



10-year Anniversary Workshop on
Focused Electron Beam Induced Processing (FEBIP)

FEBIP 2016

July 4th – 8th, 2016
Vienna, Austria



July 6th – July 8th: FEBIP Workshop on Fundamentals,
Chemistry, Processing, and Applications

July 4th – July 5th: Tutorials on FEBIP Modeling, Technical
Setup, Patterning, and Purification

FEBIP 2016

6th Workshop on Focused Electron Beam Induced Processing

Introduction

July 4th – July 8th

Vienna, Austria



Dear participant,

it is a great pleasure to welcome you at the **6th workshop on Focused Electron Beam Induced Processing (FEBIP)** in our charming **capital Vienna**, a city rich of history and culture you will meet at literally every corner. Like the very buildings we chose to house the 10th FEBIP anniversary conference: the *Haus der Ingenieure* (House of Engineers) and the *Palais Eschenbach*, where you are right now. Both date back to the 19th century and are remarkable examples of the back then *in vogue* style of Palladian classicism. Home to keen thinkers, explorers, engineers, and organisers they have a long tradition of conferences, exhibitions and experiments: e.g. the first public test-flight of Wilhelm Kress' flight model took place in the ballroom of the *Palais Eschenbach* in 1868. In that spirit we hope that the upcoming workshop will be a successful event linking the past to the future and creating a stimulating atmosphere for all of us.

Ten years ago the first workshop on **Focused Electron Beam Induced Processing** was held in Delft (The Netherlands), followed by four highly successful events in Thun (Switzerland, 2008), Albany (USA, 2010), Zaragoza (Spain, 2012), and Frankfurt (Germany, 2014). Since its initiation, this workshop series has become the most important assembly meeting in its field and we proudly celebrate its 10th anniversary in Vienna. Like its predecessor in Frankfurt the FEBIP anniversary workshop will be jointly held with the members of the COST Action CELINA (CM 1301: **C**hemistry for **E**lectron-Induced **N**anofabrication) supported by the EU Framework Programme Horizon 2020.

During the last decade, FEBIP has developed from a flexible bottom-up and top-down nanofabrication method into a **versatile 3D nano-printing tool**, which is subsequently attracting increasing attention from different industry branches. However, the need for more cooperation between multiple disciplines including precursor design, instrumentation, material analysis, and application development remains evident. Therefore, the programme reflects the latest developments: from fundamentals of FEBIP processes over related chemistry and new approaches to applications in science and technology.

Thematic tutorials are a new element to this workshop series. Six sessions where experts from the community will present an overview of individual topics will take place on July 4th and July 5th, prior to the traditional FEBIP workshop. Not only newcomers or interested persons will profit from these tutorials, they will also contribute to the creation and standardisation of community wide standard procedures which, as we believe, is highly beneficial to leverage the full impact of the FEBIP technology. As organizers we are very happy that these tutorials could be organized without a substantial increase of conference fees which was possible thanks to financial support from our exhibitors (*GETec, Kleindiek, Jeol, Raith, Zeiss*), the *Graz Centre for Electron Microscopy*, the *Vienna and Graz Universities of Technology*, the *COST action funding scheme*, and the Austrian government institution *bmvit*.

The programme consists of 11 invited talks, 30 contributed talks, 6 tutorials, 5 exhibitor talks, and 24 poster presentations with about 75 participants. Social activities are planned during the entire week to bring together the community in a relaxed atmosphere in order to trigger long lasting scientific and personal discussions.

As chairmen of this 6th FEBIP workshop, we also would like to mention those colleagues who strongly supported us in the background in order to make this meeting as smooth as possible. First, we would like to thank the FEBIP board and in particular Cornelis (“Kees”) Hagen not only for permanent support during the organisation but also for the possibility to host the 10th anniversary in Austria. We also would like to express our deepest gratitude to Silvia Pflug, Stefanie Stückler, Ulrike Stürzenbecher, Sabine Mitterbacher, Robert Winkler, Jürgen Sattelkow, and Sebastian Rauch – without their helping hands and ideas many things would have been way more difficult/ for their valuable contribution during the organisation.

