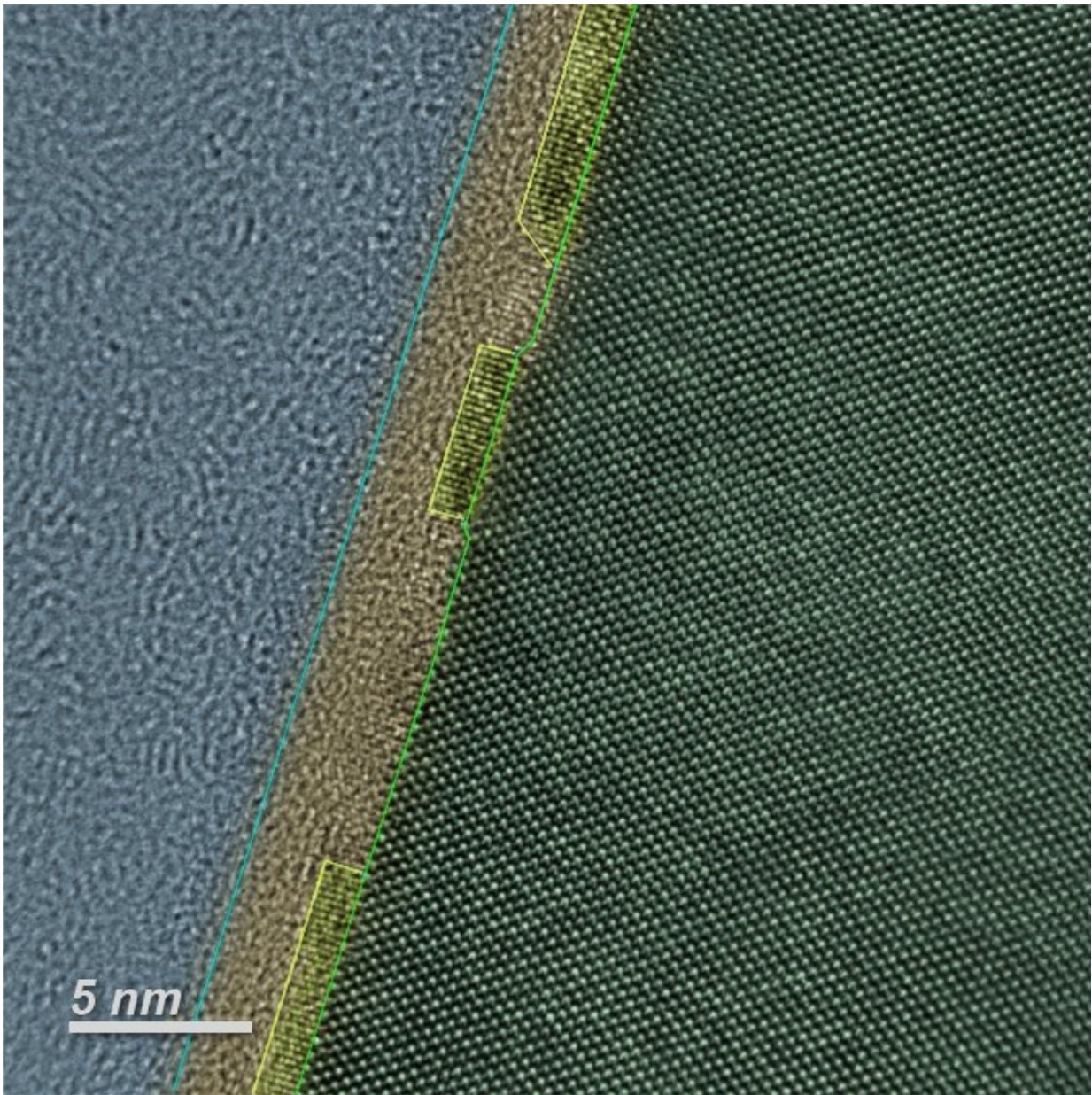


# When heat ceases to be a mystery, spintronics becomes more real

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Microscopic image of the GaAs/Fe<sub>3</sub>Si interface (GaAs marked in green, Fe<sub>3</sub>Si in yellow; the protective germanium layer in brown). Credit: IFJ PAN

The development of spintronics depends on materials that guarantee control over the flow of magnetically polarized currents. However, it is hard to talk about control when the details of heat transport through the interfaces between materials are unknown. This thermal gap in our material knowledge has just been filled thanks to a Polish-German team of physicists, who now describe in detail the dynamic phenomena occurring at the interface between a ferromagnetic metal and a semiconductor.

