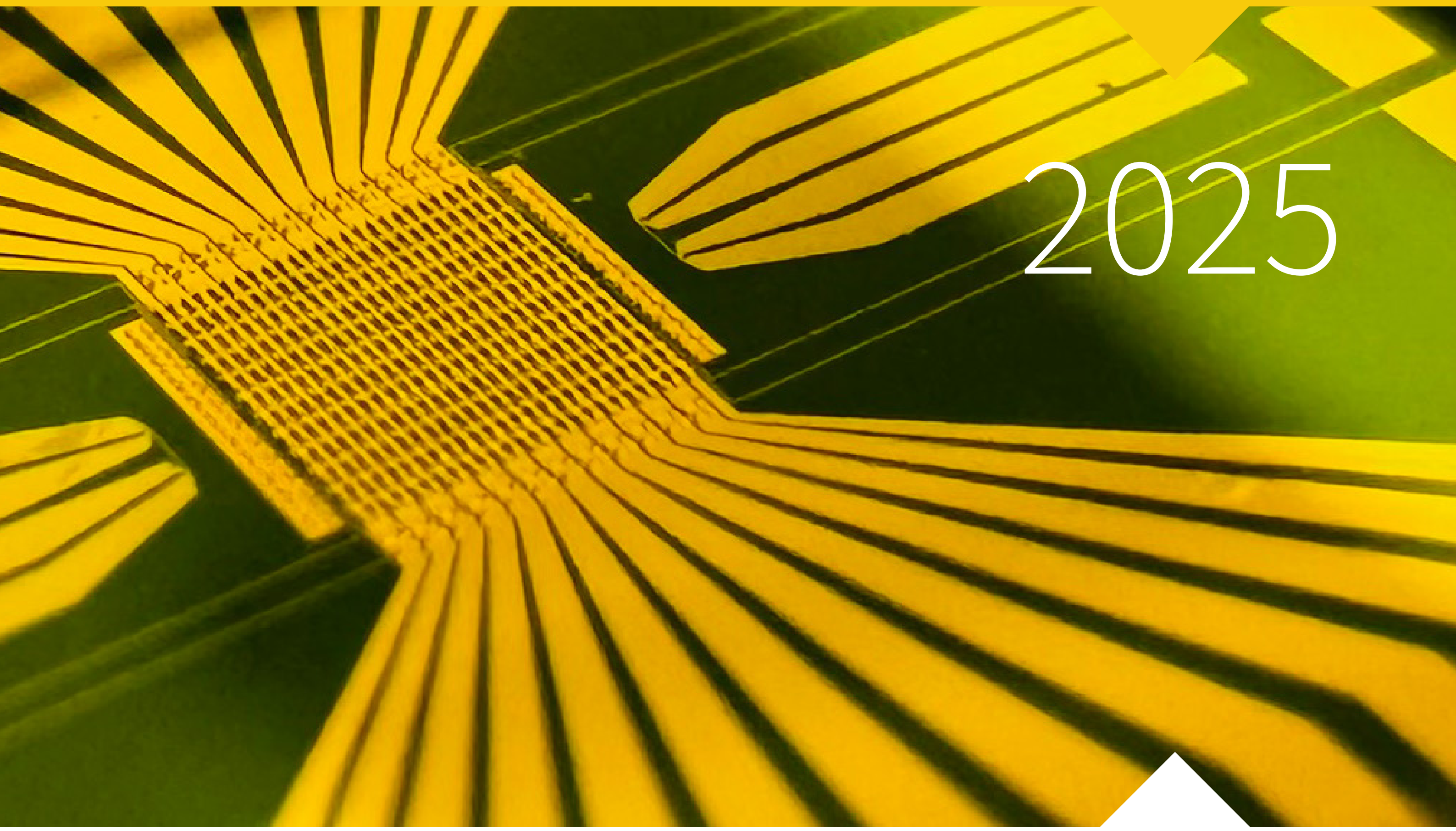
Jahresbericht
Annual Report

2025



Leibniz-Institut
für Festkörper- und
Werkstoffforschung
Dresden

Bild Umschlagseite: Mikrothermoelektrischer Generator auf einem Silizium/Siliziumdioxid-Substrat. Der Generator dient der Umwandlung thermischer Gradienten in elektrische Energie. Die Aufnahme gewann 2025 den 2. Preis im internen Fotowettbewerb. Fotograf: Adhiraj Sundar.
Cover image: Micro-thermoelectric generator on a silicon–silicon dioxide substrate. The generator is used to convert thermal gradients into electrical energy. The photograph won 2nd prize in the internal photo competition in 2025. Photographer: Adhiraj Sundar.

Im Jahr 2025 feierte die gesamte Leibniz-Gemeinschaft ihren 30. Jahrestag. Die gelebte Interdisziplinarität und der Austausch unterschiedlicher Perspektiven sind nicht nur wissenschaftlich, sondern auch für die Gestaltung unserer Lebenswirklichkeit so bereichernd wie unverzichtbar. Im Bild: Unser social media post zu 30 Jahren Leibniz-Gemeinschaft.
In 2025, the entire Leibniz Association celebrated its 30th anniversary. The lived practice of interdisciplinarity and the exchange of diverse perspectives are enriching and indispensable—not only for science, but also for shaping the reality of our everyday lives. In the image: Our social media post marking 30 years of the Leibniz Association.

Liebe Leserinnen und Leser,

unser wissenschaftlicher Anspruch verbindet exzellente Forschung mit gesellschaftlicher Relevanz. Beides entsteht nicht im Alleingang – Forschung ist Teamarbeit. Sie lebt von der Neugier unserer Forschenden genauso wie von einer leistungsfähigen Infrastruktur und den Menschen, die diese planen, am Laufen halten, weiterentwickeln und kontrollieren. Trotz oder gerade in Zeiten, in denen Künstliche Intelligenz neue Maßstäbe setzt, ist menschliche Expertise verbunden mit visionärem Denken unabdingbar.
Als visionär galt vor 100 Jahren auch die Beschreibung der Quantenmechanik – ein Meilenstein, der zeigt, wie nachhaltig neues Wissen unsere Welt prägen kann. Mit dem Internationalen Jahr der Quantenphysik 2025 haben wir diesen Fortschritt weltweit gefeiert.
Wir wünschen eine erkenntnisreiche Lektüre.
Mit herzlichen Grüßen

Dear readers,

Our scientific mission combines excellence in research with societal relevance. Neither can be achieved alone – research is a team effort. It thrives on the curiosity of our researchers just as much as on a strong infrastructure and the people who plan it, keep it running, continuously develop it, and ensure its quality. Especially in times when artificial intelligence is setting new standards, human expertise paired with visionary thinking remains indispensable.
A century ago, the description of quantum mechanics was also regarded as visionary – a milestone that shows how profoundly new knowledge can shape our world. With the International Year of Quantum Science and Technology 2025, we celebrated this progress worldwide.
We wish you an insightful read.
Best wishes

Juliane Schmidt, Kaufmännische Direktorin und Prof. Dr. Bernd Büchner, Wissenschaftlicher Direktor.
Juliane Schmidt, Administrative Director and Prof. Dr. Bernd Büchner, Scientific Director.

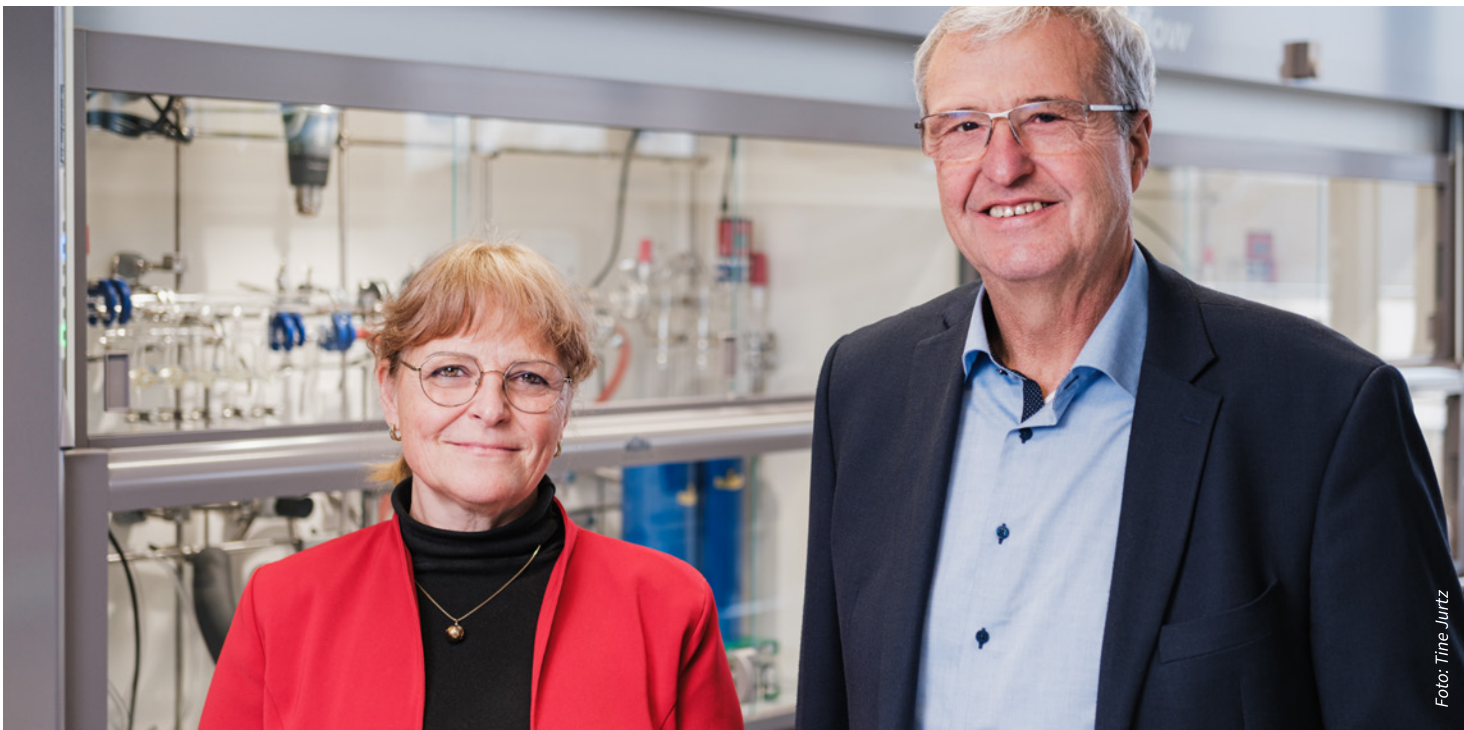


Foto: Tine Jurtz

Annual Report 2025

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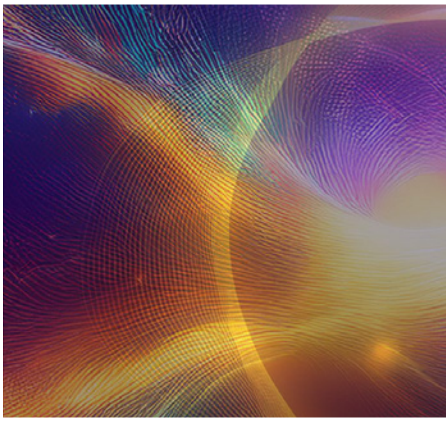


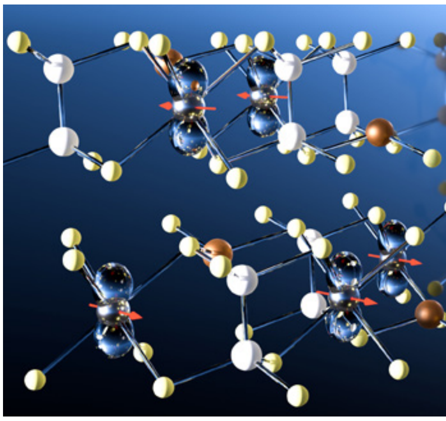


Foto: Sven Döring

Jahresrückblick 2025

Das IFW Dresden erlebte im Jahr 2025 eine wichtige Phase der Konsolidierung und strategischen Weiterentwicklung. Mit Blick auf die 2028 anstehende Leibniz-Evaluation und vor dem Hintergrund neuer großer Netzwerke und Projekte sowie kontinuierlicher Fortschritte bei der Infrastrukturentwicklung konnten wir unsere wissenschaftliche Exzellenz, unsere gesellschaftliche Relevanz sowie die interne Zusammenarbeit weiter stärken.
Diese Erfolge wären nicht möglich gewesen ohne unsere Einbindung in starke lokale Netzwerke mit Universitäten, Forschungseinrichtungen und Industriepartnern sowie in internationale Kooperationen. Wir danken unseren Zuwendungsgebern und Förderorganisationen für ihr Vertrauen und ihre finanzielle Unterstützung unserer Arbeit. Unser besonderer Dank gilt allen Mitarbeitenden des IFW Dresden – den Forschenden einschließlich des wissenschaftlichen Nachwuchses, dem wissenschaftsunterstützenden und technischen Personal sowie den Beschäftigten in der Verwaltung. Ihr Engagement, ihre Kreativität und ihr Teamgeist bilden das Fundament der wissenschaftlichen Leistungsfähigkeit des IFW Dresden.

Strategische Weichenstellungen und zentrale Meilensteine

in zentrales Ereignis des Jahres 2025 war die Entscheidung über die Exzellenzcluster-Anträge. Die Beteiligung des IFW Dresden an zwei erfolgreichen Exzellenzclustern der Technischen Universität Dresden – „Complexity, Topology and Dynamics in Quantum Matter“ (ctd.qmat, zweite Förderperio-

Review of 2025

IFW Dresden marked 2025 as an important phase of consolidation and strategic development. Against the backdrop of major evaluations, new large-scale projects, and ongoing infrastructural progress, we further strengthened our scientific excellence, societal relevance, and internal collaboration.

These achievements would not have been possible without the strong support and commitment of our partners, sponsors, and collaborators.
We gratefully acknowledge the trust and funding provided by our national and European funding organizations, as well as the excellent cooperation with universities, research institutions, industry partners, and networks at regional, national, and international levels. Above all, IFW Dresden thanks its co-workers – researchers, engineers, technicians, administrative staff, and early-career scientists – whose dedication, creativity, and teamwork form the foundation of our success. Their daily commitment and shared responsibility continue to drive the institute’s scientific excellence and societal impact.

Strategic Outlook and Key Milestones

A central event in 2025 was the decision on the Excellence Cluster applications. IFW Dresden’s involvement in two Excellence Clusters at TU Dresden — “Complexity, Topology and Dynamics in Quantum Matter” (ctd.qmat, 2nd funding period) and “Responsible Electronics in the Climate Change Era” (REC², a new cluster

Links: Supraleitende Materialien sind seit der Gründung des Instituts Gegenstand unserer Forschung. Supraleitung – also elektrischer Stromfluss ohne Widerstand – tritt nur in bestimmten Materialien und unter speziellen Bedingungen auf. Einen unserer Schwerpunkte bildet derzeit die Erforschung von Platin-Bismut, da es vielversprechende Eigenschaften für mögliche zukünftige Anwendungen in der Quantentechnologie aufweist. Abgebildet ist das keramische Material Yttrium-Barium-Kupferoxid (YBCO), das im tiefkalten Zustand bei -196° Celsius supraleitend wird.

Left: Superconducting materials have been a focus of our research since the institute was founded. Superconductivity — the flow of electrical current without resistance — occurs only in certain materials and under specific conditions. One of our current research focuses is the study of platinum bismuth, as it shows promising properties for potential future applications in quantum technologies. The image shows the ceramic material Yttrium barium copper oxide (YBCO), which becomes superconducting at low temperatures of −196 ° Celsius.

de) sowie „Responsible Electronics in the Climate Change Era“ (REC², neues Cluster unter der Koordination von Yana Vaynzof) – stellt einen bedeutenden Schritt für unsere langfristige Positionierung sowohl in den lokalen Netzwerken als auch in der deutschen Forschungslandschaft dar.

Zur weiteren Stärkung der interdisziplinären Zusammenarbeit innerhalb des Instituts beschloss das Direktorium des IFW mehrere strategische Maßnahmen zur Schärfung unseres Forschungsprofils. Dazu zählen neun Forschungsthemen mit großem Potenzial für eine breite Beteiligung verschiedener IFW-Gruppen, darunter Projekte in den Bereichen Quantenmaterialien und topologische Physik sowie eine verstärkte Grundlagenforschung zu Thermoelektrika und akustischen Oberflächenwellen. Besondere Schwerpunkte legten wir zudem auf neue Forschungsfelder wie Altermagnetismus, neuartige topologische Supraleiter und maschinelle Lernmethoden in der Materialwissenschaft. Parallel dazu initiierten

coordinated by Yana Vaynzof) — represents a crucial step for our long-term positioning within local networks as well as in the German research landscape.

In order to enhance interdisciplinary collaboration across the organizational units of the institute, the Board of Directors of IFW Dresden decided on several strategic measures to further sharpen our research profile, including nine emerging topics with strong potential for broad involvement of various IFW research groups. These included large collaborative projects in quantum materials and topological physics, as well as increased fundamental research on thermoelectrics and surface acoustic waves. We placed particular emphasis on emerging fields such as altermagnetism, new topological superconductors, and machine-learning methods in materials science. In parallel, we launched a bottom-up process that generated new ideas for cooperative

Schnittstelle zwischen Forschung und Anwendung: Der Bereich Forschungstechnik mit rund 50 Mitarbeitenden ist zentraler Bestandteil der Forschungsinfrastruktur des IFW Dresden. Hier werden hochspezialisierte Geräte und technische Lösungen für Schlüsseltechnologien wie Wasserstofftechnik sowie Vakuum- und Kryotechnik entwickelt und betrieben – darunter auch die institutseigene Heliumverflüssigungsanlage. Im Bild zu sehen ist die Halle mit der gelben Sammelblase für bereits verwendetes Helium aus den Laboren.
Interface between research and application: With around 50 employees, the Research Technology department is a central part of IFW Dresden’s research infrastructure. It develops and operates highly specialized equipment and technical solutions for key technologies such as hydrogen technology as well as vacuum and cryogenic engineering—including the institute’s own helium liquefaction plant. The photo shows the helium hall with the yellow collection balloon for used helium returned from the laboratories.

Foto: Sven Döring

wir einen Bottom-up-Prozess, aus dem neue Ideen für kooperative Projekte hervorgingen. Nach Begutachtung und Priorisierung durch den Wissenschaftlichen Beirat erhielten drei dieser Projekte eine zusätzliche Förderung.

Ein weiterer wichtiger Meilenstein war das erfolgreiche gemeinsame Berufungsverfahren mit der HTW Dresden für die zukünftige Leitung des Bereichs Forschungstechnik. Mit dem Amtsantritt von Prof. Baumann im September 2025 sichern wir nicht nur die Kontinuität nach dem Ruhestand des bisherigen Bereichsleiters, sondern bauen zugleich die wissenschaftliche Zusammenarbeit sowie die gemeinsame Nutzung von Laborinfrastrukturen zwischen IFW Dresden und HTW Dresden deutlich aus.

Im Jahr 2025 fand zudem die turnusmäßige Evaluation ausgewählter Forschungsthemen durch den Wissenschaftlichen Beirat statt. Die Bewertung fiel sehr positiv aus und würdigte insbesondere unsere

projects. After evaluation and ranking by the Scientific Advisory Board, three of these projects received additional funding.

Another important milestone was the successful joint appointment procedure with HTW Dresden for the new Head of the Research Technology Division. Starting in September 2025, this appointment not only ensures continuity after the retirement of the former division head, but also significantly expands scientific cooperation and shared laboratory infrastructure between IFW Dresden and HTW Dresden.

In 2025, IFW Dresden underwent a Scientific Advisory Board (SAB) evaluation of selected research topics as part of the regular evaluation cycle required for Leibniz funding. The SAB provided a very positive assessment, highlighting our strong scientific performance, strategic development, and outstanding success in acquiring

Das neu eingerichtete Labor im Südflügel des IFW Dresden ist mit modernster Robotertechnologie ausgestattet und wird künftig wichtige experimentelle Untersuchungen an Perowskit-Materialien für zukünftige Photovoltaik-Anwendungen ermöglichen.
Das Team wird von Yana Vaynzof geleitet, Initiatorin des Exzellenzclusters REC² der Technischen Universität Dresden und Direktorin des Instituts für Neuartige Elektronik-Technologien am IFW Dresden.
The newly established laboratory in the south wing of IFW Dresden is equipped with state-of-the-art robotics technology and will enable important experimental investigations of perovskite materials for future photovoltaic applications. The team is led by Yana Vaynzof, initiator of the REC² Cluster of Excellence at TU Dresden and Director of the IET – Institute for Emerging Electronic Technologies – at IFW Dresden.

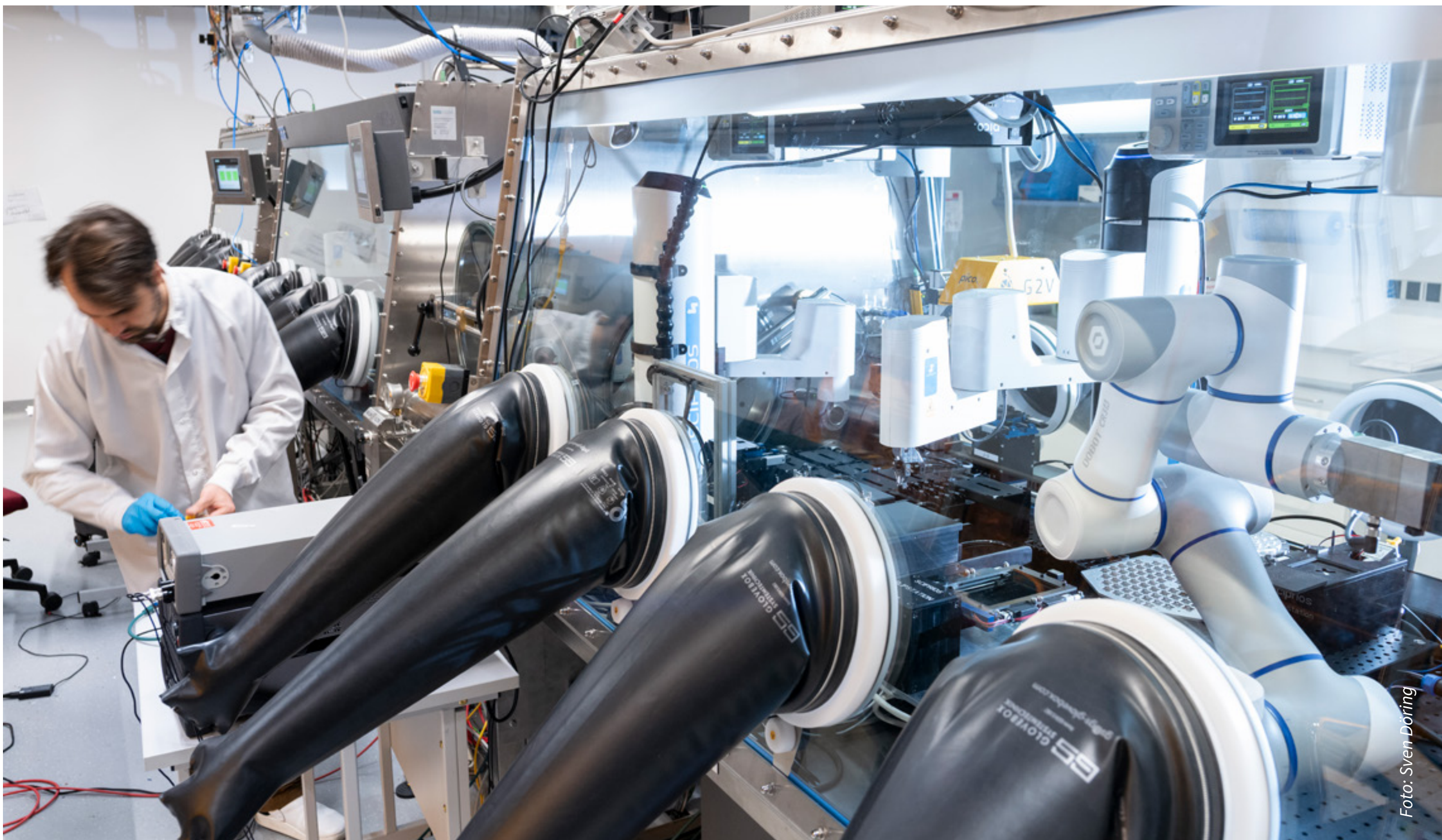


Foto: Sven Döring

hohe wissenschaftliche Leistungsfähigkeit, die strategische Weiterentwicklung sowie den außerordentlichen Erfolg bei der Einwerbung von Drittmitteln. Der Wissenschaftliche Beirat bestätigte die nationale und internationale Sichtbarkeit des IFW Dresden und gab wertvolle Empfehlungen mit Blick auf die Leibniz-Evaluation im Jahr 2028.

Große Projekte, Netzwerke und internationale Zusammenarbeit

Das IFW Dresden war 2025 aktiv an mehreren neu bewilligten Großprojekten und Forschungsnetzwerken beteiligt. So übernehmen wir eine zentrale Rolle in zwei neuen EFRE-geförderten sächsischen Netzwerken: dem Sächsischen Netzwerk Quantentechnologien (SAX-QT) und dem Sächsischen Netzwerk für Integrierte Sicherheit und Nachhaltigkeit (I2SN). Im Rahmen von SAX-QT koordinieren wir das Teilnetzwerk zu Quantenmaterialien, während wir im Netzwerk I2SN unsere ausgewiesene Expertise im Bereich metallischer Werkstoffe einbringen. Beide Netzwerke stärken unsere regionale Vernetzung mit Universitäten, außeruniversitären Forschungseinrichtungen und

third-party funding. The evaluation confirmed IFW Dresden's excellent national and international standing and provided valuable recommendations for further development in view of the upcoming Leibniz evaluation in 2028.

Large Projects, Networks, and International Cooperation

IFW Dresden was actively involved in several newly approved large-scale projects and Saxon research networks. We play a central role in two EFRE-funded Saxon networks established in 2025: the Saxon Network on Quantum Technologies (SAX-QT) and the Saxon Network on Integrated Safety and Sustainability (I2SN). IFW Dresden coordinates the sub-network on quantum materials within SAX-QT and contributes key expertise in metallic materials within I2SN. Both networks strengthen our regional cooperation with universities, other research institutes, and industry, while underlining the societal relevance of research at IFW Dresden.

Wissenschaftlicher Fortschritt für Sachsen: Das Sächsische Staatsministerium für Wissenschaft, Kultur und Tourismus stärkt sächsische Netzwerke, um Kompetenzen effektiv zu bündeln. Auch das IFW Dresden ist in zahlreiche wissenschaftliche Netzwerke sowie in Kooperationen zu Technologietransfer und Wissenschaftskommunikation eingebunden. Staatssekretärin Dr. Heike Graßmann (2. v. r.) bei ihrem Besuch im IFW Dresden im September.
Scientific progress for Saxony: The Saxon State Ministry for Science, Culture and Tourism strengthens regional networks to effectively bundle expertise. IFW Dresden is involved in numerous scientific networks as well as in cooperations focused on technology transfer and science communication. State Secretary Dr. Heike Graßmann (2nd from right) during her visit to IFW Dresden in September.

Foto: Patricia Bäuchler

der Industrie und unterstreichen zugleich die gesellschaftliche Relevanz der Forschung am IFW Dresden. Die internationale Zusammenarbeit bauten wir durch zahlreiche bilaterale und multilaterale Projekte sowie durch unsere aktive Beteiligung an internationalen Konferenzen und Workshops weiter aus. Ein besonderes Highlight war unsere Teilnahme an einer sächsischen Delegationsreise nach Taiwan, die neue Perspektiven für Kooperationen mit der Halbleiterindustrie und akademischen Partnern eröffnete, unter anderem mit der National Taiwan University.

Transfer, Innovation und Ausgründungen
Der Wissens- und Technologietransfer blieb auch 2025 ein zentraler Schwerpunkt des IFW Dresden. Ein herausragender Erfolg war die Ausgründung der Firma SONOJET, die sich der Aerosolerzeugung mithilfe oberflächenakustischer Wellen widmet. Mit Unterstützung durch Bundesmittel im Rahmen der Transferförderung verfolgen wir gemeinsam mit dem Unternehmen das Ziel, kompakte und integrierbare Aerosolquellen zur Marktreife zu bringen. SONOJET wurde bereits kurz nach seiner Gründung mit dem

International collaboration was further expanded through numerous bilateral and multilateral projects, as well as through our active participation in international conferences and workshops. A particular highlight was IFW Dresden's participation in a Saxon delegation visit to Taiwan, which opened new perspectives for cooperation with the semiconductor industry and academic partners, including joint activities with the National Taiwan University.

Transfer, Innovation, and Spin-offs
Technology transfer remained a strong focus in 2025. A major success was the foundation of the new IFW spin-off SONOJET, dedicated to aerosol generation using surface acoustic wave technology. Supported by federal funding, we aim together with the company to bring compact, integrable aerosol sources to market. SONOJET was awarded the Leibniz Founder Prize shortly after its foundation.

Die Ausgründung SONOJET GmbH wurde im Dezember 2025 mit dem Leibniz-Start-up-Preis 2026 ausgezeichnet, welcher mit 50.000 Euro dotiert ist. Mit einer neuen Aerosol-Jet-Drucktechnologie möchte das Spin-off den industriellen Mikrodruck in der Halbleiter- und Elektronikindustrie signifikant voranbringen. Das Gewinnerteam der SONOJET GmbH (v. l. n. r.): Dr. Stefanie Hartmann, Dr. Mehrzad Roudini, Dr. Andreas Winkler, Dr. Uhland Weißker und Dr. Paul Günther.
The spin-off SONOJET GmbH was awarded the Leibniz Start-up Prize 2026 in December 2025, endowed with 50,000 euros. With a new aerosol jet printing technology, the spin-off aims to significantly advance industrial microprinting in the semiconductor and electronics industries. The winning team of SONOJET GmbH (l. t. r.): Dr. Stefanie Hartmann, Dr. Mehrzad Roudini, Dr. Andreas Winkler, Dr. Uhland Weißker, and Dr. Paul Günther.

Foto: David Ausserhofer/ Leibniz-Gemeinschaft

Leibniz-Gründerpreis ausgezeichnet.
Darüber hinaus starteten wir ein umfassendes Validierungsprogramm zur Beschleunigung des Marktzugangs neuer Materialien und Technologien. Das Programm stieß institutsweit auf außerordentlich großes Interesse und etablierte einen klar strukturierten und transparenten Prozess zur Bewertung und Unterstützung transferorientierter Projekte.

Infrastruktur und Organisationsentwicklung
Auch im Bereich der Infrastruktur erzielte das IFW Dresden sichtbare Fortschritte. Nach dem symbolischen ersten Spatenstich im Frühjahr 2025 schritt der Bau des neuen Forschungsgebäudes kontinuierlich voran und stellt eine wichtige Investition in unsere langfristige Zukunftsfähigkeit dar.

Große Aufmerksamkeit widmeten wir zudem der Organisationsentwicklung und den Arbeitsbedingungen. Wir initiierten eine umfassende psychische Gefährdungsbeurteilung, um arbeitsbedingte Belastungen frühzeitig zu erkennen und zu reduzieren sowie

In addition, IFW Dresden launched a comprehensive validation program to accelerate market access for new materials and technologies. The program met with exceptionally high interest across the institute and established a structured and transparent process for evaluating and supporting transfer-oriented projects.