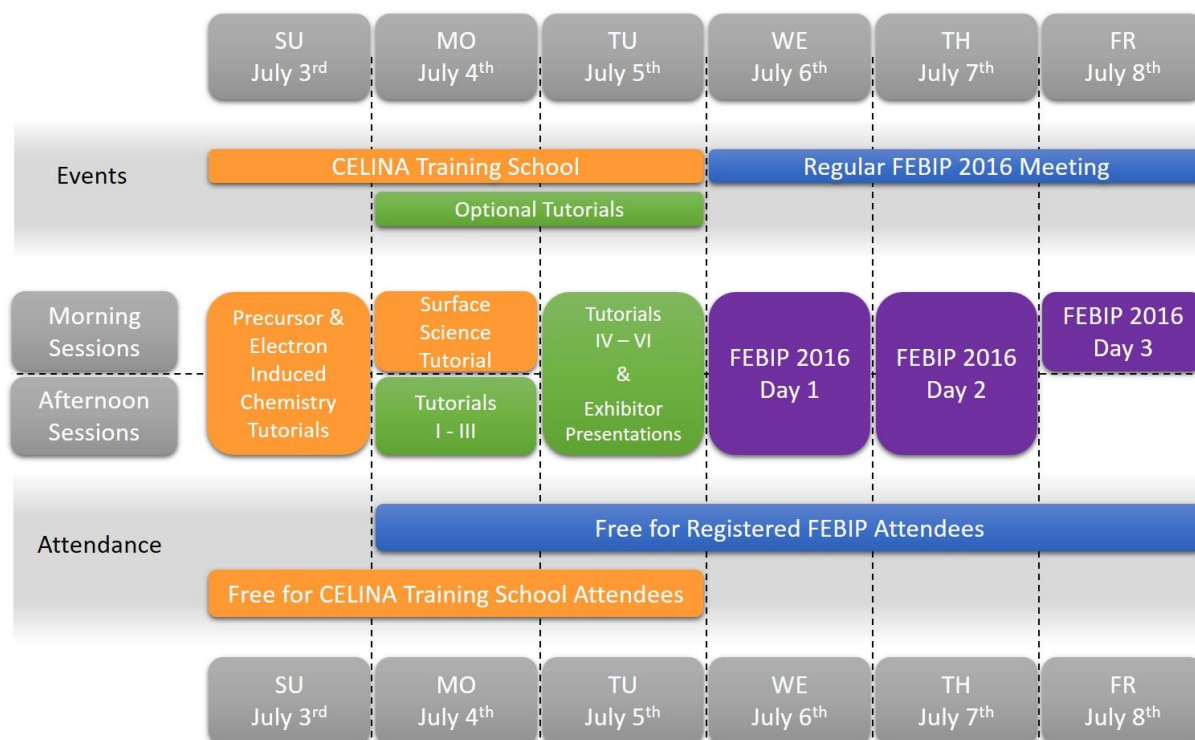
We truly hope, you will find some time to follow our late emperors’ footsteps or try our famous *Sachertorte* (Sacher cake). We wish you a stimulating workshop and lots of inspiring discussions!

Harald Plank & Heinz Wanzenböck

FEBIP 2016

6th Workshop on Focused Electron Beam Induced Processing

Graphical Overview



July 4th – July 8th

Vienna, Austria



Monday, July 4th 2016
TUTORIAL Day 1
Palais Eschenbach

12:00 – 12:45	Get Together
12:45 – 13:00	Tutorial - Opening
13:00 – 14:30	Tutorial I Milos Toth (<i>University of Technology Sydney, Australia</i>) Modelling FEBIP Processes – Module I
14:30 – 15:00	Coffee Break
15:00 – 16:30	Tutorial II Milos Toth (<i>University of Technology Sydney, Australia</i>) Modelling FEBIP Processes – Module II
16:30 – 17:00	Coffee Break
17:00 – 18:00	Tutorial III Ivo Utke (<i>Empa Thun, Switzerland</i>) Simulating Gas Flux with the GIS Simulator @ Empa
18:00 – 18:30	Podium Discussion

