COMMENTS AND OPINIONS

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A pioneer in magnetic semiconductors — Professor Stephan von Molnár

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Professor Stephan von Molnár (Figs. 1 and 2), known for his groundbreaking work on magnetic semiconductors and spintronics, passed away peacefully on 17 November 2020 in Tallahassee, Florida, USA.

Stephan was born in Leipzig, eastern Germany in 1935. After a tumultuous childhood through World War II, he immigrated to the United States in 1947. He received his Ph.D. at University of California, Riverside in 1965. He then joined the IBM T.J. Watson Research Center as a Research Staff, and later held positions as manager and senior manager. Upon arriving at IBM, he commenced a highly influential and consequential study of magnetic semiconductors, which would last for nearly six decades. The effort was broadly motivated by the goal of combining magnetism with semiconductors, the two fundamental pillars of IBM's business interests in magnetic information storage and semiconductor electronics. The research foreshadowed the emergence of the field of spin-based electronics, long before the word "spintronics" was minted in 1990s. In 1994, he joined the Florida State University (FSU). In addition to leading a research group focusing on spin related physics and bionanotechnology, he served as the director of the Center for Materials Research and Technology (MARTECH) for nearly 14 years. Stephan was a Distinguished Research Professor of FSU, a fellow of the American Physical Society, and a recipient of the Alexander von Humboldt Senior U.S. Scientist Award. In early 2000s, he chaired a panel sponsored by several US government agencies, which surveyed the worldwide research efforts in spintronics and provided important guidance in its subsequent development.

Beginning with his Ph.D. work on the magnetic resonance studies of EuS, a model system for the first generation of magnetic semiconductors, Stephan was intimately involved in the investigation of all three generations of magnetic semiconductors. He contributed to the inception of the field and heralded its spectacular growth and development into the mainstream of materials science and condensed matter physics. His work resulted in 170 scientific papers and garnered at least 24 000 citations. Many of Stephan's seminal contributions to the field of magnetic semiconductors have found far-reaching impact in other areas; it is informative to briefly review a few of them here:

(1) Magnetic tunnel junction. In 1967, working with Phil Stiles and Leo Esaki, Stephan fabricated metal/EuSe heterostructures by thin film deposition method. Deftly utilizing the spin-splitting of the Schottky barrier height as the magnetic semiconductor EuSe enters the ferromagnetic state, they demonstrated that decreasing temperature or applying a magnetic field could greatly modify the field emission current (Fowler-Nordheim tunneling). This was widely regarded as the first conceptual demonstration of a spintronic device, for the realization of spin-polarized tunneling current and the control of the charge current by way of the magnetic state of the semiconductor.

(2) Giant negative magnetoresistance. In 1967, in transport measurements of Gd-doped magnetic semiconductor EuSe, Stephan and coworkers observed an apparent metal–insulator phase transition around the Curie temperature. Around the Curie temperature, the resistance of the sample could be reduced by more than 10 000-fold by applying a mag-

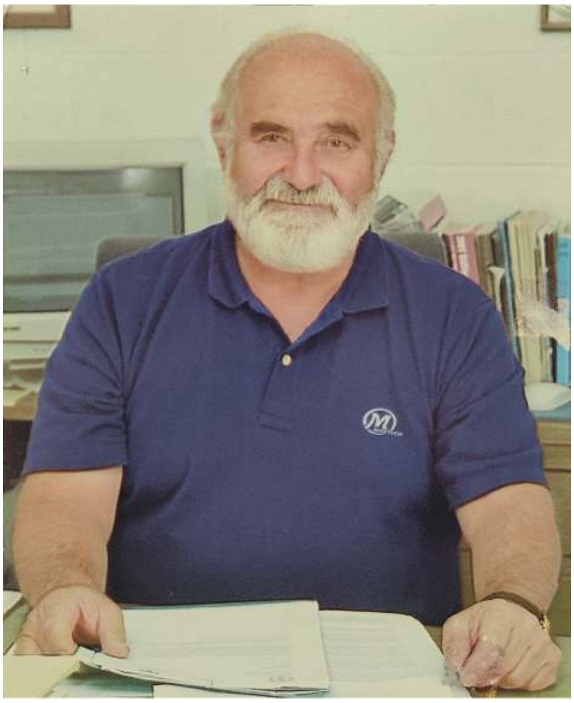

Fig. 1. Prof. Stephan von Molnár.

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netic field of 1 Tesla. Stephan coined the term "giant negative magnetoresistance" to describe the enormous changes of resistance by a magnetic field. In 1993, a similar negative magnetoresistance associated with a magnetic phase transition was observed in mixed-valence manganites by a group in Germany; this observation in the manganites was named "colossal magnetoresistance", which attracted the intense focus of the condensed matter and materials physics community for more than a decade.

