Ultramicroscopy Low-Voltage Electron Microscopy Issue

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October 12, 2014 – Ultramicroscopy publishes a special issue on low-voltage electron microscopy, with Ute A. Kaiser as guest editor. SALVE's publication lists show how strongly the field has been represented in high-impact journals.

Ultramicroscopy, the Elsevier journal edited by Angus I. Kirkland of the University of Oxford, has published a special issue on low-voltage electron microscopy (LVEM). It covers new results and prospects in theory, instrumentation and applications. The guest editors are Ute A. Kaiser, scientific leader of the SALVE project and head of the group Electron Microscopy of Materials Science at Ulm University, and Michael Stöger-Pollach of TU Wien. The issue appears as research turns from graphene to a whole family of other atomically thin crystals: in 2013, Andre K. Geim and Irina V. Grigorieva showed how graphene, h-BN, MoS_2 and other 2D crystals can be stacked layer by layer into van der Waals heterostructures[1]. Many of these crystals are damaged by the electron beam at conventional voltages, which makes low voltage the natural way to image them atom by atom. Lowering the voltage, however, costs resolution: the electron wavelength grows from 2.0 pm at 300 kV to 4.2 pm at 80 kV and 8.6 pm at 20 kV, and chromatic aberration weighs ever more heavily. Low voltage therefore needs the best resolution that can be achieved, with correction of both the spherical and the chromatic aberration – the goal of SALVE. Two papers of the issue make the same point: Raymond F. Egerton concludes that phase-contrast TEM reaches atomic resolution at low voltage only with correction of the chromatic aberration, preferably together with a monochromator[2], and Zhongbo Lee and co-workers show that the highest resolution of an aberration-corrected image also demands a high electron dose, which only a few samples withstand[3]. Shortly after the issue, Stephen J. Pennycook and Sergei V. Kalinin explained in Nature why the best possible resolution is worth chasing[4]. Small deviations of atoms from their ideal positions decide whether a material can store charge, information or energy, so bond lengths and angles have to be measured precisely, ideally in three dimensions. Correctors with larger apertures would resolve atoms in depth as well, and a series of images at different foci would build up a three-dimensional map. As the resolution improves, the noise falls, so images can be recorded faster before the electron beam destroys the sample, and monochromators that narrow the energy spread of the beam from 300 to 10 meV or less would let electron energy loss spectroscopy map band gaps and phonons. At low voltage these arguments weigh even more: the longer wavelength has to be compensated by larger corrected apertures, and beam-sensitive 2D materials tolerate only a limited dose. Pennycook and Kalinin also named the obstacle: manufacturers invest little where demand is low, so partnerships between academia and industry and government seed funding are needed – exactly the model on which SALVE is built.

Theory, instruments and applications

In their foreword, the guest editors name radiation damage as the driving force behind all these developments; atomic resolution is now reached down to about 20 kV[5]. Three papers treat the theory needed to record and evaluate low-voltage TEM data: Lee and co-workers at Ulm University show how electron dose sets signal-to-noise ratio, atom contrast and resolution[3], Jannik C. Meyer and co-workers at the University of Vienna recover atomic structure from large-area, low-dose exposures[6], and Tatiana Latychevskaia and co-workers at the University of Zurich reconstruct low-energy electron holograms free of artefacts[7].

New instruments for beam-sensitive materials come from industry: Mitsuru Konno and co-workers at Hitachi High-Technologies image crystal lattices at 30 kV in a scanning electron microscope[8], Marian Mankos and co-workers at Electron Optica present a low-energy electron microscope for DNA sequencing and surface analysis[9], and Takeo Sasaki and co-workers at JEOL record aberration-corrected STEM and TEM images at 15 kV[10].

Four papers apply low voltage to real materials. David C. Bell and co-workers at Harvard University show how practical materials problems benefit from it, from a graphene sheet imaged at 40 kV below the knock-on threshold to thin silicon nanowires[11]. Chris B. Boothroyd and co-workers at the Ernst Ruska-Centre in Jülich image barium atoms and functional groups on graphene oxide[12], Lawrence F. Drummy of the Air Force Research Laboratory studies organic–inorganic interfaces[13], and Jean-Nicolas Longchamp and co-workers in Zurich image gold nanorods on graphene by low-energy holography[14]. Finally, Egerton of the University of Alberta asks which operating voltage is best for a given specimen[2], and Michael Stöger-Pollach explains how a conventional analytical TEM becomes a low-voltage one and how low EELS can go[15],[16].