Tuesday, July 5th 2016
TUTORIAL Day 2
Palais Eschenbach

8:00 – 8:15	Get Together	
8:15 – 8:30	Tutorial - Opening	
8:30 – 9:00	<p><i>Exhibitor Contribution</i> To be announced (JEOL GmbH, Germany) Latest developments in focused electron- and focused ion-beam lithography from JEOL</p>	
9:00 – 10:15	<p>Tutorial IV Hans J.L. Mulders (FEI Electron Optics Eindhoven, The Netherlands) Technical Setup of FEBIP Instrumentation</p>	
10:15 – 10:45	Coffee Break	
10:45 – 11:15	<p><i>Exhibitor Contribution</i> Frank Nouvertne (RAITH GmbH, Germany) Device Optimization by Smart Nanopatterning Strategies using Focused Electrons and Ions</p>	
11:15 – 12:30	<p>Tutorial V Harald Plank (Graz University of Technology, Austria) Patterning Procedures and their Consequences</p>	
12:30 – 13:30	Lunch Break (buffet provided at the tutorial location)	
13:30 – 14:00	<p><i>Exhibitor Contribution</i> Marcel Winhold (GETec Microscopy GmbH, Austria) The AFSEM™ - Correlative <i>in-situ</i> Analysis of Nanostructured (FEBID) Materials</p>	
14:00 – 14:30	<p><i>Exhibitor Contribution</i> Lars Kautschor (Carl Zeiss Microscopy, Germany) Towards Sub-10 nm Nanofabrication of Plasmonic and Graphene Devices using Multiple Ion Beams</p>	
14:30 – 15:00	Coffee Break	
15:00 – 15:30	<p><i>Exhibitor Contribution</i> Andrew J. Smith (Kleindiek, Germany) A Compact and Versatile Gas Injection System and Applications for IBID Combined with <i>in-situ</i> Nanoprobng in Circuit Edit</p>	
15:30 – 16:45	<p>Tutorial VI Philip D. Rack (University of Tennessee & Oak Ridge National Laboratory, USA) Overview of Purification Strategies for Electron Beam Induced Deposition</p>	
16:45 – 18:00	Coffee Break & Exhibition	
18:00 – 20:30	Social Event I	
18:00 – 20:30	Opening Reception (TU the Sky Lounge)	

Wednesday, July 6th 2016

Morning Session

Haus der Ingenieure

8:00 – 8:30	Get Together
8:30 – 8:45	FEBIP 2016 - Opening
8:45 – 10:30	Precursor Fundamentals (chair: Ivo Utke)
8:45 – 9:15 (invited)	Cornelis W. Hagen (<i>Delft University of Technology, The Netherlands</i>) FEBIP Control and Instrumentation
9:15 – 9:45 (invited)	Petra Swiderek (<i>University of Bremen, Germany</i>) COST Action CM1301 CELINA: A Concerted European Approach to the Advancement of FEBID
9:45 – 10:00	Oddur Ingolfsson (<i>University of Iceland, Iceland</i>) Dissociative Electron Enhancement for Site-Selective and Efficient Cross-Linking of SAMs in Carbon Nano-Membrane Production
10:00 – 10:15	Céline Dablemont (<i>CNRS, Université Paris Saclay, France</i>) Water Surface Wetting at Very First Stages of Deposition: Quantification and Interactions
10:15 – 10:30	Iwona Szymanska (<i>Nicolaus Copernicus University, Poland</i>) Electron-Impact Mass Spectrometry Application for Studies of Copper(II)/Silver(I) Carboxylate Systems
10:30 – 11:00	Coffee Break
11:00 – 12:35	Precursor Design (chair: Hubertus Marbach)
11:00 – 11:15	Willem van Dorp (<i>University of Groningen, The Netherlands</i>) Au(I) Precursors: Volatility, Stability and Rational Design
11:15 – 11:45 (invited)	Mats Tilset (<i>University of Oslo, Norway</i>) Synthesis and Characterization of Gold Complexes, with a FEBID Perspective
11:45 – 12:05	Lisa McElwee-White (<i>University of Florida, USA</i>) Mechanism Based Design of Precursors for FEBID
12:05 – 12:35 (invited)	Ivo Utke (<i>Empa Thun, Switzerland</i>) What can we Learn from Growth / Etch Rate Modelling in FEBIP?
12:35 – 14:00	Lunch Break (buffet provided at the conference location)