Infrastructure and Organizational Development
Visible progress was made toward the construction of IFW Dresden's new research building. After the ceremonial groundbreaking in spring 2025, construction advanced steadily, marking an important investment in our long-term research infrastructure.

Organizational development and working conditions also received strong attention. We initiated a comprehensive psychological risk assessment to identify and reduce work-related stress and to improve leadership culture and communication. In parallel, IFW Dresden

Erster Spatenstich für den Laborverbund-Neubau südlich der Nöthnitzer Straße: (v.l.n.r.): Prof. Dr. Bernd Büchner (Wissenschaftlicher Direktor IFW Dresden), Oberbürgermeister der Landeshauptstadt Dresden Dirk Hilbert, Juliane Schmidt (Kaufmännische Direktorin IFW Dresden), Falk Reinhardt (Technischer Geschäftsführer SIB), Kanzler der TU Dresden Jan Gerken, Staatssekretärin Prof. Dr. Heike Graßmann (SMWK), Dr. Babett Gläser (SMWK), Oliver Gaber (Kaufmännischer Geschäftsführer SIB), Prof. Dr. Alexey Chernikov (ct.qmat) sowie Prof. Dr. Matthias Vojta (Sprecher ct.qmat).
Groundbreaking ceremony for the new laboratory complex south of Nöthnitzer Straße: (l. to r.) Prof. Dr. Bernd Büchner (Scientific Director, IFW Dresden), Dirk Hilbert, Lord Mayor of the City of Dresden, Juliane Schmidt (Administrative Director, IFW Dresden), Falk Reinhardt (Technical Managing Director, SIB), Jan Gerken, Chancellor of TU Dresden, State Secretary Prof. Dr. Heike Graßmann (SMWK), Dr. Babett Gläser (SMWK), Oliver Gaber (Administrative Managing Director, SIB), Prof. Dr. Alexey Chernikov (ct.qmat), and Prof. Dr. Matthias Vojta (Spokesperson, ct.qmat), April 2025.


Foto: Nils Eisfeld

zuentwickeln. Parallel dazu startete das IFW Dresden neue Audits zu den Themen „Beruf & Vielfalt“ sowie „Beruf & Familie“, die unser klares Bekenntnis zu Diversität, Chancengleichheit und familienfreundlichen Arbeitsbedingungen unterstreichen.

Führungs- und Kommunikationsstrukturen weiter-

Gemeinschaft, Nachwuchsförderung und Öffentlichkeitsarbeit

Die Ausbildung und Förderung des wissenschaftlichen Nachwuchses ist für uns ein zentrales Anliegen. Doktorandinnen und Doktoranden sowie Studierende sind in nahezu alle wissenschaftlichen Projekte und die daraus resultierenden Publikationen eingebunden. Im Jahr 2025 schlossen insgesamt 35 Promovierende ihre Promotion erfolgreich ab, davon sechs mit der Bestnote summa cum laude, die zusätzlich mit der Tschirnhaus-Medaille ausgezeichnet wurden.

Zahlreiche Seminare, Kolloquien, Workshops und Konferenzen belebten unseren wissenschaftlichen

launched new audits on “Work & Diversity” and “Work & Family,” underlining our commitment to diversity, equality, and family-friendly working conditions.

Community, Outreach, and Young Researchers

The training of young scientists remains a central concern of IFW Dresden. PhD students and undergraduates are involved in almost all scientific projects and the resulting publications, demonstrating our strong commitment to promoting early-career researchers.
In 2025, 35 doctorates were successfully completed, six of which achieved the highest possible grade — summa cum laude — and were awarded IFW Dresden’s Tschirnhaus Medal.

Numerous seminars, colloquia, workshops, and conferences stimulated scientific exchange, as did the internal program retreat for intensive discussion of the IFW research program. IFW Dresden

Am stadtweiten Bildungsformat JUNIORDOKTOR beteiligt sich das IFW Dresden seit Jahren aktiv. Die Förderung von Nachwuchs in den MINT-Fächern – auch auf außerschulischer Ebene – ist dem Institut ein großes Anliegen. Auch in der 17. Staffel des JUNIORDOKTOR-Programms konnten Kinder und Jugendliche ihr Wissen zu vielfältigen Themen rund um Dresdens Wissenschaft und Kultur erweitern. Für die erfolgreiche Teilnahme gab es am Ende den JUNIORDOKTOR-Hut und der wurde traditionell gemeinsam in die Luft geworfen.
IFW Dresden has been actively involved in the city-wide JUNIORDOKTOR education program for many years. Supporting young talent in STEM subjects – also beyond the school environment – is an important priority for the institute. In the 17th season of the JUNIORDOKTOR program, children and teenagers were once again able to expand their knowledge on a wide range of topics related to Dresden’s science and culture. At the end, participants received the JUNIORDOKTOR hat as an award – and, in keeping with tradition, it was thrown into the air together.

Foto: Frank Grätz

Diskurs ebenso wie die jährliche IFW-Programmklausur zur intensiven Diskussion des Forschungsprogramms. IFW Dresden war Gastgeber und Mitorganisator einer Vielzahl wissenschaftlicher Veranstaltungen, darunter der Internationale Workshop zu unkonventionellem Magnetismus in Quantenmaterialien in Kiew (Ukraine), die Konferenz Acoustofluidics sowie die Summer School zur Spektroelektrochemie am IFW Dresden.

Ein Höhepunkt unserer Öffentlichkeitsarbeit war die Dresdner Lange Nacht der Wissenschaften, die erneut zahlreiche Besucherinnen und Besucher anzog und unsere Forschung einer breiten Öffentlichkeit präsentierte. Außerschulische Bildung im MINT-Bereich ist uns ein wichtiges Anliegen, dem wir in zahlreichen Laborführungen für Schulklassen, einen 2-stündigem Grundschulprogramm im Institut, in Form von Lehrerfortbildungen und der Betreuung von Schülerpraktika (in 2025 waren es knapp 20 SuS) nachkommen. Ergänzend beteiligte sich das IFW Dresden an übergreifenden Veranstaltungsformaten mit großer Reichweite wie dem Girls' Day, dem JUNIORDOKTOR-Programm und der bundesweiten Nacht der Bibliotheken.

Fazit und Dank

Insgesamt war das Jahr 2025 für das IFW Dresden von zahlreichen Erfolgen und strategischen Fortschritten geprägt. Die Verbindung aus exzellenter Forschung, erfolgreichen Evaluationen, starker regionaler und internationaler Vernetzung, sichtbaren Fortschritten bei Infrastrukturmaßnahmen sowie einem klaren Engagement für Transfer, Vielfalt und gute Arbeitsbedingungen bildet eine solide Grundlage für unsere zukünftige Entwicklung.

Hierfür bedanken wir uns nochmals herzlich bei allen, die zu diesem Erfolg beigetragen haben.

hosted and co-organized a wide range of scientific events, including the International Workshop on Unconventional Magnetism in Quantum Materials in Kyiv (Ukraine), the Acoustofluidics conference, and the Summer School on Spectroelectrochemistry at IFW Dresden.

A highlight of our public outreach activities was the Dresden Science Night, which once again attracted a large number of visitors and presented our research to a broad audience. Extracurricular STEM education is an important concern for us, which we pursue through numerous laboratory tours for school classes, a two-hour primary school program at the institute, teacher training courses, and the supervision of student internships (in 2025, nearly 20 pupils participated). In addition, IFW Dresden took part in cross-institutional, high-visibility event formats such as Germany's Girls' Day, the JUNIORDOKTOR program, and the nationwide Night of Libraries.

Conclusion and Thanks

Overall, 2025 was a year of significant achievements and strategic progress for IFW Dresden. The combination of excellent research, successful evaluations, strong international and regional networking, visible infrastructural development, and a clear commitment to transfer, diversity, and good working conditions provides a solid foundation for our future development.

Once again, we sincerely thank all who contributed to this success.

Der Bereich Forschungstechnik stellt die institutseigene Forschungsinfrastruktur des IFW Dresden bereit und betreibt sie – eine zentrale Voraussetzung für den wissenschaftlichen Fortschritt am Institut. Darüber hinaus ist der Bereich aktiv an der Weiterentwicklung von Methoden beteiligt und schafft wichtige Grundlagen, beispielsweise in der Kryotechnik. Das Foto zeigt die Heliumhalle des IFW Dresden: Aus den Laboren wird das Helium in die gelbe Blase rückgeführt, anschließend verflüssigt und kann so ressourcenschonend erneut genutzt werden.
The Research Technology department provides and operates IFW Dresden's in-house research infrastructure—an essential basis for scientific progress at the institute. Beyond this, the team actively contributes to the further development of methods and establishes key foundations, for example in cryogenics. The photo shows IFW Dresden's helium hall: helium from the laboratories is returned to the yellow storage balloon, then liquefied and can be reused in a resource-efficient way.

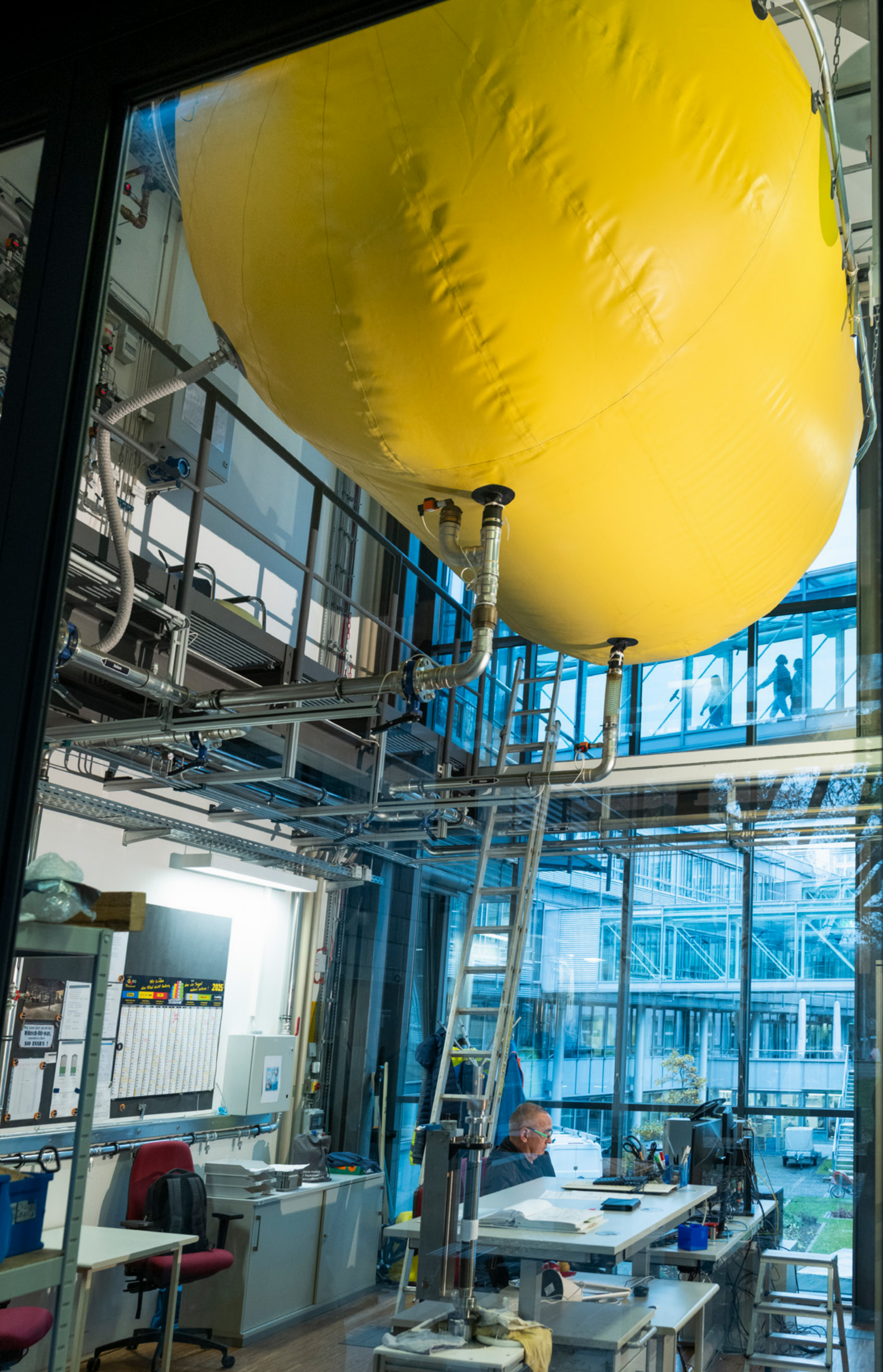


Foto: Sven Döring

INTERNATIONAL YEAR OF

Quantum Science and Technology

International Year of Quantum Science and Technology 2025

Das Internationale Quantenjahr 2025

Hundert Jahre nach der Formulierung der Quantenmechanik rückte das Internationale Jahr der Quantenwissenschaft und -technologie 2025 (Quantum 2025) die grundlegende Bedeutung quantenphysikalischer Phänomene für Forschung, Technologie, Kultur und Alltag in den Mittelpunkt. Das Jubiläum würdigte nicht nur die wissenschaftshistorische Zäsur der 1920er-Jahre, sondern betonte zugleich die anhaltende Innovationskraft der Quantenphysik als Schlüsseltechnologie des 21. Jahrhunderts.

Das IFW Dresden ist ein aktiver Teil der globalen Forschungsgemeinschaft im Bereich der Quantenmaterialien. Durch langjährige wissenschaftliche Kooperationen, unter anderem und im Besonderen mit Partnerinstitutionen in der Ukraine, fördern wir den internationalen Austausch in der fachlichen Community der Quanten- und Festkörperphysik, unterstützen wissenschaftliche Kontinuität auch unter schwierigen Rahmenbedingungen und setzen ein klares Zeichen für internationale Solidarität und Verantwortung in der Forschung.

Darauf aufbauend engagieren wir uns in vielfältiger Weise für die Weiterentwicklung und Sichtbarkeit der Quantenphysik auf regionaler und nationaler Ebene. Mit unserer Expertise in der Grundlagenforschung sowie in der Erforschung zukünftiger Anwendungen leistet das IFW Dresden einen substanziellen Beitrag zur wissenschaftlichen Exzellenz und zum Transfer in kommende Quantentechnologien. Darüber hinaus fördern wir aktiv den interdisziplinären Austausch und die Stärkung des dringend benötigten wissenschaftlichen Nachwuchses. Der Neubau unseres Forschungsgebäudes für Quantenmaterialien mit modernsten infrastrukturellen Voraussetzungen im Dresdner Süden unterstreicht dieses Engagement.

International Year of Quantum Science and Technology 2025

One hundred years after the formulation of quantum mechanics, the International Year of Quantum Science and Technology 2025 (Quantum 2025) placed the fundamental importance of quantum phenomena for research, technology, culture, and everyday life at center stage. The anniversary not only commemorated the scientific turning point of the 1920s but also emphasized the continuing innovative power of quantum physics as a key technology of the 21st century.

IFW Dresden actively contributes to the global research community in the field of quantum materials. Through long-standing scientific collaborations, particularly with partner institutions in Ukraine, we promote international exchange within the quantum and solid-state physics community, support scientific continuity even under challenging conditions, and send a clear signal of international solidarity and responsibility in research.

Building on this foundation, we are committed to advancing and strengthening the visibility of quantum physics at regional and national levels. With our recognized expertise in fundamental research as well as in exploring future applications, IFW Dresden makes a substantial contribution to scientific excellence and to the transfer of knowledge into emerging quantum technologies. In addition, we actively foster interdisciplinary exchange and support the urgently needed next generation of scientists. The construction of our new research building for quantum materials, equipped with state-of-the-art infrastructure in the south of Dresden, underlines this commitment.

Ein zentraler Bestandteil regionaler Bestrebungen mit internationaler Strahlkraft ist unsere Beteiligung am Netzwerk SAX-QT. In diesem Verbund bringt das IFW Dresden seine wissenschaftliche Kompetenz gezielt ein, intensiviert die Vernetzung von außeruniversitärer Forschung, Hochschulen und Industrie und trägt zum Aufbau eines leistungsfähigen sächsischen Quantennetzwerks bei. Zugleich fördert SAX-QT den Dialog über Chancen, Herausforderungen und gesellschaftliche Auswirkungen quantentechnologischer Entwicklungen zwischen Wissenschaft, Wirtschaft, Politik und Öffentlichkeit.

Im Internationalen Jahr der Quantenwissenschaft und -technologie 2025 war uns darüber hinaus die gezielte Stärkung des Bildungsbereichs ein besonderes Anliegen.
Mit der Lehrerfortbildung „Quantenphysik in Klassenstufe 12“ vermittelten wir aktuelle wissenschaftliche Erkenntnisse unmittelbar an diejenigen, die heute die Forschenden von morgen ausbilden.

A key element of regional initiatives with international impact is our participation in the SAX-QT network. Within this consortium, IFW Dresden contributes its scientific expertise in a targeted manner, strengthens collaboration between non-university research institutions, universities, and industry, and supports the development of a high-performance quantum network in Saxony. At the same time, SAX-QT promotes dialogue on the opportunities, challenges, and societal implications of quantum technologies among science, industry, policymakers, and the public.

During the International Year of Quantum Science and Technology 2025, strengthening the educational sector was a particular priority for us. Through the teacher training program “Quantum Physics in Grade 12,” we directly conveyed current scientific insights to those educating the researchers of tomorrow. In addition,

Der gemeinsam mit den Technischen Sammlungen, dem JUNIORDOKTOR-Programm und dem IFW Dresden entwickelte „Tag der Quantenphysik“ ermöglichte vor allem jungen Besuchenden einen anschaulichen Zugang zu zentralen Phänomenen der Quantenphysik. Im Bild der „Schwingende Ring“, an dem stehende Wellen mit Knoten und Bäuchen sichtbar werden – ein eindimensionales, anschauliches Modell für die dreidimensionalen Orbitale von Elektronen im Atom, deren Form und Knotenzahl von der Energie abhängen (rechts).
The “Day of Quantum Physics,” developed jointly with the Technische Sammlungen, the JUNIORDOKTOR program, and IFW Dresden, provided especially young visitors with an accessible introduction to key phenomena of quantum physics. The image shows the “Oscillating Ring,” where standing waves with nodes and antinodes become visible— a one-dimensional illustrative model for the three-dimensional orbitals of electrons in atoms, whose shape and number of nodes depend on their energy.

Illustration zum "Tag der Quantenphysik" generiert mit Adobe firefly / IFW Dresden.

Ergänzend dazu fand Anfang April der „Tag der Quantenphysik“ in den Technischen Sammlungen Dresden statt. In diesem Rahmen wurde ein interaktiver Ausstellungsbereich eröffnet, der die Gesetzmäßigkeiten der Quantenphysik anschaulich vermittelt. Besucherinnen und Besucher – insbesondere junge Interessierte – konnten an den interaktiven Exponaten, einer Quiz-Rallye sowie dem spielerischen Wettbewerb „QuantumCurling“ teilnehmen und Quantenphänomene unmittelbar erleben.

Das Internationale Quantenjahr 2025 hat eindrucksvoll die gesellschaftliche Relevanz, Zukunftsperspektiven und auch die immer noch großen Fragzeichen dieses Forschungsfeldes aufgezeigt. Auch hundert Jahre nach der Formulierung der Quantenmechanik bleibt die Neugier auf die fundamentalen Gesetzmäßigkeiten der Physik eine treibende Kraft – und zugleich unsere Motivation für Zusammenarbeit, neue wissenschaftliche Horizonte und Innovationen.

the “Day of Quantum Physics” took place at the Technische Sammlungen Dresden in early April. An interactive exhibition area was opened to illustrate the principles of quantum physics in an accessible way. Visitors—especially young people—were able to engage with interactive exhibits, take part in a quiz rally, and participate in the playful “QuantumCurling” competition, experiencing quantum phenomena firsthand.

The International Year of Quantum Science 2025 clearly demonstrated the societal relevance, future perspectives, and also the many open questions that still characterize this field of research. Even one hundred years after the formulation of quantum mechanics, curiosity about the fundamental laws of physics remains a driving force—and continues to motivate us in our collaboration, our exploration of new scientific horizons, and our pursuit of innovation.

Quantenorte in Deutschland: Im Internationalen Jahr der Quantenwissenschaft und -technologie präsentierte sich das IFW Dresden als sichtbarer Standort der Quantenforschung und -vermittlung. Im Rahmen der Initiative der Deutschen Physikalischen Gesellschaft (DPG) sind auf einer interaktiven Karte 89 Quantenorte in Deutschland verzeichnet, an denen Einrichtungen mit besonderer Bedeutung für die Quantenwissenschaft ausgewiesen und vor Ort durch Plaketten gekennzeichnet werden.
Designated Quantum Locations in Germany: During the International Year of Quantum Science and Technology, IFW Dresden highlighted its role as a visible site of quantum research and outreach. Under the initiative of the German Physical Society (DPG), an interactive map lists 89 Quantum Locations across Germany, identifying institutions of particular significance in quantum science that are marked with plaques on site.

Foto: IFW Dresden

Unser Forschungsprogramm

Dem Unerforschten auf der Spur

Das IFW Forschungsprogramm bringt die Disziplinen, Methoden und Kompetenzen der fünf IFW-Institute zusammen.
Bei aller Breite und Interdisziplinarität gilt für all unsere Forschungsaktivitäten, dass sich Wissenschaftler*innen mit noch unerforschten Eigenschaften neuer Materialien beschäftigen. Das Ziel dabei ist, neue Funktionalitäten und Anwendungen für zukunftsfähige Technologien zu erschließen und herauszuarbeiten.

Our Research Program

On the track of the unexplored

The IFW research program brings together many disciplines, methods and competences of the five IFW institutes.
Despite its breadth and interdisciplinarity, all IFW research activities have in common that scientists are investigating still unresearched properties of matter with the aim of developing new functionalities and applications.

quantum
function
Sustainability

quantum
Quantenmaterialien

Quantenmaterialien sind Stoffe, die besondere Quantenphänomene zeigen. Diese werden von unkonventionellen Spin-Wechselwirkungen, elektronischen Korrelationen, Elektron-Photon-Wechselwirkungen und / oder topologischen Bandstrukturen verursacht. Beispiele sind Supraleitung und Magnetismus. Auch in nanoskaligen Systemen spielen Quanteneffekte eine wichtige Rolle.

function
Funktionsmaterialien

Funktionsmaterialien können auf Grund ihrer physikalischen und chemischen Eigenschaften bestimmte Aufgaben erfüllen: zum Beispiel den Strom leiten, elektromagnetische Wellen einer bestimmten Frequenz filtern, ein magnetisches Feld abschirmen oder Energie speichern.

Sustainability
Nachhaltigkeit als Voraussetzung für die Anwendung

Die Umwelt- und Klimaverträglichkeit neuartiger Materialien wird zunehmend zur unabdingbaren Voraussetzung für ihre Anwendung in neuen Technologien. Umgekehrt haben neue Materialien und neue Synthesewege aus sich heraus ein großes Potential, um einen verantwortungsvolleren Umgang mit Energie und Ressourcen zu befördern. In jedem Fall ist ein grundlegendes Verständnis der beteiligten chemischen und physikalischen Prozesse die Voraussetzung für Innovationen in eine nachhaltige Technologie.

quantum
Quantum Materials

Quantum materials are solids showing peculiar quantum phenomena related to unconventional spin interactions, electronic correlations, electron-photon interactions and/or topological band structures. Examples are superconductivity and magnetism. Quantum effects have also a strong influence in materials with spatial extension constraint to the nanometer scale, like nanoparticles, thin films or nanotubes.

function
Functional Materials

Functional materials exhibit special physical, mechanical or chemical properties which enable them to fulfil a specific function in devices, e.g. conducting electric current, filter acoustic waves of a certain frequency, shielding magnetic fields or storing energy.

Sustainability
Prerequisite for Application

The environmental and climate compatibility of new materials is increasingly becoming an indispensable prerequisite for their use in new technologies. Conversely, new materials and new synthesis methods have great potential in themselves to promote a more responsible use of energy and resources. In any case, a fundamental understanding of the chemical and physical processes involved is the prerequisite for innovations in sustainable technology.

Unsere Forschungsgebiete

Die Mission des IFW Dresden besteht darin, Grundlagenforschung und anwendungsorientierte Forschung und Entwicklung auf dem Gebiet der Festkörper und Werkstoffe zu betreiben. Kernelemente der Forschungsaktivitäten sind experimentelle und theoretische Untersuchungen von Phänomenen, die sich auf der Ebene von Elektronen, Atomen, Molekülen und Nanostrukturen abspielen. Die Arbeiten reichen von der Charakterisierung physikalischer und chemischer Materialeigenschaften bis hin zur Entwicklung neuer Materialien und elektronischer Bauelemente mit neuen Funktionalitäten für eine nachhaltige Zukunft.

Forschungsgebiet 1:
Funktions-Quanten-Materialien

Forschungsgebiet 2:
Materialien für nachhaltige Anwendungen

Forschungsgebiet 3:
2D-Materialien und topologische Zustände

Forschungsgebiet 4:
Vom Material zu neuen Technologien

Our Research Areas

The mission of IFW is to pursue fundamental as well as application-oriented research and development in the field of solid-state matter and materials science. Key elements of the research activities are both experimental and theoretical studies of phenomena that take place at the level of electrons, atoms, molecules and nanostructures as well as the characterization of physical and chemical material properties. This includes also application-oriented research up to the development of new materials and devices based on investigated physical effects and on new functionalities for a sustainable future.

Research Area 1:
Functional quantum materials

Research Area 2:
Materials for sustainable applications

Research Area 3:
2D materials and topological states

Research Area 4:
From materials to novel technologies

Unsere fünf IFW-Institute
Our five IFW Institutes

Institut für Festkörperforschung - Institute for Solid State Research (IFF)

Director: Prof. Dr. Bernd Büchner
Das IFF beschäftigt sich mit materialorientierter Festkörperforschung mit den besonderen Schwerpunkten Quantenmaterialien und nanoskalige Substanzen.
The IFF does research in the field of material-oriented experimental solid state physics with a special focus on quantum materials and nanoscale substances.

Institut für Metallische Werkstoffe - Institute for Metallic Materials (IMW)

Director: Prof. Dr. Kornelius Nielsch
Das IMW befasst sich vor allem mit thermoelektrischen, magnetischen und supraleitenden Materialien, funktionellen Dünnschichten sowie mit Metallphysik.
Main research topics of IMW are thermoelectric, magnetic and superconducting materials, functional thin films and metal physics.

Institut für Materialchemie - Institute for Materials Chemistry (IMC)

Director: Prof. Dr. Anjana Devi
Die Forschungsaktivitäten des IMC fokussieren sich auf die Chemie funktioneller Materialien mit Schwerpunkt bei nanoskaligen und 2D-Materialien, Strukturanalytik sowie Legierungsdesign und Prozesstechnologien.
The research activities of the IMC are concerned with the chemistry of functional materials with a focus on nanoscale and 2D materials, structural analysis as well as alloy design and process technologies.