What the publication record shows

Low-voltage aberration-corrected TEM is now pursued worldwide, and FEI, JEOL, Hitachi and Nion sell microscopes that run at 80 kV or below. A look back at the years 2006 to 2013 shows how productive the field has been. SALVE keeps lists of publications on aberration-corrected TEM, about 1700 papers up to the end of 2013. At 20–80 kV, about 27 % of the papers appeared in journals with an impact factor above 10, compared with about 9 % at 100–300 kV (Fig. 1). Research on beam-sensitive materials is clearly of high scientific interest.

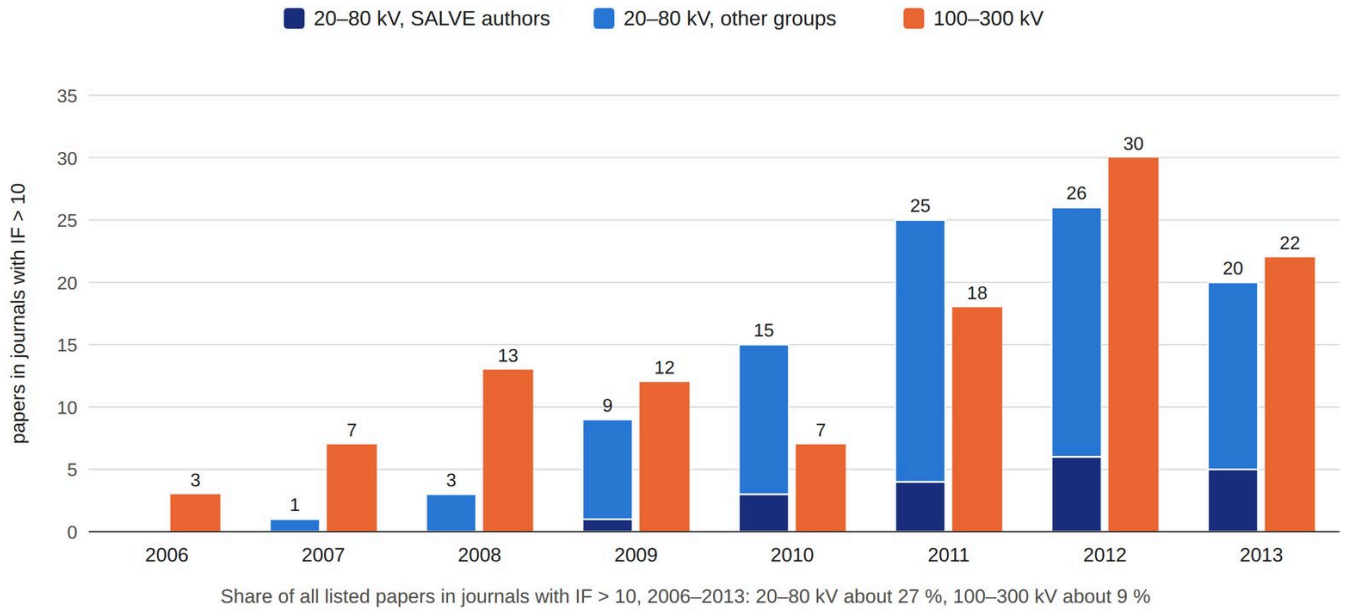

Fig. 1: High-impact papers per year.

A closer look at the 99 low-voltage papers in high-impact journals (see the list of publications in journals with IF > 10) shows where and how this research is done (Fig. 2). Most appeared in ACS Nano, Nano Letters, Nature Materials and Science. Oxford leads, followed by Ulm and AIST in Tsukuba. FEI microscopes were used most often, most papers worked at 80 kV and the rest at 60 kV, and conventional TEM imaging dominated. Chromatic aberration was corrected in only about 3 % of the papers; the others corrected spherical aberration alone. Low-dimensional materials, above all graphene, were studied far more often than semiconductors, oxides, nanocrystals or biological matter. The check of these numbers is described in the box.

Validation: the 2014 statistics vs. the publication lists and a trend database

In October 2026 the figures were checked again. The list of publications in journals with IF > 10 contains exactly 99 papers at 20–80 kV (19 by SALVE authors, 80 by other groups) and 120 at 100–300 kV; per year, the high-impact papers at 20–80 kV rose from 1 in 2007 to 26 in 2012. Among all 1318 listed papers at 100–300 kV up to 2013, 120 are in high-impact journals, 9 %; at 20–80 kV it is 99 of about 370, 27 %. Both shares match the article. The total of all listed papers is about 1700 rather than the 2000 stated originally.

