An in-plane cobalt–nickel microresonator sensor with magnetic actuation and readout

O. Ergeneman\textsuperscript{a,∗}, P. Eberle\textsuperscript{a}, M. Suter\textsuperscript{b}, G. Chatzipirpiridis\textsuperscript{a}, K.M. Sivaraman\textsuperscript{a}, S. Pané\textsuperscript{a},
C. Hierold\textsuperscript{b}, B.J. Nelson\textsuperscript{a}

\textsuperscript{a} Institute of Robotics and Intelligent Systems, ETH Zurich, Zurich, Switzerland
\textsuperscript{b} Micro and Nano Systems, ETH Zurich, Zurich, Switzerland

A R T I C L E   I N F O

Article history:
Received 12 October 2011
Received in revised form 22 May 2012
Accepted 22 May 2012
Available online 30 May 2012

Keywords:
Magnetic actuators
Wireless readout
Passive microresonator
Cobalt–nickel

A B S T R A C T

We present magnetic microresonators that utilize magnetic actuation and readout for use as mass sensors. A magnetic readout method was developed for the detection of microresonator vibration. The wireless actuation combined with the wireless magnetic readout results in completely passive microresonators. The magnetic readout is based on the induced voltage on a pair of differential pick-up coils, which is generated by the movement of the magnetized microresonator. The successful operation of the readout was demonstrated with CoNi microresonators under atmospheric pressure in air and in water. The microresonator can be readily functionalized and used as a mass sensor for bio-applications.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Advances in micro and nanotechnology are accelerating the development of miniaturized devices for biosensing applications [1]. Biosensing platforms are designed to recognize specific biochemical entities in confined locations, the human body, or environments with a complex biochemistry. In general, biosensing is based on the use of a bioreceptor that interacts with a specific bioanalyte. The effect caused by this interaction is measured by a transducer and processed as a quantifiable property. Microresonators are widely used as transducers because they provide high sensitivity, rapid detection, and easy operation [2,3]. The microresonator surface is chemically or biochemically functionalized to enable recognition of specific analytes [4]. The accumulation of the analyte on the microresonator surface changes the mass load on the resonator thus changing the vibration characteristics (resonant frequency) of the resonator upon excitation. Research on microresonators-based sensors is currently focused on two broad areas: developing new methods to detect and readout the change in vibration characteristics of the resonator, and identifying specific analyte-receptor reactions and implementing them on the resonator platform [5].

For the actuation of microresonators many different methods have been employed by researchers [6]. Thermal, piezoelectric, and electrostatic actuation are the most common methods used to date. Piezoelectric microcantilevers are easy to actuate and sense, however, they require more complex structures. They usually require two electrodes for applying electric fields for actuation and sensing. In conductive media insulation of the electrodes is necessary. Electrostatic actuators also suffer from the same problems. Thermal actuation can be achieved without contacting the device, however, bio-samples are extremely sensitive to thermal changes making this method unsuitable for bio-applications. Magnetic actuation provides contactless and efficient excitation of microresonators. The actuation can be done with off-chip electromagnets allowing simple passive microresonators. This significantly decreases the fabrication and packaging efforts, enabling cost-effective, even disposable, microdevices for bio-applications. Magnetic microresonators can be actuated in liquids (i.e., solutions and colloidal dispersions).

A variety of techniques can be used for the detection of microresonators. There is increasing interest in non-contact measurements using microresonators [7]. This is particularly important in applications where access to the sensor is limited due to constraints of the environment like the human body or in closed packages [8]. Optical detection methods are the most common readout strategy for microdevices. Typically, deflection is measured by a laser spot that is reflected from the top surface of the microresonator onto a position sensitive detector (PSD). The output of the PSD
changes as a function of deflection. This method allows detection in the sub-nanometer range. A majority of bio-sensors utilize optical detection. They provide linear, reliable, and simple measurements. However, they have limitations. They require precise alignment of both a laser beam on the microresonator and alignment of the reflected beam on the PSD. They require a clear optical path to the device and reflective surfaces for the laser beam, which hinders their usage in opaque mediums. A focused laser beam can cause thermal management issues that can be critical in biosensing applications. Additionally, in-plane motions cannot be detected with this method. Other microresonators use piezoresistive or capacitive detection methods. These methods provide high sensitivity but the transducers have a more complex design. The isolation of electrodes or piezo elements are necessary. The piezoresistors can cause heating of the microdevice and capacitive readout does not work in electrolyte solutions. The magnetic readout eliminates the need for conductive wires associated with electrical detection. It can be utilized when the microdevice is not reflective or when there is no direct optical path to the device. They can also be used in colloidal bio-solutions, where optical readout cannot be utilized.