Institut für Neuartige Elektronik-Technologien - Institute for Emerging Electronic Technologies (IET)

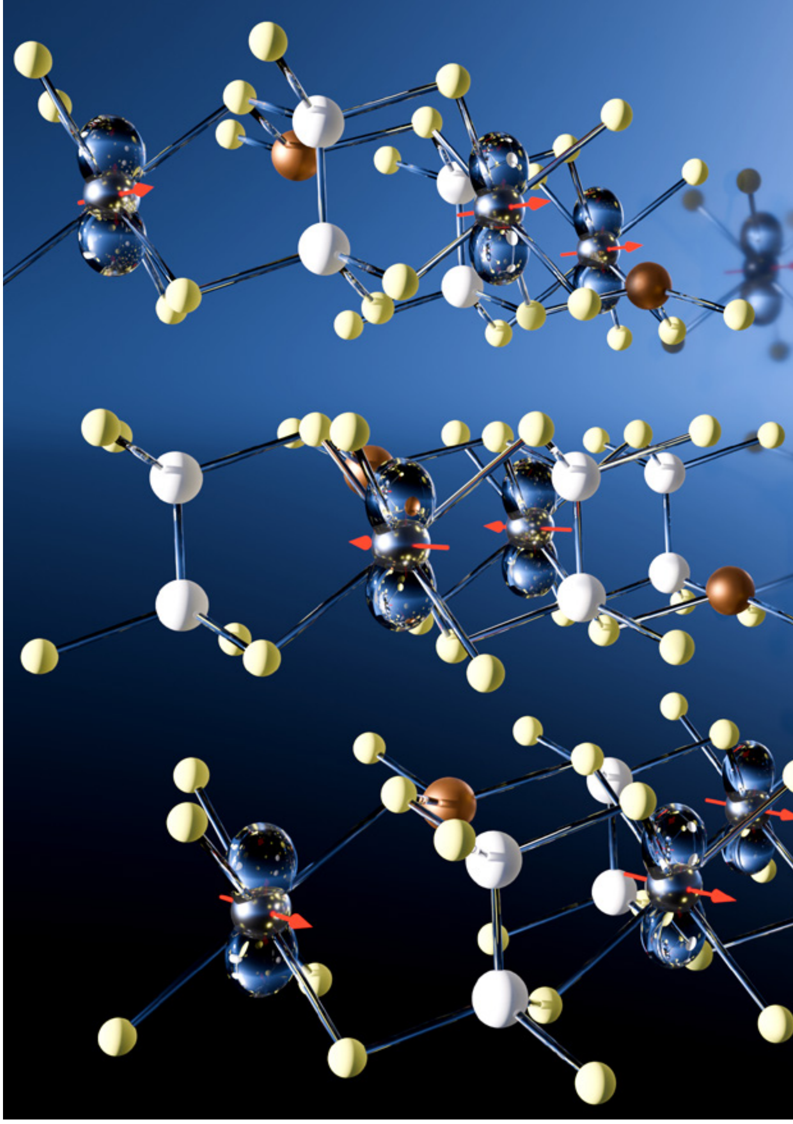
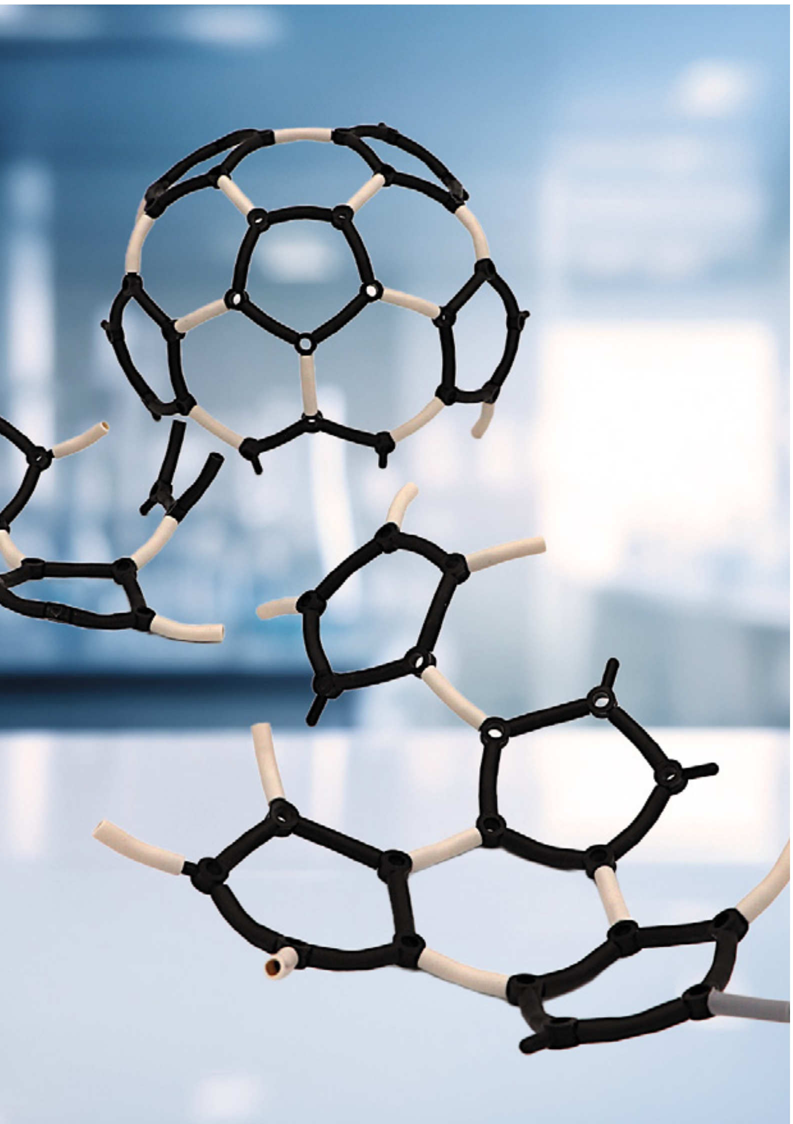
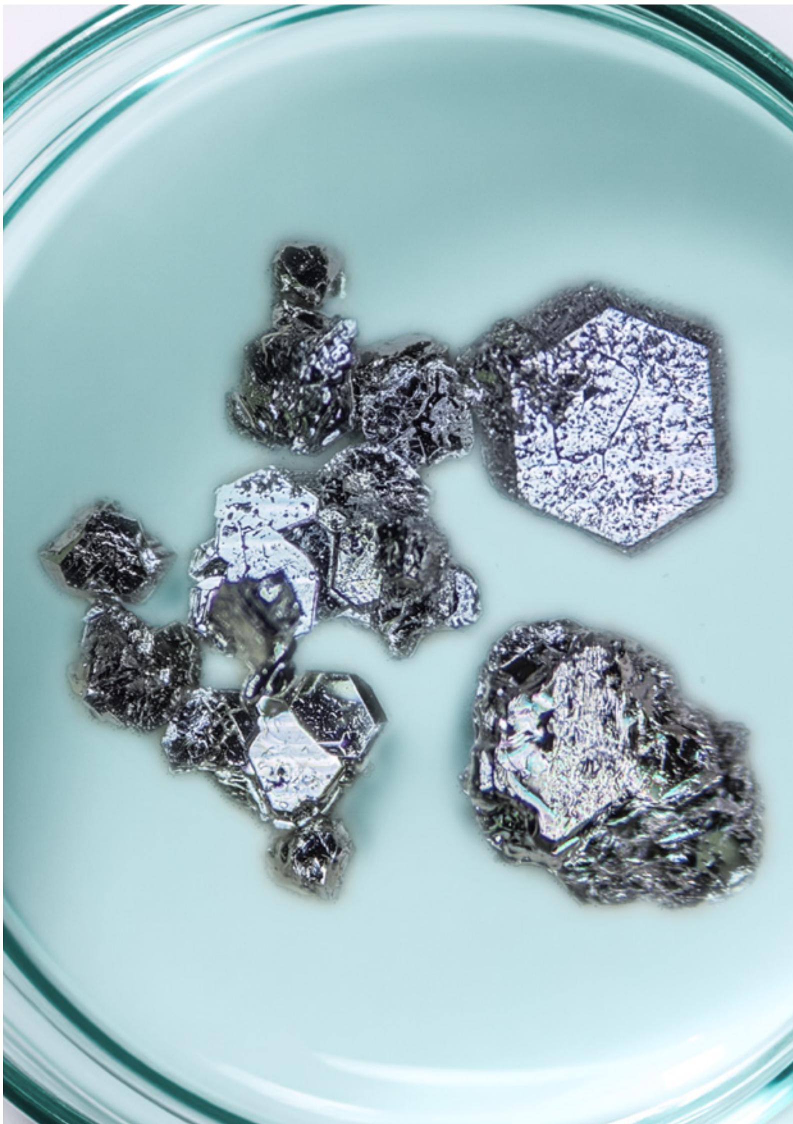
Director: Prof. Dr. Yana Vaynzof
Das IET konzentriert sich auf die Entwicklung von Materialien und Geräten für neue elektronische und optoelektronische Technologien.
The IET focuses on the development of materials and devices for emerging electronics and optoelectronic technologies.

Institut für Theoretische Festkörperphysik - Institute for Theoretical Solid State Physics (ITF)

Director: Prof. Dr. Jeroen van den Brink
Die Forschung am ITF konzentriert sich auf die theoretischen Aspekte der Physik der kondensierten Materie und der Materialwissenschaften.
The ITF focuses on theoretical aspects of condensed matter physics and materials science.

Forschung aktuell

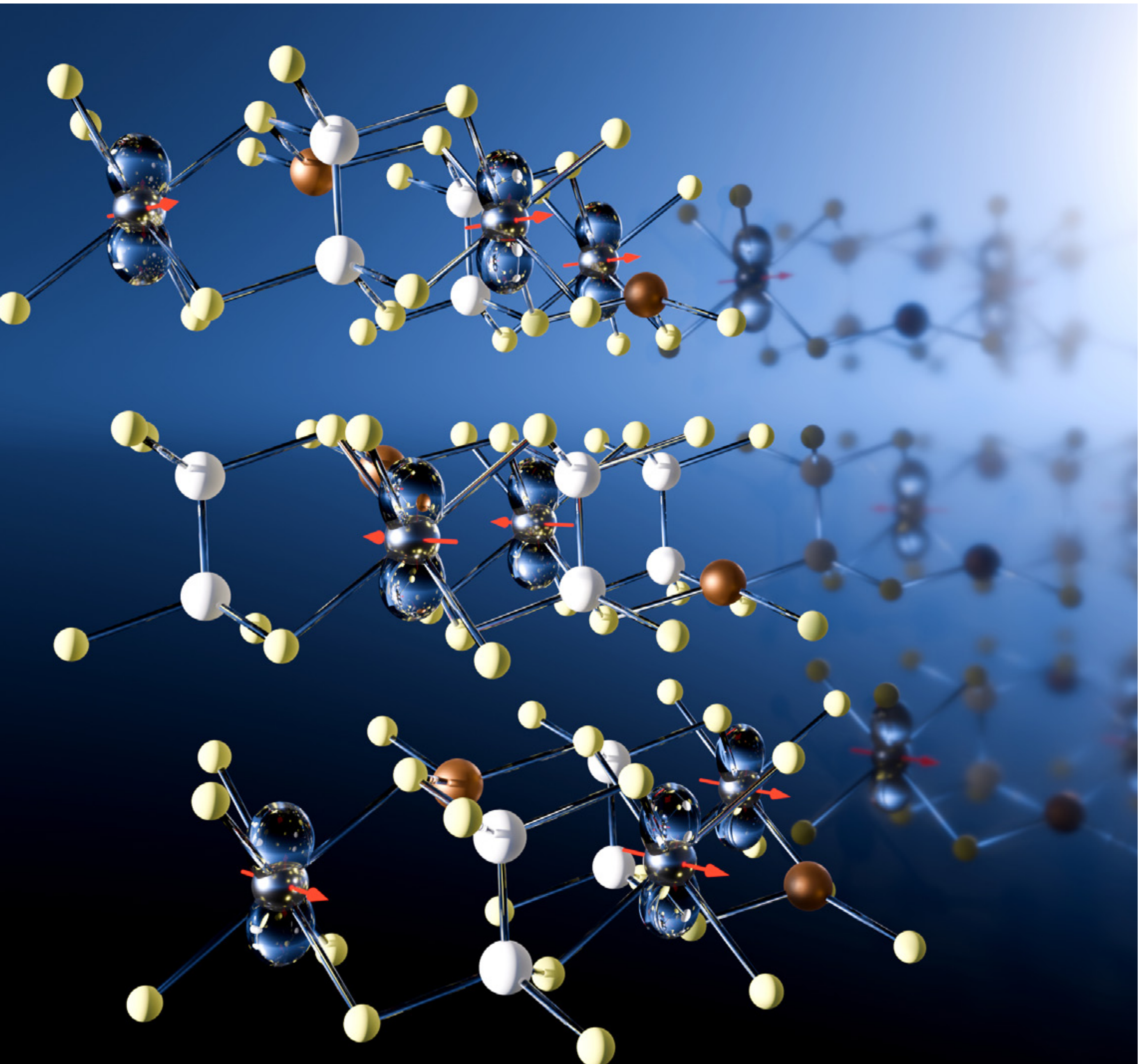
Current **Research**

Current Research 1

Magnetic-Field Tuning of the Spin Dynamics in the Quasi-2D Van der Waals Antiferromagnet $CuCrP_2S_6$

J. J. Abraham, Y. Guo, Y. Shemerliuk, S. Selter, S. Aswartham, K. K. Bestha, L. T. Corredor, A. U. B. Wolter, O. Kataeva, L. Rogić[1], N. Somun[1], D. Pelc[1], O. Janson, J. van den Brink, B. Büchner, V. Kataev, and A. Alfonsov



Antiferromagnete sind vielversprechende Materialien für zukünftige magnetoelektronische Bauelemente. Dabei sind geschichtete van-der-Waals-Antiferromagnete besonders interessant, weil sie eine hohe Einstellbarkeit ihrer Eigenschaften bieten und sich leicht in einzelnen Schichten herstellen lassen. Das ermöglicht eine unkomplizierte Integration in die Bauelemente.
Ein solches Material ist $CuCrP_2S_6$, an dem wir einen inhärent zweidimensionalen Charakter der Spindynamik aufzeigen konnten. Noch wichtiger: Wir identifizierten dabei zwei antiferromagnetische Magnonmoden mit unterschiedlichen Energien, die sich unter dem Einfluss eines Magnetfeldes in ferromagnetische Moden umwandeln lassen. Diese Ergebnisse etablieren $CuCrP_2S_6$ als Prototypmaterial für die unidirektionale Übertragung von Spinströmen in magnonischen Bauelementen, bei der verschiedene „Übertragungskanäle" gezielt geschaltet werden können.

Antiferromagnets are promising for future magnetoelectronic devices, and layered van der Waals antiferromagnetic materials are in particular attractive, as they offer a high tunability of properties and can be easily exfoliated down to a monolayer, which facilitates their integration into such devices. Focusing on such a system - $CuCrP_2S_6$ - we discovered an intrinsically two-dimensional character of the spin dynamics, and, more importantly, two distinct in energy antiferromagnetic magnon modes, which could be tuned into ferromagnetic ones using a magnetic field.
Our findings suggest $CuCrP_2S_6$ as a prototype material for transmitting the unidirectional spin current in magnonic devices with controllable switching of different transmission "channels".

Abb. 1: Darstellung der kristallographischen und magnetischen Strukturen von $CuCrP_2S_6$. Die Cu-Ionen sind in Kupferfarbe dargestellt, P ist durch weiße und S durch gelbe Kugeln symbolisiert. Bei den Cr-Ionen mit metallischen Oberflächen stellen die Pfeile geordnete Spins dar und glasartige Oberflächen zeigen die magnetische Anisotropie. (Illustration: A. Alfonsov/IFW Dresden)
Fig. 1: Illustration of the crystallographic and magnetic structures of $CuCrP_2S_6$. Cu ions are shown in copper color, P is white and S is yellow. At the Cr ions with metallic surfaces, arrows represent ordered spins and glassy surfaces depict the magnetic anisotropy. (Illustration: A. Alfonsov/IFW Dresden)

Antiferromagnets are gaining visibility as prospective spintronic materials. In comparison to ferromagnetic materials, they offer several advantages which make them attractive in this respect. The most important ones are their natural tendency to have larger magnetic anisotropy and zero total magnetization in the ground state. These properties of antiferromagnets, first, lead to a relatively high robustness against external influences, making them attractive for potential application in non-volatile memory cells. Second, compared to ferromagnets, they have higher energies of the magnon excitations at zero magnetic fields. Since energy is directly related to the frequency of the excitation, that naturally expands the frequency bandwidth of the potential device. However, in the case of usual 3D antiferromagnets there are some disadvantages, one of them is related to the excitation energies at zero magnetic field which might be too large for a feasible application. Additionally, these magnon excitation modes at zero magnetic field are often degenerate, which hinders the spin angular momentum propagation and, therefore, prevents the transmission of the unidirectional spin current. Therefore, there is a need for a suitable antiferromagnetic compound, which can be looked for among exotic material families. Indeed, there is such a material family of layered van der Waals antiferromagnets, which attracted significant attention in recent years due to a high flexibility in tuning the structure and composition, and most importantly due to a naturally layered structure, where these layers are held together by weak van der Waals forces. The latter makes them low-dimensional even in the bulk, which enables the emergence of exotic ground states with respective excitations, and offers a possibility to exfoliate the samples down to a monolayer, which, additionally, makes them promising for the integration into nanoscale devices.

A particularly interesting subclass of these van der Waals materials, which was intensively studied at IFW Dresden, is represented by the chemical formula $AA'P_2S_6$, where A and A' refer to transition metal ions, P is phosphorus and S is, respectively, sulfur. In the absence of strong chemical bonding between the layers of the van

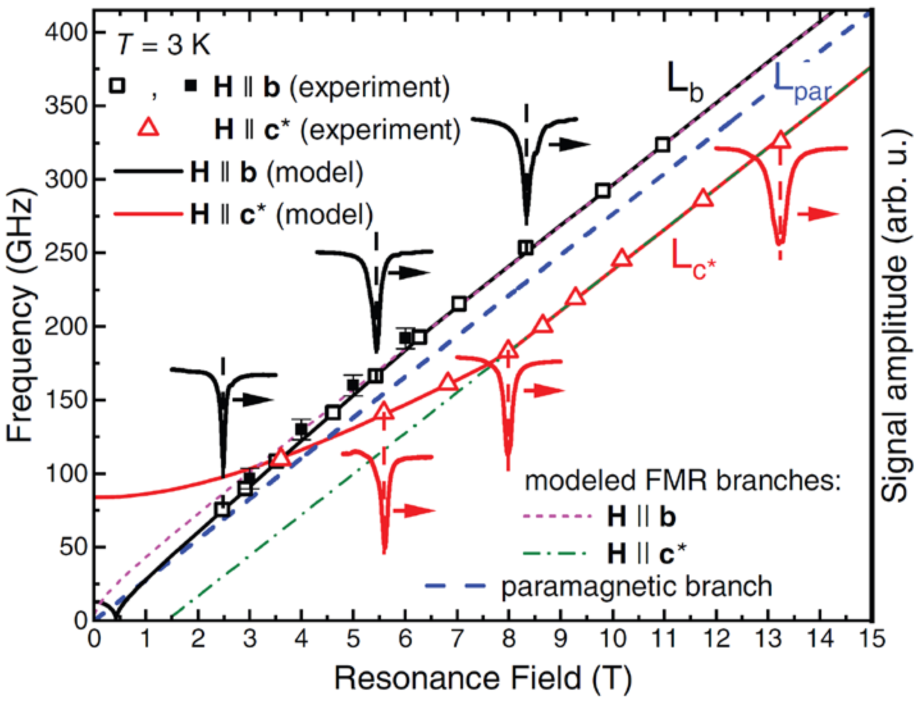


Abb. 2: Magnetfeldabhängigkeit der Resonanzmoden bei 3 K für die Feldkonfigurationen parallel und senkrecht zur Van der Waals-Ebene (Symbole). Durchgezogene Linien sind das Ergebnis der Modellierung der experimentellen Daten mithilfe der linearen Spinwellentheorie. Die gestrichelte Linie stellt die paramagnetische Mode dar. Die punktiert-gestrichelte Linie und die kurz-gestrichelte Linie sind modellierte ferromagnetische Moden, die die Hochfeld-Spindynamik illustrieren. Rechte vertikale Achse: Exemplarische Spektren (normalisiert und vertikal verschoben) bei ausgewählten Frequenzen.

Fig. 2: Magnetic field dependence of the resonance modes at 3 K for the in-plane and out-of-plane field configurations (symbols). Solid lines are the result of the modeling of the experimental data using linear spin wave theory. Dashed line represents the paramagnetic response. The dot-dashed line and the short-dashed line are modeled ferromagnetic modes, illustrating high-field spin dynamics. Right vertical axis: Exemplary spectra (normalized and shifted vertically) at selected frequencies.

der Waals structure, the transition metal ions form quasi-two-dimensional magnetic lattices in these layers, which are weakly coupled in the third dimension. There is also a high flexibility in selecting different transition metal ions at the A and A' sites yielding a variety of magnetic properties. For instance, $Fe_2P_2S_6$ is an Ising-type antiferromagnet that preserves long-range magnetic order up to a significantly high transition temperature even in the monolayer limit. In $Ni_2P_2S_6$, which is an easy-plane antiferromagnet with a zigzag spin structure, magnetic order is completely suppressed in the two-dimensional case. Interestingly, in this compound a remarkable coupling of photoexcitations with antiferromagnetic order has been observed, which may be relevant for developing antiferromagnet-based quantum information technologies. Another member of this family, $Mn_2P_2S_6$ showing the antiferromagnetic spin order of a Néel type with a weak easy-axis anisotropy, is found to host long-distance magnon transport important for magnon-based spintronics.

This work focuses on the van der Waals antiferromagnet $CuCrP_2S_6$. A remarkable difference from its above-mentioned counterparts is in the structure with the A site in the individual $CuCrP_2S_6$ layers being occupied by the nonmagnetic copper (Cu^{1+}) ions alternating with the magnetic chromium (Cr^{3+}) ions at the A' sites (Fig.1). The chromium triangular magnetic sublattice undergoes a transition to the magnetically ordered state at the ordering temperature $T_N \approx 30$ K. Here Cr spins in each layer order ferromagnetically in the ab-plane with their corresponding moments aligned along the b-axis. The neighboring layers are coupled antiferromagnetically resulting in the A-type antiferromagnetic spin structure (Fig.1).

High-quality single crystals of $CuCrP_2S_6$ studied in this collaborative work between several groups at IFW Dresden [1] were synthesized using the chemical vapor transport technique with iodine as the transport agent. Our static magnetic properties investigations confirmed the magnetic ordering at $T_N \approx 30$ K. Moreover, they enabled the determination of the average Curie-Weiss temperature $\Theta \approx 32$ K, which is the measure of all magnetic interactions acting in the system. The positive sign of Θ indicates the predominance of ferromagnetic interactions, consistent with the A-type antiferromagnetic order. The fundamental questions of the spin dynamics and the properties of the magnetic ground state of $CuCrP_2S_6$ we addressed experimentally by means of electron spin resonance (ESR) spectroscopy and its related antiferromagnetic and ferromagnetic resonance techniques. Moreover, in order to obtain deeper insights into the nature of the magnetic interactions and anisotropies in this system we performed density functional theory (DFT) calculations. First of all, we found that in the paramagnetic regime, signatures of the in-plane ferromagnetic correlations between the Cr spins can be seen in the ESR response far above the ordering temperature, becoming particularly pronounced in strong magnetic fields, evidencing an inherent quasi-2D character of the magnetism of bulk $CuCrP_2S_6$. Second, in the antiferromagnetically ordered state below the ordering temperature we discovered new, previously unreported, resonance modes and studied the dependence of their energies on the magnitude and direction of the applied magnetic field (Fig.2). Our analysis of the data using linear spin wave theory (LSWT) enabled a precise quantification of the uniaxial and biaxial magnetic anisotropy constants ($K_{uniaxial} = 5 \cdot 10^5$ erg cm^{-3} and $K_{biaxial} = 1 \cdot 10^4$ erg cm^{-3}) which determine the in-plane orientation of the Cr spins with the preferable direction along the b-axis. Additionally, this analysis directly yielded the strength of the interplane magnetic coupling ($A_{interplane} = 2.3 \cdot 10^6$ erg cm^{-3}) necessary for the stabilization of the A-type antiferromagnetic order, and enabled us to identify that two magnon excitation modes have distinct energies in the zero-field limit ($\Delta 1$ = 13 GHz and $\Delta 2$ = 84 GHz). Importantly, the calculated parameters of the spin Hamiltonian using DFT with generalized gradient approximation for the antiferroelectric structural configuration showed a very good agreement with those estimated from the measurements, which supports our understanding of the nature of the magnetic interactions and anisotropies in $CuCrP_2S_6$.

Finally, we observed a remarkable effect of the field-tuning of the character of the collective spin excitations from the antiferromagnetic type at magnetic fields below 6 - 8 T to the ferromagnetic type at stronger fields. This unusual effect can be explained by considering the closeness of the scales of the interplane exchange and the magnetic anisotropy energies.

All our observations highlight new interesting magnetic functionalities of $CuCrP_2S_6$ that may make it relevant for prototype magnonic devices. Specifically, the non-degeneracy of the magnon excitation modes in zero magnetic field offers a possibility to use this compound as a transmitter of the unidirectional spin current, i.e., the flow of spin angular momentum. This can be achieved by exciting the magnons with distinct energies $\Delta 2$ and $\Delta 1$ without the application of an external magnetic field which in many cases is required to lift the modes' degeneracy. Furthermore, the application of moderate magnetic fields enables a controllable switching of the character of the spin excitations between AFM and FM types, which can be treated as different "channels" for the transmission of the spin current in the same material.

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[1] J. J. Abraham et al., Adv. Funct. Mater. e11057 (2025)

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[1] University of Zagreb, Croatia

Current Research 2

A new type of superconductivity: evidence for i-wave pairing in Platinum-Bismuth

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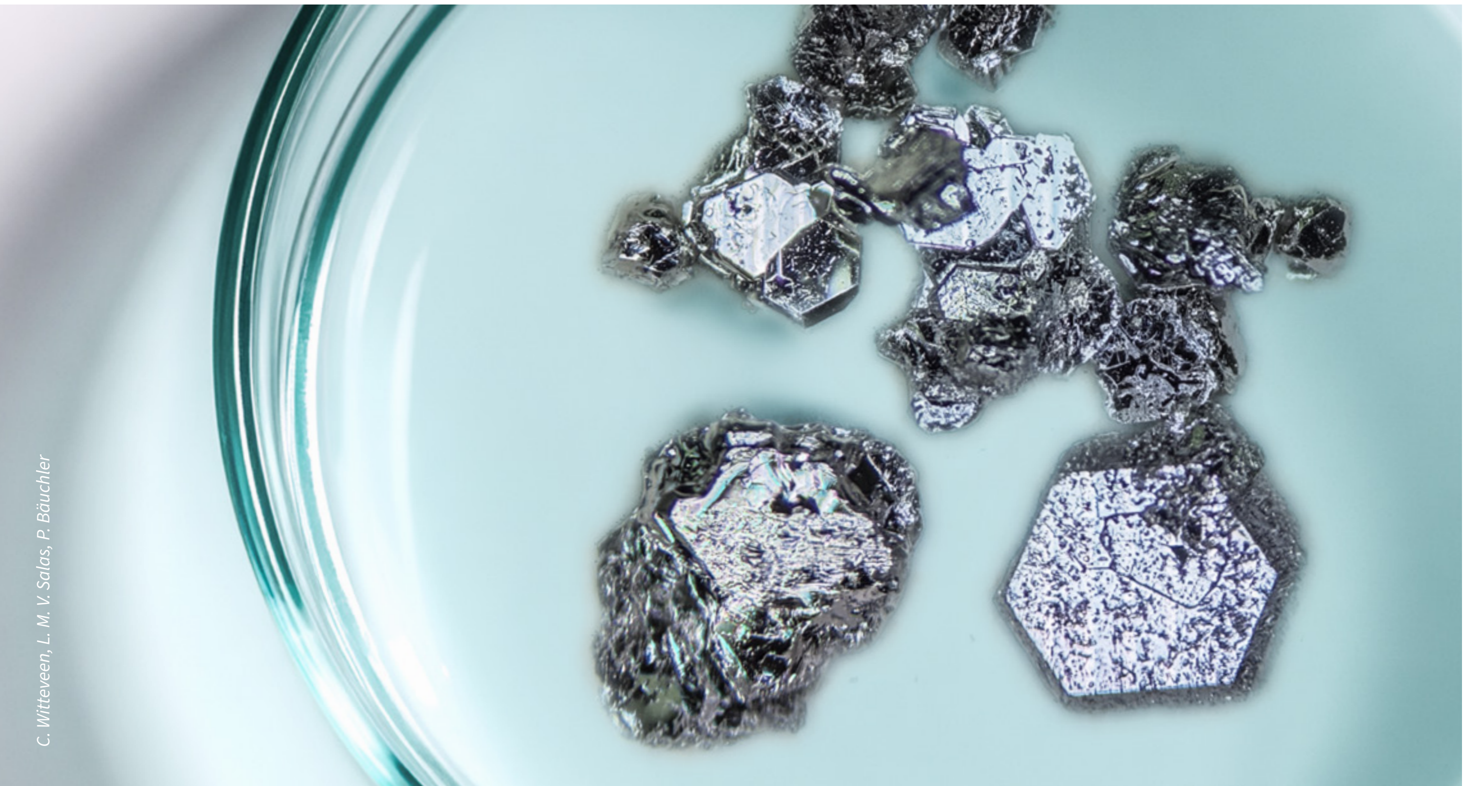
Unsere Forschung hat eine neue und ungewöhnliche Form der Supraleitung entdeckt – also einen elektrischen Stromfluss ganz ohne Widerstand – die auf der Oberfläche eines besonderen Materials namens Platin-Bismut ($PtBi_2$) auftritt. Auch wenn es sich um Grundlagenforschung handelt, könnte dieses neu identifizierte Materialsystem langfristig neue Perspektiven für supraleitende Quantentechnologien und zukünftige Einsatzmöglichkeiten eröffnen. Solche Erkenntnisse könnten künftig dazu beitragen, robustere Bausteine für Quantencomputer sowie für weitere hocheffiziente elektronische Anwendungen zu entwickeln.

Our research uncovers a new and unusual kind of superconductivity — electric current flowing without resistance — on the surface of a special material called Platinum-Bismuth ($PtBi_2$), a topological semimetal. Although this is fundamental research, discovering such a new material system could open future paths for superconducting quantum technologies and novel device concepts. In the long term, insights like these may even contribute to building more stable components for quantum computers and other ultra-efficient electronic devices.

Abb. 1: Rohkristall aus Platin-Bismut ($PtBi_2$). Das IFW Dresden erforscht dieses besondere Material seit mehreren Jahren intensiv – unter anderem wegen seiner außergewöhnlichen topologischen Eigenschaften und neuartigen supraleitenden Effekte, die Perspektiven für zukünftige Quantentechnologien eröffnen.
Fig. 1: Platinum bismuth ($PtBi_2$) raw crystal. IFW Dresden has been intensively studying this remarkable material for several years, particularly for its unusual topological properties and novel superconducting effects that may open up new perspectives for future quantum technologies.



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Superconductivity, the phenomenon in which electrical current flows without resistance, occurs at low temperatures in some materials such as lead or niobium. The latter two belong to the most common class of so-called conventional superconductors. Their electrons pair up as "Cooper pairs" with zero angular momentum (called s-wave pairing), and this pairing is essentially uniform in all directions.

In theory, more exotic superconductors are also possible, in which the pairing has a larger angular momentum quantum number. Up until recently, the only example observed in real life was d-wave pairing (angular momentum quantum number $l = 2$) which was first seen in cuprates in the late 80s and early 90s [1]. In this new type of pairing the superconducting gap has nodes, i.e. directions in momentum space along which the gap vanishes. Since its observation, d-wave superconductivity has led to a flurry of activity in condensed matter physics, with the 1987 APS March meeting (the one where the first cuprate superconductors were reported) being dubbed "The Woodstock of Physics" [2].

This year, together with collaborators from TU Dresden, the Bose National Centre for Basic Sciences in India, and the Kiev Academic University in Ukraine, we have found the first spectroscopic evidence of superconductivity with angular momentum $l = 6$, so-called i-wave pairing [3]. It occurs in a metallic material called $PtBi_2$, not inside the bulk, but on its surface.

Bulk Weyl semimetal and surface superconductor

$PtBi_2$ is not a typical metal. In its normal (non-superconducting) state it is a Weyl semimetal [4]. Its electronic bands cross at so-called Weyl points, and on the surfaces one finds characteristic "Fermi arcs": open curves in momentum space connecting the projections of the Weyl points. These Fermi arcs are in fact topological surface states, whose existence is not accidental but enforced by the topology of the bulk band structure (i.e. of the Weyl nodes).

Previous work showed that the $PtBi_2$ becomes superconducting below about 10 K, but in a highly unusual fashion [5]. The superconductivity seems confined to the surface states (the Fermi arcs), while the bulk remains metallic. What our new study adds is a detailed map of how the superconducting gap behaves in this "surface-only" superconductor, which leads to an unexpected result.

Evidence for i-wave pairing

Using ultrahigh-resolution angle-resolved photoemission spectroscopy (also known as ARPES, see Photo), we measured the energy gap of the superconducting surface states as a function of momentum along the Fermi arcs. Taking advantage of the extremely sharp spectral features of these surface states, among the sharpest ever observed in photoemission from a solid [3, 5], we obtained an unprecedentedly precise map of the gap function.
Moving along the Fermi arc in momentum space, we found that the superconducting gap first decreases until becoming vanishingly small in the center of the arc, and then begins to grow again (see Fig. 3). Thus, the ARPES data is consistent with nodes of the superconducting gap at the Fermi-arc centers: a hallmark of unconventional pairing. Such nodes are incompatible with a simple s-wave ($l = 0$) gap, and also do not match d-wave symmetry ($l = 2$) known from cuprates. Instead, symmetry analysis shows that this number and position of nodes corresponds to $l = 6$ pairing, i.e., to i-wave pairing. To the best of our knowledge, this is the first spectroscopic evidence for a superconducting gap beyond d-wave symmetry in any material.

Intrinsic topological superconductivity

Beyond its inherent interest from a purely fundamental point of view (a superconductor with a new type of pairing), i-wave superconductivity in $PtBi_2$ also has important consequences in the study of topological phases of matter. Since the Fermi arcs are nondegenerate topological surface states, a node occurring in the middle of the arc automatically implies that the superconductor is itself topologically nontrivial. The nodes then form so-called Majorana cones, named after the Italian scientist Ettore Majorana, who first proposed the existence of particles which are their own anti-particles [6]. Similar to the Dirac cones in the bulk of graphene [7], Majorana cones on the surface of $PtBi_2$ are necessarily associated with protected boundary states. In this case, these are Majorana modes positioned at the Fermi level and localized at "the boundary of the surface," i.e. on the hinges or step edges of the crystal.

