MEET A MAT SCI

Professor Alexander Balandin

Back to UCLA. Distinguished Professor Alexander Balandin is enjoying a nice day in Westwood – behind him is Fox Theatre, a historic landmark cinema near UCLA.

Some of the most renowned writers of science fiction have predicted the discoveries of the most remarkable materials. In one of his greatest works, The Fountains of Paradise, Arthur Clarke tells the story of an engineer, Dr. Vannevar Morgan, who is tasked with constructing an elevator to space. As one might expect, however, the project was not without its problems. For starters, even an elevator cable built of "the finest steel" was sure to buckle and yield under its own weight, long before it reached space. Yet despite this, Dr. Morgan pressed on and, after much toiling, discovered the perfect solution: a "pseudo-one-dimensional diamond crystal."

Thinner and lighter than spider silk, but hundreds of times stronger than traditional steel, this mysterious material captivated the imaginations of readers. Thirteen years after Clarke first published his story, carbon nanotubes were discovered and shown to possess strikingly similar properties [1].

Although dreams of space elevators and alien encounters will remain in fiction for the foreseeable future, the importance of studying lower-dimensional materials has since been proven very real. All varieties of lower-dimensional materials–including quasi-one-dimensional carbon nanotubes but also two-dimensional graphene and even zero-dimensional quantum dots–have been responsible for some of the most incredible physical phenomena and material properties observed in the past several decades. Our newest faculty member of the Department of Materials Science and Engineering, Distinguished Professor Alexander Balandin, has built up an internationally acclaimed career discovering properties of new low-dimensional materials and using them in a variety of electronic and energy-conversion applications [2].

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His passion and aptitude for science and research were clear early on. As a young man, Balandin was an avid reader of science fiction, and it was the tales of space exploration told by Arthur Clarke, Stanisław Lem, and many other writers that first stimulated his interests in physics, mathematics, and natural science. His interests led him to attend a highly selective Moscow Institute of Physics and Technology and obtain a master’s degree in Applied Physics. Looking back, he thanks his alma mater – nicknamed Moscow PhysTech – for giving him a strong fundamental education, focus on creative thinking rather than memorizing, and a pragmatic ability to use his knowledge to solve problems. These characteristics allowed him to find success in a variety of research fields throughout his career. While an undergraduate, Balandin worked as a research assistant in an electromagnetics laboratory but thanks to his broad educational background, in later years, he was able to switch his focus to materials and electronics.

After graduating from Moscow PhysTech, he aspired to become a professor. He decided that graduate education in the United States of America would provide him with such an opportunity. He applied to several U.S. universities, and owing to his undergraduate research experience, was awarded a fellowship to study at the University of Notre Dame. Although halfway across the world away from his place of birth, he jokes that the University of Notre Dame, with its impressive, ancient-looking architecture, soon became his own “piece of Europe, in America.” In the late nineties, he earned his second M.S. degree and Ph.D. in Electrical Engineering from Notre Dame. Though in graduate school his research focus shifted towards electronic materials and electronics, having studied electromagnetics in undergrad would prove useful later in his career.

Balandin started his investigation of low-dimensional quantum materials with the theoretical and computational study of semiconductor quantum wires. While unusual, it sometimes happens in engineering departments that one person can conduct both theoretical and experimental research. Balandin is an example of such a rare breed of experts. Though the name of the objects of his early research interests – “quantum wires” – may suggest one-dimensionality, this is not quite the case. Rather than being restricted to only a single chain of atoms, i.e. true one-dimensionality, these semiconductor nanowires are better thought of as material samples with cross-sections made exceptionally narrow so as to approach true one-dimensionality. These materials, as Balandin puts it, have a “quantum flavor”, e.g. quantum confinement of charge carriers, which results in new properties, useful for applications in electronics and photonics. Just like these quasi-1D quantum wires, quasi-2D quantum wells and quasi-0D quantum dots can be constructed in a similar fashion.

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Despite the “approximate” low-dimensional nature of these quantum wires, Balandin found that truncating dimensions could lead to new phenomena and materials properties. In fact, this statement can be thought of as the axiom underlying a great deal of Balandin’s research. With regards to quantum wires, he extended the concept of “spatially confined” electrons to phonons – quanta of crystal lattice vibrations that carry heat and scatter electrons. The “phonon wave-interference effects” became the basis for his approach to gain unique material functionalities otherwise unattainable in traditional bulk semiconductors. He found that spatial confinement of acoustic phonons can greatly decrease the material’s thermal conductivity. This marked the beginning of Balandin’s research of phonon transport phenomena in low-dimensional materials and his position as a trailblazer in the field of “phonon engineering,” i.e. the tuning of phonon characteristics to elicit desired material properties [3]. He published his first paper on the phonon wave interference effects while a postdoctoral associate at UCLA and continued this line of research as a professor at UC Riverside, expanding it to the experimental domain. Nowadays, the practical applications of the ideas of phonon engineering in nanostructured materials include thermoelectric energy conversion and thermal management.

