NATIONAL INSTITUTE FOR MATERIALS SCIENCE

NIMS NOW INTERNATIONAL

2025 No.2

NIMS Award 2024
Exclusive Interviews
with the Recipients

RESEARCH DIGEST 2024

Research Digest

2024

NIMS released many press releases in 2024.
This issue highlights seven research achievements featuring unique materials and technologies.
It also includes exclusive interviews with the recipients of the NIMS Award 2024.
Discover the latest advancements and emerging trends in materials science!

Scan the QR code for details on each release.

2024 NIMS Press Releases

Jan. 15 **Development of a Thick-Film Conductive Ink Suitable for Large-Area, Large-Current Printed Electronics**

Jan. 16 **In-situ Observation of Nanoscale Heat Propagation**
New Electron Microscopy Technique Developed for Thermal Diffusion Measurements

Jan. 19 **Data Science Approach to Identifying Thermal Conductivity-Related Structural Factors in Amorphous Materials**
A Breakthrough in Metastable Materials Research

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A Step Forward in Developing Diamond CMOS Integrated Circuits

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Technology May Be Used to Develop Thermoelectric Devices with Simpler Structures

Mar. 27 **Proof-of-Principle Demonstration of 3-D Magnetic Recording**
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Oct. 23 **Significantly Improving Thermoelectric Module Performance Using a New Material Developed by NIMS**
Highest-Performing Records Facilitate the Development of Practical Devices

Oct. 28 **New Facility for Evaluating Hydrogen-Compatible Materials Now Complete**
Expanded Temperature and Pressure Ranges Critical for Advancing the Hydrogen Economy

Nov. 14 **Enhancing Transverse Thermoelectric Conversion Performance in Magnetic Materials with Tilted Structural Design**
A New Approach to Developing Practical Thermoelectric Technologies

Nov. 15 **New Technique for Measuring Extremely Low Metabolic Activity in Dormant Bacteria**
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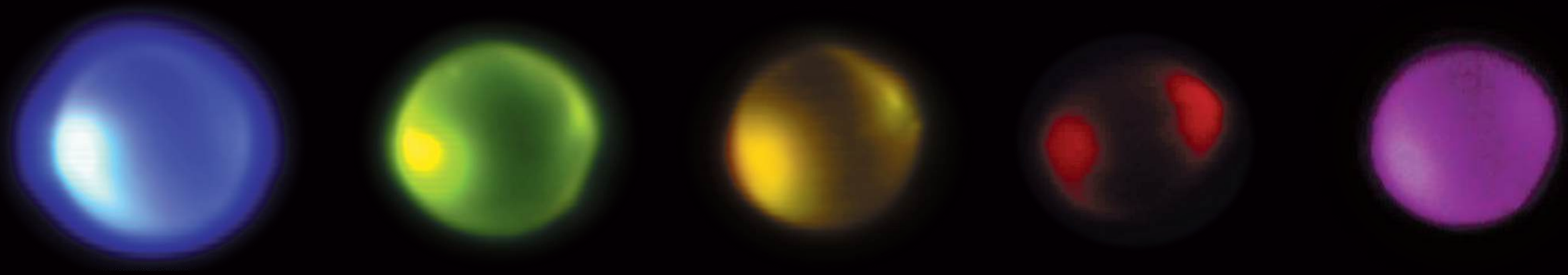


PICK UP

01 Microbeads with Luminescence from Visible to Near-Infrared Light

Vivid colors illuminating the darkness—all originating from the same particle. Dr. Tadaaki Nagao and Dr. Barun Barman have developed micrometer-sized spheres called "microbeads." These microbeads can change their luminescence color (emission wavelength) across the visible to near-infrared spectrum simply by altering the incident light (excitation wavelength). No other luminescent material is known to cover such a broad wavelength range using a single substance.

The primary components of these microbeads are naturally derived citric acid and polyamino acids. They do not contain rare metals essential for conventional luminescent materials and can be synthesized through a simple one-step heating process. Microbeads emit light due to their nanographene structure, like graphene quantum dots (GQDs) and carbon dots (CDs), which are known for their low environmental impact and excellent luminescent properties. However, microbeads offer a unique advantage: they can exist in a dry solid state. In GQDs and CDs, densely packed nanographene aggregate upon drying, leading to luminescence quenching. In contrast, microbeads maintain an optimal spatial distribution of nanographene, preserving their luminescence even in solid form.

Additionally, the luminescence mechanism of these materials involves light emitted from graphitic emission center traveling along multiple paths around the bead's surface, where it resonates to produce amplified luminescence. This phenomenon, known as the "whispering gallery mode (WGM)," causes variations in the emission spectrum depending on the unique characteristics of each bead (see Figure). This property makes microbeads promising candidates for use as identification tags. Potential applications include anti-counterfeiting inks and biomarkers.

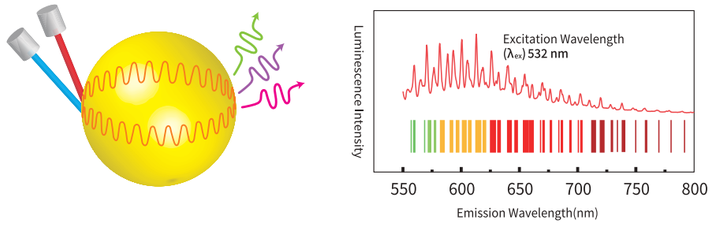
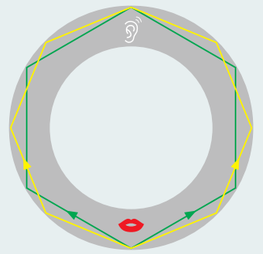


Figure: Luminescence of microbeads (left) and an example of their emission spectrum (right).
The microbeads developed by Dr. Nagao and his team change their luminescence color based on the wavelength of incident light (exitation wavelength). Their emission spectrum exhibits sharp lines due to the WGM effect, with variations in peak positions, spacing, and intensity reflecting the unique structural characteristics of each bead. This feature enables their use in a barcode-like authentication technology, where wavelength distribution corresponds to bar patterns and intensity represents bar thickness.