The institutions of 96 of the 99 papers were determined from the author affiliations: Oxford 26, Ulm 17, AIST 15, Lawrence Berkeley National Laboratory 11, UC Berkeley 10, IFW Dresden 9, Oak Ridge 7 and Nottingham 6, the same order as in 2014. Vienna and JEOL, with five papers each, were missing from the old chart and are now included.

Microscope, voltage, method, chromatic correction and material cannot be read from titles and abstracts; only 15 of the 99 abstracts even name 80 kV. These charts therefore show the classification made by hand in 2014, read from the original pie charts. A trend database of low-voltage papers from 2007 to 2013 confirms the order of the manufacturers (FEI, JEOL, Nion, Zeiss, Hitachi), but gives a larger share of STEM: about 60 % TEM and 40 % STEM, against 78 % TEM in the 2014 sample of high-impact papers.

Biological materials

Despite a large effort to image biological objects at high resolution, only about 30 of the roughly 1700 papers, under 2 %, use aberration-corrected TEM on biological materials (see the list of publications for AC-TEM of biological materials); Fig. 3 shows their statistics. In 2011, Yu and co-workers solved the structure of a whole virus at 3.1 Å by single-particle cryo-electron microscopy at 300 kV[17]. Any clear improvement on such values would raise the number of biological studies with aberration-corrected TEM and could transform structural biology.

An old challenge

In 1959, Richard P. Feynman stressed how important it would be to see biological molecules and viruses in the electron microscope. Albert V. Crewe imaged DNA as early as 1971 and reported on radiation damage. Otto Scherzer wrote in 1970 that radiation damage puts a big question mark behind all efforts to observe the processes of life in an electron microscope and to image biomolecules at atomic resolution[18]. The community still faces these challenges, and strategies are being developed to meet them.

In Germany, one project is devoted to the atomic and electronic structure of radiation-sensitive matter with 20–80 kV electrons. In the SALVE project, academia and industry work together with funding from the German Research Foundation (DFG) and the Ministry of Science, Research and Arts of Baden-Württemberg (MWK). It began in January 2009 with Ulm University as academic partner and Carl Zeiss NTS and CEOS (Corrected Electron Optical Systems GmbH) as industrial partners. Carl Zeiss is leaving the project in 2014, and a new indus-

trial partner will take its place. About one third of SALVE's peer-reviewed papers have appeared in journals such as Science, the Nature family or Nano Letters.