True to his principle of not going with the flow but rather finding his own, sometimes surprising, research topics, Balandin has started his investigation of the low-frequency electronic noise in materials. The electronic noise, i.e. current fluctuations, originate from the discrete nature of the electrical charges and randomness of their motion in materials. The low-frequency current fluctuations often have the spectral density inversely proportional to frequency, f. This type of noise, referred to as 1/f noise, is common in metals and semiconductors. Normally one wants to decrease the level of this noise since it contributes to the phase noise of the communication systems and limits the sensitivity of detectors. Contrary to what majority of the researchers do, Balandin focuses on measurements of noise and its analysis to obtain information about the materials [4]. In his interpretation, the noise measurement becomes the “noise spectroscopy” of the material’s properties. Current fluctuations are more sensitive to the defects in the materials than the average current values. Noise spectroscopy has proven a useful tool to assess the quality of materials and reliability of devices, as well as to monitor phase transitions in the low-dimensional materials that cannot be electronically detected by other means.

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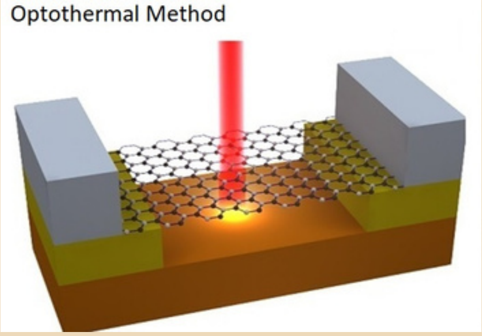
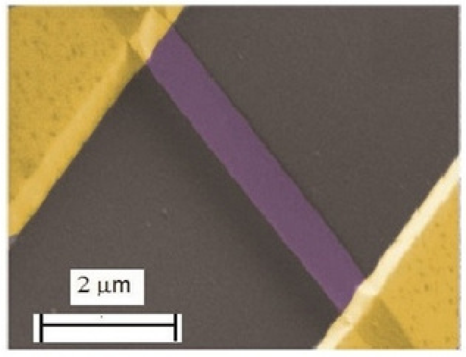
In 2004, lower-dimensional materials research saw a surge of attention following the Nobel-Prize-winning work on exfoliation and electrical measurements of graphene done by Andre Geim and Konstantin Novoselov, who are also in fact alumni of Moscow PhysTech. This marked the beginning of true low-dimensional materials, more specifically 2D van der Waals materials, and much excitement began to surround the surprising electrical conductivity of graphene. Amongst this excitement, Balandin observed that very little was being done to study graphene's phononic properties. And so, equipped with the tools and methodologies he had spent the last several years inventing to study phonons, Balandin seized the opportunity to conduct groundbreaking research into the phononic and thermal properties of graphene [5]. And conduct groundbreaking research he did. First, in order to measure the thermal conductivity of a sample that has the thickness of only one atom, he invented a whole new experimental technique, which is called the optothermal method. In this technique, a Raman spectrometer is used as a "thermometer" to measure the local temperature of the suspended material using the shifts in its spectral features. This technique is now used worldwide to measure thermal conductivity of various two-dimensional materials.

His discoveries, included the fact that graphene's intrinsic thermal conductivity, measured near room temperature, can exceed that of any other known material, and that the thermal conductivity of few-layer graphene reveals unusual thickness dependence. He proposed the first applications of graphene materials as fillers in thermal composites, which are used to remove heat from computers and battery packs. Balandin's pioneering work created a whole new graphene thermal, or graphene phononics, field that led to numerous practical applications in thermal management [6]. Even athletic wear benefited from his research – one can now buy sports jackets made with textiles that incorporate graphene for better heat spreading. In 2013, in recognition of his achievements, the Materials Research Society awarded him The MRS Medal with the citation, "for the discovery of the extraordinary high intrinsic thermal conductivity of graphene, development of an original optothermal measurement technique, and theoretical explanation of the unique features of the phonon transport in graphene" [7].



Schematic of the Balandin optothermal technique for measuring the thermal conductivity of 2D materials.



SEM image of the suspended graphene layer, similar to the one used in the discovery of unique heat conduction properties of graphene. The pseudocolors are used for clarity.