NOTE

Whispering Gallery Mode (WGM)

The central dome of St. Paul's Cathedral in London, with its vast 34-meter-wide interior, is known for an acoustic phenomenon where whispers near the wall can be heard on the opposite side. This occurs because, at certain frequencies, sound waves resonate and travel along the dome's walls, allowing the sound to carry over long distance. Similarly, light—an electromagnetic wave—exhibits WGM effect, where optical waves propagate along the surface of spherical materials like the microbeads.



Title
Microbeads with Adaptable Fluorescent Colors form Visible to Near-Infrared
Date: Jun. 13, 2024

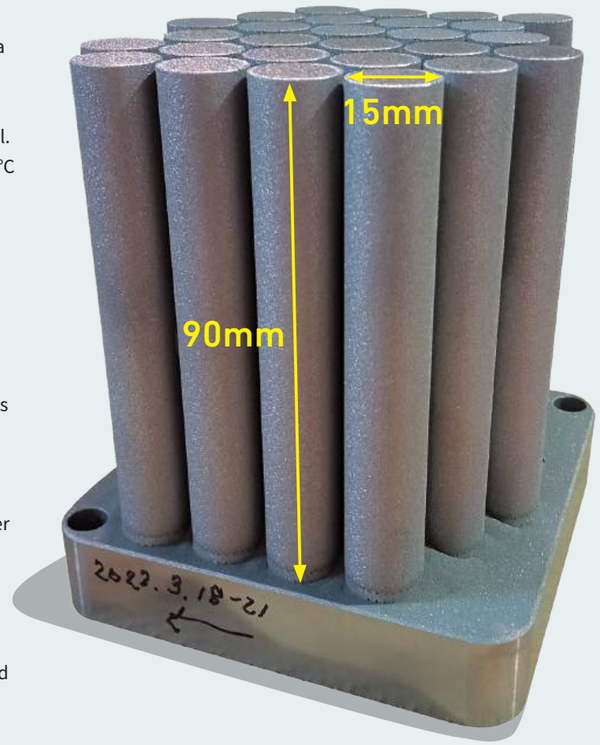
PICK UP

02 Creep Life Extended by Over 10 Times: The Heat-Resistant Steel Made with Metal 3D Printing

Metal 3D printers can directly mold complex-shaped components, but their applications for heat-resistant steel in high-temperature, high-pressure environments are limited due to insufficient data on the strength and durability. Dr. Tomotaka Hatakeyama discovered that heat-resistant steel manufactured using the “Laser Powder Bed Fusion (LPBF)” method exhibits over 10 times the creep life* of conventional heat-resistant steel. This result was obtained through a creep test conducted at 650°C for approximately 10,000 hours (about 1 year and 2 months).

Microscopic observations using an electron microscope revealed a unique microstructure predominantly composed of the ferrite phase, which enhances creep life. In conventional heat-resistant steel manufacturing, molten metal solidifies and cools, undergoing phase transformations from ferrite to austenite and then to martensite, making it difficult to obtain a microstructure dominated by the ferrite phase. So, why was this ideal microstructure achievable in this case? The answer lies in the unique process of 3D printing.

In the LPBF method, a laser is irradiated onto metal powder, causing localized melting and solidification. The molten powder cools rapidly at about 1,000,000 °C per second, freezing the ferrite phase before it transforms into other phases. This 3D printing heat-resistant steel not only enables the fabrication of complex shapes but also extends creep life. NIMS leverages long-term creep testing technology to evaluate the strength and durability of 3D printed materials, promoting standardization and widespread adoption.



Ferritic heat-resistant steel (modified 9Cr-1Mo steel) fabricated using the LPBF method.

∗ Creep life: The time it takes for a material specimen, heated to a high temperature and subjected to a constant tensile force, to reach fracture.