Wednesday, July 6th 2016

Afternoon Session

Haus der Ingenieure

14:00 – 15:15	Poster Session I
15:00 – 15:15	Coffee at the end of Poster Session I
15:15 – 16:35	Precursor / Purification (chair: Petra Swiderek)
15:15 – 15:45 (invited)	Hubertus Marbach (<i>Friedrich-Alexander University Erlangen-Nürnberg, Germany</i>) A Surface Science Approach to FEBIP: Fabrication of Clean Metallic Nanostructures and Perspectives for the Reduction of Proximity Effects
15:45 – 16:00	Sven Barth (<i>Technical University Vienna, Austria</i>) Synthesis and Characterization of Heterometallic Carbonyls for Focused Electron Beam Induced Deposition
16:00 – 16:15	Martin Drost (<i>Friedrich-Alexander University Erlangen-Nürnberg, Germany</i>) Fabrication of Nanostructures on Thin Organic Layers by Focused Electron Beam Processing
16:15 – 16:35	Howard Fairbrother (<i>Johns Hopkins University, USA</i>) Purifying FEBIP Deposits with Atomic Radicals
16:45 – 20:00	Social Event II
16:45 – 17:00	Common Walk to the <i>Palmenhaus</i>
17:00 – 20:00	Cheese & Wine

Thursday, July 7th 2016
Morning Session
Haus der Ingenieure

8:30 – 9:00	Get Together
9:00 – 10:45	Purification (chair: Michael Huth)
9:00 – 9:30 (invited)	Philip D. Rack (<i>University of Tennessee & Oak Ridge National Laboratory, USA</i>) Laser Assisted Focused Beam Induced Processing
9:30 – 9:45	Rosa Córdoba (<i>Eindhoven University of Technology, The Netherlands</i>) Patterning Functional Nickel-Based Deposits by Focused Beams Induced Processing
9:45 – 10:00	Markus Rohdenburg (<i>University of Bremen, Germany</i>) Novel Insights into the Water-Assisted Purification of FEBID Deposits Produced from MeCpPtMe ₃
10:00 – 10:15	Mostafa M. Shawrav (<i>Technical University Vienna, Austria</i>) Highly Conductive & (Almost) Pure Gold Deposition Without Post Treatment – A Fairy Tale has Come True?
10:15 – 10:30	Katja Höflich (<i>Helmholtz Center Berlin for Materials and Energy, Germany</i>) Electron Beam Induced Deposition of Silver Based Nanostructures
10:30 – 10:45	Charlene Lobo (<i>University of Technology Sydney, Australia</i>) Electron Beam Processes for Surface Functionalization and Directed Nanostructure Assembly
10:45 – 11:15	Coffee Break
11:15 – 12:45	Magnetism (chair: José-Maria de Teresa)
11:15 – 11:45 (invited)	Michael Huth (<i>Goethe University Frankfurt, Germany</i>) Perspectives of FEBID-Based Superconducting Nanostructures for Basic and Applied Research
11:45 – 12:00	F. Tu (<i>Friedrich-Alexander University Erlangen-Nürnberg, Germany</i>) On the Magnetic Properties of Clean Iron Nanostructures Fabricated by Focused Electron Beam Induced Processing
12:00 – 12:15	L. Keller (<i>Goethe University Frankfurt, Germany</i>) Magnetic Dot Lattices prepared by FEBIP
12:15 – 12:30	J. Pablo-Navarro (<i>Universidad de Zaragoza-CSIC, Spain</i>) Three-Dimensional Co/Pt and Fe/Pt Core-Shell Ferromagnetic Nanowires Grown by Focused Electron Beam Induced Deposition
12:30 – 12:45	A. Fernández-Pacheco (<i>University of Cambridge, United Kingdom</i>) 3D Cobalt Nanowires Grown by FEBID: Fabrication Challenges and Advanced Magnetic Characterization
12:45 – 14:00	Lunch Break (buffet provided at the conference location)