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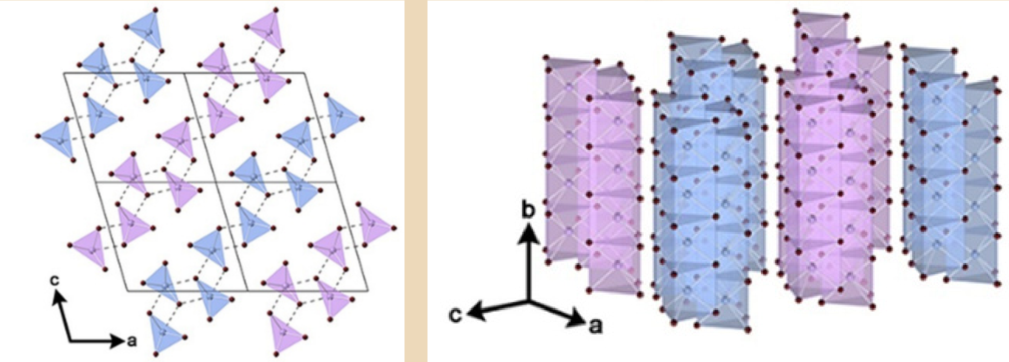
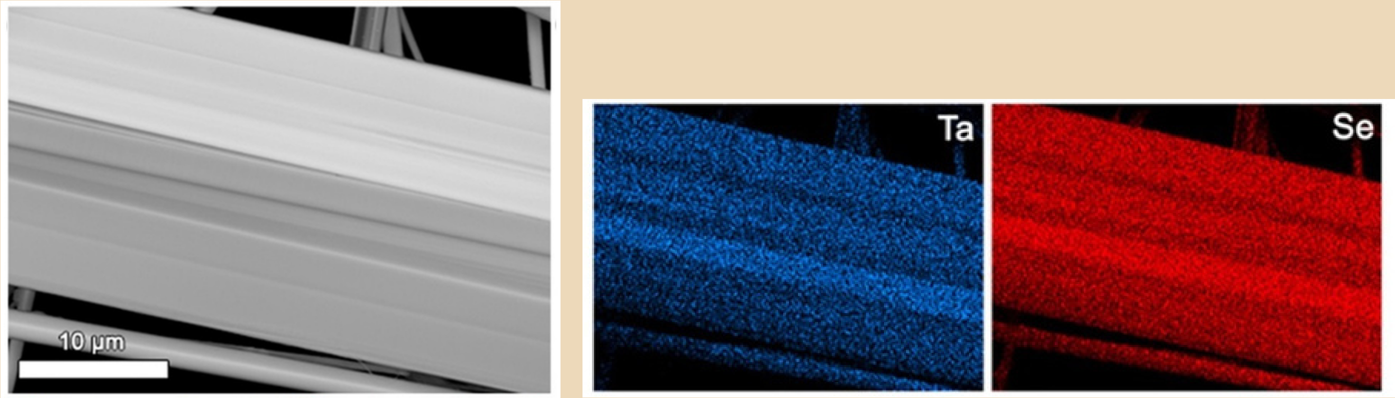
It goes without saying that the evolution from three-dimensional semiconductors to two-dimensional van der Waals materials, namely graphene and transition metal dichalcogenides, brought about an incredible amount of research and discovery. Furthermore, this trend echoes what Balandin had realized while studying quantum wires: truncating dimensions can lead to the discovery of new phenomena and materials properties. And so, in 2014, he considered what would happen if he again studied materials one-dimension lower: from two-dimensional van der Waals materials to one-dimensional van der Waals materials. From this, he discovered that these materials like quasi-1D transition metal trichalcogenides have the breakdown current densities far surpassing that of conventional materials, like copper. Such materials may find applications in ever decreasing in size integrated circuits and interconnects, like the ones in cell phones. Balandin's work on one-dimensional van der Waals materials started the new cycle of research on quantum materials with reduced dimensionality [8]. In recognition of his efforts in establishing this research direction he received a highly prestigious Vannevar Bush Faculty Fellowship.



Crystal structure of quasi-1D material $TaSe_3$ showing the adjacent chains of threads colored in purple and blue.



Scanning electron microscopy image of the $TaSe_3$ crystal.