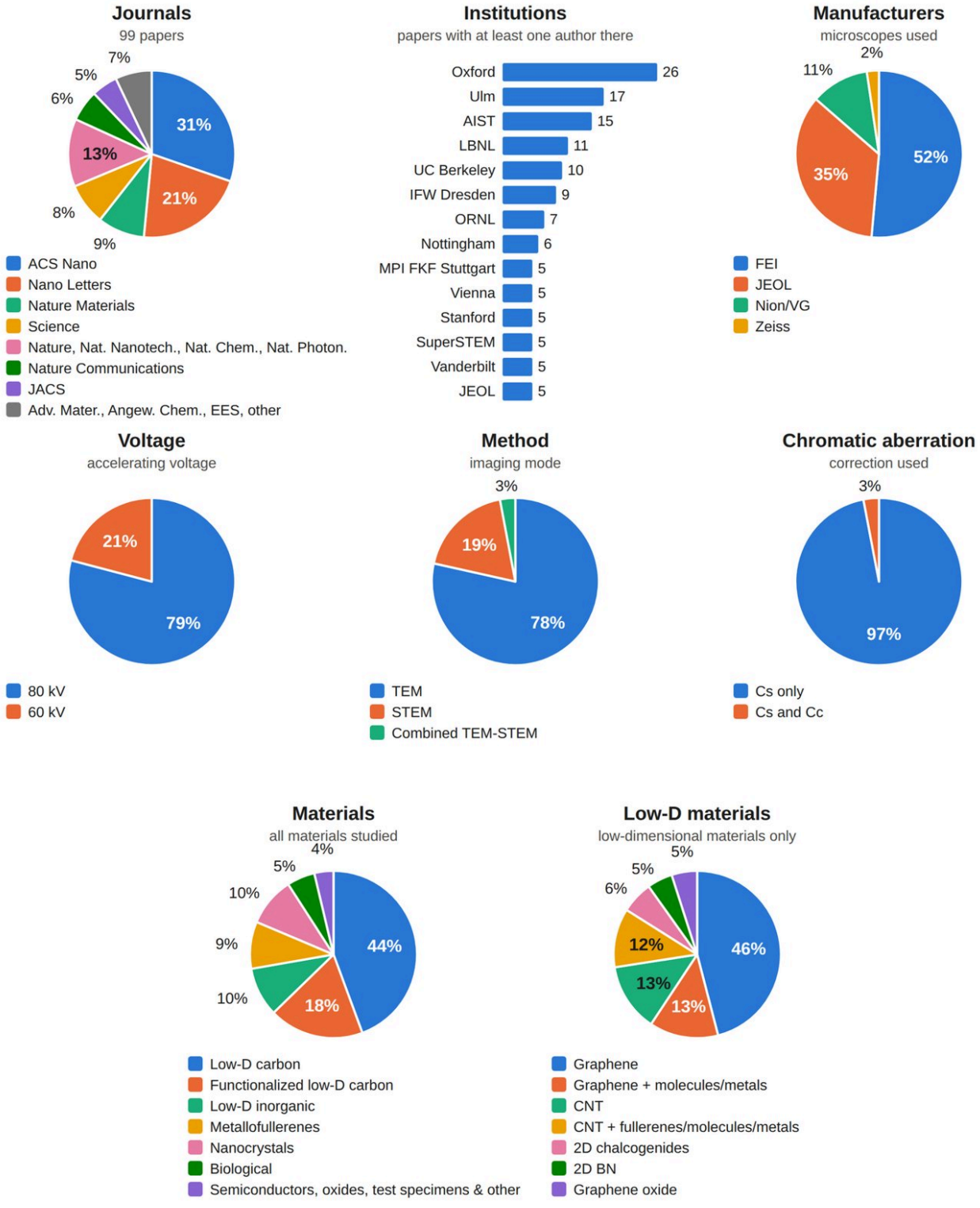

Fig. 2: High-impact low-voltage papers in detail.

"Over the past years, the crux of the matter has been identified, and we are quickly advancing towards our objectives," says Ute A. Kaiser. "In five years, the SALVE project has produced more than 50 publications in major journals, one patent application and two prototype microscopes. We hope that the results are convincing enough to take aberration-corrected low-voltage hardware from instrument development to applications in materials science and biology." Much work remains before aberration-corrected TEM becomes an established method for beam-sensitive organic materials. In this issue, Harald H. Rose, academic supervisor of the paper by Lee and co-workers[3], stresses the stability of the microscope and its environment and the suppression of noise in the chromatic and spherical aberration corrector[19]. New

ways to reduce radiation damage are needed as well, such as enclosing sensitive objects in carbon nanotubes or between graphene layers, or isotope substitution.

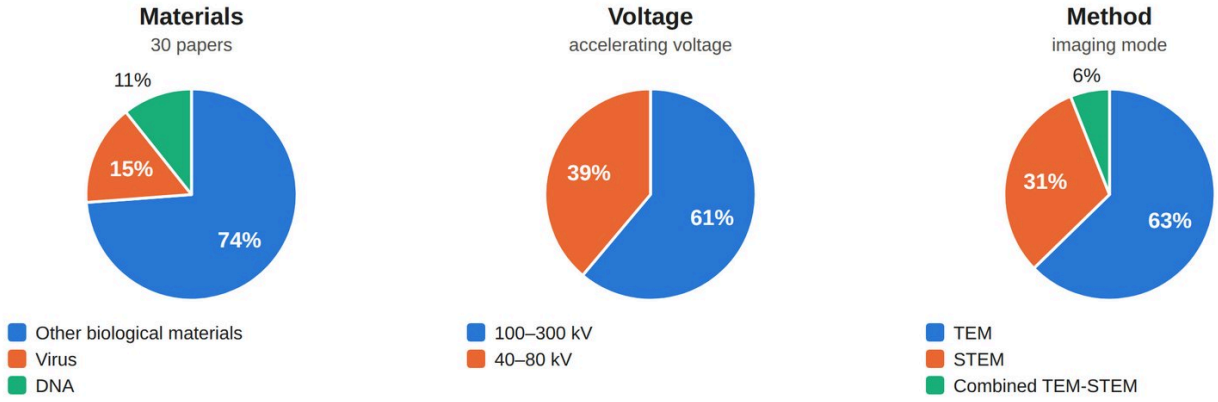

Fig. 3: Biological materials.

Update – October 12, 2026

The news article of October 12, 2014 ends above.

Does the lead of low-voltage microscopy in high-impact journals still hold? The same yardstick was applied to later years: the journals with an impact factor above 10 in 2014, so that shifts in individual impact factors do not distort the comparison (Fig. 4).