In this work, we present a complete magnetic microsystem that utilizes magnetic actuation and readout for use as a mass sensor for bio-applications. Many magnetic microresonators have been reported [9], most of them utilizing optical readout methods. The contactless electromagnetic excitation of resonant sensors made of conductive materials is presented in [10]. The readout of these devices is performed by piezoelectric and optical methods. This excitation principle is attractive for the operation in environments with limited access or incompatibility with active electronics. In [11], a contactless magnetic readout method that works based on induced eddy currents on a conductive non-magnetic MEMS device is presented. Miniaturized acoustic resonator sensors with electromagnetic actuation are presented in [12]. The excitation coils are connected to an impedance analyzer to excite and detect the mechanical resonances. Here, we present a contactless magnetic readout method for a soft magnetic microresonator. The presented magnetic resonator is shown in Fig. 1 and it consists of a magnetic plate suspended by a beam anchored at one end to the thick SU-8 anchor layer. It is excited by a coil placed under the device. A Helmholtz coil pair is used to magnetize the microresonator in plane. A probe coil is placed above the microresonator encircling two differentially connected pick-up coils. The resonance of the device is detected with the pick-up coils and the magnetic field from the probe coil amplifies the readout signal by modulating the deflection signal. A lock-in amplifier is utilized to recover the deflection signal from the noisy readout signal.

2. Fabrication

The microresonators consist of a device layer made of CoNi (i.e., the suspended component and the spring) and an anchor layer made of SU-8 (Fig. 1). CoNi has low coercivity and high saturation magnetization. Among soft-magnetic materials, CoNi alloys offer both good mechanical and magnetic properties. Although, other materials widely used such as NiFe or CoNiFe exhibit lower coercivities and higher saturation magnetization values, the presence of Fe leads alloys with poorer corrosion resistance [13]. The microfabrication of the device is based on two lithography steps, an electroplating step, and a sacrificial layer etching step. The fabrication of the microresonator is shown in Fig. 2. Subsequent to the cleaning step, a 25 nm adhesion Ti layer (not shown) and 500 nm sacrificial Cu layer are deposited on a Si substrate by e-beam evaporation (1). The Cu layer also acts as a seed layer for electrodeposition. The device layer is defined by the first lithography (2) and formed by electroplating CoNi. After electrodeposition the positive photosensitive AZ4562 (Microchem Inc.) is removed (3). Adhesion of SU-8 to metals is generally weak, hence an adhesion promoter is used to improve the adhesion between SU-8 and CoNi (not shown) [14,15]. The adhesion promoter Omnicote (Micro Chem Inc.) is applied by spin-coating and prebaked at 200 °C for 1 min. A thin layer of Au (i.e., 10 nm) can be electroplated after CoNi electrodeposition to further enhance the adhesion between SU-8 and CoNi. An 80 μm-thick layer of SU-8 is applied over the devices (4) and a second photolithography step forms anchors (5). The microdevices are released from the substrate by etching the sacrificial Cu layer. The fabricated microresonator is shown in Fig. 1.
2.1. Characterization of the CoNi microresonator

The magnetic characteristics are crucial for the actuation and readout of the CoNi microresonators. High saturation values provide high magnetization values, which benefit both the actuation and the readout. Low coercivity values are also desired as hysteresis losses can heat the microresonator and linear-like $\mathbf{M} \cdot \mathbf{H}$ characteristics are needed for the readout. The magnetization characteristics of the CoNi used to make microresonators are obtained using a VSM (Micromag 3900, Princeton Measurements Corp.). Fig. 3 shows the magnetization of CoNi film as a function of the applied magnetic field. The deposits showed a saturation magnetization of 680 kA/m (0.85 T) and a coercivity of 1.6 kA/m (20 Oe).

3. Actuation

One approach to the wireless actuation of microdevices is through externally applied magnetic fields. Magnetic microdevices can be actuated by external electromagnets enabling contactless passive microdevices.