Thursday, July 7th 2016
Afternoon Session
Haus der Ingenieure

14:00 – 15:15	Poster Session II
15:00 – 15:15	Coffee at the end of Poster Session II
15:15 – 16:45	New Processing Trends I (chair: Milos Toth)
15:15 – 15:45 (invited)	Jason D. Fowlkes (<i>Oak Ridge National Laboratory & University of Tennessee, USA</i>) Three-Dimensional FEBID
15:45 – 16:00	Robert Winkler (<i>Graz University of Technology, Austria</i>) FEBID Based 3D Nanoprinting of Plasmonic Gold Structures: Beyond Current Limitations
16:00 – 16:15	Brett B. Lewis (<i>University of Tennessee, USA</i>) Electrical and Mechanical Characterization of 3-Dimensional Nanostructures Grown and Purified Using Laser Assisted Electron Beam Induced Deposition
16:15 – 16:30	Sangeetha Hari (<i>Delft University of Technology, The Netherlands</i>) Combined Top-Down and Bottom-Up 3D Nanofabrication
16:30 – 16:45	Andrei Fedorov (<i>Georgia Institute of Technology, USA</i>) New Capabilities for FEBIP Using Supersonic Carrier Gas Micro-Jet and Liquid Nanoelectrospray for Precursor Delivery
16:45 – 17:15	Coffee Break
17:15 – 18:45	New Processing Trends II (chair: Jason D. Fowlkes)
17:15 – 17:45 (invited)	José-Maria de Teresa (<i>Universidad de Zaragoza-CSIC, Spain</i>) Unconventional Use of FEBID for Non-Standard Applications
17:45 – 18:00	Thomas Ganner (<i>Graz University of Technology, Austria</i>) Fabrication of Cellulose Structures via Focused Electron Beam Induced Conversion: Approaching the Nanoscale
18:00 – 18:15	Christopher Elbadawi (<i>University of Technology Sydney, Australia</i>) Electron Beam Restructuring of Hexagonal Boron Nitride for Applications in Photonics and Polaritonics
18:15 – 18:45 (invited)	Todd Hastings (<i>University of Kentucky, USA</i>) Recent Progress in Focused Electron-Beam Induced Processing using Liquid Reactants on Bulk Substrates
19:00 – 22:00	Social Event III
19:00 – 20:00	Transfer to Conference Dinner (<i>Schüberl - Auer</i>)
20:00 – 22:00	Conference Dinner & Image Contest Ceremony

Friday, July 8th 2016
Morning Session
Haus der Ingenieure

8:30 – 9:00	Get Together
9:00 – 10:35	Applications I (chair: Philip D. Rack)
9:00 – 9:20	Gian C. Gazzadi (<i>S3 Center – Nanoscience Institute – CNR, Italy</i>) FEBID and FIB meet Mr. Feynman and other Curious Fellows ... Not a Joke!
9:20 – 9:35	Roland Sachser (<i>Goethe University Frankfurt, Germany</i>) TiO ₂ -Based Memristors Prepared by FEBID
9:35 – 9:50	Giorgia Di Prima (<i>Goethe University Frankfurt, Germany</i>) Electrical Studies of Nanoparticle Arrays Contacted by Pt-FEBID Deposits
9:50 – 10:10	Hans W.P. Koops (<i>HaWilKo GmbH Ober-Ramstadt, Germany</i>) Applications of Nano-composite Materials Produced by Focused Electron Beam Induced Processing Carrying at Room Temperature GA/cm ² Current Density due to a Bose-Einstein Condensate
10:10 – 10:45	Coffee Break
11:00 – 12:20	Applications II (chair: Kees Hagen)
10:45 – 11:15 (invited)	Milos Toth (<i>University of Technology Sydney, Australia</i>) Electron Beam Induced Etching and Processing of Nanophotonic Materials for Quantum-Effect Devices
11:15 – 11:30	Aleksandra Szkudlarek (<i>Carl AGH University of Science and Technology, Poland</i>) Granular Metals for Gas-Sensing Applications prepared by Focused-Electron-Beam-Induced-Deposition
11:30 – 11:45	Nicole Auth (<i>Carl Zeiss SMT GmbH, Germany</i>) Challenges for Electron Beam Mask Repair in the Semiconductor Industry Environment
11:45 – 12:05	Andrei G. Fedorov (<i>Georgia Institute of Technology, USA</i>) FEBIP of Graphene: Etching/Patterning, Doping and Contact Modification
12:05 – 13:00	Podium Discussion
13:00 – 13:30	Concluding Remarks
13:30 – 14:30	Lunch (buffet provided at the conference location)

TiO₂-based Memristors prepared by FEBID

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Memristors are passive circuit elements, which were theoretically predicted in the 1970s [1]. The resistance of such a device can be tuned by appropriate current-bias conditions. Its IV-curve typically shows a pinched hysteresis loop. Due to the increasing possibilities in the field of nanostructuring, the experimental realization made a large progress in the last 10 years [2]. The application of a memristor is not only limited to memory devices. It can also be used, e.g., for neuronal networks, transmitters and filter elements [3]. Even first commercial memristors are available now [4].