A full-text search in Europe PMC, for aberration-corrected papers naming the voltage, first confirms the picture of 2014: 33 % against 9 % for 2006–2013. From 2016 the medium-voltage papers catch up, for example with atomically resolved catalysts and 4D-STEM, and from 2021 both ranges are level: 47 % against 48 % for 2021–2025, and 55 % against 54 % for 2025, an estimate for the latest complete year. Europe PMC contains only the open-access part of the literature, which inflates the absolute shares, so the ratio is the meaningful number: from about 3.7 to 1 before 2014 to about 1 to 1 today.

The SALVE publication lists of aberration-corrected TEM papers confirm this trend: the lead of low voltage before 2014 and the catch-up of medium voltage since.

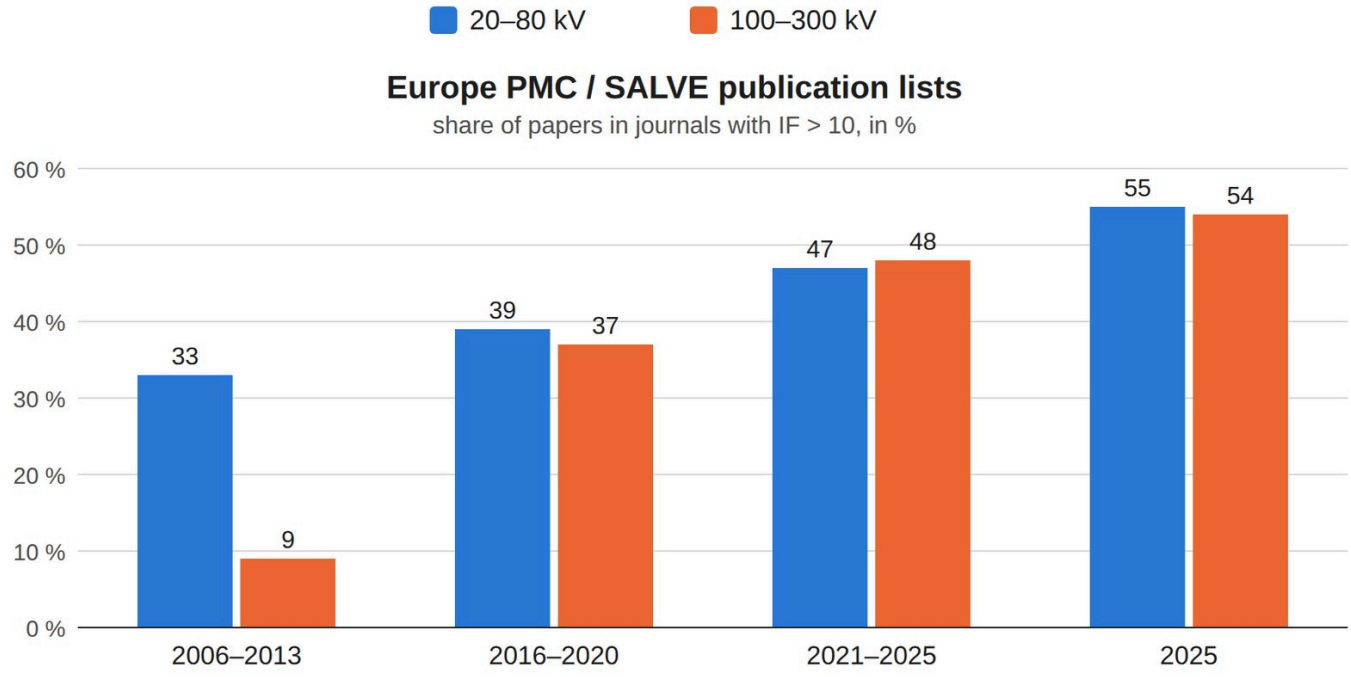

Fig. 4: High-impact share until 2025.

Why low voltage pays off: 2D materials below the knock-on threshold

Biological matter remains the greatest challenge. What low voltage has achieved instead is atomic-resolution imaging of the new low-dimensional materials without knock-on damage. An electron knocks an atom out of the lattice when it can transfer more en-