An AC electromagnet and two DC electromagnets are utilized to actuate the CoNi microresonator. The setup to actuate the CoNi microresonator together with readout coils is shown in Fig. 4. The AC coil is positioned so that its axis is parallel to the normal of the microresonator plate. The two DC coils are placed in a Helmholtz configuration to generate uniform magnetic fields to magnetize the microresonator plate in-plane as shown in Fig. 4. The electromagnet generates a gradient in both axial and radial directions of the coil. The size and the location of the coils were optimized by FEM simulations with COMSOL Multiphysics. The magnetic force, $\mathbf{F}$ [N], on the microresonator depends on the magnetization of the plate, $\mathbf{M}$ [A/m], and magnetic field gradient generated by the actuation coil [16].

$$\mathbf{F} = \mu_0 \nabla (\mathbf{M} \cdot \nabla) \mathbf{H}$$

where $\mu_0$ [N/A²] is the permeability of free space, $\nabla$ [m²] is the volume of the microresonator, $\nabla$ is the gradient operator, and $\mathbf{H}$ [A/m] is the applied magnetic field. Due to the in-plane magnetization of the plate forced by the Helmholtz pair, the microresonator experiences an in-plane force. The plate is actuated near the in-plane resonance frequency of the microresonator. Once the magnetization of the CoNi plate is known, the calculation of force is straight-forward. Since the microresonator is intended to be actuated in-plane, the relatively stronger DC field generated by the Helmholtz coils magnetize it in the deflection direction. The image of a typical in-plane resonator and an illustration showing the direction of the magnetization, the field gradient, and the deflection is shown in Fig. 1. The effect of the magnetic field generated by the AC coil is negligible for the magnetization of the microresonator. However, the AC coil generates the magnetic field gradient needed for force generation. The force on the CoNi plate is induced by the magnetic field gradient $\nabla \mathbf{H}$ and the magnetization $\mathbf{M}$ of the plate, which in turn is related to the magnetic field $\mathbf{H}$. Since the magnetization $\mathbf{M}$ does not change direction under the strong DC magnetic field $\mathbf{H}$, the magnetic forces experienced by the plate changes direction based on the alternating magnetic field gradient.

In order to find the damped resonant frequency and the quality factor of the microresonator, the excitation frequency is swept over a band that includes the resonant frequency of the microresonator. At the resonant frequency, the deflection amplitude of the microresonator is maximum, and the phase lag between excitation signal and the deflection signal changes distinctively. Either effect can be used to detect the resonant frequency.

4. Readout

Fig. 4 shows the setup used for the actuation and readout of the CoNi microresonator. In addition to the AC actuation coil and Helmholtz coils, a pair of symmetrically positioned pick-up coils and a probe coil are utilized for the magnetic readout (Fig. 5). The probe coil generates the probe field necessary for the detection of the microresonator vibration. The probe field is superimposed on the excitation field and generates an additional magnetization on the microresonator. The pick-up coils are placed symmetrically with respect to the probe coil and connected differentially to cancel...
the voltage induced by the probe field. The differential configuration is necessary to increase the sensitivity of the system. When the microresonator vibrates, a voltage will be induced on the pick-up coils due to the vibrating magnetized body given by Faraday’s law:

$$U_p = -\frac{d}{dt} \int_S B \cdot d\mathbf{S}$$  

(2)

where $U_p$ is the induced voltage on the pick-up coils, $B$ is the magnetic flux density, and $S$ is the surface enclosed by pick-up coils. The induced voltage on the pick-up coil closer to the microresonator is significantly higher than the induced voltage on the distant one. The differential voltage can be used to determine the microresonator vibration.

4.1. Magnetic modulation effect

The magnetization of the microresonator generates a spatially changing magnetic field. The magnetic field intensity tends to decay with increasing distance from the microresonator. When the microresonator deflects by an amount $x_d$ the spatial magnetic field intensity also shifts linearly by the amount of deflection $x_d$, hence, the magnetic field intensity changes. When the microresonator deflects sinusoidally, the magnetic field at the location of the pick-up coil, $x_p$ also changes sinusoidally if the magnetic field distribution is linear around $x_p$. For small deflections this is a valid assumption. The time varying magnetic field caused by the vibration of the microresonator induces a sinusoidal voltage on the pick-up coil.