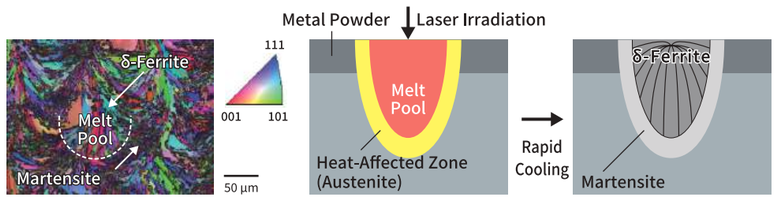
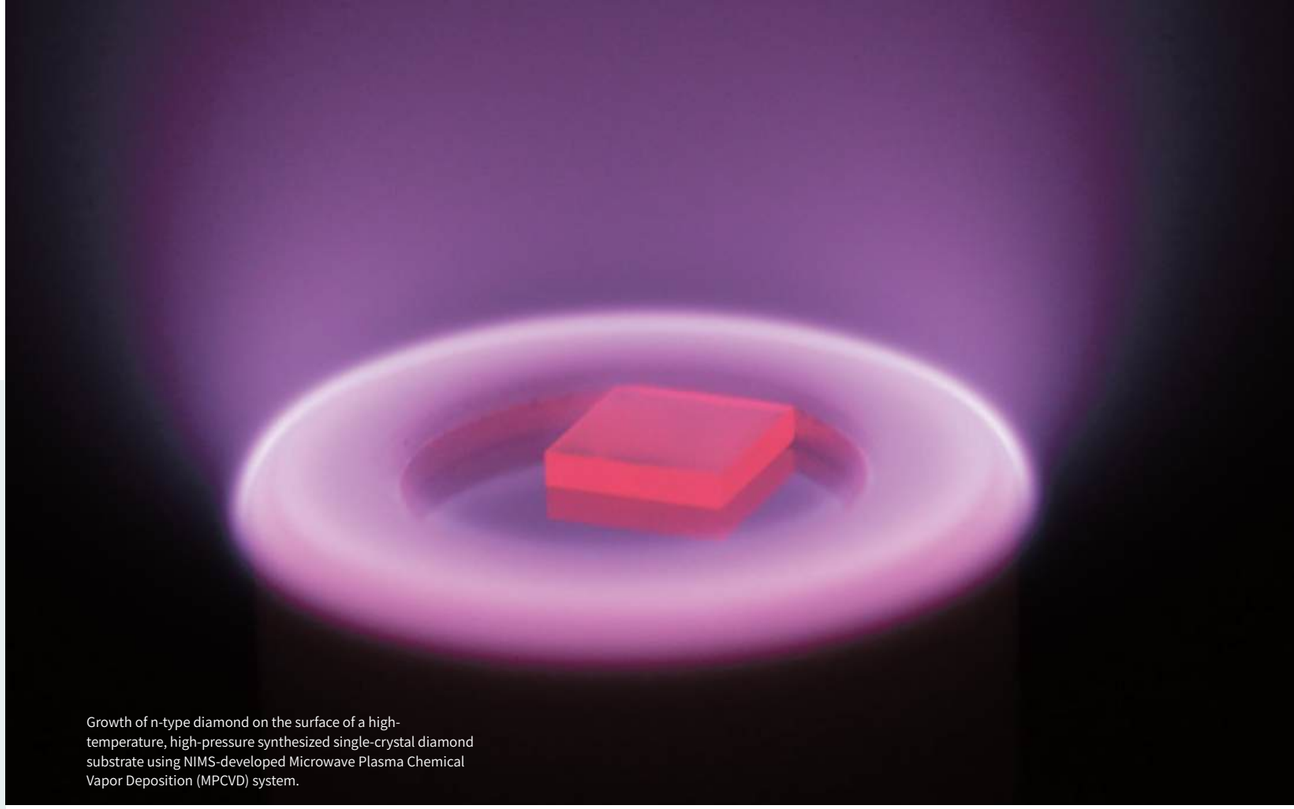


Figure: Microstructure of LPBF steel (left) and schematic diagram of microstructure formation mechanism (right).
In the melt pool formed by laser irradiation, rapid cooling and solidification lead to the formation of the ferrite phase. In the surrounding heat-affected zone, phase transformation from austenite to martensite occurs, similar to conventional heat treatment. As a result, a two-phase microstructure is formed, with the ferrite phase as the primary phase.

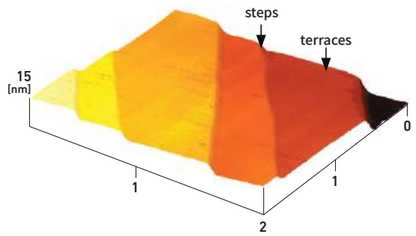
Title
Over 10-Fold Increase in Creep Life of Heat-Resistant Steel Using Metal 3D Printing
Date : Nov. 21, 2024



Growth of n-type diamond on the surface of a high-temperature, high-pressure synthesized single-crystal diamond substrate using NIMS-developed Microwave Plasma Chemical Vapor Deposition (MPCVD) system.