Finding a system in which Majorana cones occur spontaneously is remarkable, since topological superconductors are extremely scarce in nature, unlike topological insulators and metals. While the theoretical description of topological superconductivity is in many ways analogous to that of metals and insulators [8], to date only a handful of material candidates are considered as potentially realizing intrinsic topological superconductivity. In many such systems, however, different experimental methods often produce contradictory results, leading a recent review to suggest that there is as of yet no convincing evidence for intrinsic topological superconductivity [9]. In fact, it is this scarcity which has prompted an intense effort towards engineering this phase of matter, for example by means of superconductor-semiconductor heterostructures with atomically precise interfaces [10], or by individually positioning magnetic atoms on superconducting substrates [11]. In $PtBi_2$, instead, the topological superconductivity seems to occur by itself; what is needed is a temperature below 10 K.

Just getting started…

Many challenges remain before this new form of superconductivity can be fully understood or put to use. We still don't know what microscopic mechanism drives this unusual i-wave pairing. How does such a high-angular-momentum state emerge in $PtBi_2$, and why just on the surface? Moreover, even though our results provide strong evidence for the appearance of Majorana quasiparticles, which could one day serve as building blocks for topological quantum computation [12], we are not yet able to control them. Real progress toward such applications might require thinning down the material to suppress unwanted metallic bulk states, leaving behind just the Majoranas. What is clear right now is that the field remains wide open: the discovery is an important first step, but much work still lies ahead.

Abb. 2: Das IFW verfügt über eine langjährige Expertise in der winkelaufgelösten Photoemissionsspektroskopie (ARPES), darunter auch das hier gezeigte Messgerät „mini-ARPES“. Der Monitor auf der linken Seite des Fotos zeigt Messungen der Fermifläche in $PtBi_2$.
Fig. 2: The IFW has a long-standing expertise in angle-resolved photoemission spectroscopy (ARPES), including the “mini-ARPES” measurement device shown here. The monitor on the left side of the photo shows measurements of the Fermi surface in $PtBi_2$.

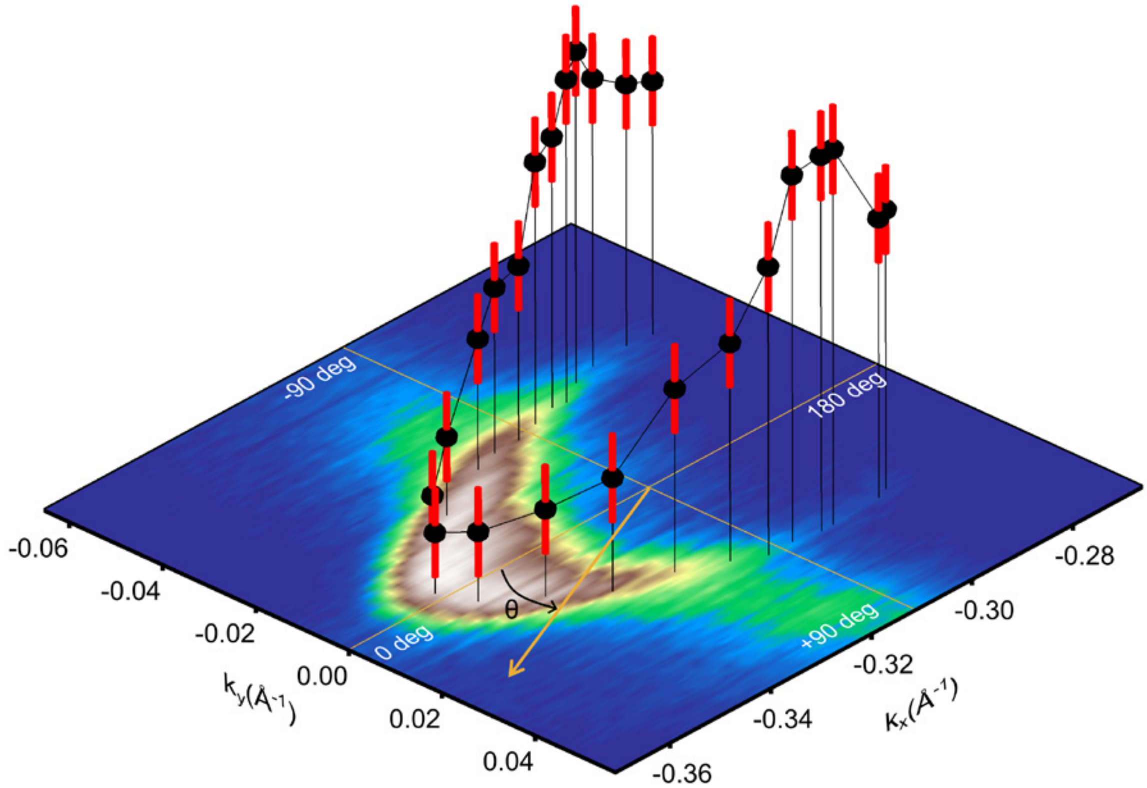

Abb. 3: Messung der Energielücke (Datenpunkte mit Fehlerbalken) entlang des Fermi-Bogens (Farbkarte). Die Lücke nimmt zunächst ab, bis sie in der Mitte des Bogens praktisch verschwindet; anschließend steigt sie wieder an. Diese spektroskopischen Befunde weisen auf die Existenz einer nodalen Supraleitung vom i-Wellen-Typ auf der Oberfläche von $PtBi_2$ hin.

Fig. 3: Measurement of the energy gap (data points with error bars) along the Fermi arc (color map). The gap first decreases until becoming vanishingly small at the center of the arc, after which it increases again. This spectroscopic evidence points to the existence of nodal, i-wave superconductivity on the surface of $PtBi_2$.

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Current Research 3

Tuning the single-molecule magnetism in Dysprosium metallofullerenes by chemical modification

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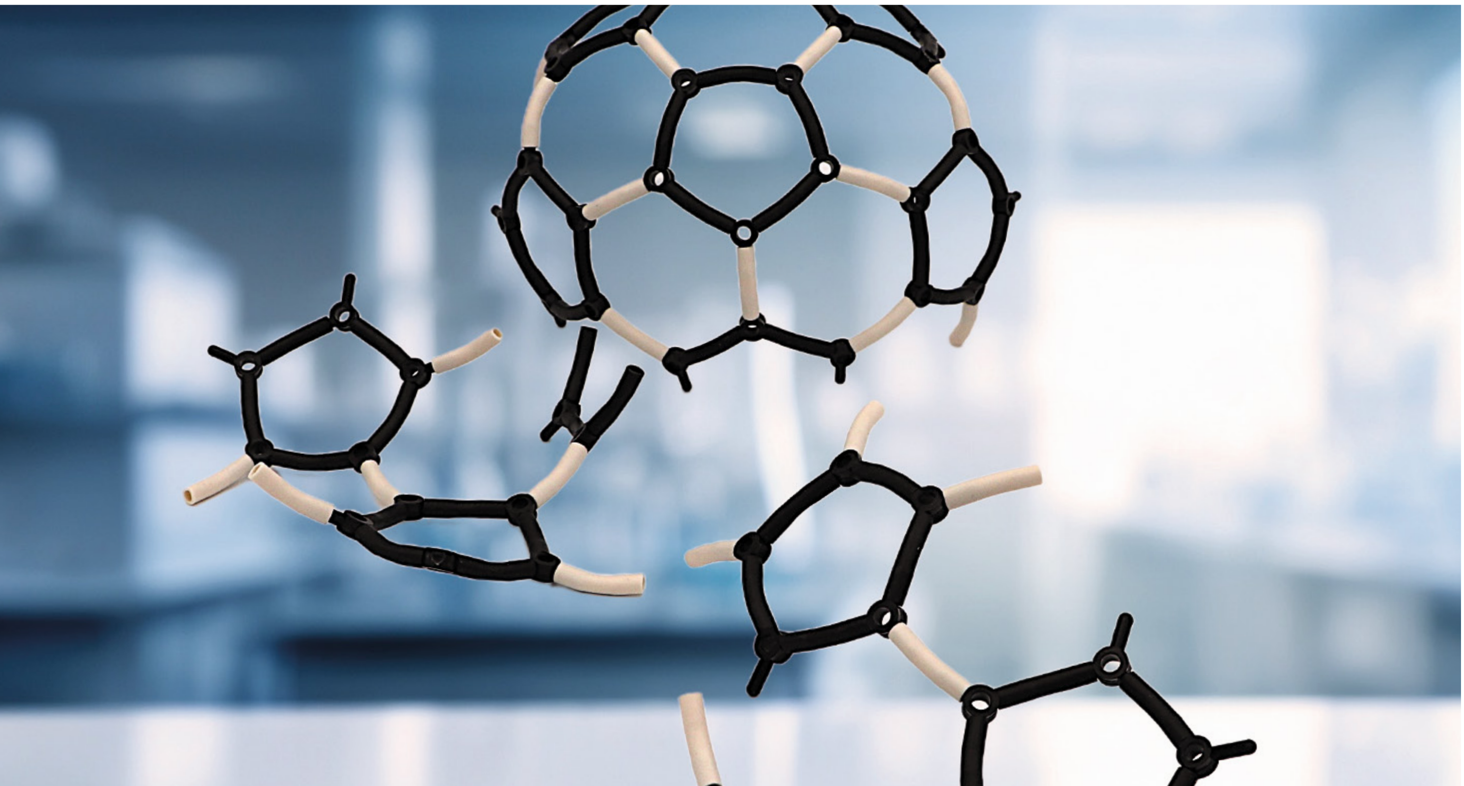
Untersucht wurde, wie eine chemische Veränderung der Kohlenstoffhülle die magnetischen Eigenschaften einzelner Moleküle beeinflusst. Dazu wurden die Verbindungen $DySc_2N@C_{80}$, $Dy_2ScN@C_{80}$ und $Dy_3N@C_{80}$ betrachtet.
Durch eine Anlagerungsreaktion entstanden jeweils zwei Varianten [Isomere] mit einer zusätzlichen Adamantyliden-Gruppe, deren genaue Struktur bestimmt wurde. Auch die elektronischen Eigenschaften und das Magnetverhalten wurden experimentell und theoretisch untersucht.
Je nach Bindungsstelle der Gruppe und Anordnung der Metallatome kann diese chemische Veränderung die magnetischen Eigenschaften verbessern oder verschlechtern.

The study investigated how chemical modification of the carbon cage influences the magnetic properties of individual molecules. The compounds $DySc_2N@C_{80}$, $Dy_2ScN@C_{80}$, and $Dy_3N@C_{80}$ were examined.
A chemical addition reaction produced two variants [isomers] in each case, bearing an additional adamantylidene group, and their precise structures were determined. The electronic properties and magnetic behavior were studied using both experimental and theoretical methods.
Depending on the binding site of the group and the arrangement of the metal atoms, this chemical modification can either enhance or reduce the magnetic properties.

Abb. 1: Die chemische Modifikation von Kohlenstoffverbindungen verändert auch deren magnetische Eigenschaften. Am IFW Dresden werden solche Kohlenstoffmodifikationen seit Jahren intensiv erforscht. Darüber hinaus kommen sie in unserer Bildungsarbeit zum Einsatz: Anhand anschaulicher Modelle werden Schülerinnen und Schülern die vielfältigen Strukturmöglichkeiten und die daraus resultierenden Veränderungen von Materialeigenschaften verständlich vermittelt.
Fig. 1: The chemical modification of carbon compounds also alters their magnetic properties. At IFW Dresden, such carbon modifications have been intensively researched for many years. In addition, they are used in our educational outreach: with the help of illustrative models, students are introduced to the wide range of structural possibilities and the resulting changes in material properties in a clear and accessible way.



Metallofullerenes with endohedral lanthanides form a versatile class of single-molecule magnets (SMMs) owing to the strong single-ion magnetic anisotropy, which can be realized in the interior of the carbon cage.[1] Furthermore, magnetic properties of metallofullerenes are strongly modulated by intramolecular metal-metal interactions.[2]
Since exohedral chemical modification of fullerenes is often used to adjust their properties and processability for prospective applications, [3,4] it is necessary to understand how it can affect magnetic properties. Once its influence on magnetic properties is understood, chemical modification can be also used as a tool to tune these properties.

In this work we explored how a typical cycloaddition reaction, photochemical addition of adamantylidene (Ad) (Fig. 2), affects single-ion magnetic anisotropy, Dy–Dy interactions, and relaxation of magnetization in the series of nitride clusterfullerenes $Dy_xSc_{3-x}N@C_{80}$ (x = 1–3).[5,6] In all these molecules, Dy ions experience strong axial ligand field imposed by the nitride ion, Dy magnetic moments are aligned along Dy–N bonds, and their magnetic ground state is separated from higher-energy states by hundreds cm^{-1}. But despite the very similar single-ion properties, a very different SMM behavior is observed. $DySc_2N@C_{80}$ shows magnetic hysteresis with a pronounced zero-field quantum tunneling of magnetization (QTM). In $Dy_2ScN@C_{80}$, ferromagnetic Dy–Dy coupling suppresses zero-field QTM, leading to a large remanence and coercivity. In $Dy_3N@C_{80}$, a triangular arrangement of Dy ions results in geometric frustration and a highly-degenerate ground state; zero-field QTM is allowed again, resulting in closing of the magnetic hysteresis in zero field.

C_{80}-I_h carbon cage has two types of C–C bonds located at the pentagon/hexagon and hexagon/hexagon edges (denoted as *[5/6]* and *[6/6]*, respectively). As adamantylidene group can attach to either of these bond types, reaction between $M_3N@C_{80}$ and AdN_2 produces two isomers for each studied fullerene (Fig.2), which are then separated by a high-performance liquid chromatography. Since *[6/6]* and *[5/6]* isomers of $M_3N@C_{80}$(Ad) have different number of inequivalent protons, they can be identified by ^{1}H nuclear magnetic resonance (NMR) spectroscopy.
The relative yield of *[6/6]* isomers increases dramatically in the $DySc_2N$–Dy_2ScN–Dy_3N series, indicating that the size and shape of the endohedral cluster has a strong influence on how the fullerene cage reacts with exohedral reagents.

Derivatization of the fullerene cage has a strong influence on the position and dynamics of the endohedral cluster. In non-functionalized $M_3N@C_{80}$, the M_3N cluster rotates almost freely at room temperature and adopts random orientations upon cooling. However, in $M_3N@C_{80}$(Ad) derivatives, metal atoms coordinate to the Ad addition site, which hinders rotation of the M_3N cluster and improves structural ordering at low temperature.
Still, asymmetric $DySc_2N$ and Dy_2ScN clusters in $M_3N@C_{80}$(Ad) can adopt two coordination forms, with Sc atom pointing towards the Ad addition site (denoted as ^{Ad}Sc) and with Dy atom in that position (denoted as ^{Ad}Dy). The preferable coordination mode can be established by ^{1}H NMR spectroscopy because Dy ions produce local magnetic field, which shifts the resonance position of protons. The size of this shift is very sensitive to the distance between proton and Dy atoms, and the ^{Ad}Dy form of $DySc_2N@C_{80}$(Ad) is predicted to exhibit tenfold stronger paramagnetic ^{1}H shifts of Ad protons than in the ^{Ad}Sc form. By virtue of this high sensitivity of the ^{1}H nuclear spin probe to positions of magnetic Dy ions, we established the dominant ^{Ad}Sc coordination in the *[5/6]* isomers and coexistence and interconversion of both ^{Ad}Sc and ^{Ad}Dy forms in *[6/6]* isomers of $DySc_2N@C_{80}$(Ad) and $Dy_2ScN@C_{80}$(Ad).

To address the magnetic anisotropy of Dy ions in synthesized derivatives, we first performed multiconfigurational *ab initio* calculations using the complete-active-space self-consistent-field approach (CASSCF). This method allows prediction of the ligand-field splitting and orientations of magnetic moment for each ligand-field state of lanthanide ions. Calculations revealed that the chemical derivatization has a considerable influence on the anisotropy of endohedral Dy ions, but this influence strongly depends on how the nitride cluster is coordinated to the Ad addition site. In Ad adducts with ^{Ad}Dy coordination, the ligand field splitting is decreased in comparison to Dy in non-derivatized fullerene, which has a detrimental effect on the magnetic axiality. On the other hand, ^{Ad}Sc coordination results in Dy ion

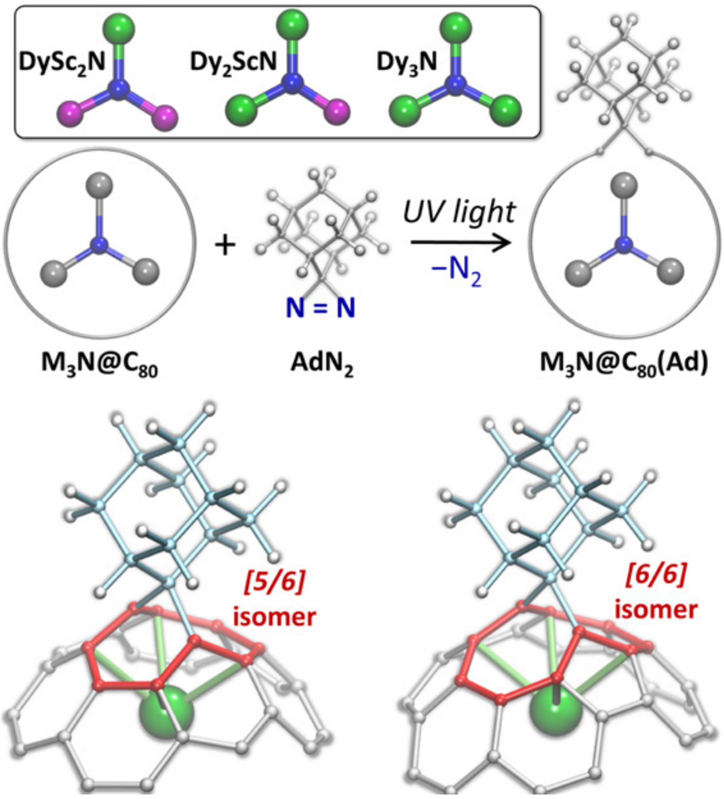


Abb. 2: Adamantyliden-Cycloadditionsreaktion mit $M_3N@C_{80}$ (M_3N = $DySc_2N$, Dy_2ScN und Dy_3N), die zu zwei Isomeren von $M_3N@C_{80}$(Ad) führt. Der untere Teil zeigt die Molekülstrukturen der [5/6]- und [6/6]-Isomere mit der Adamantyliden-(Ad)-Gruppe sowie einem Fullerenderivat, an das die Gruppe gebunden ist.
Fig. 2: Adamantylidene cycloaddition reaction with $M_3N@C_{80}$ (M_3N = $DySc_2N$, Dy_2ScN, and Dy_3N), yielding two isomers of $M_3N@C_{80}$(Ad). Lower part shows molecular structures of [5/6] and [6/6] isomers with Ad moiety and a fullerene fragment, to which the group is attached.

showing comparable or stronger single-ion anisotropy than in pristine metallofullerenes.
The ligand-field splitting of lanthanide ions can be studied experimentally by photoluminescence spectroscopy. Lanthanide compound often exhibit transitions within the 4f shell in their spectra, and the information on the ligand field splitting is contained in the fine structure of these transitions. Because the luminescence of Dy ions in metallofullerenes is suppressed by absorption of visible light by the carbon cage, the photoluminescence study was performed for Nd analogs. $NdSc_2N@C_{80}$ and $NdSc_2N@C_{80}$(Ad) isomers showed 4f-4f emission bands in the near-infrared range, which developed well-resolved fine structure attributed to the ligand-field splitting when the samples were cooled down to 5–10 K (Fig.3).[5,7]

Analysis of this fine structure demonstrated that the *[5/6]* isomer of $NdSc_2N@C_{80}$(Ad) with the predominant ^{Ad}Sc coordination has larger LF splitting of the endohedral Nd^{3+} ion than in the pristine $NdSc_2N@C_{80}$, whereas the *[6/6]* isomer has less pronounced splitting and more complex spectrum caused by the presence of both ^{Ad}Sc and ^{Ad}Nd forms.

The ultimate information on the magnetization behavior and dynamics was obtained by SQUID magnetometry. The study of *[6/6]* isomer of $DySc_2N@C_{80}$(Ad) demonstrated that the ^{Ad}Dy coordination leads to a reduced blocking temperature of magnetization and narrower magnetic hysteresis than in $DySc_2N@C_{80}$. On the other hand, the *[5/6]* isomer showed increase of the blocking temperature and elongation of relaxation times of magnetization, demonstrating that the enhanced magnetic axiality, determined for the ^{Ad}Sc coordination by *ab initio* calculations and photoluminescence study, indeed improves the SMM performance of $DySc_2N@C_{80}$(Ad).

For $Dy_2ScN@C_{80}$ and $Dy_3N@C_{80}$, the role of the single-ion magnetic anisotropy appeared less important than the intramolecular Dy–Dy coupling. Magnetization measurements demonstrated that the Ad addition has almost no effect on the strength of the Dy–Dy coupling in the *[6/6]* isomer of $Dy_2ScN@C_{80}$(Ad), but it does increase the coupling in the *[5/6]* isomer by 20% in comparison to pristine $Dy_2ScN@C_{80}$. The blocking temperature of magnetization and the coercivity are both softened in $Dy_2ScN@C_{80}$(Ad) irrespective of the isomeric structure and coordination type.

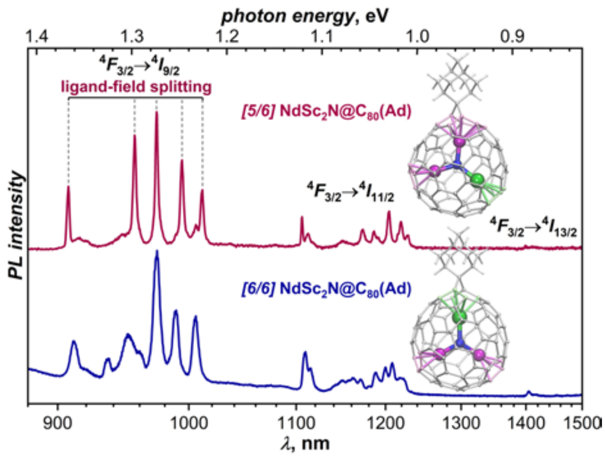


Abb. 3: Photolumineszenzspektren der [5/6]- und [6/6]-Isomere von $NdSc_2N@C_{80}$(Ad), gemessen bei 5 K im Energiebereich der Nd-4f–4f-Übergänge. Die Feinstruktur der $^4F_3/_2\rightarrow{}^4I_9/_2$-Bande liefert Informationen über die Ligandenfeldaufspaltung im Grundzustand. Die eingefügten Abbildungen zeigen die Molekülstrukturen (Nd – grün, Sc – magenta, N – blau).

Fig. 3: Photoluminescence spectra of [5/6] and [6/6] isomers of $NdSc_2N@C_{80}$(Ad) measured at 5 K in the energy range of Nd 4f-4f transitions. Fine structure of the $^4F_3/_2\rightarrow{}^4I_9/_2$ band gives information on the ligand-field splitting in the ground state. Insets show molecular structures (Nd – green, Sc – magenta, N – blue).

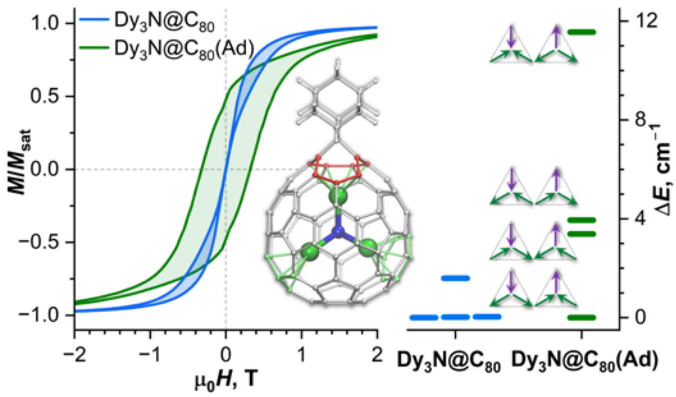


Abb. 4: Form der magnetischen Hysteresekurven von $Dy_3N@C_{80}$ (blau) und $Dy_3N@C_{80}$(Ad) (grün), gemessen bei 1,8 K. Auffällig ist das Schließen der Hysterese von $Dy_3N@C_{80}$ im Bereich geringer Magnetfelder um das Nullfeld. Die rechte Abbildung zeigt die magnetischen Energieniveaus niedrigster Energie von $Dy_3N@C_{80}$ und $Dy_3N@C_{80}$(Ad); jeder Strich entspricht einem Kramers-Dublett, wobei für jedes Dublett die Orientierung der magnetischen Momente dargestellt ist.

Fig. 4: The shape of magnetic hysteresis of $Dy_3N@C_{80}$ (blue) and $Dy_3N@C_{80}$(Ad) (green) measured at 1.8 K. Note the closing of hysteresis of $Dy_3N@C_{80}$ near zero magnetic field. Panel on the right shows the lowest-energy magnetic levels of $Dy_3N@C_{80}$ and $Dy_3N@C_{80}$(Ad); each dash corresponds to the Kramers doublet; orientations of magnetic moments are plotted for each doublet.

A much stronger effect of the Ad addition was found for $Dy_3N@C_{80}$. Dy ions prefer ferromagnetic alignment of their magnetic moments. But since magnetic moments are pinned to Dy–N bonds, their triangular arrangement in $Dy_3N@C_{80}$ results in the magnetic frustration: All three Dy–Dy pairs in the symmetric Dy_3N cluster cannot be aligned ferromagnetically at once, and one of the pairs has to adopt antiferromagnetic alignment. Frustration results in the degenerate magnetic ground state of Dy_3N and activation of the quantum tunneling of magnetization, which is manifested as the closing of magnetic hysteresis near zero field. However, addition of the Ad group to $Dy_3N@C_{80}$ substantially increased the strength of Dy–Dy interactions. Furthermore, as the symmetry of the Dy_3N cluster in $Dy_3N@C_{80}$(Ad) is reduced, the geometric frustration and degeneracy of the ground state are lifted, while the energy spread of the exchange-coupled states is strongly increased in comparison to $Dy_3N@C_{80}$ (Fig. 4). As a result, both $Dy_3N@C_{80}$(Ad) isomers exhibit open hysteresis without pronounced QTM signatures and have higher blocking temperature of magnetization than the pristine $Dy_3N@C_{80}$.

In summary, our study demonstrated that the chemical derivatization of the carbon cage can have a profound influence on magnetic properties of endohedral metallofullerenes even when endohedral lanthanide atoms are situated remotely from the functionalization site. The carbene addition can considerably modify the single-ion magnetic anisotropy and the metal-metal coupling in endohedral species, leading to enhancement or deterioration of the single-molecule magnetism depending on the regioisomerism and on the lanthanide-cage coordination geometry in the derivatives.

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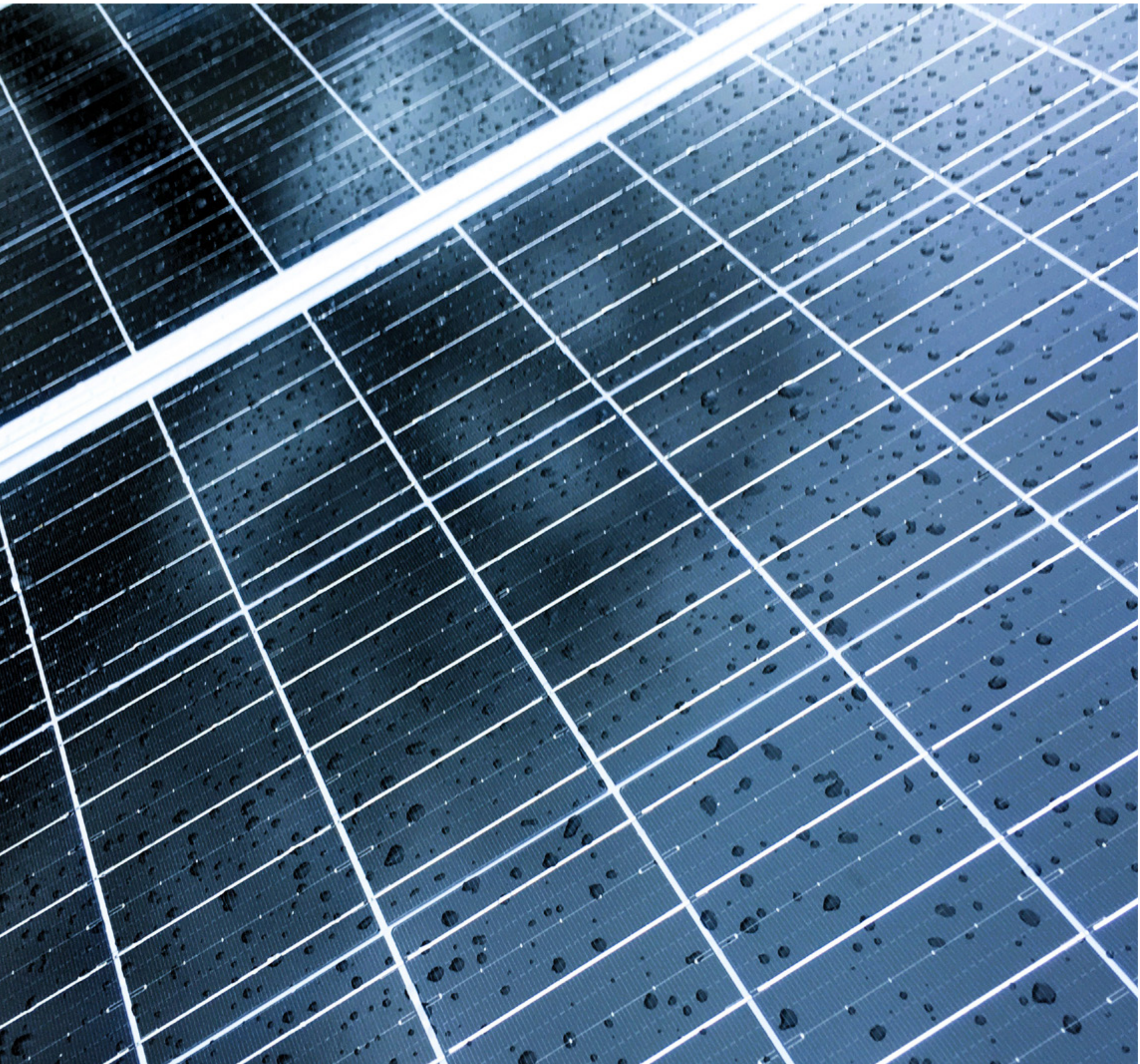
Current Research 4

New methods to identify imperfect charge extraction in perovskite solar cells

Herman Heffner, Kurt Taretto[1], and Yana Vaynzof



Der weltweite Energiebedarf ist in den vergangenen Jahrzehnten infolge des anhaltenden Bevölkerungswachstums exponentiell gestiegen. Zugleich erhöht der notwendige Rückgang von Treibhausgasemissionen den Druck, auf saubere und erneuerbare Energien umzusteigen. Solarzellen sind dabei eine zentrale Technologie für eine nachhaltige Stromerzeugung. Perowskit-Solarzellen erreichen mit Wirkungsgraden von etwa 27 Prozent bereits das Niveau etablierter Siliziumtechnologie. Da sich Einfachzellen der theoretischen Effizienzgrenze von rund 33 Prozent nähern, rückt die gezielte Optimierung der Grenzflächen in den Fokus. Forschende des IFW Dresden entwickelten gemeinsam mit Prof. Dr. Kurt Taretto (Universität Comahue, Argentinien) eine einfache Methode zur Bewertung der Grenzflächenqualität, die eine schnelle Analyse des Ladungstransports ohne komplexe Messverfahren ermöglicht und so die Optimierung von Photovoltaiksystemen effizienter gestaltet.