The microresonator is magnetized by the DC magnetic field generated by the Helmholtz pair. At the same time the excitation field and the probe field magnetizes the microresonator at the excitation frequency $f_m$ and probe frequency $f_p$, respectively. The total magnetic field applied to the microresonator should not exceed the field strength which saturates the microresonator. The total magnetization of the microresonator is the sum of all these components $M_{DC}$, $M_{AC}$, and $M_p$. The magnetic field $B$ generated by the magnetized microresonator is determined by $M_{DC}$, $M_{AC}$, and $M_p$, and, hence, it changes with the alternating parts $M_{AC}$ and $M_p$ (Fig. 6). This results in a magnetic field with different frequency components. The addition of the microresonator deflection gives rise to an amplitude modulation of the three magnetic field components generated by $M_{DC}$, $M_{AC}$, and $M_p$. The induced voltage on the pick-up coil has frequency components at $f_m, f_m \pm f_p, f_p \pm f_m$ where $f_m$ refers to the mechanical vibration frequency. The modulation effect is illustrated for the AC and probe magnetization in Fig. 6.

The DC component of magnetization $M_{DC}$ is significantly higher than the AC component $M_{AC}$ under normal operation. The main force component acting on the microresonator oscillates at the excitation frequency, and, therefore, the microresonator vibrates at the excitation frequency $f_m = f_m \pm f_m$. The induced voltage will have its main component at this frequency. Additionally, a signal component will be induced on the pick-up coil at the second harmonic of the excitation frequency due to the modulation effect of the excitation frequency, and its amplitude depends linearly on deflection amplitude of the microresonator. Detecting the microresonator vibration at the excitation frequency is nearly impossible, since the signal part induced from the excitation field is significantly larger than the signal from the microresonator vibration. The second harmonic of the excitation frequency is more favorable for the readout.

In the presence of a probe magnetic field the same modulation effects occur at the probe frequency. The microresonator vibration induces two sidebands at $f_p \pm f_m$ due to the modulation effect. The probe frequency is an arbitrary selectable parameter and is favorably selected as high as possible, since the amplitude of the probe sidebands are amplified with the probe frequency. However, it is limited by the bandwidth of the used power amplifier.

4.2. Simulations and modeling

The magnetic field generated by the magnetized body can be predicted using a model developed for predicting the magnetic field of a permanent magnet. Fig. 7 illustrates the arrangement of the pick up coil with respect to the magnetized body of the microresonator. $r_m$ denotes the center of the magnetized body, $r_p$ denotes the center of the pick-up coil, and $r_{up}$ denotes the center of the pick-up coil with respect to the coordinate frame whose origin is located at the center of the magnetized body. It is more convenient to use the coordinate frame located at the center of the magnetized body, which is denoted by unprimed coordinates. The coordinate transformation is $r_p = r_{up} - r_m$ and the vibrational velocity of the magnetized body is transformed into a velocity of the pick-up coil: $\mathbf{v}'(r_{up}) = -\mathbf{v}(r_p)$.

The induced voltage in the pick-up coil can be found from (2) where $S$ is the surface the pick-up coil covers. It is assumed that the magnetized body vibrates translationally in one direction and rotational movements are not considered. Therefore, the pick-up coil vibrates in the transformed coordinate frame and, hence, $r_p$ changes as a function of time. Eq. (2) can be written as:

$$U_p = \left( \frac{d}{dt} \mathbf{v}'(r_p) + \frac{\partial}{\partial t} \right) \int_S B \cdot d\mathbf{S}$$

(3)
shows out of 124 to needed. The between the positive and negative peaks (Fig. 8). The encirclement of one of the two negative lobes is unavoidable when a macro coil is used, however, about 50% of the maximally achievable pick-up voltage can still be obtained. It is important not to encircle both negative lobes which would result in cancellation of the pick-up voltage. Fig. 8 shows that the induced voltage in the pick-up coil depends on the position of the pick-up coil with respect to the microresonator. The line that represents the edge of the pick-up coil shows the optimum position for successful readout.

It can be seen that the graph of the derivative field (Fig. 8) depends on the selected magnetic body geometry and the distance between the body and the pick-up coil. Therefore, the optimized pick-up coil geometry depends on these parameters. The alignment of the pick-up coil’s edge at the zero crossing line is always valid.