PICK UP

03 World’s First N-Channel Diamond Field-Effect Transistor is Developed

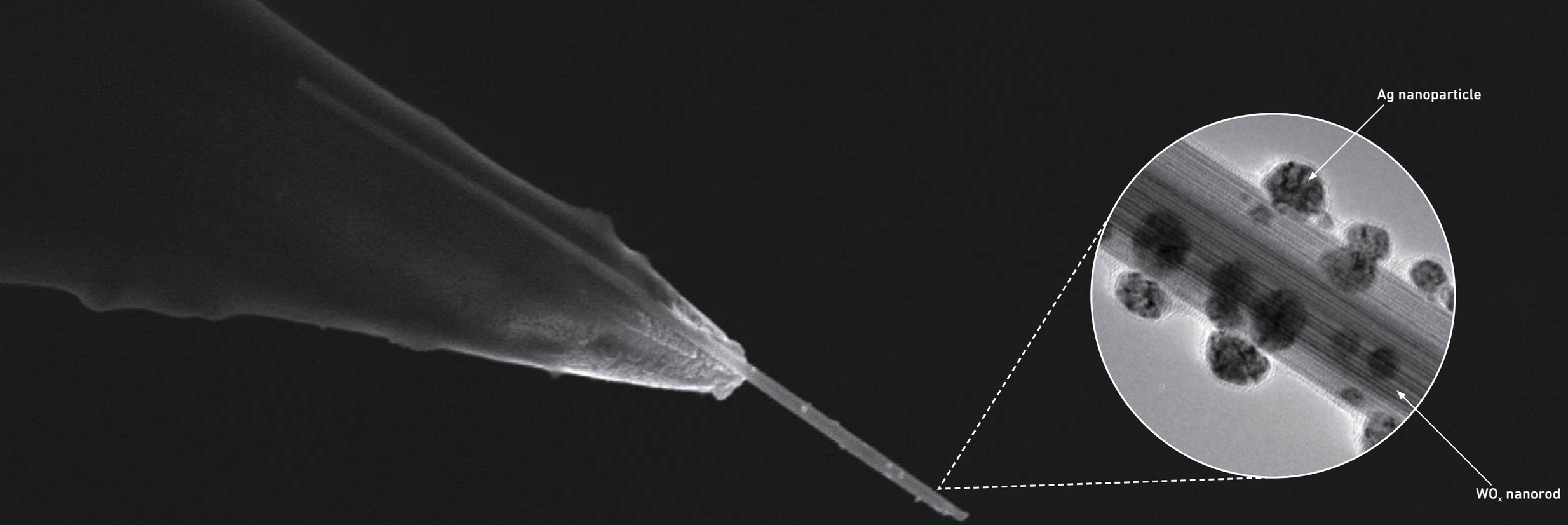


Surface of the diamond layer observed with AFM. To obtain a high-quality diamond crystal with minimal defects, the “step-flow method” was employed, in which a diamond crystal was grown on a vicinal substrate. The image clearly shows the formation of atomically flat terraces and steps.

Diamonds, renowned for their brilliance, are also emerging as promising semiconductor materials for next-generation power devices and integrated circuits (ICs), capable of operating even under extreme conditions. Mainstream ICs are predominantly based on CMOS technology, which incorporates Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) with two types of conductive channels: p-type and n-type. However, in diamond-based devices, the development of n-type channel MOSFETs was long considered unachievable, making diamond transistors an elusive dream.

Dr. Satoshi Koizumi and his team have achieved a groundbreaking milestone by developing the world’s first n-type diamond MOSFETs. This breakthrough was made possible through advanced technologies at NIMS. By utilizing high-quality n-type single-crystal growth techniques, the team successfully implemented high-precision phosphorus doping essential for forming n-type channels and defect-free, atomically flat surfaces. As a result, the contact resistance between the electrodes and the semiconductor was reduced, ensuring high conductivity. Potential applications for this technology include sensors for radiation environments. The team continues to optimize the MOSFET structure and aims to develop diamond CMOS circuits. In the future, diamond is expected to play an even greater role in enhancing our daily lives.

Title
World’s First N-Channel Diamond Field-Effect Transistor
Date : Jan. 25, 2024



PICK UP

04 Organic Molecules That "Think" Accurately Predict Blood Glucose Fluctuations

Numerous particles are attached to the tip of a thin rod. It may be hard to imagine that this serves as a "stage for thinking." However, when information is given as a physical stimulus, this system as a whole can indeed generate meaningful outputs.

In recent years, research on physical reservoir computing —where materials perform AI computations—has gained attraction. This approach offers significantly lower power consumption than conventional neural networks. Dr. Takashi Tsuchiya's team has developed an AI-based predictive device using tungsten oxide (WO_x) nanorod electrodes modified with silver nanoparticles.

The prediction process involves immersing the nanorod in a sodium chloride electrolyte containing dissolved p-Mercaptobenzoic Acid (pMBA) molecules and applying voltage (see Figure 1). This induces subtle vibrational changes in pMBA molecules adsorbed onto the silver nanoparticles. These changes are detected as Raman spectra via surface-enhanced Raman scattering (SERS), and a dedicated algorithm analyzes the time-dependent spectral variations to generate predictive outputs (see Figure 2).

To validate its accuracy, Dr. Tsuchiya's team converted approximately 20 hours of diabetic patients' blood glucose data into voltage signals and input them into the nanorods. The device predicted blood glucose fluctuations over a 5-minute period, producing output waveforms closely matching actual variations. This study is the first demonstration of a physical reservoir's effectiveness using only a few organic molecules.

Title
High-Precision Blood Glucose Level Prediction Achieved by Few-Molecule Reservoir Computing
Date : Feb. 29, 2024

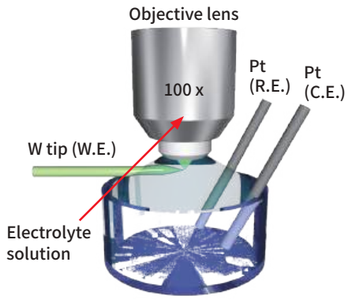


Figure 1: Three-electrode electrochemical cell used in this study
A tungsten chip with a tungsten oxide nanorod at its tip was used as the working electrode (W.E.), with a platinum electrode serving as both the reference (R.E.) and counter electrode (C.E.).