Global energy demand has increased exponentially in recent decades, driven by continuous population growth. At the same time, the urgent need to reduce greenhouse gas emissions has accelerated the transition toward clean and renewable energy sources. Solar cells are a key technology for sustainable electricity generation. Perovskite solar cells, with efficiencies of around 27 percent, already compete with established silicon technology. As single-junction devices approach their theoretical efficiency limit of about 33 percent, optimizing interfaces becomes increasingly important. Researchers at IFW Dresden, together with Prof. Dr. Kurt Taretto (National University of Comahue, Argentina), developed a straightforward method to evaluate interface quality, enabling rapid assessment of charge transport without complex characterization techniques and thereby facilitating more efficient photovoltaic optimization.

Abb. 1: Fortschritte in der Forschung an Materialien wie Perowskiten helfen, verborgene Energieverluste in Solarzellen besser zu verstehen und die Effizienz zukünftiger Photovoltaik-Module zu steigern.
Fig. 1: Advances in research on materials such as perovskites help to better understand hidden energy losses in solar cells and increase the efficiency of future photovoltaic modules.

Seeing Inside Solar Cells: A New Way to Identify Hidden Energy Losses

Solar energy is rapidly transforming the world's energy landscape. Among the most promising new technologies are perovskite solar cells, which are lightweight, inexpensive, and remarkably efficient devices that can already compete with traditional silicon technology. Their efficiency has increased rapidly over the past decade, and they are now considered one of the strongest candidates for large-scale renewable energy deployment [1].

However, while perovskite solar cells are highly efficient in laboratory-scale, converting them into reliable and long-lasting commercial products requires a much deeper understanding of how they function internally. Strangely enough, one of the biggest mysteries lies not in how perovskites absorb sunlight, but in how they transport and extract the resulting electrical charges. Even in very high-quality perovskite devices, some of the generated electrical current fails to reach the electrodes, reducing the power output. Determining the causes and locations of this loss is a crucial scientific and technological challenge. Traditionally, answering this question requires highly specialized laser-based equipment that measures ultrafast processes, techniques that are expensive, time-consuming, and not easily accessible to most laboratories or industry [2]. But there is a simpler and more elegant path.

A New Perspective on a Familiar Measurement

In this work, we introduce a powerful way to uncover performance losses in solar cells using a measurement that nearly every solar cell laboratory already performs: the internal quantum efficiency, also known as IQE. IQE describes how effectively the perovskite converts absorbed photons into electrical current. Until now, IQE has been commonly used to estimate how well charges move through the bulk of a semiconductor, a method that has been very successful for silicon technology. However, perovskites behave differently from silicon: they contain mobile ions that move under illumination and voltage, making the internal electric field difficult to predict accurately. As a result, classical models are not adequate.

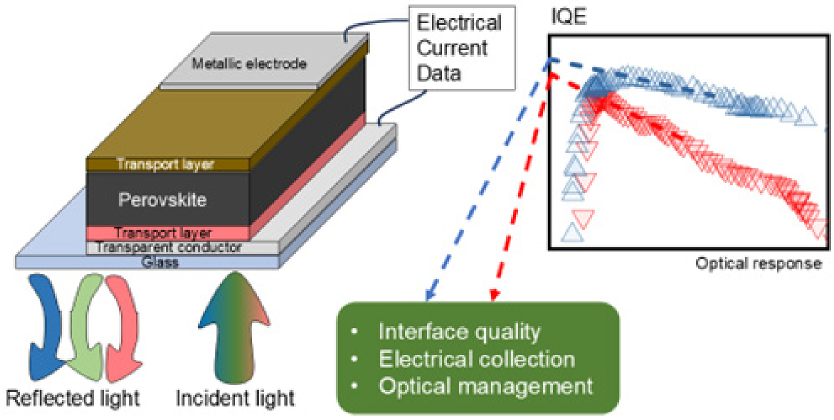


Abb. 2: Aufbau des vorgeschlagenen Experiments. Durch Beleuchtung der Solarzelle mit verschiedenen Wellenlängen und Messung des reflektierten Lichts und des elektrischen Stroms können wir die interne Quanteneffizienz berechnen. In Kombination mit den Informationen zur optischen Response konnten wir die Qualität der Frontschnittstelle der Perowskit-Solarzelle abschätzen.

Fig. 2: Setup of the proposed experiment. By illuminating the solar cell with different wavelengths and measuring the reflected light and the electrical current, we can calculate the internal quantum efficiency. Combined with the optical response information, we were able to estimate the quality of the perovskite solar cell front interface.

Our research revisits IQE from an entirely new perspective. Instead of assuming idealized behavior, we let the device tell us what is really happening.

By carefully analyzing the shape of the IQE spectrum under two special conditions, we can mathematically separate contributions from the bulk material and the interfaces. This allows us to extract meaningful physical quantities such as the collection efficiency at the device surface and the average collection efficiency across the entire absorber. In simple terms, we developed a method to determine how much current is lost and where it is lost, without requiring complex time-resolved experiments [3].

Why This Matters

Solar cell interfaces play a crucial role in determining performance. They are responsible for guiding charges out of the material and into the electrodes, but they can also become traps where energy is wasted. Our method offers a direct and intuitive approach to measuring the performance of these interfaces in real devices.

To demonstrate the power of this approach, we applied it to two identical perovskite solar cells, except for one crucial feature: one device includes a dedicated layer to collect electrons, while the other does not.
Our analysis immediately reveals a dramatic reduction in interfacial charge collection in the device lacking this layer, which explains its lower performance and highlights the importance of proper interface engineering. Most importantly, this method requires only standard optical measurements, making it fast, low-cost, and broadly accessible.

A Tool for the Future of Solar-Cell Innovation

Perovskite devices are complex. Their electronic behavior depends on their composition, processing, interfaces, and even their history of illumination and applied voltage. Researchers often face the challenge of disentangling multiple interacting effects simultaneously. This new IQE-based approach helps simplify the problem by offering a direct experimental window into interfacial losses, even when the electric field inside the device is uncertain or evolving.

This gives researchers and engineers a practical tool to:

- rapidly screen new materials and device architectures,
- identify bottlenecks in charge collection,
- quantify how much performance could be gained by improving interfaces, and
- reduce reliance on advanced, high-cost characterization techniques.

Ultimately, this approach accelerates the feedback loop between device fabrication, characterization, and optimization, a critical step for moving perovskite technology from the lab to commercial reality.

Abb. 3: Am IFW Dresden hergestellte Perowskit-Solarzelle im Labormaßstab. Sie umfasst acht Elemente mit einer aktiven Fläche von etwa 49 mm². Unten: Abb. 4: Prof. Dr. Kurt Taretto (links) und Dr. Dr.-Ing. Herman Heffner am Campus der Nationalen Universität Comahue. Während eines kurzen Besuchs in der Stadt Neuquén führte Herman Gespräche darüber, wie eine Zusammenarbeit initiiert werden kann, die Experiment und Theorie miteinander verbindet.

Fig. 3: Laboratory-scale perovskite solar cell fabricated at the IFW Dresden. It contains eight devices with an active area of approximately 49 mm². Below: Fig. 4: Prof. Dr. Kurt Taretto (left) and Dr. Dr.-Ing Herman Heffner at the National University of Comahue Campus. During a brief visit to the city of Neuquén, Herman held discussions on how to initiate a collaboration that combines experiment and theory.

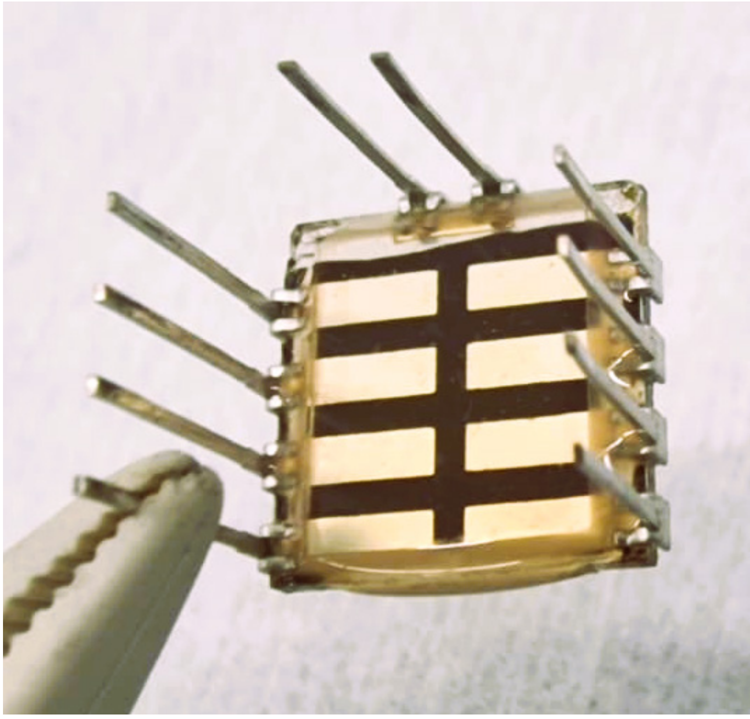


Foto: H. Heffner

Toward a Brighter Energy Future

Perovskite solar cells hold immense promise for transforming solar energy production thanks to their high efficiency, low cost, and versatile processing methods. Yet realizing their full potential requires precise understanding and control of how they move electrical charges, especially at their interfaces. By unlocking this information through simple and widely available measurements, our work opens the door to faster innovation, more reliable devices, and ultimately, more affordable clean energy.

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Current Research 5

New Magnesium Precursor Chemistry Enables Low-Temperature MgO Thin Films by Atomic Layer Deposition

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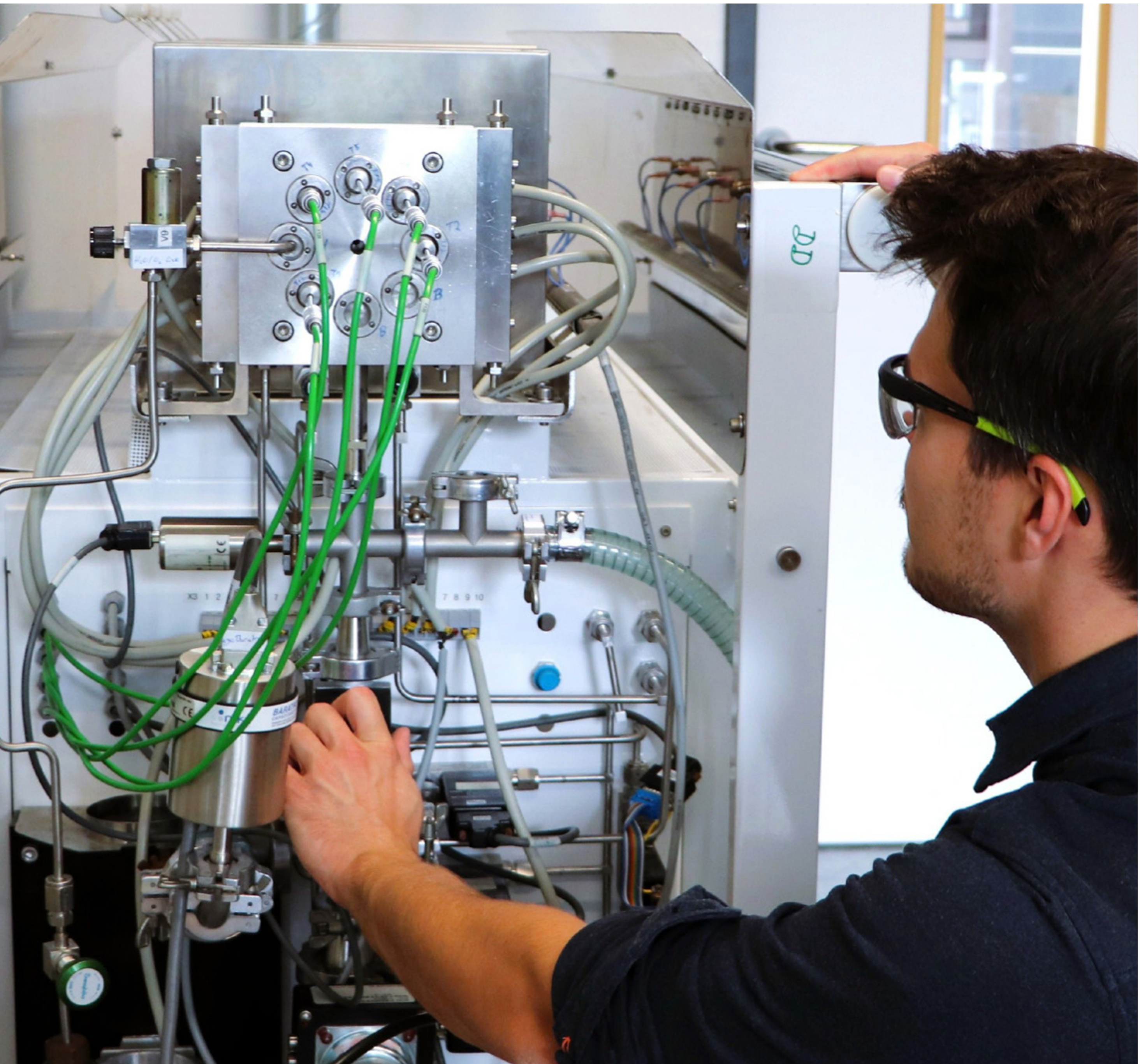


Im Rahmen unserer laufenden Forschungsaktivitäten haben wir eine neue Magnesiumverbindung entwickelt, die als Präkursor für die Atomlagenabscheidung (ALD) von MgO-Dünnschichten dient. Die Verbindung ist sicher in der Handhabung, nicht pyrophor und ermöglicht es uns, verschiedene Oberflächen bei nahezu Raumtemperatur mit ultradünnen Schichten aus Magnesiumoxid zu beschichten. MgO-Dünnschichten sind aufgrund ihrer großen Bandlücke, hohen Transparenz und isolierenden Eigenschaften für optoelektronische, magnetische und elektronische Geräte von technologischer Bedeutung. Sie werden insbesondere als Schutzschichten in Plasma-Bildschirmen (PDPs) zur Verlängerung der Lebensdauer sowie als magnetische Tunnelbarrieren in Festplattenlaufwerken geschätzt. Darüber hinaus dienen sie als biokompatible Beschichtungen und können Elektronik und andere Geräte vor Hitze, Feuchtigkeit und Verschleiß schützen. Da die neue Mg-Verbindung an der Luft nicht selbstentzündlich ist und das MgO-Wachstum bei niedrigeren Temperaturen fördert, verbraucht sie weniger Energie, ist sicherer in der Handhabung und unterstützt eine nachhaltigere Produktion flexibler Elektronik, Barrierefolien und Beschichtungen für medizinische Geräte und Implantate.

In our ongoing research, we developed a new magnesium compound that acts as a precursor for the atomic layer deposition (ALD) of MgO thin films. The compound is safe to handle, non-pyrophoric, and enables the coating of various surfaces with ultra-thin layers of magnesium oxide at nearly room temperature. MgO thin films are important for optoelectronic, magnetic, and electronic devices due to their wide bandgap, high transparency, and insulating properties. They are especially useful as protective layers in plasma display panels (PDPs) to extend lifespan and as magnetic tunnel barriers in hard disk drives. Additionally, they serve as biocompatible coatings and can protect electronics and other devices from heat, moisture, and wear. Because the new compound does not self-ignite in air and promotes MgO growth at lower temperatures, it consumes less energy, is safer to handle, and supports more sustainable production of flexible electronics, barrier films, and coatings for medical devices and implants.

Abb. 1: Florian Preischel am F-120 ALD-Reaktor, in dem die MgO-Dünnschichten mit Hilfe des neuen Mg-Präkursors hergestellt wurden.
Fig. 1: Florian Preischel operating the F-120 ALD reactor, where the MgO thin films were deposited using the new Mg precursor.

Within IFW Dresden's research focus on green chemistry and processes, we develop safer, more sustainable, and scalable methods for depositing thin films of advanced functional materials. Many modern devices, from smartphones and solar panels to medical implants, rely on ultra-thin coatings just a few nanometers thick. Typically, creating these layers requires high temperatures and hazardous chemicals. Our goal is to achieve equal or better performance while enabling new functionalities, using less energy, and safer chemistry.

In this project, an IFW-led team, together with partners from Ruhr University Bochum and Tyndall National Institute in Ireland, developed a new magnesium compound that serves as a building block for high-quality magnesium oxide (MgO) thin films. MgO is an abundant, non-toxic material [1] that can serve as a protective barrier against oxygen and water vapor [2], or as the active layer in photomultipliers [3] and magnetic tunnel junctions (MTJs) [4], which are promising for spintronics and non-volatile memory applications. Due to its biocompatibility and antimicrobial properties, it is also of interest for medical uses, including coating implants and medical devices.[5,6]

For depositing thin films, ALD is an essential gas-phase technique in which two chemicals (precursors) are alternately pulsed into a reactor. Due to its unique growth mechanism based on self-limiting surface reactions, it allows the deposition of high-quality, precisely controlled, uniform, and conformal thin films, even on complex three-dimensional (3D) structures. However, current magnesium precursors for ALD require high process temperatures and often have limited reactivity or are pyrophoric, meaning they ignite spontaneously in air. These issues pose challenges for safe operation, industrial-scale-up, and coating of temperature-sensitive substrates, such as polymer films.

To address these challenges, the new magnesium precursor $[Mg(DMP)_2]$ was synthesized in this work. As shown by single crystal X-ray diffraction (SC-XRD) analysis (Fig. 2a), the new compound is a monomer, stabilized intramolecularly by dative bonds from the free electron pairs on the nitrogen functionalities of the DMP ligand (Fig. 2b). This unique structure results in properties that meet all key requirements for an ALD process.
Based on its monomeric structure and low molecu-

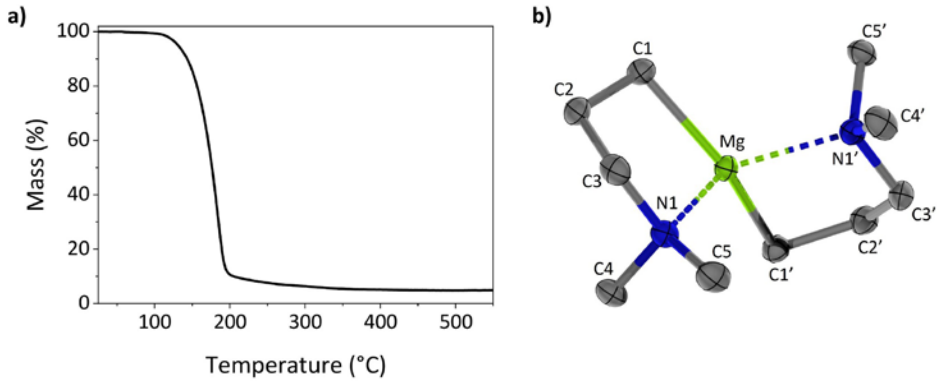


Abb. 2: a) Verdampfungskurve des neuen Mg-Präkursors [Mg(DMP)₂] anhand des Massenverlustes bei steigenden Temperaturen in einer Thermogravimetriemessung. b) Kristallstruktur des monomeren Präkursors, die die Ringstruktur der DMP-Liganden durch intramolekulare Koordination der Stickstoffatome zum zentralen Mg zeigt.

Fig. 2: a) Evaporation curve of the new Mg precursor [Mg(DMP)₂] based on mass loss at increasing temperatures in a thermogravimetry measurement. b) Crystal structure of the monomeric precursor, illustrating the ring structure of the DMP ligands, which is formed by intramolecular coordinative bonds from the nitrogen atoms to the Mg center.

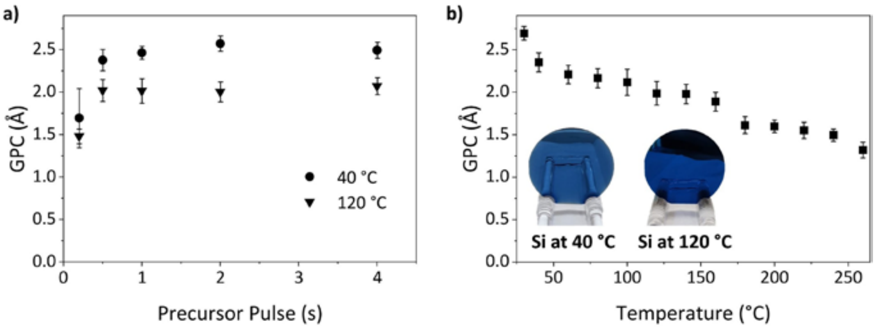
lar weight, the compound is highly volatile and evaporates in a single step, while intramolecular stabilization enhances its thermal stability, resulting in clean evaporation with minimal residue (Fig. 2a).
This stabilization also helps make [Mg(DMP)₂] non-pyrophoric, as shown by its exposure to air (Fig. 3, left), reducing safety concerns common with many traditional Mg precursors. At the same time, the Mg–C bonds remain highly reactive, as demonstrated by their reaction with water (Fig. 3, right). Simulations conducted with our partners clarified the reactions that occur during water exposure, which are critical for understanding film growth and guiding future precursor development. For ALD, such reactivity is essential for enabling growth with mild co-reactants and low temperatures. Additionally, [Mg(DMP)₂] has a low melting point and is liquid at its processing temperature, ensuring consistent and reliable evaporation over long periods.

Using the new Mg precursor and water as a co-reactant, we demonstrated the growth of MgO thin films over an unusually wide temperature range from 30 °C to 260 °C. Even at temperatures just above room temperature, the coatings are uniform, dense, and adhere well to the substrates, with the characteristic linear, self-limiting ALD growth (Fig. 4).
IFW researchers conducted extensive structural and chemical characterization to confirm the high purity and smoothness of MgO thin films. A key achievement is the successful deposition of MgO on flexible polymer substrates. These materials cannot endure the high temperatures used in traditional processes. Therefore, low-temperature ALD enables robust encapsulation and functionalization of flexible and wearable electronics. Additionally, MgO deposition was demonstrated on stainless steel, which is promising for biocompatible coating of medical implants and underscores the versatility and wide applicability of the new precursor and ALD process.

The project builds upon the strong ALD activities at IFW Dresden's Institute for Materials Chemistry by transforming the new precursor concept into a dependable process with enhanced sustainability. First, lower process temperatures reduce overall

Abb. 3: Bildserie aus einem Video, die die Exposition von etwa 500 mg reinem [Mg(DMP)₂] gegenüber Luft über einen Zeitraum von etwa zwei Minuten sowie die anschließende Reaktion mit H_2O zeigt.
Fig. 3: Image series captured from a video showing the exposure of about 500 mg of pristine [Mg(DMP)₂] to air for approximately two minutes, followed by reaction with H_2O.

Abb. 4: Entwicklung des MgO-ALD-Prozesses anhand des Schichtwachstums pro Zyklus (engl. growth per cycle, GPC). a) Sättigung des Präkursorpulses bei 40 °C und 120 °C. b) GPC der optimierten ALD-Prozesse im Temperaturbereich von 30 bis 260 °C. Die eingefügten Bilder zeigen 2-Zoll-Silizium-Wafer, die bei 40 °C und 120 °C mit 500 Zyklen der optimierten ALD-Sequenz mit etwa 120 nm bzw. 95 nm MgO beschichtet wurden.
Fig. 4: Development of the MgO ALD process based on growth per cycle (GPC). a) Saturation of the precursor pulse at 40 °C and 120 °C. b) GPC of the optimized process across a temperature range from 30 to 260 °C. The insert images show 2-inch silicon wafers coated with 500 cycles of the optimized ALD process at 40 °C and 120 °C, yielding MgO film thicknesses of approximately 120 nm and 95 nm, respectively.



energy use in thin film production. Second, MgO is abundant, non-toxic, and compatible with biomedical settings. Third, unlike many of its traditional predecessors, the new compound no longer poses a fire hazard, making handling in the laboratory and scaling up to industrial reactors safer. This reduces the risk of accidents and simplifies transport and storage. This work also demonstrates how molecular-level design can replace problematic, difficult chemistries with more sustainable alternatives without sacrificing performance. By carefully choosing the organic ligands in the magnesium compound, we created a precursor that reacts efficiently at low temperatures to produce high-quality MgO thin films and can be produced in large quantities. These factors are essential for applying the ALD process in industrial settings and support greener manufacturing on a larger scale.

In the next steps, we will test MgO films produced with the new process directly in devices.
For example, we plan to evaluate their performance in biocompatible layers for metallic implants in collaboration with colleagues at IFW. Simultaneously, we are expanding the design principles developed here to other metals, aiming for safe yet effective and versatile precursors that enable greener thin-film processing across a broad range of applications. By combining targeted precursor design with advanced thin-film technology and green chemistry principles, IFW Dresden aims to develop more sustainable electronic and functional materials from the very first atomic layer.

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Current Research 6

Grain Boundary Engineering Enhances the Thermoelectric Properties of Y_2Te_3

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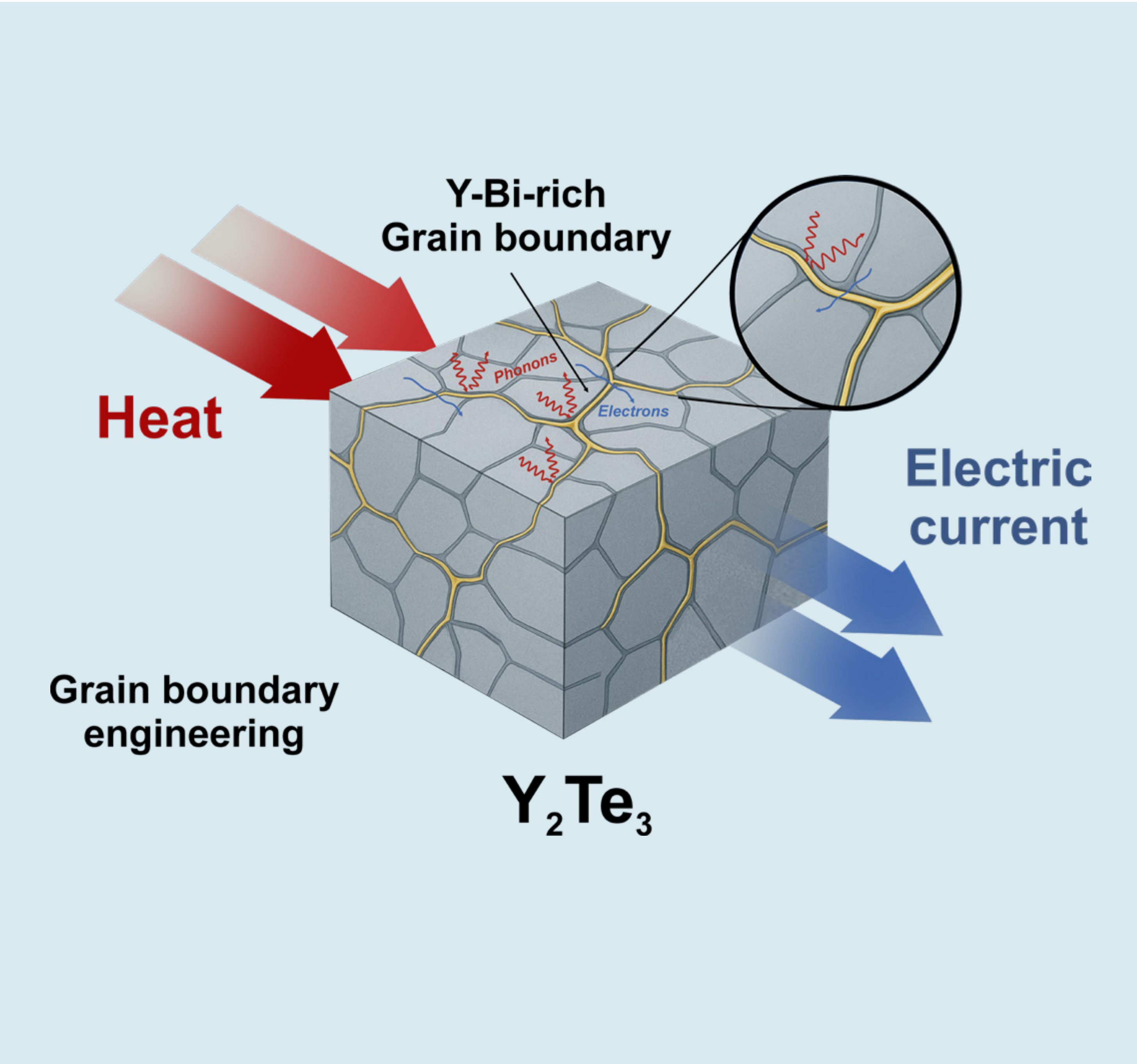

**Thermoelektrische Materialien spielen eine wichtige Rolle für die nachhaltige Energieumwandlung, da sie Abwärme direkt in elektrische Energie umwandeln können.
In diesem Beitrag zeigen wir, wie Korngrenzen-Engineering gezielt genutzt werden kann, um die thermoelektrischen Eigenschaften des Selten-Erden-Chalkogenids Y_2Te_3 zu verbessern, das von Natur aus eine geringe Gitterwärmeleitfähigkeit aufweist. Durch die Zugabe kleiner Mengen Bismut (Bi) entstehen Y-Bi-reiche Korngrenzen, die den Ladungsträgertransport begünstigen und den Seebeck-Koeffizienten erhöhen. Auf diese Weise erreicht das Material einen hohen Gütefaktor von zT = 1,23 bei 973 K sowie einen prognostizierten Umwandlungswirkungsgrad von über 10 Prozent. Die vorgestellten Ergebnisse unterstreichen das Potenzial des Korngrenzen-Engineerings als effektive Strategie zur Optimierung von Hochtemperatur-Thermoelektrika und liefern wichtige Impulse für die Entwicklung effizienter Materialien zur Nutzung industrieller Abwärme.**

**Thermoelectric materials play an important role in sustainable energy conversion, as they enable the direct conversion of waste heat into electrical energy.
In this contribution, we demonstrate how grain boundary engineering can be deliberately employed to improve the thermoelectric properties of the rare-earth chalcogenide Y_2Te_3, which intrinsically exhibits low lattice thermal conductivity. The addition of small amounts of bismuth (Bi) leads to the formation of Y–Bi-rich grain boundaries, which facilitate charge carrier transport and enhance the Seebeck coefficient. As a result, the material achieves a high figure of merit of zT = 1.23 at 973 K, along with a predicted conversion efficiency exceeding 10 percent. The presented results highlight the potential of grain boundary engineering as an effective strategy for optimizing high-temperature thermoelectric materials and provide important insights for the development of efficient materials for the utilization of industrial waste heat.**

Abb. 1 (links): Schematische Darstellung der thermoelektrischen Energieumwandlung in Y_2Te_3, verbessert durch Korngrenzen-Engineering. (Illustration von Jamil Ur Rahman, IFW Dresden)
Fig. 1 (left): Conceptual illustration of thermoelectric energy conversion in Y_2Te_3 enhanced by grain boundary engineering. (Illustration by Jamil ur Rahman, IFW Dresden)

As the global energy demand continues to increase, the need for sustainable technologies to improve energy efficiency has become more urgent. Thermoelectric (TE) technology offers a promising route toward a sustainable energy economy by directly converting waste heat into electrical power. The performance of a thermoelectric material is quantified by the dimensionless figure of merit, $zT = \sigma S^2 T/\kappa$, where S is the Seebeck coefficient, σ is the electrical conductivity, κ is the total thermal conductivity ($\kappa = \kappa_e + \kappa_L$), and T is the absolute temperature [1]. Achieving high zT values in bulk polycrystalline materials requires precise control over both electronic and phononic transport, particularly at grain boundaries (GBs), which strongly influence carrier mobility and heat flow. Among emerging thermoelectric materials, Y_2Te_3 has attracted growing attention as a promising high-temperature candidate due to its intrinsically low lattice thermal conductivity [2]. The concept of this work, enhancing thermoelectric performance in Y_2Te_3 through the formation of Y-Bi-rich grain boundaries that promote electrical transport and suppress heat flow, is schematically illustrated in Figure 1.