ergy than the displacement threshold; the lighter the atom and the weaker its bonds, the lower the accelerating voltage at which this sets in. Fig. 5 summarizes the voltages at which knock-on damage sets in, and Fig. 6 shows the resulting displacement cross sections for 2D materials studied by SALVE and its partners, calculated with the McKinley–Feshbach formula from the threshold energies of the cited papers. Lattice vibrations, already the zero-point motion of the atoms, smear out the sharp onset of the static lattice, so that damage begins some kV earlier[20],[21]. In perfect graphene, knock-on damage sets in at about 86 kV (108 kV for a static lattice)[20]. In h-BN, boron atoms are displaced from about 80 kV, and at the edges of holes already from 40 kV[22]. The sulfur atoms of MoS_2 follow from about 75 kV (90 kV static) [23],[24]. WS_2 has almost the same lattice threshold (7.0 eV, 94 kV static), but at the edges of WS_2 ribbons sulfur needs only 4.2 eV and is sputtered from about 58 kV[23]. Further members of the library of 2D crystals of Geim and Grigorieva[1], the metallic disulfides PtS_2, VS_2, NbS_2, TiS_2 and TaS_2, behave like MoS_2: their sulfur atoms need 5.95–7.25 eV, so knock-on damage of the static lattice sets in between about 81 kV (PtS_2) and 97 kV (TaS_2), and at 60 kV the cross sections of all of them are practically zero[23]. Phosphorene is the most fragile: the perfect lattice survives 60 kV but is damaged at 80 kV, and only at 30 kV is knock-on damage of edge and defect atoms largely avoided[25]. MXenes, metal carbides whose surfaces are terminated by F, O and OH groups, behave differently: at the exit surface fluorine is sputtered from about 46 kV, oxygen from about 65 kV and OH groups from about 72 kV, while hydrogen is lost at almost any voltage; graphene layers on both sides protect all terminations except hydrogen[26].

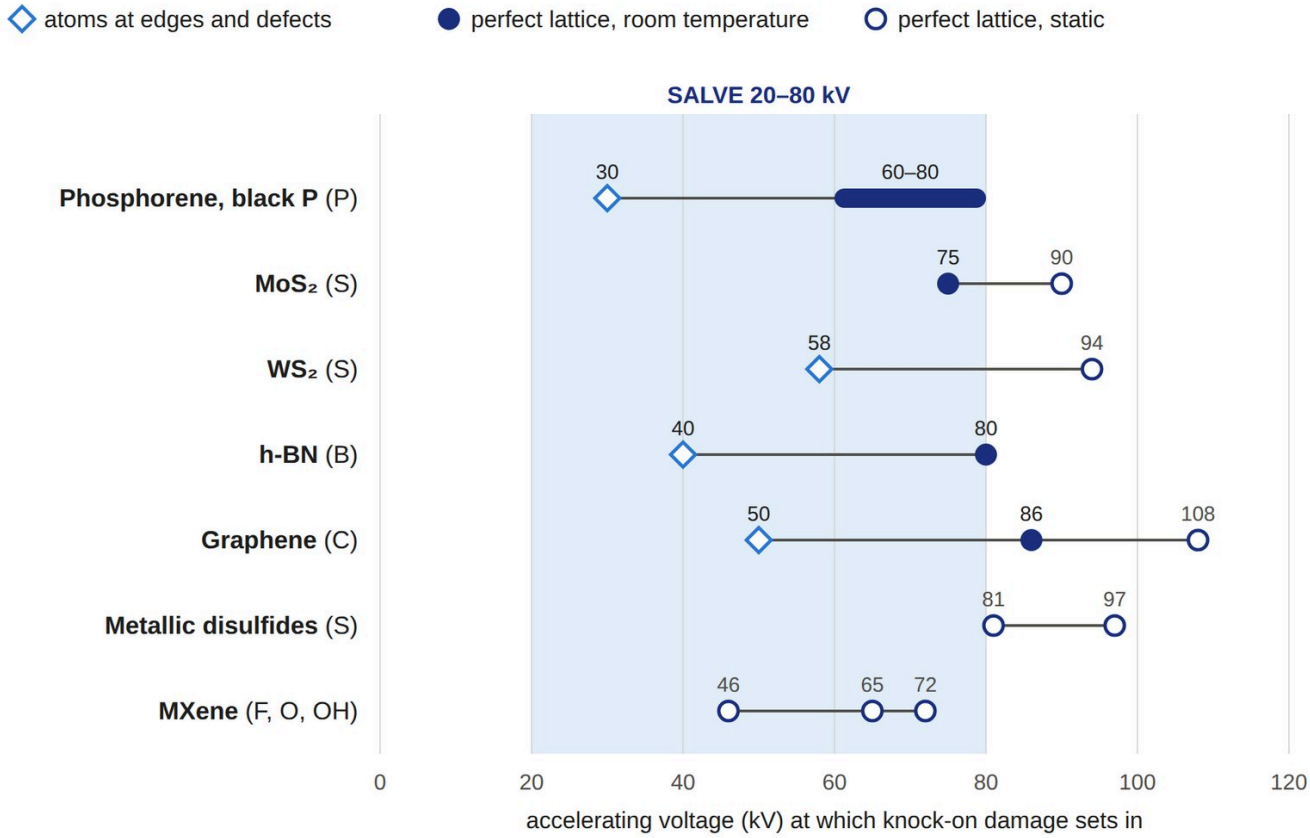

Fig. 5: Onset of knock-on damage.