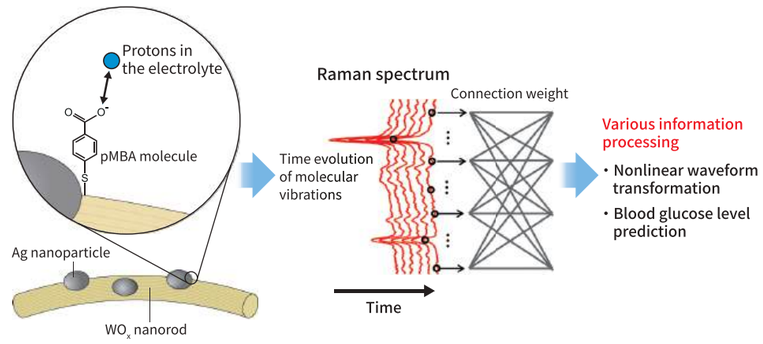
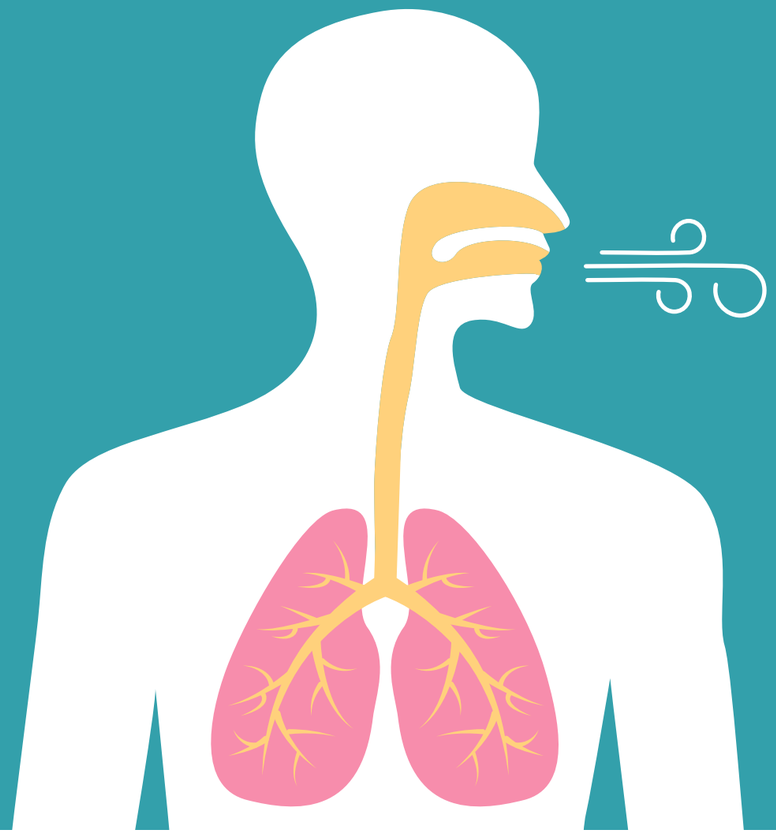
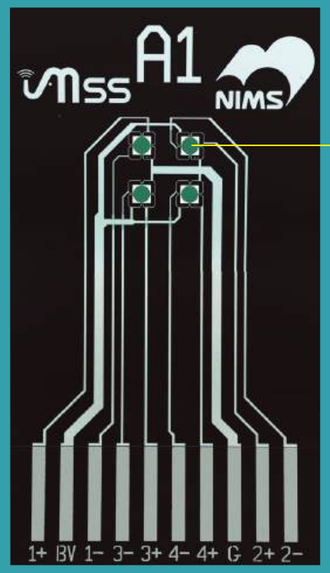
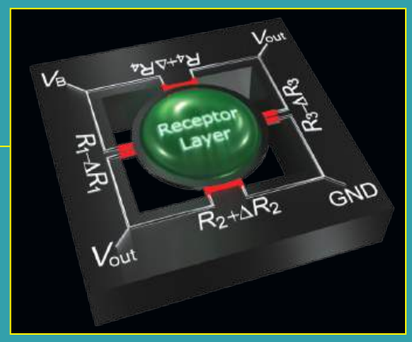


Figure 2: Mechanism of information input and prediction process in a "physical reservoir" using organic molecules
The vibration of pMBA molecules depends on the amount of hydrogen ions adsorbed onto the pMBA molecules. In the device developed by Dr. Tsuchiya and his team, the adsorption of hydrogen ions is controlled by applying voltage (corresponding to information input). The time-dependent changes in molecular vibration detected as Raman spectra were used for information storage and computation.





Four-channel MSS chip



Schematic of the MSS element
The central circular membrane is coated with a receptor layer tailored to the target molecules. When molecules adsorb onto the layer, surface stress deforms the membrane. The four surrounding bridges (red) contain piezoresistive elements that detect this deformation as a change in electrical resistance.

PICK UP

05 A Breakthrough in Cancer Diagnosis: Exploring the Potential of Breath Analysis for Predicting Lung Cancer

Imagine detecting lung cancer simply by exhaling into a small device. Efforts are underway to turn this innovative diagnostic approach into reality. The key lies in the “scent” of exhaled breath.

Breath contains a complex mixture of molecules and serves as a valuable source of information. While specially trained dogs have demonstrated the ability to detect cancer through scent, a practical breath-based screening method has yet to be developed. The complexity of breath components, influenced by environmental and individual factors, makes identifying reliable biomarkers challenging. To address this, Prof. Yukio Sato of the Department of Thoracic Surgery at the University of Tsukuba Hospital turned to the Membrane-type Surface stress Sensor (MSS), an odor sensor primarily developed at NIMS. A collaborative project involving the University of Tsukuba, NIMS, and Ibaraki Prefectural Central Hospital aims to evaluate its potential for lung cancer screening through breath analysis.

The study examined breath samples from 66 lung cancer patients, collected before and after surgery. Prof. Sato’s research team carefully gathered the samples in a temperature- and humidity-controlled room, following a protocol developed by the collaborative team. The NIMS team then analyzed the MSS response signals and built machine learning models. The results indicated that lung cancer could be detected with over 80% accuracy (see Figure). However, further verification is required, such as identifying the specific molecules associated with cancer. The research team continues to refine this method, working toward a future where cancer screening is simple and reliable for everyone.