One class of memristors are the metal-oxide based memristors. They consist of a metallic top and a bottom electrode, and an active metal-oxide layer. Above this normally insulating metal-oxide layer a large electrical field is applied. Thereby a path of oxygen vacancies is formed, which allow the transport of electrical current through the device. Depending on the history of the applied voltage, the concentration gradient of oxygen vacancies can be modified which is associated with a resistance change.

Typically, high-resolution metal-oxide based memristors are prepared by at least three steps of electron-beam-lithography, combined with different sputtering processes for the electrode and the metal-oxide. FEBID allows the direct fabrication of high resolution TiO₂-based memristors in a bottom up approach.

The memristors presented in this work are realized as stacked electrodes. A bottom electrode is written by the standard FEBID process using the platinum precursor trimethylmethylcyclopentadienyl-platinum. The resulting deposit consists mainly of carbon (around 80 at%). To make the bottom electrode usable for a memristive device, an additional step is necessary. After deposition, the sample is purified directly in the SEM using oxygen pulses at a sample temperature of 150°C [5]. As a result the bottom electrode consists now of pure platinum. As next step, titaniumisopropoxide is used in a FEBID process [6], to deposit a TiO₂-layer of approx. 20nm thickness on a small area of the platinum bottom electrode. Next, the top electrode is written on top of the TiO₂-deposit using the same deposition and purification technique as for the bottom electrode. The resulting memristor structure with an active area of about 100nm x 100nm is shown in Fig. 1.

Directly after preparation, metal-oxide based memristors are typically insulating. Before use a special forming process is necessary. In our experiment the forming process was carried out directly in-situ in the SEM. One exemplary measurement is shown in Fig. 2. To form the memristor, an increasing current was applied to the memristor device in series with a shunt resistor. The voltage across the memristor was measured. At about 8µA the forming process took place and the resistance dropped by factor of 4, thereby completing the forming procedure.

In Fig. 3 IV-curves measured on the memristor after the forming process are depicted. They show a pinched hysteresis loop, which is characteristic for memristors. At a voltage of about 2V the resistance of the memristor can be switched between two different states.

[1] L. O. Chua; Memristor – The Missing Circuit Element; *IEEE Transactions on Circuit Theory* **CT-18** (1971), 507

[2] J. J. Yang, M. D. Pickett, X. Li, D. A. A. Ohlberg, D. R. Stewart, R. S. Williams; Memristive switching mechanism for metal/oxide/metal nanodevices; *nature nanotechnol.* **3** (2008), 249

[3] M. Potrebic, D. Tosic; Application of memristors in microwave passive circuits; *Radioengineering* **24** (2015), 408

[4] Knowm Inc., <http://www.knowm.org>, press release, 07/06/2015

[5] R. Sachser, H. Reith, D. Huzel, M. Winhold, M. Huth; Catalytic Purification of Directly Written Nanostructured Pt Microelectrodes; *ACS Appl. Mater. Interfaces* **6** (2014), 15868

[6] M. Schirmer, M. M. Walz, F. Vollnhals, T. Lukaszczuk, A. Sandmann, C. Chen, H. P. Steinrück, M. Marbach; Electron-beam-induced deposition and post-treatment process to locally generate clean titanium oxide nanostructures on Si(100); *Nanotechnology* **22** (2011), 085301

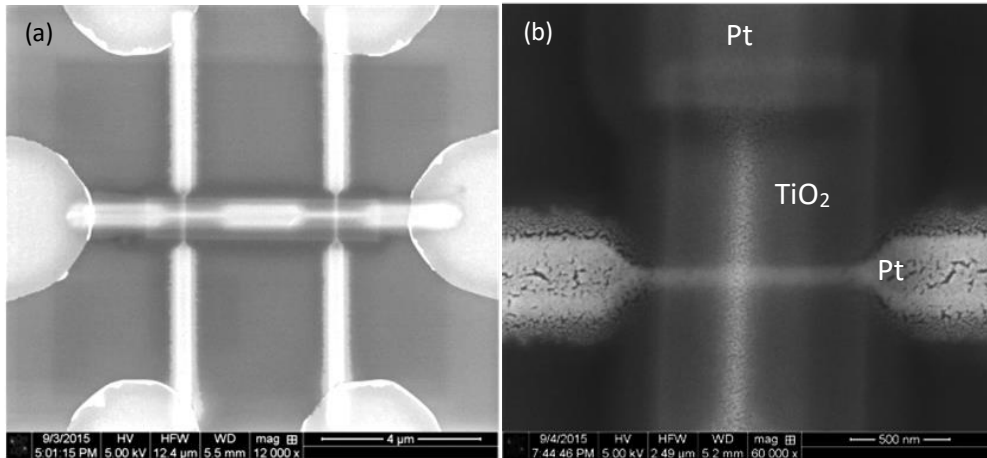


Fig. 1: (a) Two memristors prepared by means of FEBID, consisting of platinum top and bottom electrode and a TiO₂-layer. (b) Zoom-in on the active area of one memristor.