Vacancy control to tune carrier concentration

Polycrystalline Y_2Te_3 was synthesized using high-energy ball milling and spark plasma sintering. Guided by defect chemistry, we introduced excess Y to create a $Y_{2+x}Te_3$ series. Structural analysis and first-principles calculations indicate that excess Y preferentially occupies intrinsic cation vacancy sites, thereby increasing the electron concentration and improving electrical conductivity. An optimized composition around $Y_{2.11}Te_3$ exhibited a higher power factor and zT compared with stoichiometric Y_2Te_3, demonstrating that controlled vacancy filling is an effective strategy for optimizing the thermoelectric performance.

Grain boundary modification via Bi incorporation

To further reduce GB-related carrier scattering and improve interfacial transport, we incorporated a small amount of Bi in $Y_{2.11}Te_3$. Advanced electron microscopy and compositional mapping revealed preferential Bi segregation at GBs and formed nanometer-scale Y-Bi-rich interfacial regions (Fig. 2). These interfaces effectively enhance the Seebeck coefficient and carrier-weighted mobility across the

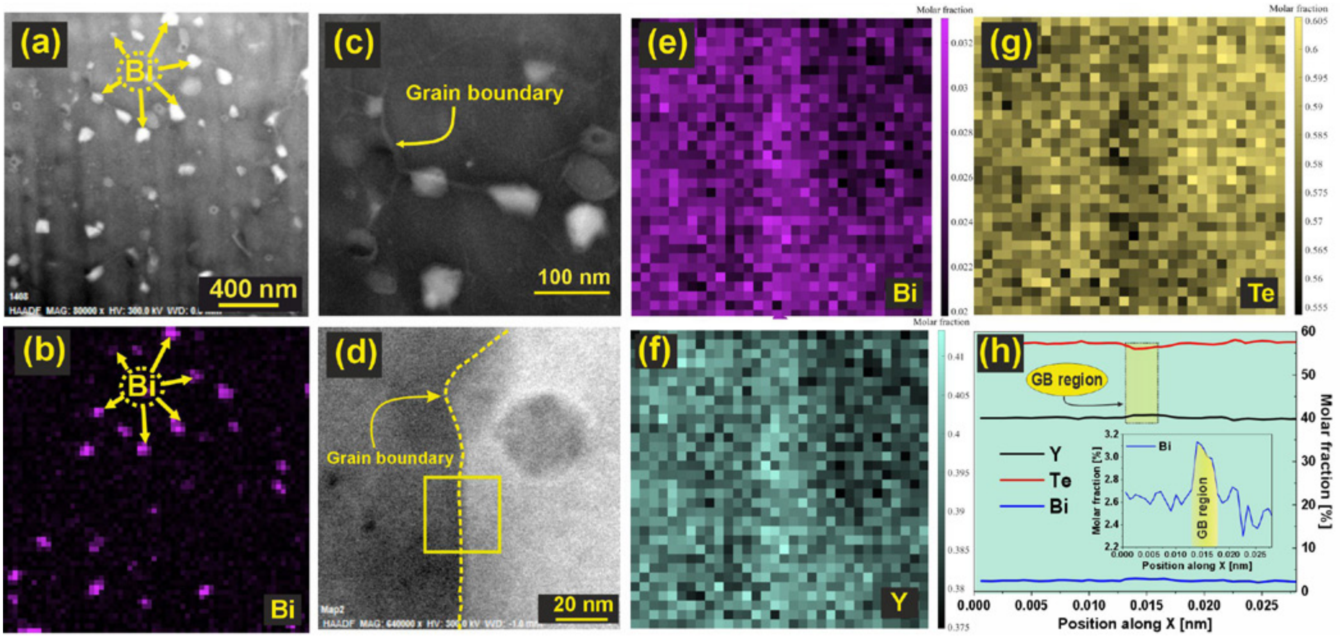

Abb. 2: Elektronenmikroskopische Aufnahme, die Y-Bi-reiche Korngrenzen zeigt, die den Ladungsträgertransport verbessern.
Fig. 2: Electron micrograph revealing Y-Bi-rich grain boundaries that improve charge carrier transport.

grain boundary [3]. In addition, Bi at GBs increases phonon scattering, leading to a moderate reduction in lattice thermal conductivity.
The combined effects of excess-Y vacancy filling and Bi-engineered GBs yielded a fourfold enhancement in power factor and produced a peak $zT \approx 1.23$ at 973 K [3], as shown in Figure 3. Finite-element method modelling based on the measured properties indicates a maximum conversion efficiency of ~10% under a ΔT of 673 K. These results establish Y_2Te_3 as a credible high-temperature TE material and, more broadly, validate grain boundary engineering as a powerful strategy for bulk TE materials.

This work shows that the chemistry at the grain boundaries can be deliberately tuned, here via Bi segregation, to enhance thermoelectric transport in Y_2Te_3. Together with controllable vacancy filling, this approach provides a practical route to decouple, or at least rebalance, electrical and thermal transport. Future efforts should explore (i) the long-term stability of Y-Bi-rich interfacial regions under thermal cycling, (ii) integration into device-scale thermoelectric modules, and (iii) the extension of this grain boundary design strategy to other rare-earth chalcogenide systems.

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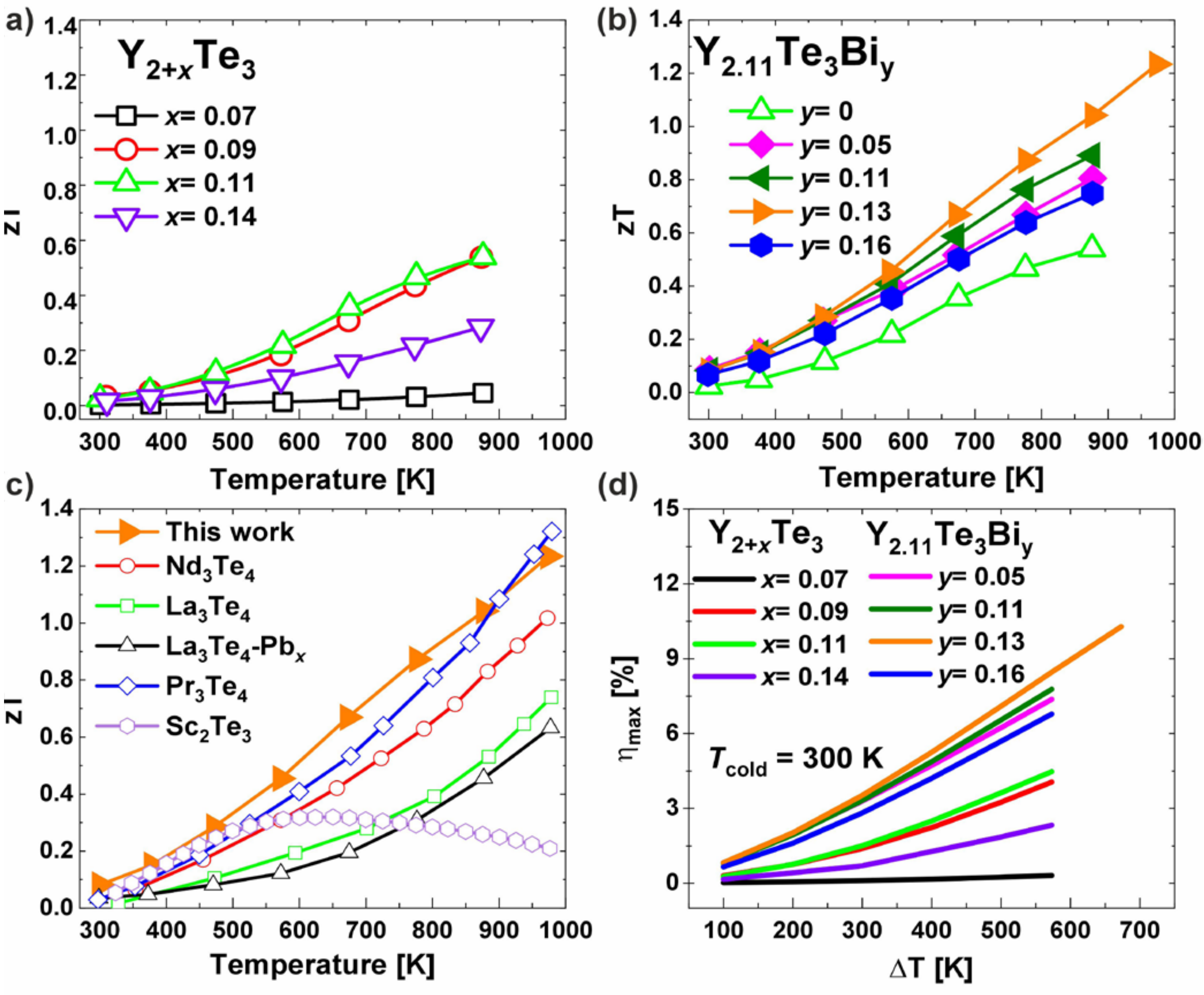

Abb. 3: Temperaturabhängigkeit von zT für Y_2Te_3- und Bi-haltige Proben im Vergleich zu zuvor beschriebenen thermoelektrischen Materialien auf Te-Basis, wobei die Bi-haltige Y_2Te_3-Probe bei 973 K einen Spitzenwert von zT = 1,23 aufweist.

Fig. 3: Temperature dependence of zT for Y_2Te_3 and Bi-incorporated samples, compared with previously reported Te-based thermoelectric materials, showing a peak zT = 1.23 at 973 K for the Bi-incorporated Y_2Te_3 sample.

Current Research 7

Low Temperature Atomic Layer Deposition of (00*l*)-Oriented Elemental Bismuth

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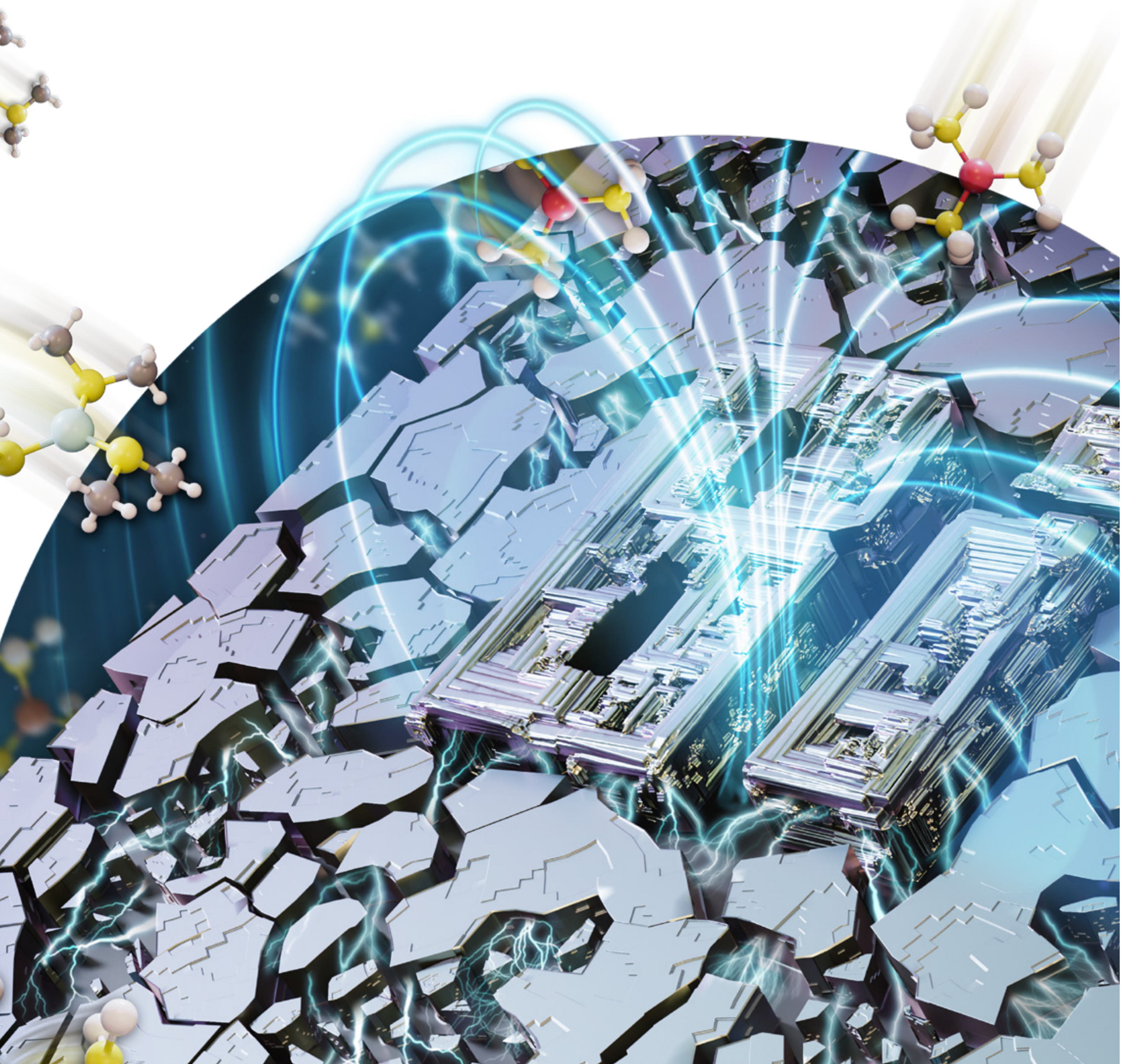

Mit der weiteren Verkleinerung und zunehmenden Komplexität elektronischer Bauelemente wächst der Bedarf an neuen Fertigungsmethoden, die extrem dünne und gleichmäßige Materialschichten erzeugen können. Herkömmliche Beschichtungsverfahren stoßen hierbei zunehmend an ihre Grenzen. Atomlagenabscheidung (ALD) stellt eine vielversprechende Methode dar, da selbst hochkomplexe und nanoskalige Strukturen präzise beschichtet werden können. In dieser Studie wird erstmals gezeigt, dass reine Bismut-Metallschichten bei nur 100 °Celsius mittels thermischem ALD und einer neuen Precursorchemie abgeschieden werden können. Die resultierenden Schichten weisen eine hervorragende Bedeckung und stabile elektrische Eigenschaften auf, die mit anderen Herstellungsverfahren vergleichbar sind. Damit entstehen neue Möglichkeiten für zuverlässige, nanoskalige Metallschichten in zukünftigen elektronischen Anwendungen.

As electronic devices continue to shrink and increase in complexity; new fabrication methods are needed to produce extremely thin and uniform material layers. Traditional coating techniques are expected to reach their limits in addressing these demands. Atomic Layer Deposition (ALD) offers a promising alternative, as it can precisely coat even highly complex and nanoscale structures. In this study, we demonstrate for the first time that pure bismuth metal films can be grown by thermal ALD at only 100 °Celsius using a new precursor chemistry. The resulting films show excellent coverage and stable electrical properties comparable to films produced by other methods, opening a new pathway toward reliable nanoscale metal layers for future electronic applications.

Abb. 1 (links): Die Illustration zeigt das erfolgreiche Wachstum dünner Schichten aus elementarem Bismut mittels eines schichtweisen Abscheideverfahrens. Dargestellt ist der Übergang von einer inselartigen Keimbildung zu einer geschlossenen Schicht. Grafik von INMYWORK Studio. Publiziert als Front-Cover im Journal Angewandte Chemie Volume 137 im April 2025.

Fig. 1 (left): The illustration depicts the successful growth of thin films of elemental bismuth using a layer-by-layer deposition process. It highlights the transition from island-like nucleation to a continuous film. Artwork by INMYWORK Studio. Published as Front Cover of Angewandte Chemie: Volume137 in April 2025.

As device miniaturization continues, traditional deposition methods like CVD and PVD struggle to deliver conformal films in high-aspect-ratio nanostructures. Atomic Layer Deposition (ALD) offers an atomic-level, conformal alternative and is essential for fabricating advanced nanoscale devices, especially when metals are required for conductors or electrodes [1]. Elemental bismuth (Bi), a semimetal with unique transport properties, is particularly attractive for applications such as thermoelectrics and topological insulators. Despite ALD processes existing for bismuth compounds (e.g., Bi_2O_3, Bi_2Te_3), a reliable low-temperature thermal ALD route to elemental Bi has remained elusive. This study is the result of a synergistic effort between three IFW departments (IMW, IMC, and IET), combining their complementary expertise to demonstrate a low-temperature ALD process using $Bi(NMe_2)_3$ and $Sb(SiMe_3)_3$ at 100 °C, while exploring the growth mechanism, microstructure, and electronic properties of the films.

The computational thermodynamic analyses (reaction energetics) for possible gas-phase reactions between $Bi(NMe_2)_3$ and $Sb(SiMe_3)_3$ suggested three pathways: I) direct deposition of both Bi and Sb, II) ligand exchange producing only Bi, and III) the reverse producing only Sb. At 100 °C and under low partial pressure (10^{-3} atm), the reaction producing only Bi is slightly more favorable than the others on a per-atom basis, suggesting that Bi deposition is thermodynamically preferred under the ALD conditions used (see Fig. 2a). Nonetheless, because all considered reaction pathways are exergonic and energetically similar, some Sb incorporation is thermodynamically plausible, consistent with the small Sb detected in the films.

The process achieves a growth per cycle (GPC) of approximately 0.31–0.34 Å/cycle under optimized conditions at 100 °C. At early ALD cycles, nucleation proceeds via island formation (VolmerWeber growth behavior). SEM images reveal that after ~1000 cycles, the coverage of Bi islands reaches about 80 %, while full surface coverage is obtained only after ~2000–2500 cycles, as seen in Figure 2b. Transmission electron microscopy (TEM) cross sections show that the initially formed clusters (after 500 cycles) are only partially crystalline; as the number of cycles increases, these clusters crystallize and merge into a more continuous film (Fig. 2c). Elemental mapping

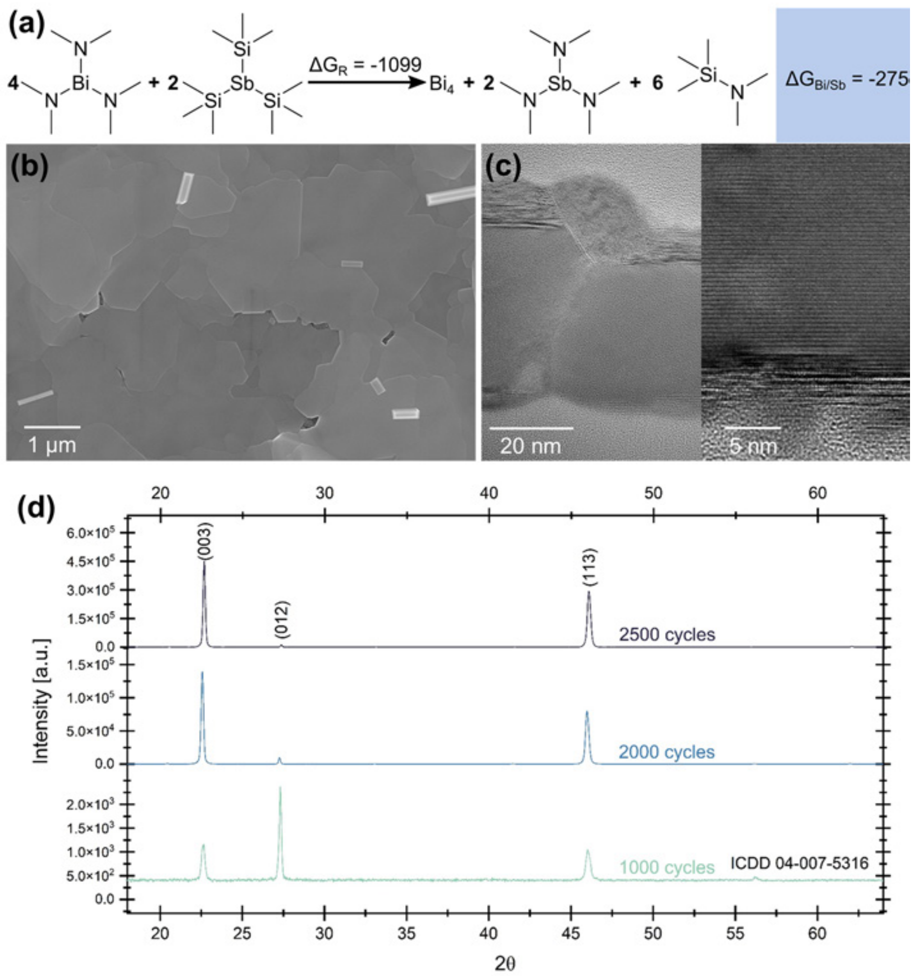

Abb. 2: a) Mögliche Gasphasenreaktionen zwischen $Bi(NMe_2)_3$ und $Sb(SiMe_3)_3$; es wird ein Ligandenaustauschmechanismus angenommen, der zur Abscheidung von reinem Bi sowie zur Desorption einer $Sb(SiMe_3)_3$-Spezies führt. b) FESEM-Aufnahmen der Morphologie der Bi-Schichten, die unter Verwendung von $Bi(NMe_2)_3$ und $Sb(SiMe_3)_3$ bei 100 °C in Abhängigkeit von der Anzahl der ALD-Zyklen abgeschieden wurden. c) Hochauflösende Aufnahme, die einen gut kristallisierten Bi-Film zeigt; die Grenzfläche weist einen Übergang von einer defektreichen zu einer hochkristallinen Bi-Region mit bevorzugter c-Achsen-Orientierung auf; darüber liegt eine stark defektbehaftete Abschlussschicht variabler Dicke (3–30 nm). d) XRD-Beugungsmuster der Bi-Schichten für 1000, 2000 und 2500 Zyklen, welche den Übergang von lateraler (in-plane) zu vertikaler (out-of-plane) Wachstumsorientierung widerspiegeln.

Fig. 2: a) Possible gas phase reactions between $Bi(NMe_2)_3$ and $Sb(SiMe_3)_3$, a ligand exchange reaction is assumed, leading to the deposition of only Bi and the desorption of a $Sb(NMe_2)_3$ species, b) FESEM micrographs of the morphology of the Bi films deposited using $Bi(NMe_2)_3$ and $Sb(SiMe_3)_3$ at 100 °C as a function of the number of ALD cycles. c) high-magnification image showing a well-crystallized Bi film; interface transitioning from defective to highly crystalline Bi with c-axis preferential orientation; and highly defective termination layer on top of the well-ordered Bi crystals, with varying thickness (3–30 nm), d) XRD patterns of the Bi films corresponding to 1000, 2000, and 2500 cycles, reflecting the transition from in-plane growth to put-of-plane growth.

(EDX) across the Bi layer confirms a well-defined interface; bismuth is clearly separated from the underlying Si/SiO_2 substrate without significant intermixing. Achieving ALD of elemental Bi at such a low temperature (100 °C) is highly significant as it enables integration of Bi into device stacks where high-temperature deposition would damage other layers.

X-ray diffraction (XRD) analysis reveals a thickness-dependent preferential orientation of the Bi grains. For thinner films (e.g. after 1000 cycles), the (012) plane dominates, indicating in-plane growth. As thickness increases (2000–2500 cycles), there is a clear shift to the (003) reflection, corresponding to a (00*l*) or c-axis out-of-plane texture, as shown in Fig. 2d. The (00*l*)-oriented growth (c-axis preferential) in thick films may be beneficial for exploiting anisotropic physical properties of Bi (e.g., thermoelectric, topological, electronic) in nanoscale devices.

X-ray photoelectron spectroscopy (XPS) of films (especially after 2500 cycles) indicates a predominantly metallic Bi composition, with only minor surface oxidation. Although TEM/EDX did not consistently detect Sb in the bulk, XPS reveals that the Bi films contain a small amount of antimony (Sb) contamination (~2.2% by XPS), likely due to incomplete reactions or side reactions with the $Sb(SiMe_3)_3$ co-reactant. This suggests that the Sb is localized at particular regions rather than uniformly distributed.

The electrical measurements show semimetallic behavior of the ALD-grown Bi films. The 2500-cycle film has a room-temperature resistivity of roughly 200 µΩ·cm, which, while higher than bulk Bi (~130 µΩ·cm), is still very low and indicative of good conductivity [2-5]. Temperature-dependent sheet resistance from 300 K down to 2 K reveals that the sheet resistance increases at

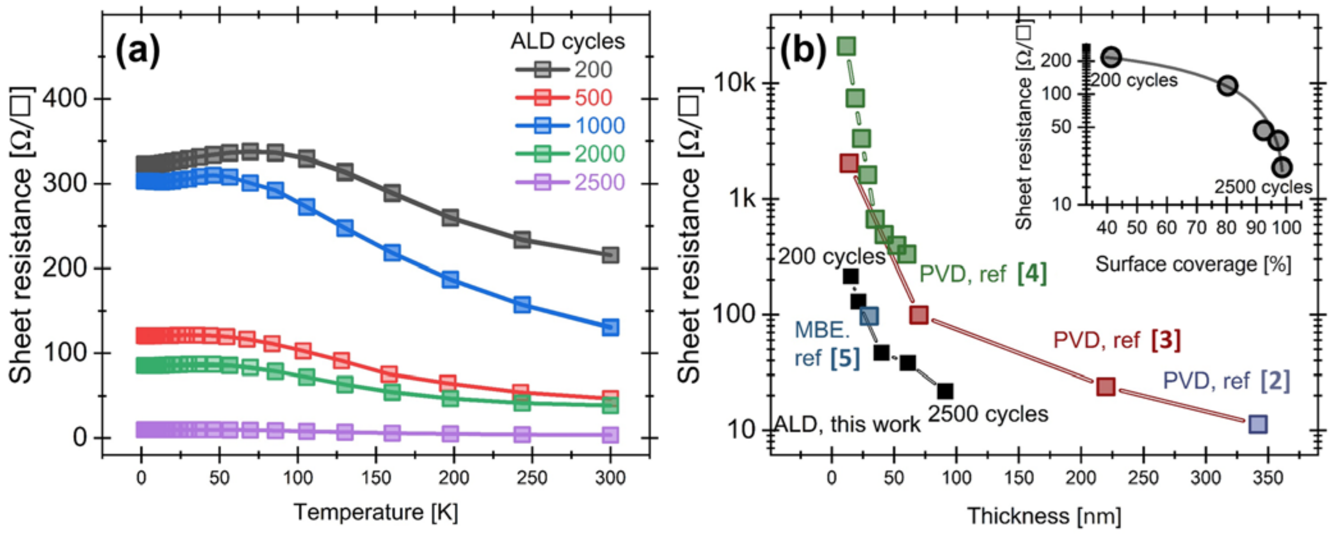

Abb 3: a) Temperaturabhängigkeit des Flächenwiderstands der Bi-Schichten im Bereich von 300 K bis 2 K. b) Flächenwiderstand der Bi-Schichten bei 300 K in Abhängigkeit von der Schichtdicke; das Inset zeigt die Abhängigkeit von der Oberflächenbedeckung.

Fig. 3: a) Temperature dependence of the sheet resistance of the Bi films from 300 K to 2 K, and (b) 300 K sheet resistance of Bi films as a function of thickness with an inset showing the surface coverage dependence.

low temperature, consistent with semimetallic conduction (Fig. 3a and b). In addition, Hall effect measurements indicate a crossover in dominant carrier type; at higher temperatures, holes dominate; at lower temperatures, electrons become more important. This behavior is interpreted in terms of quantum size effects, surface scattering, and possible semimetal-to-semiconductor transitions in the thinner films.

The combination of structural characterization (TEM, XRD), chemical analysis (XPS), and electrical transport provides a comprehensive picture of how ALD parameters control film quality, morphology, and functionality. This method opens the door for further exploration of Bi-based thin films—for example, investigating how thickness, grain orientation, and interface quality affect quantum transport, thermoelectric performance, topological effects, or integration with other materials.

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Current Research 8

High-precision droplets for technical and medical applications: Compact Surface Acoustic Wave-driven aerosol generators

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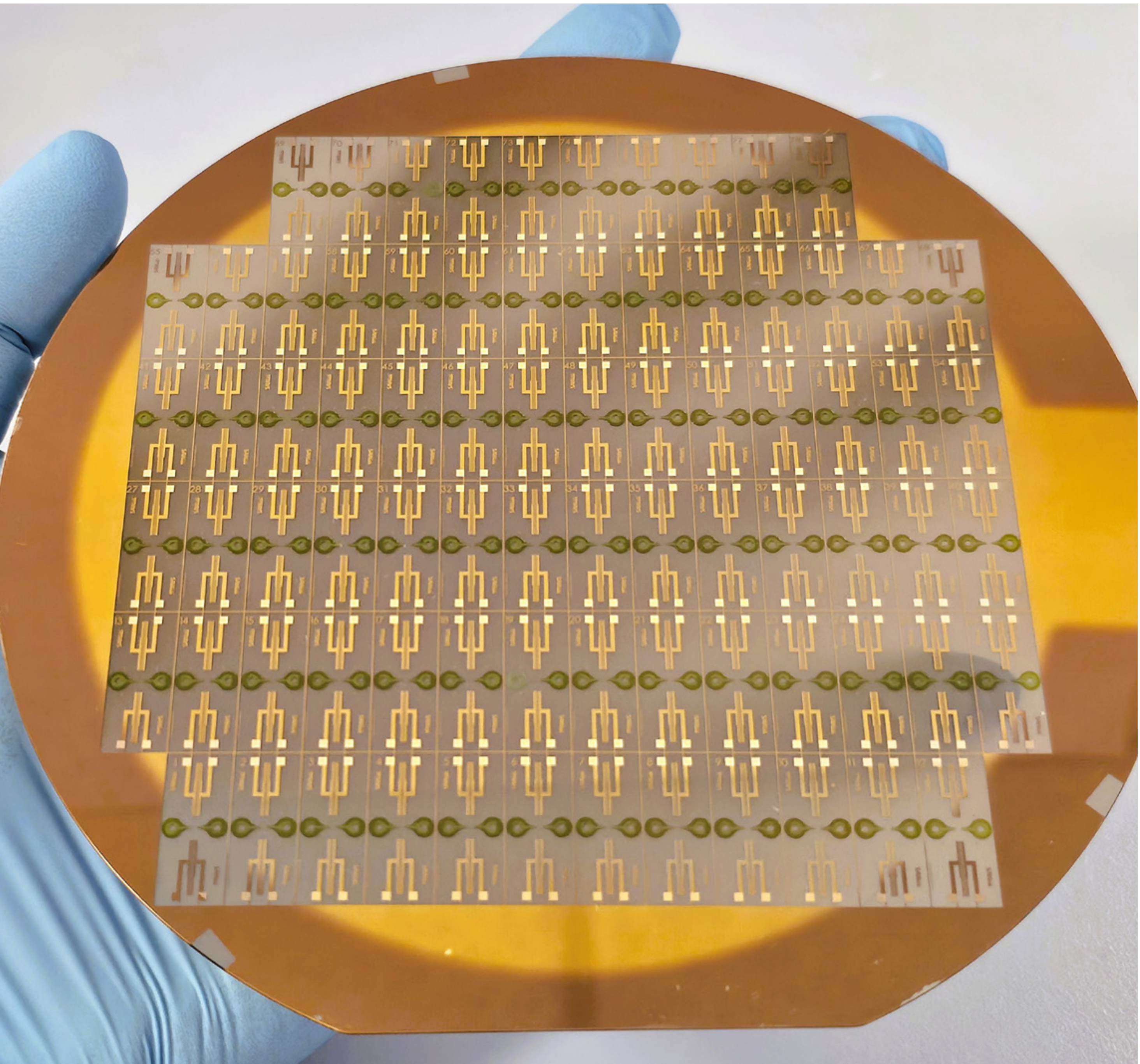

Die Erzeugung von Aerosolen ist für viele Analyse- und Diagnosetechniken unverzichtbar, da sie die präzise Anwendung von Flüssigkeitsproben in Form kleiner Tröpfchen ermöglicht. Herkömmliche Zerstäuber sind oft groß, energieintensiv und auf Hilfssysteme angewiesen. Miniaturisierte Aerosolgeneratoren auf Basis der Oberflächenwellen-Technologie (SAW), die am IFW Dresden untersucht werden, bieten eine kompakte, stromsparende Alternative mit ausgezeichneter Tröpfchenkontrolle und Kompatibilität mit kleinen Flüssigkeitsmengen. Dank ihrer geringen Größe lassen sie sich in tragbare Geräte und Lab-on-Chip-Systeme integrieren. Zu den wichtigsten Anwendungsbereichen zählen mobile Analysegeräte, kontrollierte Materialabscheidung sowie medizinische und olfaktorische Anwendungen. Diese Vorteile treiben die Entwicklung von SAW-Aerosolquellen der nächsten Generation mit einstellbarer Leistung und breiter Flüssigkeitskompatibilität voran.