Spintronics has been proposed as a successor of electronics. In spintronic devices, electric currents are replaced by spin currents. One promising material for this type of application seems to be a gallium arsenide/iron silicide heterostructure. For every four electrons passing through this interface, as many as three carry information about the direction of the magnetic moment. So far, however, little was known about the dynamic properties of the interface, which determine the heat flow. A collaboration between the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow, the Karlsruhe Institute of Technology (KIT), the Paul Drude Institut für Festkörperelektronik in Berlin and the DESY research Centre in Hamburg has finally helped to close this gap.

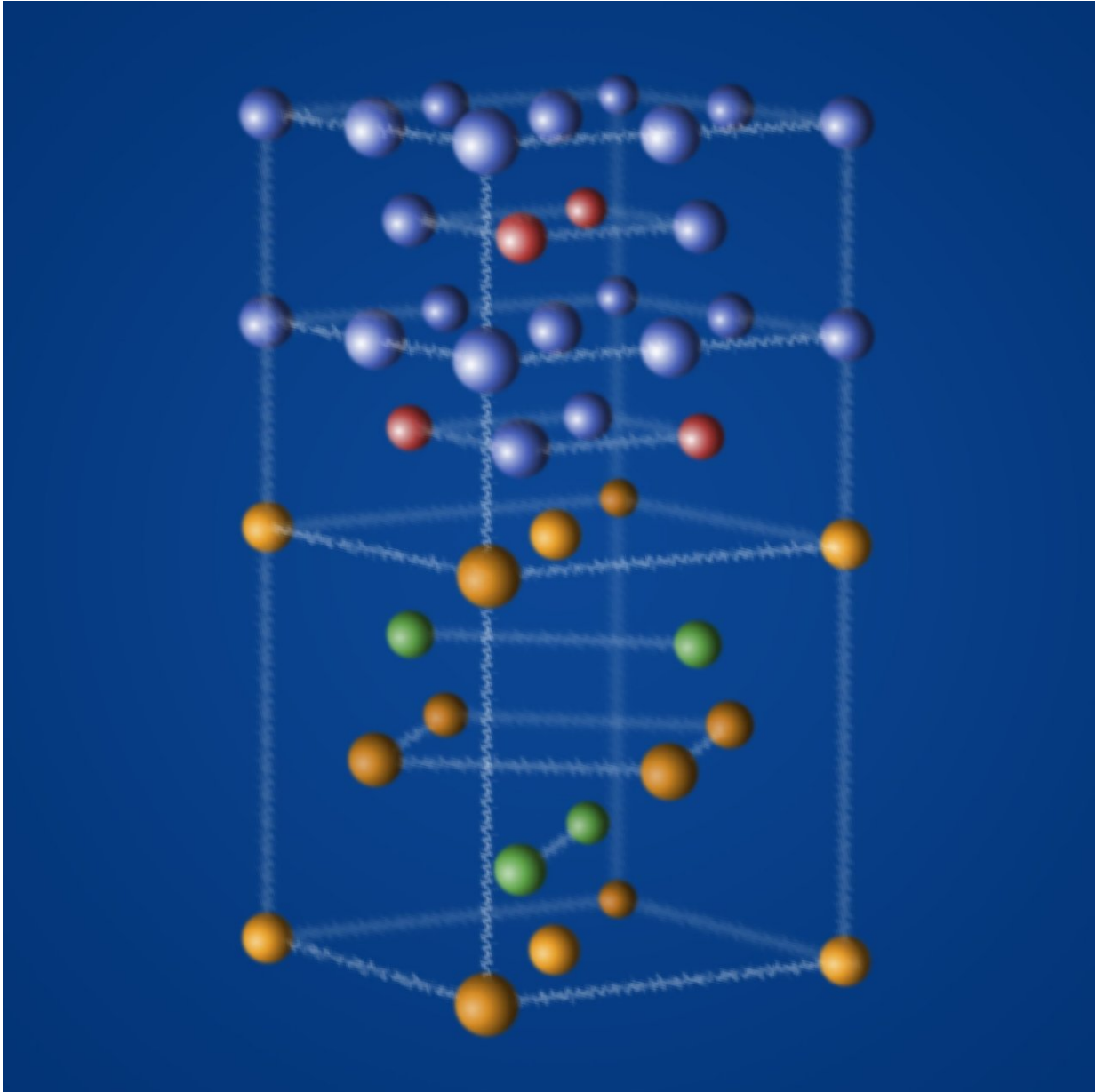
"The systems of Fe<sub>3</sub>Si iron silicide and GaAs gallium arsenide are special. The two materials differ significantly in properties: The first is a very good ferromagnetic material, the other is a semiconductor. On the other hand, the lattice constants, i.e. characteristic distances between atoms, differ only by 0.2 percent in both materials, so they are almost identical. As a result, these materials combine well, and there are no