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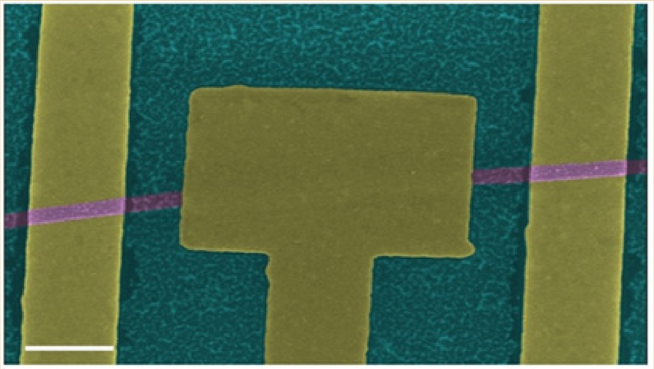
Much of Balandin's research in recent years has centered on the phenomenon of charge-density waves. In a sense, charge-density waves share a similar potential for materials engineering and property-enhancement that Balandin discovered in phonons and phonon engineering. Phonons are quanta of crystal lattice vibrations that influence properties such as thermal and electrical conductivity while charge-density waves are periodic modulations of electronic charge density that arise from phononic lattice distortions. The field of charge-density waves experienced a rebirth due to discovery of new van der Waals materials that have charge-density wave phases near or even above room temperature, opening a prospect of practical applications [9]. Materials with these strongly-correlated phases are truly quantum materials with the potential to revolutionize electronics. Collective currents of the propagating charge-density waves have the potential for the use in low-power and radiation-hard devices. Today, one of Balandin's research directions examines new functionalities of charge-density waves, particularly in the development of next-generation electronic switches, which operate on totally different principles than that of transistors.



Scanning electron microscopy image of the h-BN/NbS_3 charge-density-wave quantum device fabricated by Maedeh Taheri, UCLA PhD student in Balandin Group. The device was used to demonstrate electrical gating of the quantum condensate. The pseudo colors are used for clarity. The scale bar is 1 μm.

Before returning to UCLA, where he was once a postdoctoral associate, Professor Balandin had spent the last two decades as faculty of UC Riverside's department of Electrical and Computer Engineering. While at UC Riverside, and on top of his many research obligations, Balandin led the creation of new Materials Science and Engineering Program, overseeing the development of its courses and curriculums [10]. Now, at UCLA, Balandin serves as the vice chair of graduate studies for the Department of Materials Science and Engineering, the new home for his research group, whose work continues to inspire us all — not only the next generation of scientists and engineers, but perhaps even the next greatest writers of science fiction too.

Written by Hugo Onghai

Interview and Images courtesy of Professor Alexander Balandin

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References

(1) Iijima, S. Helical Microtubules of Graphitic Carbon. Nature 1991, 354, 56. https://doi.org/10.1038/354056a0

(2) UCLA Engineering Welcomes Two New Faculty Members | MSE. https://www.mse.ucla.edu/ucla-engineering-welcomes-two-new-faculty-members/

(3) Balandin, A.A. Phonon Engineering in Graphene and van der Waals Materials. MRS Bull. 2014, 39, 817; https://doi.org/10.1557/mrs.2014.169

(4) Balandin, A.A. Low-Frequency 1/f Noise in Graphene Devices. Nature Nano 2013, 8, 549; https://www.nature.com/articles/nnano.2013.144

(5) Balandin, A.A. Thermal Properties of Graphene and Nanostructured Carbon Materials. 2011, Nature Mater., 10, 569; https://www.nature.com/articles/nmat3064

(6) Balandin, A.A. Phononics of Graphene and Related Materials. ACS Nano 2020, 14, 5170. https://doi.org/10.1021/acsnano.0c02718

(7) MRS Medal: https://www.mrs.org/careers-advancement/awards/fall-awards/mrs-medal

(8) Balandin, A.A.; Kargar, F.; Salguero, T.T.; and Lake R. One-Dimensional van der Waals Quantum Materials. 2022, Materials Today, 55, 74; https://doi.org/10.1016/j.mattod.2022.03.015

(9) Balandin, A.A.; Zaitsev-Zotov, S.V.; and Grüner, G. Charge-Density-Wave Quantum Materials and Devices—New Developments and Future Prospects. 2021, Appl. Phys. Lett., 119, 170401; https://doi.org/10.1063/5.0074613

(10) Abbaschian R. and Balandin, A.A. Materials Education in the New Century – Experience in Creating an Interdepartmental Materials Science and Engineering Program. 2022, Journal of Materials Education, 44, 1; https://icme.unt.edu/journal

THANK YOU

Thank you very much for reading the Fall 2023 edition of the MRS Alumni Newsletter. As always, we are very grateful for your continued support, and we wish you the best in all your endeavors in the new year.

If you have any questions, comments, or concerns, please do not hesitate to reach out to historian.mrs.ucla@gmail.com.