Yusuke Saeki,et al., Lung cancer detection in perioperative patients' exhaled breath with nanomechanical sensor array, Lung Cancer, April 2024

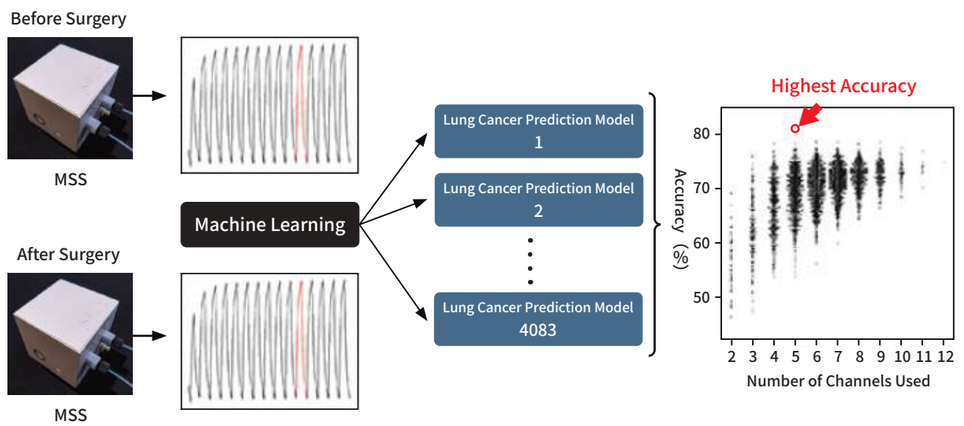


Figure : Twelve MSS sensor channels were prepared, each responding differently to components in exhaled breath. A machine learning model was built and tested using various combinations of all channels (4,083 patterns). The results demonstrated that lung cancer presence could be predicted with a maximum accuracy of 80.9%, sensitivity of 83.0%, specificity of 80.7%, positive predictive value of 80.6%, and negative predictive value of 81.2%.

PICK UP

06 Magnetic “Twin” in Virtual Space: The Birth of a “Digital Twin”

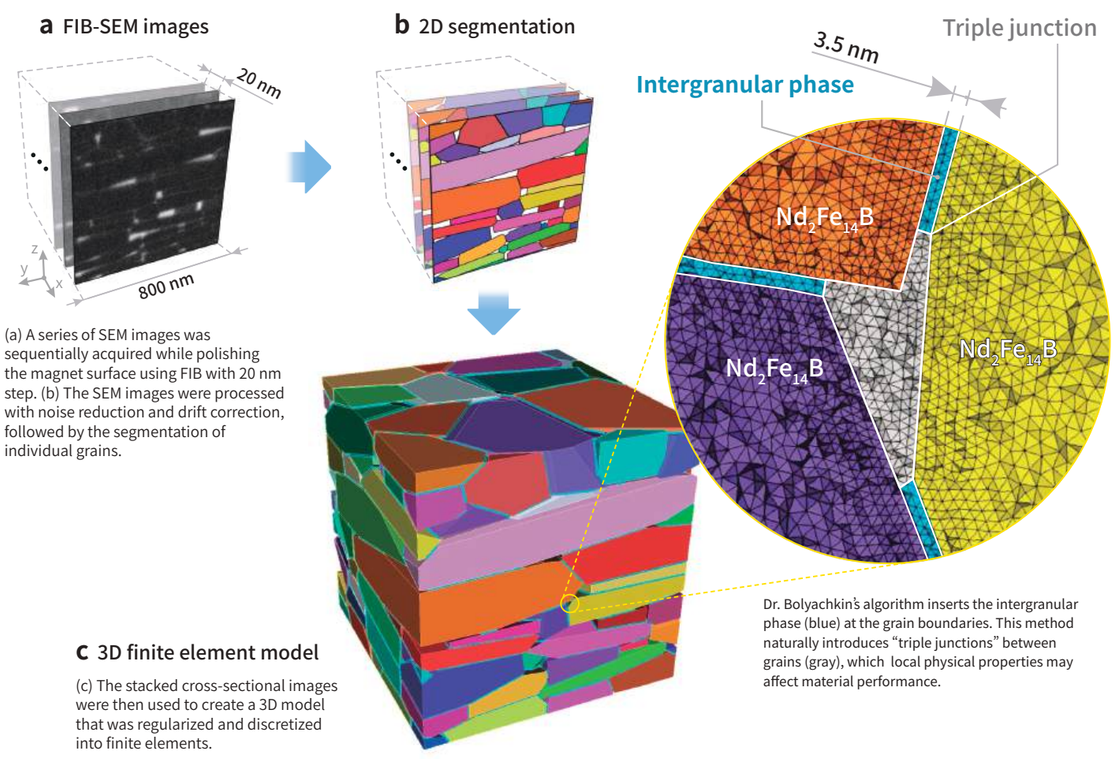
Title
Tomography-based Digital Twins of Nd-Fe-B Magnets
Date: Mar. 6, 2024

Neodymium magnets are crucial in industry and applications such as motors of electric/hybrid vehicles, although their coercivity remains only about 20% of its theoretical limit. To enhance performance, understanding the correlation between magnetic properties and microstructure is essential. However, numerical simulations, which are expected to support material development, have yet to achieve practical-level accuracy, posing a barrier to progress.

To tackle this, Dr. Anton Bolyachkin and his team developed a new approach to improve the accuracy of simulations. They used a Scanning Electron Microscopy in combination with Focused Ion Beam (FIB-SEM) to obtain tomographic set of 2D images of the neodymium magnet (see Figure a, b) and built a large-scale finite element model based on it. The finite element method (FEM) is a computational technique that divides an object into numerous small tetrahedral elements (finite elements) and solves certain mathematical equations for each of the elements.