defects or significant stresses near the interface," says Dr. Przemyslaw Piekarczyk (IFJ PAN).

The Polish group focused on the preparation of a theoretical model of crystal lattice vibrations in the tested structure. The PHONON computer program, created and developed over the last 20 years by Prof. Krzysztof Parlinski (IFJ PAN), played an important role here. Using the basic laws of quantum mechanics, the forces of interactions between atoms were calculated, and this allowed the researchers to solve equations describing the motion of atoms in crystal networks.

Dr. Malgorzata Sternik (IFJ PAN), who performed most of the calculations, explains: "In our model, the substrate is [gallium arsenide](#), and its outermost layer consists of arsenic atoms. Above it, there are alternately arranged iron-silicon and iron layers. Atomic vibrations are different for a solid crystal, and near the interface. This is why we studied how the spectrum of vibrations changes depending on the distance from the interface."

The dynamics of atoms in crystals are not random. Crystalline materials are characterized by a long-range order. As a consequence, the motion of atoms is not chaotic here, but follows certain, sometimes very complex, patterns. Transverse acoustic waves are mainly responsible for heat transfer. This means that when analyzing the lattice dynamics, the researchers had to pay special attention to the [atomic vibrations](#) occurring in the plane parallel to the interface. If the [vibration](#) waves of the atoms in both materials were matched to each other, heat would effectively flow through the interface.



The GaAs/Fe<sub>3</sub>Si interface model. Arsen atoms marked in orange, gallium - green, silicon - red, iron - blue. Credit: IFJ PAN

"Measuring the spectrum of atomic vibrations in ultrathin layers is one of the grand challenges in experimental solid state physics," explains the leading scientist Dr. Svetoslav Stankov (KIT). "Thanks to the



outstanding performance of the synchrotron radiation sources, we are able, via nuclear inelastic scattering, to directly measure the energy spectrum of atomic vibrations in nanomaterials with very high resolution. In our experiment, the synchrotron beam was oriented parallel to the plane of the interface. In this way, we were able to observe atomic vibrations parallel to the  $\text{Fe}_3\text{Si}/\text{GaAs}$  interface. Furthermore, the experimental method is element-specific, implying that the obtained data are practically free from background or other artefacts."

$\text{Ge}/\text{Fe}_3\text{Si}/\text{GaAs}$  samples containing various numbers of  $\text{Fe}_3\text{Si}$  monolayers (3, 6, 8 and 36) were prepared at the Paul Drude Institut für Festkörperelektronik by Jochen Kalt, a Ph.D. student at the Karlsruhe Institute of Technology. The experiment was carried out at the Dynamics Beamline P01 of the synchrotron radiation source Petra III in Hamburg.

It turned out that despite the similar lattice parameters of both [materials](#), the vibrations of the interface atoms differ drastically from those in the bulk. The first principles calculations were perfectly in line with the experimental observations, reproducing the novel features in the energy spectrum of interface atomic vibrations.

"The almost perfect match between theory and experiment paves the way towards interface phonon nanoengineering that will lead to the design of more efficient thermoelectric heterostructures and will stimulate further progress in thermal management and nanophononics," concludes Dr. Stankov.

The  $\text{Fe}_3\text{Si}/\text{GaAs}$  interface has proven to be a perfect model system for studying dynamic and spintronic [interface](#) phenomena. In the future the research team plans to extend this work to better understanding the electronic and magnetic properties of this promising material.

**More information:** J. Kalt et al, Lattice dynamics of epitaxial strain-

free interfaces, *Physical Review B* (2018). [DOI: 10.1103/PhysRevB.98.121409](https://doi.org/10.1103/PhysRevB.98.121409)

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