As Egerton notes in the issue, knock-on damage of specimens that are immune to radiolysis can be reduced or avoided by choosing a low accelerating voltage[2]. The strategy is therefore to lower the voltage for each material until it lies below its threshold: 80 kV for graphene, 60 kV or less for h-BN and MoS_2, and 30 kV for phosphorene; for MXenes, about 30 kV keeps even the F and O terminations in place. At the 200–300 kV of conventional high-resolution microscopes, all light 2D materials would be destroyed while being imaged. Dopants and edges lower the thresholds further. In nitrogen-doped graphene the carbon atom next to the dopant needs only 19.2 eV instead of 22.3 eV, so knock-on damage begins near 96 kV instead of 110 kV, and at 80 kV only rare conversions of the dopant sites were observed, with a cross section of at most 0.16 barn[27]. At the edge of a graphene nanoribbon, hydrogen is knocked off even at 80 kV with a cross section of about 70 barn, while sulfur stays bound up to about 150 kV; this is why sulfur-terminated nanoribbons form in carbon nanotubes under the 80 kV beam[28]. Below the knock-on threshold, damage does not vanish completely: ionization and chemical etching still remove atoms, for example at the edges of holes in graphene even at 20 kV[20], and in MoS_2 through electronic excitations, with measured cross sections of 5–12 barn at 20–80 kV (Fig. 6)[29]. The issue itself marks this limit: below about 40 kV the damage is mainly radiolytic[11], and organic materials, which damage by ionization, become less stable at low voltage[13]. For the 2D materials these channels are

much weaker, however, and encapsulation between graphene layers reduces them further: at 80 kV, few-layer black phosphorus between two graphene sheets lasted about 13 times longer than without them[30].