One of the challenges was to reconstruct ultra-small microstructural features that are below the SEM resolution. The coercivity of a magnet is strongly influenced by the “intergranular phase,” an amorphous magnetic layer just of 2–4 nanometers thickness. To overcome this, Dr. Bolyachkin developed an algorithm that constructs a 3D microstructure based on the set of segmented 2D images, then identifies grain boundaries in this microstructure, and inserts the intergranular phase (see Figure c). He also applied geometry regularization to ensure high-quality tetrahedral elements, required for reliable simulations. This breakthrough enabled the creation of a “digital twin*” of the neodymium magnet, allowing accurate simulations of demagnetization and pinning effects. This method is also applicable to other polycrystalline materials and is expected to become a powerful tool for materials development.

* Digital Twin: A technology that replicates a physical object in a virtual space as a digital model based on real-world data with all essential features.



(a) A series of SEM images was sequentially acquired while polishing the magnet surface using FIB with 20 nm step. (b) The SEM images were processed with noise reduction and drift correction, followed by the segmentation of individual grains.

(c) The stacked cross-sectional images were then used to create a 3D model that was regularized and discretized into finite elements.

Dr. Bolyachkin’s algorithm inserts the intergranular phase (blue) at the grain boundaries. This method naturally introduces “triple junctions” between grains (gray), which local physical properties may affect material performance.

PICK UP

NEWS from NIMS Joint Graduate School Program

07 New Start-up Support System Established to Assist Doctoral Students

The NIMS Joint Graduate School Program provides students with the opportunity to pursue degrees in cutting-edge research environments. Since 2004, NIMS researchers have served as faculty members, mentoring graduate students through to degree completion. Currently, NIMS has joint agreements with seven universities: University of Tsukuba, Hokkaido University, Yokohama National University, Osaka University, Kyushu University, Waseda University, and starting in April 2025, students from Institute of Science Tokyo will also be accepted.

A key feature of this program is the NIMS Graduate Research Assistantship, which employs students as NIMS Junior Researchers, allowing them to focus on their research without financial concerns. However, entrance fees and other university-related costs remain a significant barrier for many students when deciding their academic path. To address this issue, NIMS has launched a new support system that provides newly hired NIMS Junior Researchers with a one-time Start-up Support Grant of 300,000 JPY in addition to their salary. Starting in April 2025, this initiative will expand opportunities for students who might otherwise forgo a doctoral degree due to financial constraints. NIMS remains committed to advancing materials science by fostering the next generation of researchers.

NIMS Official Website
NIMS Joint Graduate School Program

Researchers List

01
Tadaaki Nagao
Group Leader
Photonics Nano Engineering Group
Research Center for Materials Nanoarchitectonics

02
Tomotaka Hatakeyama
Researcher
Creep Property Group
Research Center for Structural Materials

03
Satoshi Koizumi
Group Leader
Ultra-wide Bandgap Semiconductors Group
Research Center for Electronic and Optical Materials

04
Takashi Tsuchiya
Group Leader
Neuromorphic Devices Group
Research Center for Materials Nanoarchitectonics

05
Genki Yoshikawa
Group Leader
Olfactory Sensors Group
Research Center for Macromolecules and Biomaterials

06
Anton Bolyachkin
Researcher
Green Magnetic Materials Group
Research Center for Magnetic and Spintronic Materials

NIMS AWARD
National Institute for Materials Science

Interview with the 2024 Award Recipients

Exclusive interviews with the recipients recognized for outstanding achievements in the field of basic materials science.

Contribution to Material Interface Research through Innovations in Transmission Electron Microscopy

Prof. Yuichi Ikuhara

Distinguished Research Professor
Institute of Engineering Innovation, School of Engineering, The University of Tokyo

Research Summary

Prof. Yuichi Ikuhara pioneered innovative TEM-based material measurement techniques, enabling precise analysis of atomic structures, electronic states, and trace elements at grain boundaries and interfaces. He developed electron energy loss spectroscopy (EELS) and energy-dispersive X-ray spectroscopy (EDX) methods for analyzing local chemical compositions and states. By combining these techniques with theoretical calculations, he quantitatively evaluated the atomic structures and electronic states at grain boundaries, interfaces, and dislocations. Collaborating with manufacturers, he integrated a new spherical-aberration corrector with a 300 kV electron microscope, achieving the world's highest resolution in STEM. He also developed the annular bright-field (ABF) STEM detector, pioneering the visualization of light elements such as hydrogen and lithium. These innovations have been commercialized, driving advances in materials science.

—How do you feel about receiving this award?

I am truly delighted that electron microscopy has been recognized among the many nanoscale measurement techniques. It is an honor to share this recognition with Prof. Giessibl, awarded for his work with AFM, another powerful imaging technique. I hope this will further promote its adoption across a wider range of material science fields. I am deeply grateful to my lab staff, graduate students, and collaborators whose dedicated efforts made this achievement possible.

—What has been the driving force behind developing "eyes" at the atomic level and achieving world-first observations?

My primary motivation has always been to fundamentally understand material properties and physical phenomena. When studying mechanical properties, I consistently focused on the key factors that determine strength. Material properties, including strength, are closely linked to atomic structures and electronic states at lattice defects, such as grain boundaries and dislocations on the nanometer scale. I have always sought to clarify these correlations. In ceramics research, directly observing light elements is crucial. For instance, the distribution of oxygen and nitrogen significantly influences the properties of oxides and nitrides, while the behavior of lithium and hydrogen atoms is critical in functional materials, such as batteries. This motivation led me to develop techniques for local structural and state analysis, deepening my understanding of fundamental mechanisms behind various phenomena.