Aerosol generation is essential for many analytical and diagnostic techniques, enabling the precise application of liquid samples in the forms of small droplets. Traditional nebulizers are often large, energy-demanding, and reliant on auxiliary systems. Miniaturized aerosol generators based on Surface Acoustic Wave (SAW) technology, investigated at IFW Dresden, provide a compact, low-power alternative with excellent droplet control and compatibility with small liquid volumes. Their small size allows integration into portable instruments and lab-on-chip systems. Key applications include mobile analytical devices, controlled material deposition, and medical or olfactory uses. These advantages drive the development of next-generation SAW aerosol sources with tunable performance and broad liquid compatibility.

Abb. 1: Piezoelektrischer 6"-Wafer mit verschiedenen SAW-Aerosolerzeugungschips, gefertigt im Labor für Mikrosysteme und im Reinraum des IFW Dresden.
Fig. 1: Piezoelectric 6" diameter wafer with various surface acoustic wave (SAW) aerosol generation chips, produced in the microsystem lab and the cleanroom of IFW Dresden.

Why It Matters: Motivation and Applications

Surface Acoustic Waves (SAWs) enable new compact aerosol generators with precise droplet size control and further advantages over conventional techniques. Such miniaturized aerosol sources can operate at low voltages, have low power consumption, and require only microliter liquid volumes to start, while ensuring an aerosol generation rate up to 1 ml/min for a variety of liquids from aqueous solutions to biological suspensions. Furthermore, their small footprint enables integration into other devices, including printheads for microstructures, liquid injection systems for (bio-)chemical synthesis and characterization and inhalation / olfactory devices. These emerging use cases as well as the need for fundamental understanding of the complex physics involved motivate research and development of next-generation SAW aerosol sources at IFW Dresden.

IFW covering the whole R&D value chain

We combine fundamental research and technology development to advance SAW-based liquid nebulization. On the fundamental side, we investigate the interaction mechanisms between high-frequency SAWs and liquids, and - together with external research partners - have achieved substantial clarification of the governing physics in recent years, including acoustic radiation and streaming, capillary wave formation, liquid cavitation, and droplet ejection under SAW excitation.

In parallel, we develop materials, device concepts, and fabrication techniques aimed at real-world applicability, and systematically validate these technologies across diverse application scenarios, including various joint studies with partners from research and industry. We successfully developed compact SAW aerosol generators amenable to mass production using techniques such as photolithography, dry film resist lamination, CNC milling and 3D printing, employing transducers with optimized frequency, power, and beam-shaping characteristics. SAW-based aerosol generators have been tested under various conditions to ensure high reproducibility and reliability, with the potential for disposable or long-lifetime aerosol chips.

Our overarching goal is to deepen the understanding of high-frequency acoustic phenomena at the material–liquid interface while translating this knowledge into robust, application-ready devices that enable precise control of aerosol properties such as droplet size distributions and plume stability.

SAW-based aerosols – Background

Surface acoustic wave (SAW) aerosol generation uses sound waves in the MHz regime - so high in frequency they're far above what humans can hear - to turn liquids into fine sprays of tiny droplets. The magic happens on a small chip that has special double-comb-shaped electrode pattern on its surface, the interdigital transducer (IDT). Importantly, the chip is composed of a piezoelectric material, known from ignition devices in electric lighters or highly-accurate spatial positioning systems. Piezoelectricity describes the property of a material to react to an electric voltage by deformation, or vice-versa, to a deformation by the creation of an electric voltage, respectively. In SAW technology, typically a sinusoidal electric signal is applied to the IDTs, causing the excitation of solid-state sound waves that travel along the chip's surface. SAWs have their energy confined close to the surface and form a directed sound beam . If a small amount of liquid is placed in that beam, the sound waves push the liquid and can cause it to break up into a mist, fog or aerosol. The resulting aerosol contains droplets in the micrometer and sub-micrometer range.

In more detail, we found that several interconnected acoustic and fluidic effects drive this process:
(1) First, the SAW interaction with the liquid forms small dome-shaped liquid structures that vibrate strongly.
(2) Second, these domes act like miniature resonating chambers, focusing the sound energy and creating intense pressure fluctuations inside the liquid.
(3) Third, as the vibrations grow stronger, the liquid can be ruptured apart, even causing the formation of vacuum bubbles within the domes through a process known as cavitation.

The liquid domes and the cavitation bubbles vibrate under the influence of the acoustic waves.
On the dome surfaces, tiny ripples, known as capillary waves, appear. When these ripples become unstable, they eject typically nm-sized droplets. Cavitation bubbles appearing within the liquid domes, however, eventually collapse violently after few µs, sometimes near the surface of the liquid, releasing powerful jets that shoot µm-sized liquid droplets into the air. Together, the collapsing bubbles, the vibrating domes, and the unstable ripples cause the liquid film to break apart in multiple ways, producing droplets of different sizes in the nanometer to micrometer range.

Our studies also observed that repeated bubble collapse, depending on the liquid and the surface materials, as well as the acoustic wave properties, can gradually erode the chip surface. While being essentially absent when e.g. organic solvents are used, water is known to cause strong cavitation bubble collapse effects. By revealing these mechanisms, IFW researchers provide insights that can help improve SAW aerosol generators, allowing engineers to better control droplet size, enhance efficiency, and reduce device wear.

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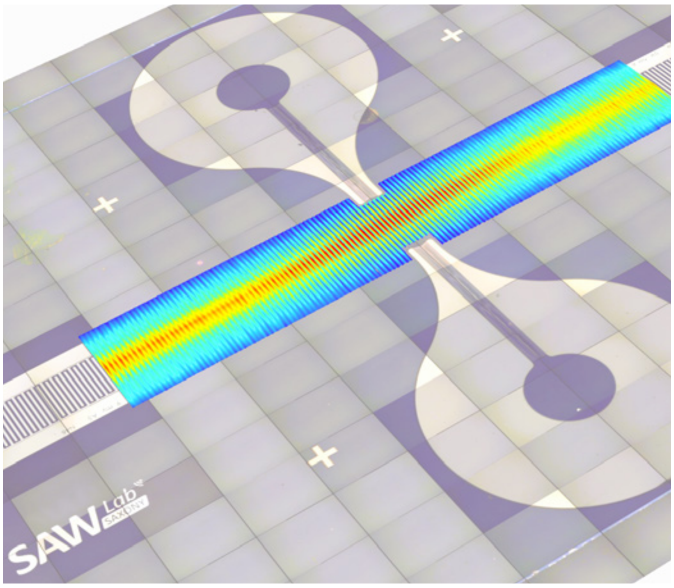
BMWi WIPANO „MehrZAD“



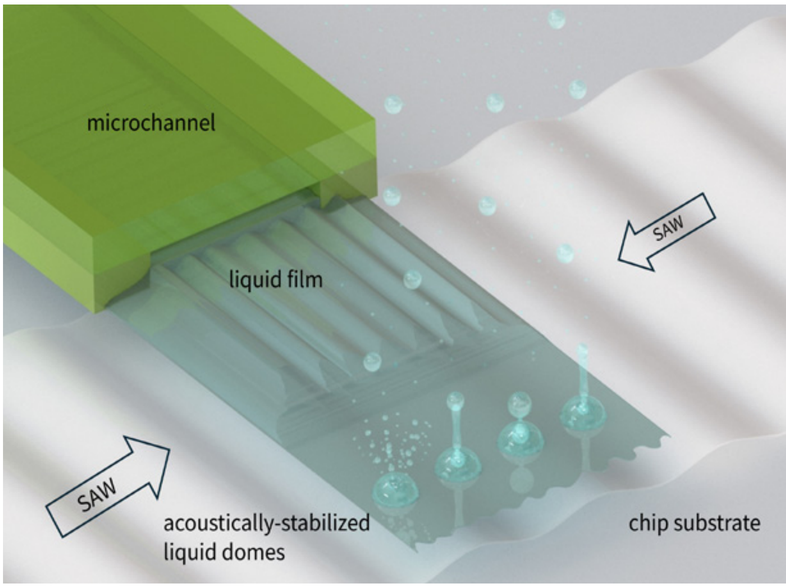


Abb. 2: Montageskizze der gemessenen Amplitudenverteilung einer stehenden Oberflächenakustikwelle (sSAW), angeregt zwischen zwei Interdigitalwandlern (IDTs) auf der Oberfläche eines piezoelektrischen Aerosolerzeugungschips; die Chipoberfläche ist aus mehreren zweidimensional zusammengesetzten optischen Mikroskopieaufnahmen rekonstruiert.
Fig. 2: Assembly sketch of the measured amplitude distribution of a standing surface acoustic wave (sSAW) excited between two interdigital transducers (IDTs) on the surface of a piezoelectric aerosol generation chip; chip surface resembled by multiple 2D-stitched optical microscopy images.

Abb. 3: Schematische Darstellung der wesentlichen physikalischen Effekte in der sSAW-Flüssigkeits-Wechselwirkungszone (Aerosolerzeugungszone): Ausbildung eines Flüssigkeitsfilms, Domstrukturen, Kavitationsblasen sowie Aerosoltröpfchen unter dem Einfluss der akustischen Welle (nicht dargestellt: Anregung kapillarer Wellen und Schwingung der Flüssigkeitsdoms).
Fig. 3: Sketch of the most important governing effects in the sSAW-liquid interaction zone, i.e. the aerosol generation zone: formation of liquid film, liquid dome structures, cavitation bubbles and aerosol droplets under acoustic wave influence (not displayed: capillary wave excitation and liquid dome vibration).

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START UP FOUNDATION

SONOJET

IFW's pioneering work in SAW-based aerosol sources has laid the groundwork for significant advancements in aerosol generation technology and the step towards real-world products.
In May 2025, **SONOJET GmbH** was founded by IFW researchers as a deep-tech start-up. The company's mission is to further develop IFWs advanced aerosol generation systems and to realize devices for producing highly-precise aerosols for commercial applications. SONOJET GmbH received the **Leibniz Gründerpreis 2026** for its business concept.

With the establishment of SONOJET, the transition from research to commercial application is underway, promising to enhance various industrial processes and applications.

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Current Research 9

HyLiqEASY – Safe and compact cryogenic test facility for experimental work under liquid hydrogen conditions

Danny Baumann, David Becker, Maximilian Grabowski[1], Christoph Haberstroh[1], Daniel Harder, Dirk Lindackers, Karsten Peukert, Knut Ulbrich, Marek Ulbrich

Wir stellen die kompakte Versuchsanlage *HyLiqEASY* vor, mit der direkt im Labor wenige Liter Flüssigwasserstoff (LH_2) erzeugt und für Materialuntersuchungen sowie Bauteiltests genutzt werden können. Das geschlossene System integriert Kryokühler, Probenkammer und automatische Steuerung mit Sicherheitsfunktionen. Forschenden am IFW Dresden und der Community darüber hinaus eröffnet es Experimente unter realen LH_2-Bedingungen – ohne aufwendige Beschaffung, komplexe Lagerung oder direkten Kontakt mit Wasserstoff. *HyLiqEASY* senkt die Zugangsbarriere zu LH_2 deutlich und macht Tests sicherer, einfacher und planbarer.

We present the compact *HyLiqEASY* experimental system, which enables the production of several liters of liquid hydrogen (LH_2) directly in the laboratory for materials research and component testing. The closed setup integrates a cryocooler, sample chamber, and automated control with built-in safety features. It provides researchers at IFW Dresden and beyond with access to experiments under real LH_2 conditions—without complex procurement, storage, or direct contact with hydrogen. *HyLiqEASY* significantly lowers the barrier to LH_2 and makes testing safer, easier, and more predictable.

Abb. 1: Präsentation des *HyLiq EASY* auf der Hannover Messe im Jahr 2024.
Fig. 1: Presentation of the *HyLiq EASY* at the Hannover Trade Fair in 2024.

In terms of global de-fossilization green hydrogen in the liquid state is becoming a key energy carrier. That applies for large scale shipping, replacing LNG in its common applications (power and heat generation), as well as for heavy duty vehicles like trucks, ships, planes and trains, which are actually covered by oil. As an energy source in everyday applications, liquid hydrogen is entering a new territory. That's why there is a great need for research and development on materials and components which are available for natural gas, diesel and kerosene for more than 100 years. Many of these future LH_2 materials and LH_2 components must prove their long-term operation at about 20 K in a hydrogen atmosphere.
Although LH_2 is widely used as an industrial commodity, access to sufficient quantities is a bottleneck. In Europe, only three large liquefaction plants supply the entire market, typically delivering more than 40.0000 litres at a time. For laboratory tests this is vastly more than needed, and the delivery time seldom matches the experimental schedule. If LH_2 is brought in by trailer, it has to be stored on site in a cryogenic tank and transferred through vacuum-insulated lines into the test rig. In addition to the costs of providing an LH_2 infrastructure on each customer's site, all handling steps are associated with considerable losses, increasing safety complexity.
This situation makes routine material and component testing in LH_2 cumbersome, expensive and in many laboratories simply impossible. The *HyLiqEASY* test facility tackles exactly this problem.

Introduction to the *HyLiqEASY* test platform

HyLiqEASY is a compact cryogenic hydrogen test environment that generates the required 2–3 litres of liquid hydrogen directly inside the experiment from pressurized hydrogen gas. A two-stage GM-type cryocooler with about 115 W cooling power at 80 K and 18 W at 20 K provides the cooling power needed for pre-cooling and liquefaction.

The heart of the facility is a cylindrical sample chamber that serves both as pressure vessel and as test bath. Depending on the design stage, it has an inner diameter of about 107–109 mm, a length close to one meter, and holds a total volume of roughly 9 liters. The lower 2–3 liters are filled with liquid hydrogen during operation, the upper part contains the hydrogen gas space. Details of the setup are depicted in Figure 2.

All cold components – sample chamber, cryocooler, heat exchangers and a copper radiation shield – are integrated into a common vacuum vessel to minimize the heat input. The entire assembly fits into a laboratory bench with approximate dimensions of 1.4 m × 0.85 m × 1.25 m, with almost all equipment located underneath the table top. This "all-in-one bench" layout is a key element of the comfortable user experience: the platform looks and behaves more like a standard test rack than like a cryogenic plant (Fig. 3).
The system allows experiments over a wide pressure range. The sample chamber is designed for up to 20 bar gauge pressure.

Mechanical and thermal design

The sample chamber is made from a thin-walled stainless-steel tube. The low wall thickness reduces thermal conduction into the cold region while still meeting the mechanical strength requirements at full pressure. The lower end of the tube is closed; the upper end is sealed with an O-ring and top flange. This top flange is deliberately the only mechanical interface between the user's experiment and the test platform. A sample holder is bolted to the flange at room temperature and then lowered into the chamber – the user never has to reach into a cold or hydrogen-filled space.

The cryocooler sits in parallel to the sample chamber inside the vacuum vessel. On its first stage, a copper coil heat exchanger precools the incoming hydrogen gas from room temperature down to around 40 K. A 1 mm thick copper radiation shield mounted to the same stage surrounds both cryocooler and sample chamber and blocks most of the thermal radiation from the warm vacuum vessel walls. At this temperature level the sample chamber is also thermally anchored via flexible copper straps.

The second stage of the cryocooler is connected to a compact copper fin condenser. Here the precooled hydrogen gas is fully liquefied and flows back into the lower part of the sample chamber. The geometry of the condenser fins is optimized so that the local heat flux is always high enough to keep the condensing film moving and to avoid dry-out or freezing.
Once the desired liquid level is reached, the condenser and the connecting tube are flooded with liquid hydrogen. The resulting density difference between slightly sub-cooled liquid in the condenser and satu-

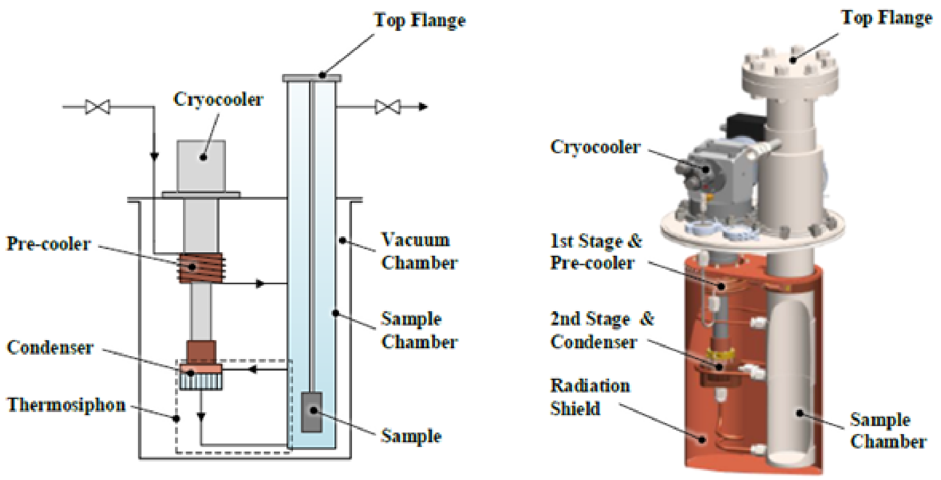

Abb. 2: Schematische Darstellung (links) und CAD-Modell (rechts) des Kryostaten einschließlich Kryokühler, Probenkammer und thermischer Ankopplung über eine Thermosiphon-Anordnung.
Fig. 2: Schematic view (left) and CAD model (right) of the cryostat including cryocooler, sample chamber and thermal coupling via thermosiphon arrangement.

rated liquid in the chamber drives a natural circulation loop – a thermosiphon – that continuously transports heat from the sample chamber to the cryocooler. This arrangement allows the cold head to remain beside the chamber instead of underneath it and therefore maximizes usable experimental space.
The static heat-inleak to the cold parts is about 10 W at the first stage and 1.9 W into the liquid hydrogen reservoir, values that the cryocooler can easily handle during steady-state operation.

Safe and largely automatic operation

A core design goal is that users can run LH_2 experiments without having to be cryogenics experts. In everyday use, only three media supplies are needed: cooling water, electrical power, and compressed gases (hydrogen and nitrogen).
The system controls the entire test sequence automatically. Before hydrogen is even allowed into the apparatus, the sample chamber and all connected lines are evacuated using an ATEX-certified rotary vane pump. A first leak test checks whether the pressure rise in the closed system remains below a defined limit. Then the chamber is filled with warm nitrogen and pressurized to the maximum intended operating pressure. After a second leak and pressure test the nitrogen is released again and the system is evacuated once more. Only upon all checks passed the control system permits cooling and hydrogen admission.

During the experiment the platform keeps pressure and liquid level within user-defined limits and monitors the temperatures at several locations in the coolant circuit and in the sample chamber. If anything deviates from the safe operating envelope, the control logic reacts, for example by stopping hydrogen inflow or shutting down the cryocooler. The users themselves are never directly exposed to a hydrogen atmosphere; their only contact is the warm top flange when installing or removing the specimen.

At the end of a test the remaining liquid hydrogen is allowed to evaporate in a controlled manner. The system is then evacuated and flushed with nitrogen again until an inert, depressurized atmosphere is restored and the sample can be safely removed.

These steps mean that experiments can be carried out in any hydrogen laboratory with the lowest safety standards, without the infrastructure normally required for handling bulk liquid hydrogen. This combination of full automation, integrated safety checks and strict separation between user and hydrogen atmosphere is the central unique selling point of the platform.

Cool-down behaviour and operation

With the system filled with hydrogen gas at pressures between 0.1 MPa am 1 MPa the LH_2 reservoir of 3 litres is filled within 4 hours. The control system allows unattended long-term operation, regulating the performance of the cryogenic cooler so that the liquid is not cooled further, but the boil-off gas is recondensed. Warm-up tests showed that, with auxiliary heaters activated, the system can return from cryogenic conditions to room temperature in roughly ten hours. Without active heating the natural warm-up in vacuum takes on the order of 40 hours. These timescales are compatible with daily laboratory operation.

User perspective and applications

From a user's point of view, the *HyLiqEASY* platform turns demanding LH_2 experiments into something much closer to routine testing. The operator mounts the sample on the warm top flange, selects the desired pressure, liquid level and test duration, and hands control over to the automation. Safety-critical steps – evacuation, nitrogen purging, leak and pressure testing, hydrogen admission and final inerting – run in the background.

The platform is designed for a broad spectrum of studies:

- long-term immersion tests to detect material degradation and permeation,
- functional checks of small devices like valves, pumps and sensors in realistic LH_2 conditions.
- mechanical tests such as tensile strength measurements can be designed for the experimental chamber,

Because the system is compact and movable through standard doors and elevators, it can be installed in many existing hydrogen laboratories without structural changes. At the same time, the modular top-flange interface makes it straightforward to adapt fixtures to new sample geometries or measurement techniques.

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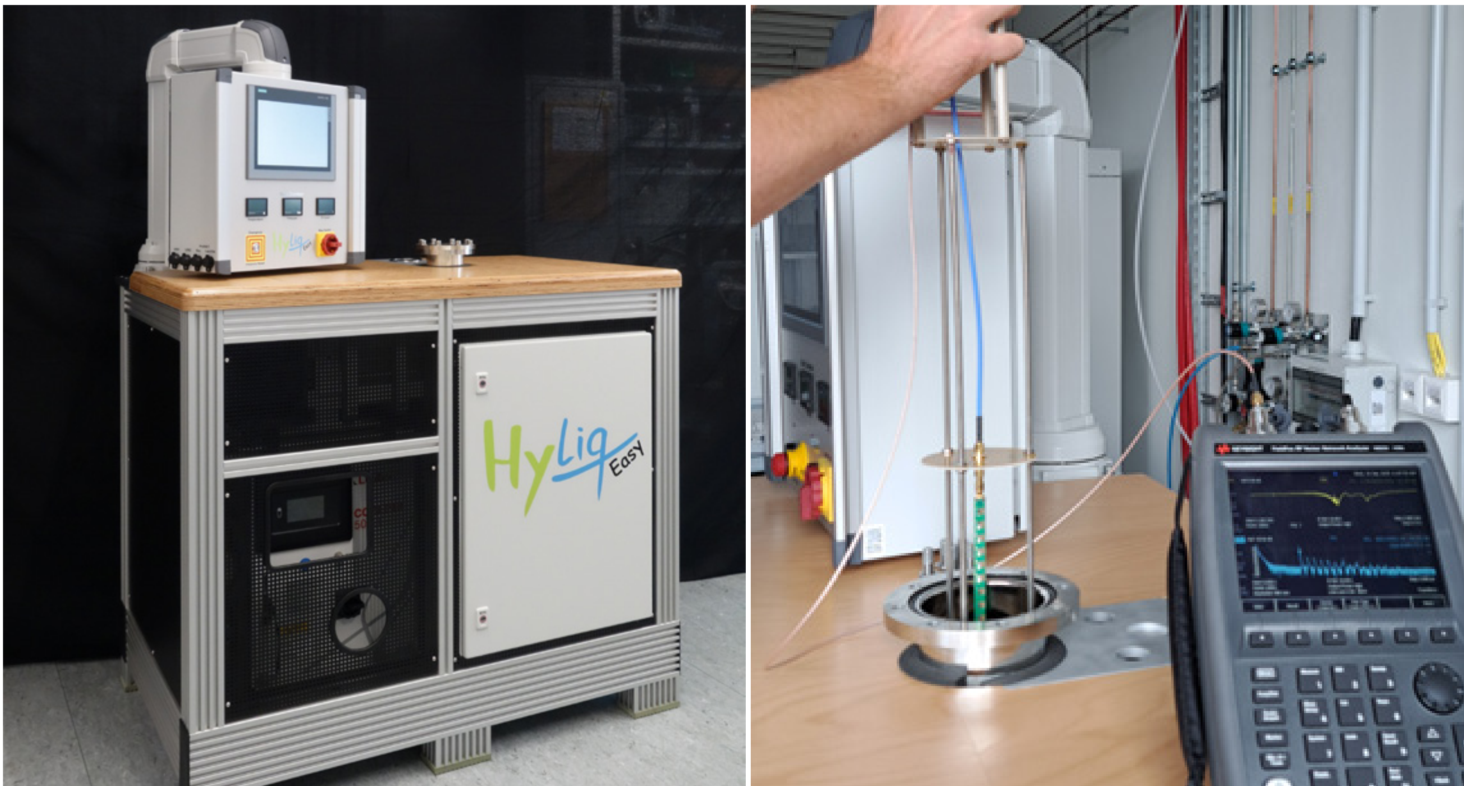
Funding

SAB-TG70-Projekt 3000962781

Cooperations

[1] TU Dresden

Abb. 3: LH_2-Testanlage *HyLiqEASY* installiert und betriebsbereit im Wasserstofflabor der TU Dresden (links). Prototyp eines neuen kryogenen Füllstandsmessgeräts auf Basis der SAW-Technologie ist in die LH_2-Testkammer eingesetzt (Thomas Windisch und Hagen Schmidt, IFW Dresden).
Fig. 3: LH_2 test facility *HyLiqEASY* installed and ready for operation in the hydrogen lab of the TU Dresden (left). Prototype of a new cryogenic level meter based on SAW technology is inserted into the LH_2 test chamber (Thomas Windisch and Hagen Schmidt, IFW Dresden).



Current Research 10

From lab to application: Highly wear-resistant tool steels for construction machinery

Anne Boehm, Sergio Scudino, Julia Hufenbach

Verschleiß stellt eine zentrale Herausforderung für Werkzeuge dar. Durch einen ganzheitlichen Ansatz wurde ein neuartiger Hochleistungsstahl mit einem auf den Gießprozess abgestimmten Legierungsdesign entwickelt. Das daraus resultierende feinkörnige Gefüge aus Martensit, Restaustenit und Karbiden verleiht dem Material eine exzellente Verschleißbeständigkeit sowie hohe Härte und Festigkeit bei guter Verformbarkeit – ganz ohne nachträgliche Wärmebehandlung. Zur Validierung unter industriellen Bedingungen wurden Radladerzähne gefertigt und in Praxistests erprobt. Die Ergebnisse zeigen eine signifikante Reduzierung des Verschleißes gegenüber kommerziellen Referenzzähnen.

Wear is a key challenge for tools. Through a holistic approach, a novel high-performance tool steel was developed, with an alloy design tailored to the casting process. The resulting fine-grained microstructure, composed of martensite, retained austenite, and carbides, provides excellent wear resistance, high hardness and strength, as well as good ductility, without the need for subsequent heat treatment. To validate the material under industrial conditions, wheel loader bucket teeth were manufactured from the novel steel and evaluated in field tests. The results demonstrate a significantly reduced wear compared with commercial reference teeth.

Wear is a key factor limiting the service life of components across many industrial sectors. In conveying systems, mining equipment, agricultural machinery, and tooling, continuous abrasive, adhesive and tribochemical loading results in material loss, reduced efficiency and costly downtime. Improving wear resistance is therefore essential for extending component lifetime and thus enhancing the resource efficiency of industrial processes.
Tool steels offer strong industrial potential due to their combination of high strength, hardness, toughness, and a broad alloy design space. By specific alloy and processing concepts, involving complex carbide structures and nanosized or martensitic microstructures, precise tailoring of hardness, strength, toughness and wear properties can be obtained. So far, two main strategies are employed to meet these demanding requirements: either highly alloyed tool steels or leaner alloys requiring extensive forming operations and multi-stage heat treatments. Although both approaches can achieve excellent performance, they are associated with substantial material costs, stemming from high alloying additions, and significant energy consumption, due to complex processing routes. Consequently, our objective was to obtain the required mechanical and wear properties within a single processing step using tailored alloy design [1, 2]. This was accomplished by introducing near-net-shape casting without subsequent heat treatment, offering a more resource- and energy-efficient route [3-6].

The novel tool steel, Fe90Cr4Mo4V1C1 (wt.%), hereafter FeCrMoVC, was evaluated for construction machinery through laboratory and field tests conducted on wheel loader bucket teeth. In the first stage, the alloy was melted out of highly pure elements via vacuum induction melting under argon atmosphere using a steel mold. The alloy solidifies into a fine-grained microstructure composed of martensite (body centered cubic, bcc), retained austenite (face centered cubic, fcc) and carbides (Fig. 2a) [6].

Abb. 1: Gegossene Radladerzähne aus einem am IFW Dresden entwickelten hochverschleißfesten Werkzeugstahl.
Fig. 1: Cast wheel loader bucket teeth out of highly wear-resistant tool steel developed at IFW Dresden.

The individual phases were confirmed by electron backscatter diffraction (EBSD) and X-ray diffraction (not shown here). Two types of carbides were identified. While both phases precipitate preferentially along the prior austenite grain boundaries, VC exhibits an elongated morphology, whereas M_2C (M=Cr, Mo) appears primarily lamellar. Austenite is typically observed in the surrounding of the carbides, but also inside the grains. Additionally, martensite is detected in a needle-like shape.