In the readout system, the voltage induced in the differentially coupled pick-up coils is first amplified and the intermodulation distortion is compensated with a custom signal-conditioning circuit. The signal is then recovered by a lock-in amplifier (Zurich Instruments HF2LI) (Fig. 5).

5. Results

First, the microresonator was characterized for reference using a planar motion analyzer (Polytec MSA-500) under magnetic excitation. An in-plane resonance frequency of 4.68 kHz was measured under atmospheric pressure in air. Next, the magnetic actuation and readout using the fabricated CoNi microresonator was successfully demonstrated. The excitation frequency was swept to find the resonance frequency. Fig. 9 shows the frequency response of the microresonator under atmospheric pressure in air and in water. The measurement in air at atmospheric pressure with the planar motion analyzer can also be seen in this figure. As expected, a lower quality factor was observed in water when compared to operation in air [17]. This is due to the higher viscosity of water, which results in a higher damping factor. Additionally, a shift in resonant frequency was detected.

5.1. Array measurements

The magnetic detection of an array of in-plane CoNi microresonators was tested. The arrangement of the microresonators is shown in Fig. 10. The six microresonators are excited in-plane with the same setup and reach a maximum deflection amplitude of 10–20 μm. The plates have a dimension of 400 μm × 400 μm and are suspended by a spring with dimension 200 μm × 11 μm. The
springs are clamped to an anchor bar. The thickness is 6 μm in the center of the plate. At the edges of the plate and at the spring the thickness is slightly higher due to the electroplating process.

Fig. 11 shows the frequency response measured with the magnetic readout and the planar motion analyzer. The magnetic readout captures the signal from several microresonators simultaneously, hence, the magnetic readout output gives the superposition of these signals. Fig. 11 shows three resonance peaks. The largest at f = 6.04 kHz comes from the sixth microresonator as depicted in Fig. 10 and is compared with the planar motion analyzer readout. All plates arranged in the row have slightly different resonant frequencies due to variations in the device thicknesses resulted from the electroplating process. Therefore, in Fig. 11 the other peaks refer to different microresonator resonances.

The amplitude of the readout signal depends strongly on the alignment of microresonator with respect to pick-up coil. Therefore, the resonance peak of the microresonator better aligned to the pick-up coil is amplified in the readout. Since the readout signal is a superposition of the induced signals of the individual microresonators, which may have different amplitudes and phases, the resulting frequency response can be a constructive or destructive superposition of these signals. Typically, the microresonator with good alignment should induce a much stronger signal at resonance than the other microresonators and should be clearly detectable in the frequency response. Similarly to the previous microresonator, there is a small deviation of about 15 Hz between the detected resonant frequencies of the two readout methods. Good agreement is found between the shapes of the resonant peaks measured with the magnetic readout and the planar motion analyzer.

(Since the planar motion analyzer does not provide phase information, the phase cannot be compared.)

6. Conclusion

A magnetic readout method was developed for CoNi microresonators. Together with wireless actuation, the wireless magnetic readout created completely passive microresonator sensors. This significantly simplifies their fabrication and packaging. It also provides many advantages, especially in bio-applications, as no wiring or on-board power sources are necessary for the device. The magnetic readout works based on the voltage induced on a pair of differential pick-up coils generated by the movement of the magnetized microresonator. To enhance the signal-to-noise-ratio and sensitivity of the readout, a probe field was applied and the readout was carried out at the side band of the probe frequency (the probe frequency plus the mechanical vibration frequency). This amplifies the readout signal by the probe frequency. The resonance peaks of the microresonators were found by sweeping the input signal over a band containing the resonance frequency. Successful operation of the readout was demonstrated with CoNi microresonators under atmospheric pressure in air and in water. Readout of multiple microresonators is demonstrated. Multiple device detection is possible when they have distinct resonance frequencies.

Acknowledgements

The authors would like to thank Dr. Eva Pellicer and Prof. Jordi Sort from Autonomous University of Barcelona for the magnetic measurements. Financial support by ETH Zurich (TH-28/06-3) is acknowledged.

