The structure of a working catalyst ; from flat surfaces to nanoparticles

Roobol, S.B.

Acknowledgements

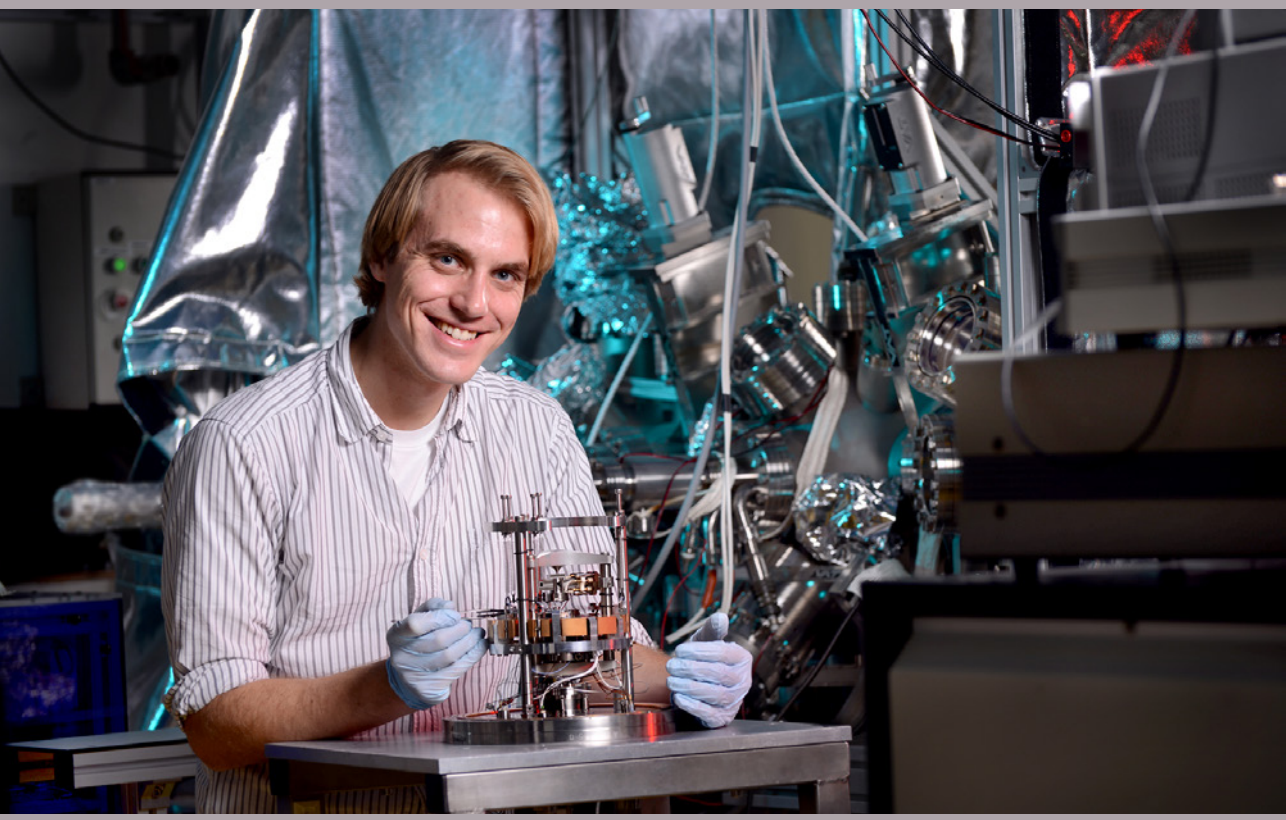
Many people have contributed in some way to the work described in this thesis, many more than can be mentioned here.

Apart from providing scientific guidance and encouragement, my promotor Joost Frenken paved the way for the joint experiments with Delft University of Technology and the European Synchrotron Radiation Facility (ESRF), in part via the NIMIC public-private partnership that also provided funding for this project.

At Leiden University, Mirthe Bergman and Peter van der Tuijn from the Fine Mechanical department played an essential role in the design and fabrication of the ReactorAFM, and my former colleague Marta Cañas-Ventura must be credited for the exceptional start of this line of development. Chapters 4 and 7 are the result of a joint effort with Willem Onderwaater. My (former) colleagues Matthijs van Spronsen, Richard van Rijn, Femke Tabak, Jan-Willem Beenakker, Marcel Rost, Johan Bakker, Irene Groot, Violeta Navarro, Kees Herbschleb, Rik Mom, Qian Liu, Marien Bremmer, Maarten van Es, and Tjerk Oosterkamp provided valuable input in scientific discussions and technical support. Chris Smiet, Jeroen Kraaij, and Olfa Jaïbi performed their BSc or MSc research projects in the context of the work described in this thesis. Raymond Koehler and Martin Moene from the Electronics Department provided assistance with the scanning probe electronics and software. Gertjan van Baarle and Alexei Ofitserof from the spin-off company Leiden Probe Microscopy provided technical support beyond what can be expected from a commercial company.