—How do you envision the future of analytical techniques, and what are your goals moving forward?

TEM has achieved sub-angstrom spatial resolutions, enabling direct observation of atoms and localized measurements of electronic states and chemical compositions. It also allows precise lattice constant measurements, electric and magnetic field observations, low-electron-dose imaging, cryo-electron microscopy, and 3D observations. The next step is to achieve "high-resolution in-situ observation" of time-dependent phenomena in real-world environment, including temperature, stress, electric and magnetic fields, and atmospheric conditions. This is crucial for nanoscale measurement. My goal is to recreate real operating environments within the TEM for higher resolution and faster observation of dynamic phenomena. By doing so, I aim to uncover fundamental mechanisms behind material behaviors and contribute to the development of advanced, high-performance materials.

Contribution to Nanomaterial Research through Innovations in Non-contact Atomic Force

Prof. Franz J. Giessibl

Chair for Quantum Nanoscience
Institute of Experimental and Applied Physics
University of Regensburg, Germany

Research Summary

Prof. Franz J. Giessibl demonstrated atomic force microscopy (AFM) with atomic resolution in a vacuum for the first time. The non-contact method he established detects minute atomic force changes between the probe and the sample without contact and without damaging the sample on an atomic scale. He then developed the highly rigid "tuning fork sensor (qPlus Sensor)," enabling smaller oscillation amplitudes than conventional cantilever-type sensors, enhancing the precision of short-range force measurements and high-contrast atomic imaging. The qPlus Sensor also self-senses atomic force changes, allowing its use in low-temperature environments and enabling the observation of internal molecular structures. Today, the qPlus Sensor is widely used in AFM systems operating under low-temperature and ultrahigh-vacuum conditions. In addition to his experimental achievements, Prof. Giessibl has significantly advanced nanoscience by proposing essential theories for high-resolution measurements.

—How do you feel about receiving this award?

I am truly honored to receive this prestigious award from NIMS, renowned for its technological and scientific excellence. I am also deeply grateful to receive a medal crafted using the same ethical gold recycling method as the Tokyo 2021 Olympic Gold Medals. This holds special meaning for me because, in 2021, while training for a triathlon in Thailand, I met the coach of the Australian swimming team, who led his athletes to win gold medals at the Tokyo Olympics. Witnessing these world-class athletes push their limits was incredibly inspiring. Receiving a medal crafted using the same ethical process fills me with an extra portion of joy and gratitude.

—Could you share the background and development process of the qPlus Sensor? How did you achieve high-resolution observations?

After obtaining my PhD, I joined Park Scientific Instruments (PSI) in California, where I achieved atomic resolution imaging of the Si(111)-(7×7) surface using AFM. I realized that reducing the oscillation amplitudes of the piezoresistive silicon cantilever to atomic diameters could achieve higher-contrast atomic images, but this required greater cantilever stiffness. When I asked Prof. Quate at Stanford University about this, he responded, "It is possible, but it would require a budget of about $60,000." At that time, I did not have such a budget, and I was also considering finding a new detection method with less Joule heating than the conventional piezoresistive method, aiming to operate at low temperatures.

In my next career step as a management consultant at McKinsey, I conducted numerous benchmarking studies. This triggered the question whether other fields also required stable frequency measurements outside of frequency modulation AFM. I found the answer in the long-established field of timekeeping technology. I particularly focused on timekeeping developments during the "Quartz Revolution" of the 1970s. Quartz watches use a U-shaped quartz tuning fork sealed in a vacuum metal can, generating alternating current proportional to oscillation amplitude without producing heat, ideal for low-temperature operations.

I disassembled a quartz watch and found its tuning fork had the ideal stiffness for my needs. To explore its application in AFM, McKinsey granted me paid and unpaid leave for theoretical investigations and preliminary experiments at home. The results confirmed the concept, leading to the development of the qPlus Sensor. Later, as a research staff member at the University of Augsburg in Germany, I modified a used vacuum AFM from PSI for qPlus operation. We soon demonstrated that the qPlus AFM could resolve not only individual atoms but also the electron clouds within them.

—What are your future goals?

My objectives are to study novel materials and artificial quantum structures on the atomic scale, to adapt qPlus AFM for atmospheric and electrochemical environments, and to simplify AFM systems for wider access to atomic and sub-atomic resolution. At the newly established Regensburg Center for Ultrafast Nanoscopy (RUN), we develop observation methods with ultra-high spatial and ultra-fast temporal resolution, aiming to study effects like bond formation and friction on an ultrafast timescale. These efforts aim to enhance AFM technology's accessibility and applicability, empowering more researchers to explore atomic-scale phenomena.

Launch of the Online Edition of NIMS NOW

Thank you for your continued readership of NIMS NOW, the public relations magazine of NIMS.

We are pleased to announce that NIMS NOW will launch its online edition in July 2025, making it more accessible to a wider audience. The online edition will be available in both Japanese and English, featuring not only the latest articles but also an archive of past issues, which will be gradually released for on-demand access at any time.

With the transition to the online edition, the print version of *NIMS NOW International* will be discontinued.
We kindly ask you to switch to the online edition.

Update info for the online edition will be announced through the NIMS official website, NIMS e-Newsletter, and NIMS social media accounts.

—— NIMS NOW Editorial Team

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