References

Biographies

Olgac Ergeneman received his B.S. degree from the Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey, in 2003, and his M.S. degree from the Department of Electrical Engineering, Koc, University, Istanbul, Turkey. He obtained his Ph.D. degree from the Institute of Robotics and Intelligent Systems, ETH Zurich, Switzerland on wireless magnetic biomicrosystems. Since July 2011 he is working in the same group as a postdoc. His research interests are micro-nanorobots, magnetic actuators, microfabrication, electroplating, and optical sensors.

Patric Eberle received his B.Sc. at the Zurich University of Applied Science. After working in the industry in the area of mechatronic actuators, he completed his M.Sc. at ETH Zurich. He did his master thesis at the Institute of Robotics and Intelligent Systems, ETH Zurich on magnetic resonator sensors with wireless read out. Currently, he is working toward his Ph.D. at the Institute of Thermodynamics in Emerging Technologies, ETH Zurich. His research interests are nanoengineered structures for nanochannels and ionicphobicity, MEMS sensors and actuators for bio applications.

Marcel Suter received his dipl. Ing. FH in System Engineering at the Interstate University of Applied Sciences of Technology Buchs NTB. He completed his B.Sc. and M.Sc. at the University of Neuchâtel in Micro- & Nanotechnology. He wrote his diploma thesis at University of California Berkeley BSAC (USA). He did his Ph.D. in the Micro and Nanosystems Group at ETH Zurich on magnetic polymer actuators. Currently, he is working on electroactive polymers at Optotune AG.

George Chatzipiripidis received his B.S. degree from Department of Mechanical and Process Engineering, ETH Zurich. Since 2010 he is working toward his Master’s at the Institute of Robotics and Intelligent Systems, ETH Zurich. His research interests are microrobotics, fabrication technologies, and medical robotics.

Kartik M. Sivaraman obtained his Bachelor of Engineering degree in Mechanical Engineering from the National Institute of Technology Karnataka (NITK) Surathkal, India in 2006 and his Master of Science degree in Micro and Nanosystems from the ETH Zurich in 2009. He is currently working toward his Ph.D. at the Institute of Robotics and Intelligent Systems, ETH Zurich, focusing on electrodeposited materials, microrobotics, and targeted drug delivery.

Salvador Pané received the B.S. and M.S. degrees in chemistry and the Ph.D. degree, working on magnetic composites obtained by electrodeposition, from the University of Barcelona, Barcelona, Spain, in 2003, 2004, and 2007, respectively. He is currently a Senior Research Scientist at the Institute of Robotics and Intelligent Systems, ETH Zurich, Switzerland where he joined in May 2007. His research interests are micro- and nanorobotics, electrodeposition, biocompatible polymers, and magnetic materials.

Christofer Hierold is Professor of Micro- and Nanosystems at ETH Zurich. His major research at ETH Zurich is focused on the field of nanotransducers, new materials for MEMS, and advanced microsystems. He has been serving in program committees of numerous scientific conferences; he is co-chair of the Steering Committee of the European Conference on Solid-State Transducers (Euroensors) and he is a member of the Steering Committee of the International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers) and of the International Conference on Micro Electro Mechanical Systems (MEMS). He is a member of the editorial boards of the IEEE/ASME Journal of Micro Electro mechanical Systems and of the IOP Journal of Micromechanics and Microengineering, and he is joint editor of Wiley-VCH’s book series on Advanced Micro and Nanosystems. Christofer Hierold is member of the Swiss Academy of Engineering Sciences (SATW).

Brad Nelson is the Professor of Robotics and Intelligent Systems at ETH Zurich. His primary research focus is on microrobotics and nanorobotics with an emphasis on applications in biology and medicine. He received a B.S.M.E. from the University of Illinois at Urbana-Champaign and an M.S.M.E. from the University of Minnesota. He has worked as an engineer at Honeywell and Motorola and served as a United States Peace Corps Volunteer in Botswana, Africa, before obtaining a Ph.D. in Robotics from Carnegie Mellon University in 1995. He became a Full Professor at ETH Zurich in 2002. He was named to the 2005 “Scientific American 50,” Scientific American magazine’s annual list recognizing fifty outstanding acts of leadership in science and technology from the past year for his efforts in nanotube manufacturing. He serves on the editorial boards of several journals, has chaired several international workshops and conferences, has served as the head of the ETH Department of Mechanical and Process Engineering, the Chairman of the ETH Electron Microscopy Center (EMEZ), and is a member of the Research Council of the Swiss National Science Foundation.