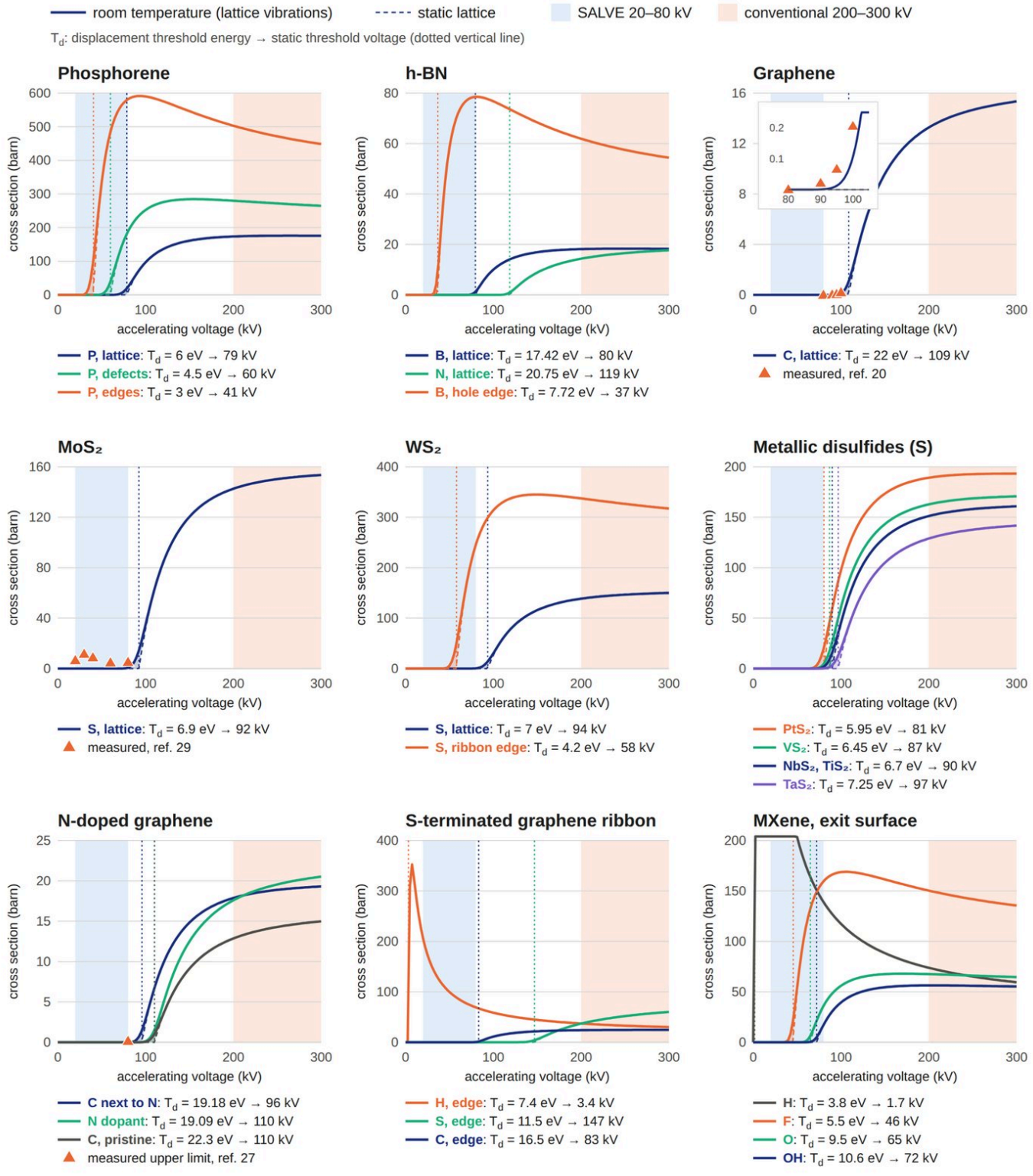

Fig. 6: Knock-on cross sections of 2D materials.

This is where the high impact of low voltage comes from. The van der Waals heterostructures of Geim and Grigorieva[1] brought a whole family of new 2D materials into focus after 2013. A classification of the high-impact papers in the SALVE lists by title keywords shows the effect (Fig. 7). At 20–80 kV, 64 % of the papers of 2006–2013 dealt with 2D materials, almost all of them with graphene (56 %). In 2015–2020 the share was 54 %, and 33 % now concerned 2D materials other than graphene, against 8 % before; in 2024 it was 50 %, again with 33 % beyond graphene. At 100–300 kV, 2D materials accounted for only 4 %

of the high-impact papers in 2006–2013 and 22 % in 2015–2020. Only papers that name the material in the title are counted, so all shares are lower limits.

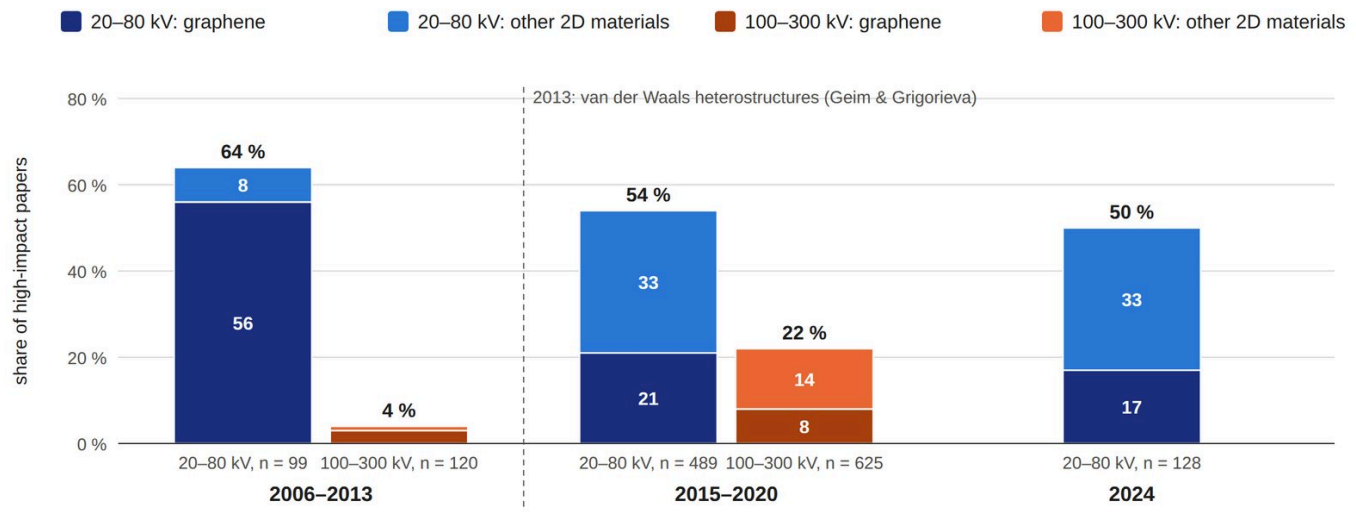

Fig. 7: 2D materials in high-impact papers.

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