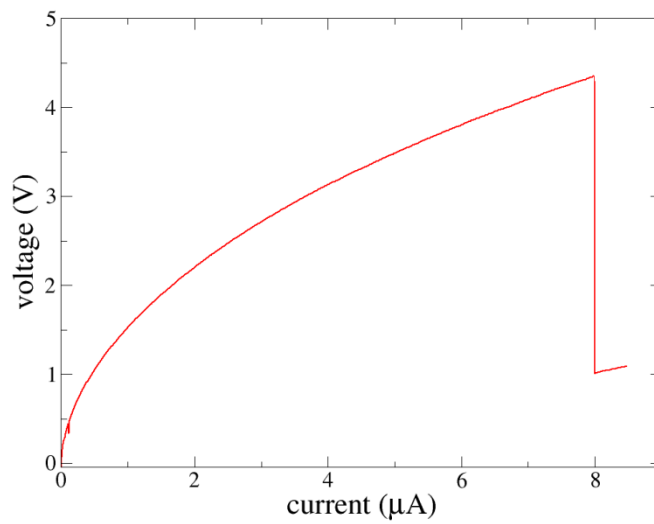


Fig. 2: Forming process of the memristor. At about 8 μA the memristor changes its resistance by factor of 4 and the forming process is finished.

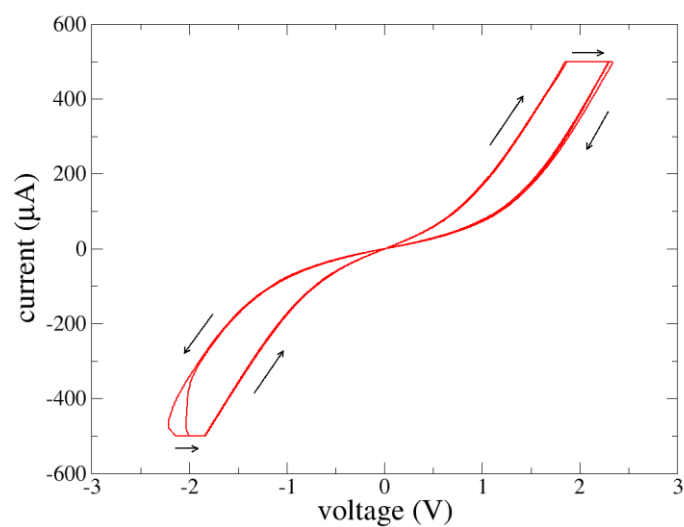


Fig. 3: IV-curve showing the typical pinched hysteresis loop of a memristor. At about 2V the resistance can be switched between two different states.



6th International Workshop on Focused Electron Beam Induced Processing

FEBIP 2016

Regular Workshop: July 6th – 8th 2016
 Technical Tutorials: July 4th – 5th 2016
 Location: Palais Eschenbach & Haus der Ingenieure, Vienna, Austria
 Conference webpage: www.febip-2016.com

Scope:

- Physico-Chemical Fundamentals Of FEBIP Processes
- Precursor Fundamentals: Electron Interactions And Its Implications
- Nanostructuring: High-Resolution And 3D Nanofabrication Via Deposition & Etching
- FEBID Materials: From Classical Towards New Materials
- Material Purification: Towards Highly Pure (Nano)Structures
- Focused Ion Beams: New Approaches And Capabilities
- Alternative Approaches: Conversion, Curing, And Modification
- New (Interdisciplinary) Processing Concepts Using Electrons And / Or Ions
- FEBIP Based Applications In Science And Technology

Tutorials:

- Modelling FEBIP Processes
- Simulating Gas Flux With The GIS Simulator @ Empa
- Technical Setup Of FEBIP Instrumentation
- Patterning Procedures And Their Consequences
- Overview Of Purification Strategies For Electron Beam Induced Deposition

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