. Edge Defects Engineering of Nitrogen-Doped Carbon for Oxygen Electrocatalysts in Zn-Air Batteries. ACS Appl. Mater. Inter. 2018, 10(35), 29448-29456.

[6] Duan. Y.; Sun, S.; Sun, Y.; Xi, S.; Chi, X.; Zhang, Q.; Ren, X.; Wang, J.; Ong, S.; Du, Y.; Gu, L.; Grimaud, A.; Xu, Z. Mastering Surface Reconstruction of Metastable Spinel Oxides for Better Water Oxidation. Adv. Mater. 2019, 31(12), 1807898(1-8).

[7] Ma, Y.; Zhou, G.; Liu, Z.; Xu, L.; Sun, D.; Tang, Y. Electronic Structural Regulation of CoP Nanorods by the Tunable Incorporation of Oxygen for Enhanced Electrocatalytic Activity during the Hydrogen Evolution Reaction. Nanoscale 2020, 12(27), 14733-14738.

[8] Hwang, J.; Kim, J.; Kim, H.; Kim, S.; Lee, K.; Kim, S. Effect of Dislocation Arrays at Grain Boundaries on Electronic Transport Properties of Bismuth Antimony Telluride: Unified Strategy for High Thermoelectric Performance. Adv. Energy Mater. 2018, 8(20), 1800065.1-1800065.7.

[9] Bian, J.; Wang, Y.; Zhu, R.; Wang, L.; Yang, Y. Mechanical-Induced Polarization Switching in Relaxor Ferroelectric Single Crystals. ACS Appl. Mater. Inter. 2019, 11(43), 40758-40768.

[10] Verstraete, L.; Smart, J.; Hirsch, B.; Feyter, S. Unidirectional Supramolecular Self-Assembly inside Nanocorrals via in situ STM Nanoshaving. Phys. Chem. Chem. Phys. 2018, 20(43), 27482-27489.

[11] Sanz-Ortega, L.; Rojas, J.; Barber, D. Improving tumor retention of effector cells in adoptive cell transfer therapies by magnetic targeting. Pharmaceutics 2020,12(9), 812.

[12] Wang, L.; Ulrich, K.; Peter, B.; Ludger, K.; Li, D.; Cao, M. Calibration of Standards for Precision Pitch Measurement in the Nanometre Region by Combined Scanning Tunneling Microscopy and X-ray Interferometry. Nanotechnology 2000,10(4), 412.

[13] Hazra, S.; Pal, S.; Kundu, S.; Sanyal, M. Scanning Probe Microscopy and X-Ray Studies of Confined Metal Films. Appl. Surf. Sci. 2001, 182(3-4), 244-250.

[14] Sloan, P.; Palmer, R. Towards Manipulation of Single Protein Molecules with the Scanning Probe Microscope (SPM) in a Physiological Environment. Abstracts of the 18th International of Vacuum Congress 2010, 156-161.

[15] Physics Today Editorial Staff. Monitoring Surface Diffusion, One Molecule at a Time. Physics Today, 2012.

[16] Barzola-Quiquia, J.; Stiller, m.; Esquinazi, P.; Molle, a.; Wunderlich, R.; Pezzagna, S.; Meijer, J.; Kossack, W.; Buga, S. Unconventional Magnetization below 25K in Nitrogen-Doped Diamond Provides Hints for the Existence of Superconductivity and Superparamagnetism. Sci. Rep. 2019, 9, 8743.

[17] Jaiswal, K.; Girish, Y.; De, M. Influence of a Tunable Band Gap on Photoredox Catalysis by Various Two-Dimensional Transition-Metal Dichalcogenides. ACS Appl. Nano Mater. 2020, 3(1), 84-93.

[18] Gan, C.; Ao, M.; Liu, Z.; Chen, Y. Imaging and Force Measurement of LDL and HDL by AFM in Air and Liquid. FEBS Open Bio. 2015, 5, 276-282.

[19] Vanchinathan, V.; Anuj, P.; Tulika, M. Unified Thread- and Data-Mapping for Multi-Threaded Multi-Phase Applications on SPM Many-Cores. Proceedings of the 23rd Conference on Design, Automation and Test in Europe 2020, 1496-1501.

[20] Antonenko, S.; Tolkacheva, S.; Frolova, V. Study of Irradiated Superconducting Films by SPM Techniques. J. Surf. Investig-X-Ra. 2010, 4(5), 766-768.

[21] An, C.; Dong, C.; Shao, L.; Deng, Q. Monitoring the Length Change of Ni@C Composite Electrodes during Charging / Discharging Processes. Electrochem. Commun. 2019, 103, 94-99.

[22] Desbiolles, B.; Hannebelle, M.; Coulon, E.; Bertsch, A.; Rohr, S.; Fantner, G.; Renaud, P. Volcano-Shaped Scanning Probe Microscopy Probe for Combined Force-Electrogram Recordings from Excitable Cells. Nano Lett. 2020, 20(6), 4520-4529.

[23] Li, C.; Ding, Y.; Soliman, M.; Lorenzo, J.; Dhasmana, N.; Chantharasupawong, P.; V. Ievlev, A.; Gesquiere, A.; Tetard, L.; Thomas, J. Probing Ternary Solvent Effect in High Voc Polymer Solar Cells using Advanced AFM Techniques. ACS Appl. Mater. Inter. 2016, 8(7), 4730-4738.

[24] Arutunow, A.; Tobiszewski, M.; Darowicki, K. Electrical and Mechanical Characterization of Two-Phase Alloys by Means of Scanning Probe Microscopy in Dynamic Impedance Spectroscopy Mode. J. Alloy. Compd. 2015, 619, 172-176.

[25] Passeri, D.; Anastasiadis, P.; Tamburri, E.; Guglielmotti, V.; Rossi, M. Scanning Probe Microscopy Techniques for Mechanical Characterization at Nanoscale. II Nuovo Cimento della Societa Italiana di Fisica, C. Geophysics and space physics 2013, 36C (2), 83-88.

[26] Xiao, W.; Luo, X.; Ma, P.; Zhai, X.; Fan, T.; Li, X. Structure Factors of Carbon Nanotubes on the Thermal Conductivity of Carbon Nanotube / Epoxy Composites. AIP Adv. 2018, 8(3), 035107.

[27] Yang, G.; Wu, H.; Wei, J.; Zheng, J.; Chen, Z.; Liu, J.; Shi, J.; Yang, Y.; Hong, W. Quantum Interference Effect in the Charge Transport through Single-Molecule Benzene Dithiol Junction at Room Temperature: an Experimental Investigation. Chinese Chem, Lett. 2018, 29(1), 147-150.