Quasi-static compression tests of the alloy cast under laboratory conditions reveal a yield strength of 1122 ± 156 MPa, a compressive strength of 4266 ± 383 MPa and a compressive strain at fracture of 28 ± 5 % (Fig. 2b). The pronounced work-hardening behavior visible in Figure 2b is primarily traced back to the transformation-induced plasticity effect, or TRIP effect, where the more ductile retained austenite transforms into the harder martensite [3, 5]. The TRIP effect also influences the abrasive wear behavior, which was characterized using a pin-on-disc test.
The novel FeCrMoVC alloy showed an abrasive volume wear rate of $6.8 \pm 1.4 \cdot 10^{-3}$ $mm^3(Nm)^{-1}$, outperforming a commercial steel for bucket teeth exhibiting $19.4 \pm 1.8 \cdot 10^{-3}$ $mm^3(Nm)^{-1}$ (Fig. 2c). Investigations using X-ray diffraction and (transmission-)EBSD delivered evidence of martensitic transformation in the near-surface region [4, 5]. Induced by friction, the retained austenite is transformed into martensite, analogous to the TRIP effect observed macroscopically under mechanical load. The transformation results in local hardening of the surface to resist the penetration of abrasive particles and hinders the formation of wear cracks [6]. Investigations confirmed that the friction-induced transformation of retained austenite at the surface fosters microploughing, a mechanism where abrasive particles displace material into lateral ridges rather than removing it, instead of wear mechanisms like microcutting or microcracking with high material loss [4-6].

Based on these promising results, the transfer of the FeCrMoVC alloy into industrial application was pursued to demonstrate its feasibility beyond controlled laboratory conditions. Such a transfer requires adjustments to the processing route, most

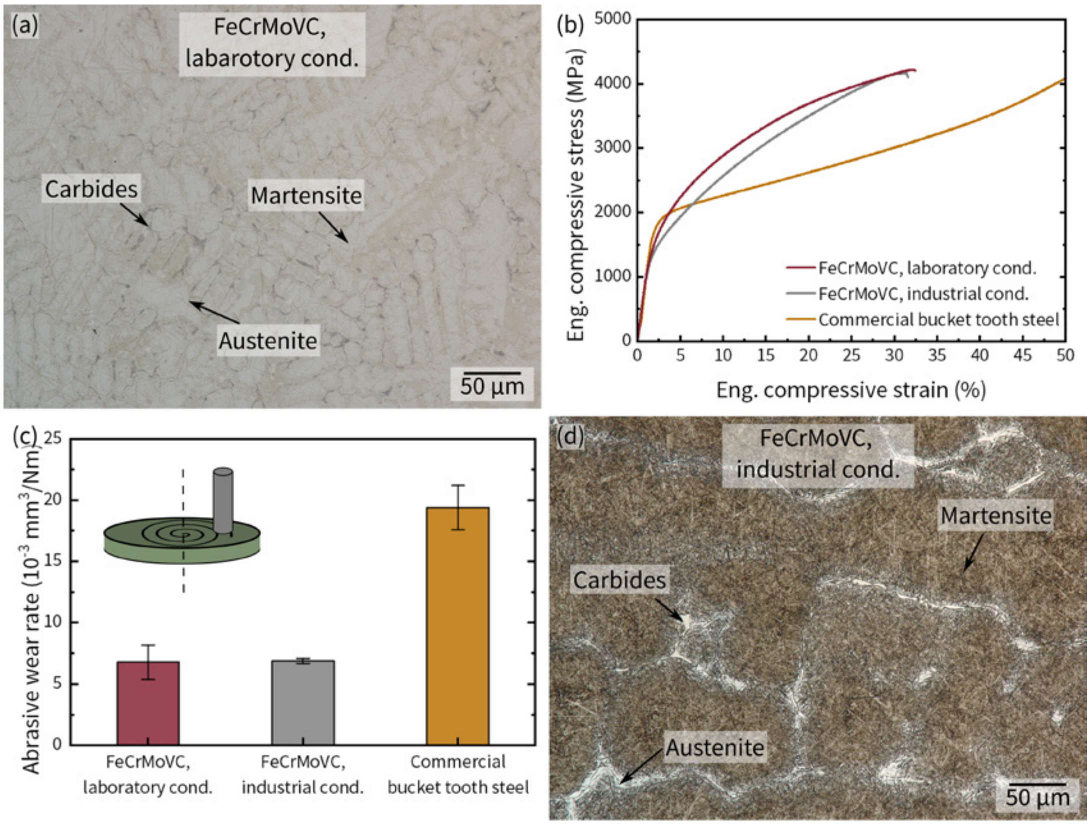


Abb. 2: Gefüge und Eigenschaftsvergleich der FeCrMoVC Legierung. a) Analyse des Gefüges (geätzt mit Nital) der unter Laborbedingungen gegossenen Legierung. b) Technische Spannungs-Stauchungskurven aus dem quasi-statischen Druckversuch sowie c) abrasive Verschleißraten der unter Labor- und Industriebedingungen hergestellten Legierung im Vergleich mit einem kommerziellen Stahl für Zahnspitzen. d) Gefüge (geätzt mit Nital) der Legierung, gegossen unter industriellen Bedingungen.
Fig. 2: Microstructure and property comparison of the FeCrMoVC alloy. a) Microstructure analysis (etched with Nital) of the alloy cast under laboratory conditions. b) Representative stress-strain curves from the quasi-static compression test. c) Abrasive wear rates of the alloy processed according to laboratory and industrial conditions, compared to a commercial bucket tooth steel. d) Microstructure (etched with Nital) of the alloy cast under industrial conditions.

notably the reduction of material costs by using recycled feedstock and avoiding the expensive protective atmosphere. Therefore, the laboratory casting process was systematically adapted to industrial conditions in a foundry and the resulting changes in microstructure and properties were critically examined. In detail, the adaptions involved the raw materials (usage of scrap and ferroalloys instead of highly-pure elements), higher part mass (5-10 kg instead of 2-3 kg), different cooling conditions (sand forms instead of steel molds), and atmosphere (air vs. argon). These adaptions result in microstructural changes (compare Fig. 2a and 2d).
While the same phases, martensite, austenite, and two types of carbides, can be identified, the slower cooling results in coarser grains and enables more extensive diffusion. This promotes the segregation of alloying elements toward the grain boundaries, which results in the formation of coarser carbides (Fig. 2d). Nevertheless, the material maintains a compressive strength of 4020 ± 130 MPa and a compressive strain at fracture of 27 ± 3 %, which are comparable to those of the laboratory modification (Fig. 2b). Furthermore, the abrasive wear rate of the alloy cast under industrial conditions remains comparable to the superior laboratory reference (Fig. 2c), and significantly outperforms the commercial benchmark.
Following the successful demonstration that the alloy's superior properties could be maintained despite the necessary process changes for large-scale production, the project moved to the next validation stage, comparative field testing. The industry-adapted casting route was utilized to manufacture full-scale wheel loader bucket teeth, which require good mechanical properties and resilience against abrasive wear (Fig. 3a). The teeth manufactured from the novel FeCrMoVC alloy were tested along with the commercial reference teeth by subjecting them to rigorous, long-duration testing on a wheel loader (Liebherr L 576 XPower) within a harsh gravel pit environment (Fig. 3b). Wear was documented at

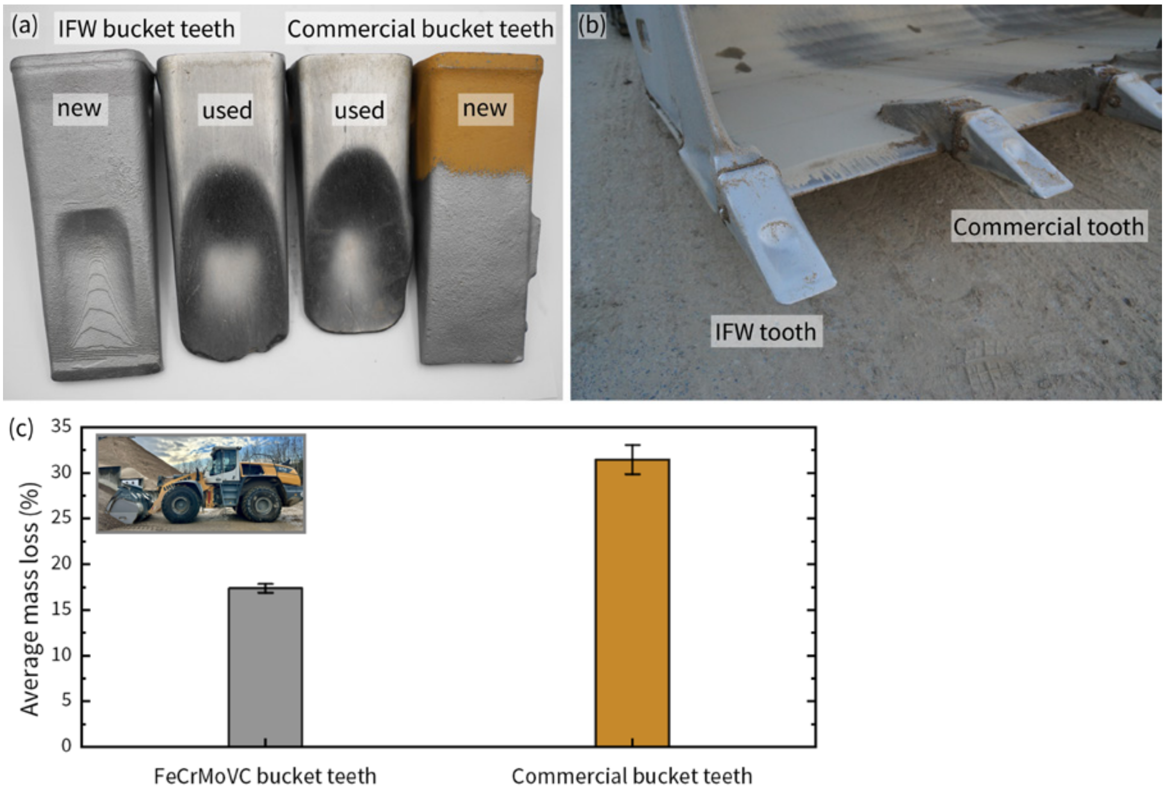


Abb. 3: a) Radladerzähne im Originalzustand und nach dem Feldtest, hergestellt aus der FeCrMoVC-Legierung (links) sowie handelsübliche Referenzzähne (rechts). b) An den Radlader montierte Testzähne mit abwechselnd FeCrMoVC Prototypen und Referenzmaterial. c) Ergebnisse aus dem Praxisversuch in der Kiesgrube dargestellt als Massenverlust der jeweiligen Zähne.

Fig. 3: a) Wheel loader bucket teeth in their original condition and after the field test, made from FeCrMoVC alloy (left) and a commercially available reference material (right). b) Mounted bucket teeth on the wheel loader made of FeCrMoVC alloy and reference material. c) Results of the wear tests in the gravel pit characterized as mass loss of the respective teeth.

regular intervals, and after 9 months of daily use, the teeth were removed and the mass loss determined (Fig. 3c). This setting combines high impact loads, complex abrasive mechanisms, and varying environmental conditions, that go far beyond the controlled parameters of the laboratory test. As shown in Figure 3a and 3c, the FeCrMoVC teeth exhibited a significantly lower material loss compared to the commercial reference over the duration of the trial. In conclusion, this project exemplifies how a holistic approach encompassing the entire development chain, from tailored alloy design to industrial-near manufacturing and testing, opens up new possibilities for developing advanced tooling solutions with significantly enhanced service life.

References

[1] U. Kühn et al., DE 10 2006 024 358 B4 (patent granted)
[2] J. Hufenbach et al., DE 10 2014 217 122 B4 (patent granted)
[3] F. Kochta et al., Mater. Sci. Eng. A 829 (2022) 142156
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[5] A. Boehm et al., Mater. Sci. Eng. A 944 (2025) 148906
[6] A. Boehm et al., 10. Fachtagung Baumaschinentechnik (2024) 277

Funding

Federal Ministry for Economic Affairs and Energy AiF/IGF project “StaGuBau” (grant no. 21664).

Cooperations

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Update: January 2026

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[1] ERC-Grant // [2] Leibniz-Junior Research Group // [3] BMFTR-Nachwuchsgruppe // [4] Joint Junior Research group with HZB

Zahlen und Fakten 2025

Das IFW Dresden ist eines der größten Forschungsinstitute Sachsens und Mitglied der Leibniz-Gemeinschaft. Als Leibniz-Institut mit gesamtstaatlicher Bedeutung wird das IFW gleichermaßen vom Bund und dem Land Sachsen gefördert. Wir unterhalten enge Kooperationen mit Universitäten, anderen außeruniversitären Forschungseinrichtungen und Partnern aus der Industrie auf nationaler und internationaler Ebene. Neben dem wissenschaftlichen Auftrag ist die Ausbildung von Nachwuchs im wissenschaftlichen, technischen und administrativen Bereich ein wichtiger Bestandteil unserer Arbeit.

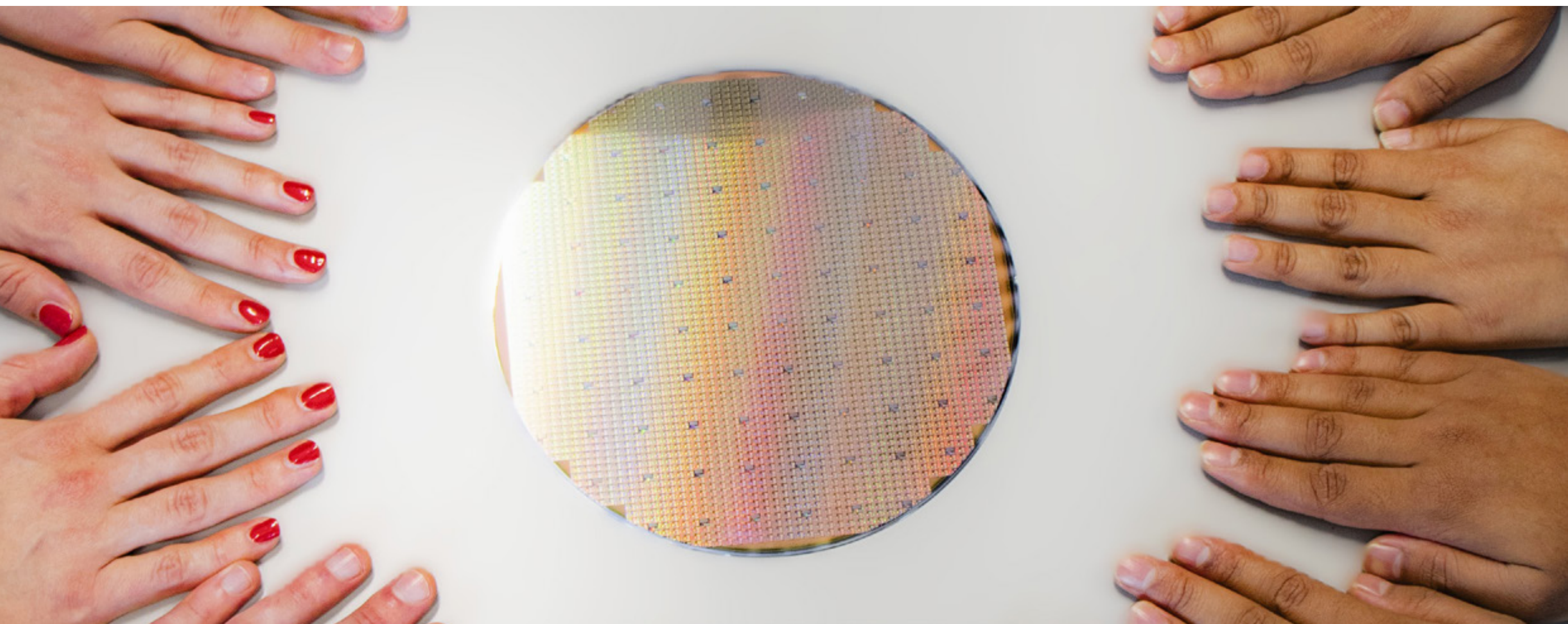
Sowohl Chancengleichheit als auch Familienfreundlichkeit sind erklärte Ziele des IFW Dresden. Im Jahr 2025 lag der Frauenanteil in wissenschaftlichen Positionen bei 32 Prozent und der Anteil von Frauen in wissenschaftlichen Führungspositionen bei 18 Prozent.
Wir unterstützen unsere Beschäftigten dabei, Familienleben und berufliche Anforderungen in Einklang zu bringen. Seit dem Jahr 2007 ist das IFW Dresden mit dem *"audit berufundfamilie"* zertifiziert.

Facts und Figures 2025

IFW Dresden is one of the largest research institutes in Saxony and a member of the Leibniz Association. As a Leibniz Institute of national importance, the IFW is supported by the federal government and the state of Saxony. We maintain national and intenational cooperations with universities, other research institutions and industrial partners.
In addition to the scientific mission, the training of the scientific, technical and administrative staff is an important part of our work.

Equal opportunities and family friendliness are declared goals of IFW Dresden. In 2025, the proportion of women in scientific positions was 32 percent and the proportion of women in scientific management positions 18 percent.

We support our employees in reconciling family life and professional requirements. IFW Dresden has been certified with the *"audit berufundfamilie"* since 2007.



2025

4
Research areas

497
Employees

11
Research topics

from **42** Nations

185 female

312 male

5
Institutes

347
journal articles

500
Participants in scientific conferences

3500
Visitors at public events

35
PhD theses

9
Diploma and master theses

2
Bachelor theses

19
Student internships

Finanzierung
Financing

Institutionelle Förderung durch Bund und Länder
Institutional funding by the federal government and the federal states

36,9 Mio. EUR

Bewilligte Drittmittel
Third party funding

16,9 Mio. EUR

davon/ including:
Deutsche Forschungsgemeinschaft/ German Research Foundation: 6,8 Mio. EUR
Leibniz-Gemeinschaft/ Leibniz Association: 1,1 Mio. EUR
Bund und Freistaat Sachsen/ Federal Government and State of Saxony: 6,1 Mio. EUR
Europäische Union/ European Union: 1,8 Mio. EUR
Industrie/ Industrial contact: 0,7 Mio. EUR
Stiftungen und andere Geldgeber/ Foundations and other donors: 0,4 Mio. EUR

Beschäftigte
Personnel

Gesamtzahl der Beschäftigten: 31.12.2025
Personnell total: 31.12.2025

497
davon/ including:
Wissenschaftliches Personal/ Scientific staff: 315
Wissenschaftsunterstützendes Personal/ Science support staff
(Technisches Personal und Verwaltungspersonal/ Technical and Administrative staff): 171
Auszubildende/ Apprentices[1)]: 11

Doktorandinnen und Doktoranden/ Doctoral students: 95
Gastwissenschaftlerinnen und Gastwissenschaftler/ Guest scientists[2)]: 81

[1)] 6 verschiedene Ausbildungsberufe sowie Student*innen der Berufsakademie/ 6 different training occupations and students of the training academy
[2)] Eingebunden in die IFW-Forschung, über Forschungskooperationen finanziert/ Integrated in the IFW research, financed by research cooperations

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Stipendien
Scholarships

Über das Jahr 2025 waren am IFW Dresden 32 externe Stipendiatinnen und Stipendiaten tätig. Darunter waren 12 Fellows der Alexander von Humboldt-Stiftung.
In 2025, IFW Dresden hosted a total of 32 external fellows, including 12 fellows supported by the Alexander von Humboldt Foundation.

Rufe
Calls on Professorships

Dr. Shu Zhang	OIST, Okinawa Institute of Science and Technology, Japan
Dr. Mikel Iroala	University of the Basque Country, Spain
Dr. Satyakam Kar	Indian Institute of Technology Gandhinagar, India
Dr. Mattia Trama	l'Università degli Studi di Salerno, Italy
Dr. Jun Yang	Shanghai University, China

Publikationen
Publications

In 2025 haben IFW-Wissenschaftler*innen 347 referierte Zeitschriftenartikel veröffentlicht, eine beträchtliche Anzahl von ihnen in sehr renommierten Zeitschriften.
In 2025, IFW scientists have published 347 refereed journal articles, a considerable number of them in high impact journals.

Eine ausführliche Publikationsliste ist auf unserer Homepage verfügbar:
A detailed list of publications is available on our homepage:

https://www.ifw-dresden.de/research/publications

Rechte Seite: Die Bilderfolge von Oscar Z. Telchow gewann beim Internen Fotowettbewerb den 3. Platz. Die Bildfolge zeigt drei Perowskitfilme, die per Spin-Coating hergestellt und durch Kationen an der Oberfläche modifiziert wurden. Das Bild ganz links ist eine optische Transmissionsmikroskopie eines fehlerhaftkristallisierten Films, die beiden anderen Bilder sind colorierte SEM-Aufnahmen.
Right page: The image series by Oscar Z. Telchow won third place in the internal photo competition. The series shows three perovskite films produced by spin coating and modified with cations at the surface. The image on the far left is an optical transmission microscopy image of a defectively crystallized film; the other two images are colorized SEM micrographs.

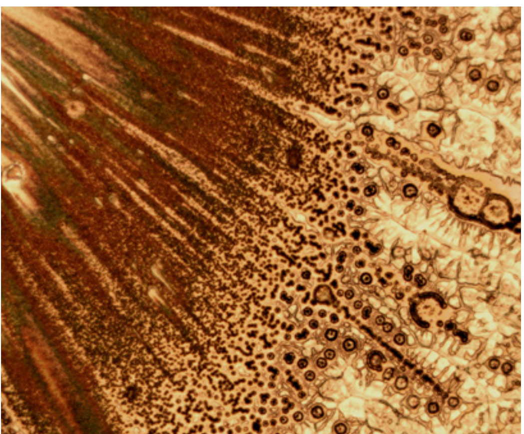
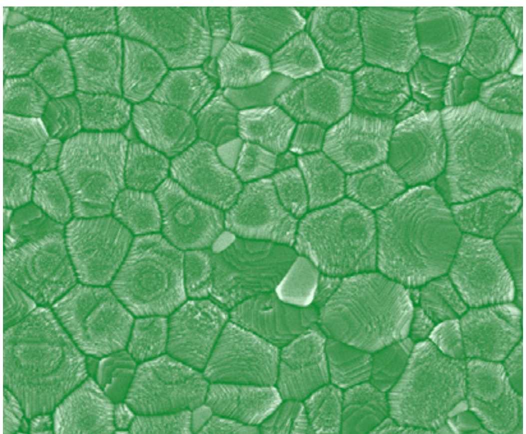
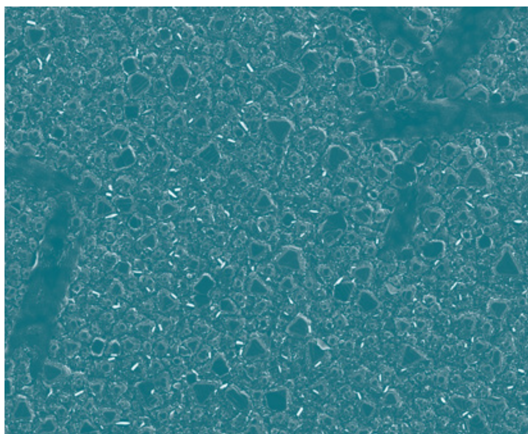
Externe Auszeichnungen
External Awards

Nour Abdelrahman	Best Poster Award at the Nanotech France Conference, June 2025 in Paris
Prof. Dr. Vladimir Fomin	IEEE Senior Member
Dr. Ran He	Deutsch-Chinesischer Nachwuchspreis
Dr. Subhankar Khatua	Best Poster Award of the International Workshop „Current Trends in Strongly Correlated and Frustrated Systems", Nov. 2025 at MPI PKS Dresden
SONOJET GmbH	Leibniz-Gründerpreis
Prof. Dr. Yana Vaynzof	Membership European Academy of Science

Interne Auszeichnungen
Internal Awards

Die **Ehrenfried Walther von Tschirnhaus-Plakette** wird jedes Jahr an Dissertationen mit dem Prädikat summa-cum-laude verliehen. Im Jahr 2025 erhielten diese Auszeichnung:
The **Ehrenfried Walther von Tschirnhaus-Medal** of the IFW Dresden for excellent PhD theses was awarded to:
Dr. Gabriele Naselli
Dr. Vira Shita
Dr. Joyal John Abraham
Dr. Martin Otto
Dr. Florian Preischel
Dr. Jorit Obenlüneschloß

Beim **Internen Fotowettbewerb** im Dezember 2025 wurden ausgezeichnet:
At the **internal photo competition** in December 2025, the following were honored:
Platz 1: Dr. Vladimir Shilovskikh
Platz 2: Adhiraj Sundar
Platz 3: Oscar Zacharias Telschow
Weihnachtsmotiv: Anitta Jose

Wissenschaftliche Konferenzen
Scientific Conferences

March 12 - 13	High K Workshop 2025, IFW Dresden
March 23 - 26	International Area Selective Deposition Workshop (ASD2025), Universität Leipzig
April 7 - 11	Workshop "Understanding and predicting materials properties by DFT - limits of reliability" and Tutorial FPLO, IFW Dresden and MPI CPfS
June 2 - 6	CORPES 2025: Strong correlations and angle-resolved photoemission, MPI PKS Dresden
June 23 - 27	3rd Joint Workshop IFW Dresden - S.N. Bose National Center for Basic Sciences
July 14 - 15	International Workshop on Unconventional Magnetism in Quantum Materials Kyiv, Ukraine and online
August 19 - 22	OPCM25 - Workshop on Orbital Physics in Correlated Materials: New Challenges and Perspectives
August 20 - 22	Acoustofluidics 2025, IFW Dresden
August 25 - 27	Microprinting 2025, Bad Schandau
Aug 29 - Sept 04	Summer School Spectroelectrochemistry, IFW Dresden
October 23 – 24	Quantenphysik in Klasse 12 - Impulse und Ideen für den überarbeiteten Lernbereich

Veranstaltungen
Events

April 2	Feierlicher Spatenstich des neuen Forschungsgebäudes
April 3	Girls'Day
April 4	Nacht der Bibliotheken
April 13	Tag der Quantenphysik
May 28	Rewe Team Challenge
June 4	IFW-Sommertag / Gesundheitstag
June 20	Dresdner Lange Nacht der Wissenschaften 2025
September 6 - 7	Kunstprojekt: Street Art trifft Science
October 25	Besuch des Deutschen Humboldt-Netzwerks

Beim diesjährigen Girls'Day lernten die Mädchen unter anderem, was Materialforschende unter Spin Coating verstehen (oben links). Die Spaten stehen bereit für den offiziellen Baustart des Neubaus südlich der Nöthnitzer Straße – ein Gemeinschaftprojekt mit der TU Dresden (oben rechts). Im Zuge des Neubaus erhielten Street-Art-Künstler*innen die Möglichkeit, unsere Bauzäune mit wundervollen Kunstwerken zu versehen (unten).

At this year's Girls' Day, the girls learned what materials researchers mean by spin coating (top left). The ceremonial spades mark the official start of construction of the new building south of Nöthnitzer Straße – a joint project with TU Dresden (top right). As part of the project, street artists were given the opportunity to transform our construction fences into wonderful works of art (bottom).

Foto: Nils Eisfeld

Geistiges Eigentum / Patente
Intellectual Properties / Patents

Zum 31. Dezember 2025 hielt das Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden 63 Patentfamilien mit 82 aktiven Patenten. Davon sind 55 Patente in Deutschland und 27 in anderen Ländern erteilt.
As of December 31, 2025, the Leibniz Institute for Solid State and Materials Research Dresden held 63 patent families with 82 active patents. Of these, 55 patents were granted in Germany and 27 in other countries.

Erteilte Patente
Patent grants

DE 10 2021 110 168.9 // 08.05.2025
EP 22 167 749.5 // 01.01.2025
Verfahren zum Speichern und zur Anwendung von Flüssigwasserstoff
Invented by Lindackers, D.; Schmidt, H.; Morgenstern, J.; Haberstroh, C.

DE 10 2022 114 128.4
08.01.2026
Verfahren zur Herstellung von thermoelektrischen Bauelementen und thermoelektrische Bauelemente
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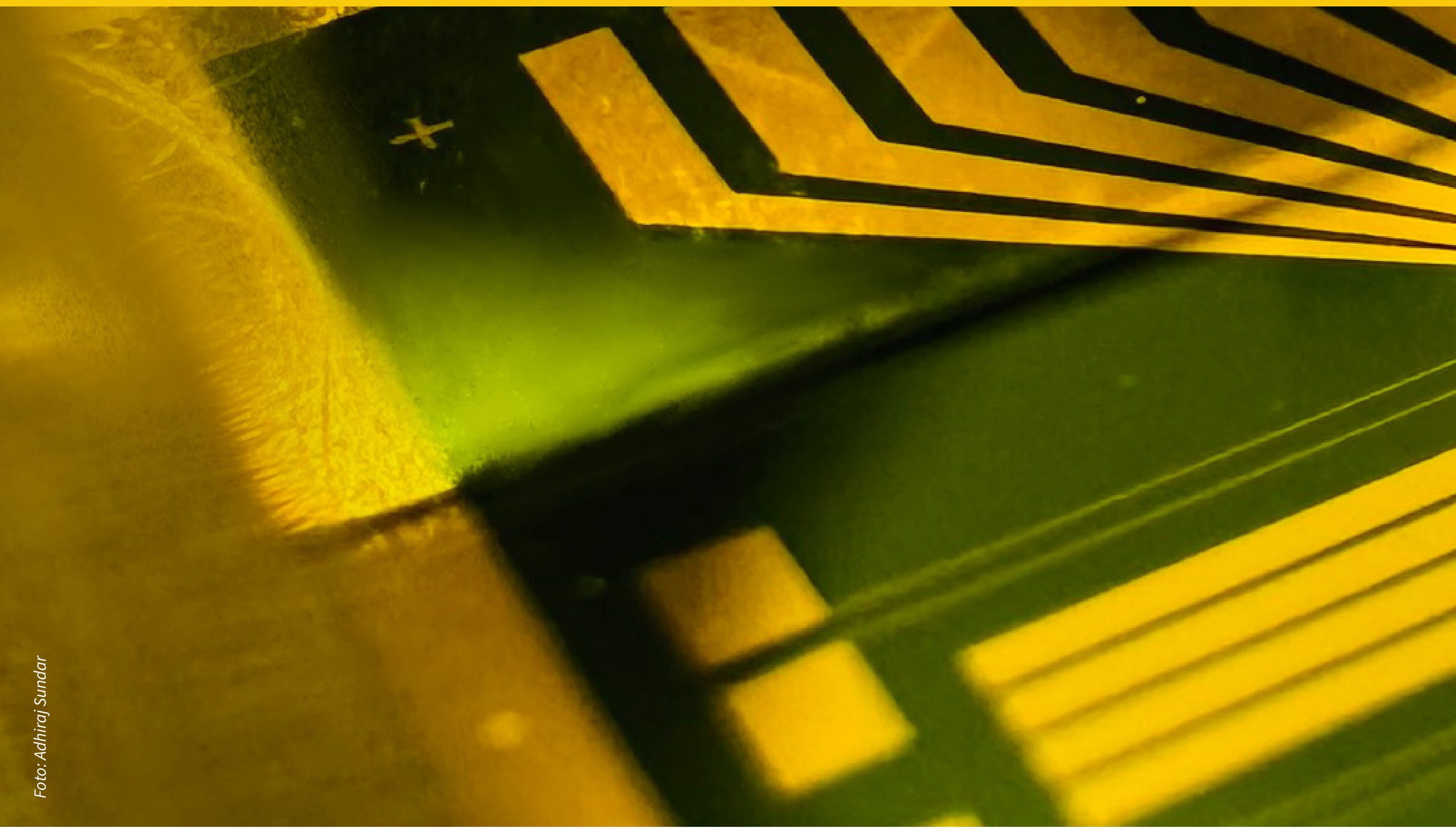

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