For the X-ray experiments I am grateful to the current and former ID03 beamline staff of the ESRF, in particular Roberto Felici, Olivier Balmes, Franscesco Carla, Jakub Drnec, Didier Wermeille, Andrea Resta, Helena Isern and Tomas Dufrane, for their input in scientific discussions, for technical support, and for participating in the measurements. Maria Messing from Lund University provided the size-selected Pd nanoparticle samples used in chapter 7. Marco Saluzzo provided the $SrTiO_3$ sample dataset for BINoculars, and Sabrina Disch the $(PbSe)_{4+\delta}(TiSe_2)_4$ dataset.

Access to the electron microscopy facility at TU Delft has been provided by Henny Zandbergen with technical support from Frans Tichelaar. Fredrik Creemer, also from TU Delft, provided the nanoreactors. Patricia Kooyman and Søren Vendelbo from TU Delft, and Christian Elkjær and Stig Helvig from Haldor Topsøe provided electron microscopy expertise and input to scientific discussions.



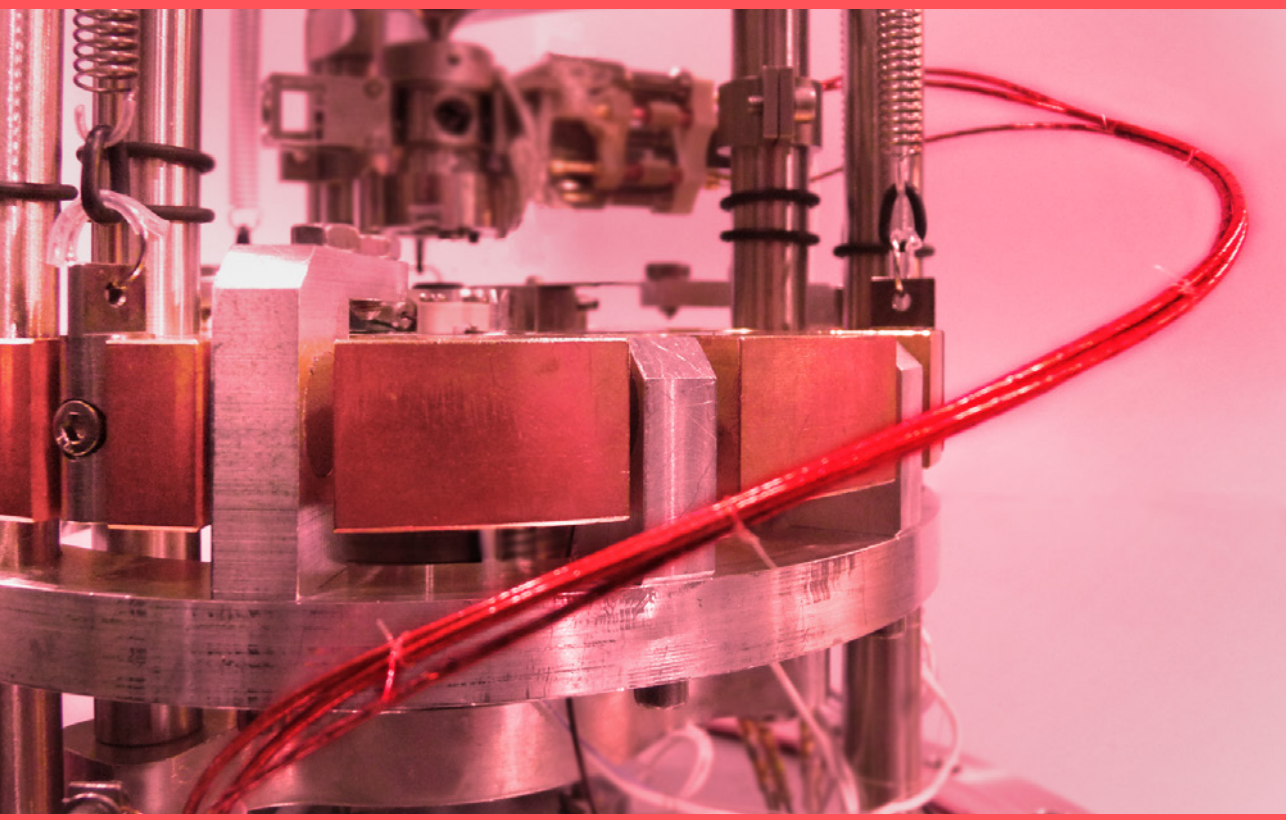
Photography: www.fotografiedenhaag.nl

Curriculum vitae

Sander Bas Roobol was born on September 30, 1985 in Zeist. He got his Gymnasium degree from the Theresialyceum in Tilburg in 2003, and went to Leiden to study mathematics and physics at Leiden University. After obtaining a BSc in Mathematics and a BSc in Physics, both in 2008, he continued with a Masters track in experimental physics. Under supervision of Dr. Ir. W. M. van Spengen he worked on a project on Micro Electro-Mechanical Systems (MEMS) before moving into the field of surface science and catalysis for an internship at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. In this project, which was supervised by Dr. R. Felici, he investigated the Fischer-Tropsch process using Surface X-ray Diffraction, and this resulted in him obtaining an MSc in Physics in 2010.

He went on to pursue a PhD under the supervision of Prof. Dr. J. W. M. Frenken, which was focused on the development of high-pressure, high-temperature surface-science instrumentation for in-situ studies on heterogeneous catalysis, and the application of such equipment to catalytic model systems. He used a combination of scanning probe microscopy, electron microscopy, and X-ray scattering to investigate several model systems concerning the catalytic conversion of CO and NO. This work is described in this thesis.

Sander Roobol continues his career as a researcher at ASML in Veldhoven.



Based on a photo by Kees Herbschleb.

List of publications

S. B. Roobol, M. E. Cañas-Ventura, M. Bergman, M. A. van Spronsen, W. G. Onderwaater, P. C. van der Tuijn, R. Koehler, A. Ofitserov, G. J. C. van Baarle and J. W. M. Frenken, "The *ReactorAFM*: Non-Contact Atomic Force Microscope operating under high-pressure and high-temperature catalytic conditions", submitted (chapter 2).

S. B. Roobol, "*Spacetime*: analysis software for microscopy data of dynamical processes", submitted (chapter 3).

S. B. Roobol, W. G. Onderwaater, J. Drnec and R. Felici, "*BINoculars*: data reduction and analysis software for two-dimensional detectors in surface x-ray diffraction", submitted (chapter 4).

S. B. Roobol, W. G. Onderwaater, M. A. van Spronsen, F. Carla, O. Balmes, V. Navarro, S. Vendelbo, P.J. Kooyman, C. F. Elkjær, S. Helveg, R. Felici and J. W. M. Frenken, "Restructuring of Pt surfaces during high-pressure, high-temperature NO and H_2 exposure", in preparation (chapter 5 and 6).

W. G. Onderwaater, S.B. Roobol, R. van Rijn, O. Balmes, M.E. Cañas Ventura, M.E. Messing, A. Resta, D. Wermeille, R. Westerström, K. Deppert, E. Lundgren, S. Vendelbo, P. J. Kooyman, C. F. Elkjær, S. Helveg, R. Felici and J. W. M. Frenken, "Oxide shell formation during spontaneous oscillations in the catalytic oxidation of CO on palladium nanoparticles", in preparation (chapter 7).

C. T. Herbschleb, P. C. van der Tuijn, S. B. Roobol, V. Navarro, J. Bakker, Q. Liu, D. Stoltz, M. E. Cañas-Ventura, G. Verdoes, M. A. van Spronsen, M. Bergman, L. Crama, I. Taminiau, A. Ofitserov, G. J. C. van Baarle and J. W. M. Frenken, "The ReactorSTM: Atomically resolved scanning tunneling microscopy under high-pressure, high-temperature catalytic reaction conditions", *Review of Scientific Instruments* **85**, 083703 (2014), DOI: 10.1063/1.4891811

W. M. van Spengen, S. B. Roobol, W. P. Klaassen and T. H. Oosterkamp, "The MEMSamp: using (RF-)MEMS switches for the micromechanical amplification of electronic signals", *Journal of Micromechanics and Microengineering* **20**, 125011 (2010), DOI: 10.1088/0960-1317/20/12/125011

Y. S. Avotina, Y. A. Kolesnichenko, S. B. Roobol and J. M. van Ruitenbeek, "Conductance of a tunnel point contact of noble metals in the presence of a single defect", *Low Temperature Physics* **34**, 207 (2008), DOI: 10.1063/1.2889410