(3) Magnetic polaron. Motivated by the observation of the giant negative magnetoresistance in Gd-doped EuSe, Stephan and Tadao Kasuya proposed the concept of magnetic polaron and used it to explain the transport properties of EuSe and several other first-generation magnetic semiconductors. In 1987, Stephan, in collaboration with David Awschalom, studied a second generation magnetic semiconductor, (Cd,Mn)Te, by optical excitation combined with magnetic measurement, and obtained direct evidence for the existence of localized magnetic polarons. It was a strong conviction by Stephan that magnetic polarons are in fact ubiquitous in a broad variety of magnetic materials and could be a microscopic driver for electronic phase separation and percolative phase transitions.

(4) Magnetic field-driven metal–insulator transition. In 1979, the landmark scaling theory of localization by the "Gang of Four" predicted that the conductivity of a three-dimensional system would change continuously to zero in the metal-insulator transition. This was in direct contradiction with the conductivity jump predicted by Sir Nevill Mott. Although several experiments appeared to support the scaling theory, the influence of electron–electron interaction could not be excluded. In 1983, Stephan, with Jacques Flouquet, examined the metal-insulator transition in the magnetic semiconductor $Gd_{3-x}v_xS_4$ (v = vacancy), in which the interaction effect is negligible; moreover, the material choice enabled the use of magnetic field as a continuous tuning parameter to drive the transition. They observed that with decreasing field, the conductivity decreases continuously in the metallic state to zero in the insulating state. This experiment provided unambiguous support to the scaling theory.

(5) III–V diluted magnetic semiconductors. In 1989, Stephan, with Hiro Munekata, Hideo Ohno and other colleagues at IBM, embarked on an effort to produce III–V based magnetic semiconductors via transition metal doping by molecular-beam epitaxy (MBE), in the hope of significantly raising their Curie temperatures. In 1992, they succeeded in fabricating ferromagnetic (In,Mn)As, and confirmed that the ferromagnetism originates from uniform Mn substitution of Ga. These efforts sowed the seeds for the successful growth of ferromagnetic (Ga,Mn)As by low-temperature MBE method in 1996 and further increase of its Curie temperature to 110 K shortly after by the Ohno group in Japan. As a canonical member of the third-generation magnetic semiconductors, (Ga,Mn)As triggered a global research boom of magnetic semiconductors. Stephan maintained a keen interest in these activities; a collaborative effort with two of us (JHZ and PX) raised the Curie temperature of (Ga,Mn)As to a record 200 K.

Stephan joined the physics faculty of Florida State University in 1994. After a long stint in industrial research,

Fig. 2. Stephan chaired the workshop held at Xijiao Hotel in Beijing in 2010.

Stephan was deeply appreciative of the freedom in the academic setting and especially the opportunity to educate and work with graduate students. At FSU, he not only continued his endeavor in magnetism and spintronics, but also developed a keen interest in biophysics, particularly bionanotechnology. Together with several generations of graduate students and postdocs, and his colleagues in physics, biology, and chemistry, he further refined the micro-Hall gradiometer technique invented at IBM, and successfully adapted it to biomolecular sensing.

Stephan was a firm believer and faithful practitioner of open scientific exchanges and international collaborations. Throughout his career, collaborations with scientists all over the world were instrumental in many of his important discoveries. He had collaborated or closely interacted with Nobel laureates Leo Esaki, Nevill Mott, and Bob Schrieffer, as well as prominent figures in the field of spintronics, David Awschalom, Robert Buhrman, Michael Coey, Hideo Ohno, Nitin Samarth among many others. Since 2007, Stephan had developed a strong professional and personal connection with colleagues and institutions in China. The collaborative activities had involved not only all three of us, but also many of our students from both sides. In 2009, Stephan, with Peng Xiong at FSU and Jianhua Zhao at IoS, CAS, secured funding from US NSF and NSFC, respectively, to commence a joint project in semiconductor spintronics. The effort was not only highly productive in its own right, but also blossomed into a far broader and robust collaboration which continues to bear fruit to this day.

Stephan leaves behind a legacy of unparalleled imagination, innovation, and scientific rigor in the field of magnetic semiconductors and spintronics. However, Stephan's passion and dedication were not confined to his science. He was an ardent enthusiast of music, theater, and fine arts. He was also an avid sports fan; his skills and competitiveness on the squash court were legendary. Always a true gentleman, Stephan's warmth, generosity, and encouragement have left indelible marks on so many researchers, from Nobel laureates to graduate students. Being able to work with him closely was our good fortune and an absolute joy. A gentle giant indeed; his presence will be missed by us all, but his spirit will always be with us and find its way into our work.

Jianhua Zhao is a professor at the Institute of Semiconductors (IoS), Chinese Academy of Sciences (CAS). She received her B.S. and M.S. degrees from Jilin University, in 1985 and 1988 respectively, and PhD degree from the Institute of Physics, CAS in 1999. From 1999 to 2002, she was a postdoc, first at IoS, CAS, and then at Tohoku University. In 2002, she became a professor at IoS, CAS. Her current interests include semiconductor spintronics, low-dimensional semiconductor physics.

Yongqing Li is a professor at the Institute of Physics (IoP), Chinese Academy of Sciences (CAS). He received his B.S. degree from Tianjin University in 1992, and PhD degree from the Florida State University in 2003. From 2003 to 2005, he was a postdoc at the University of California at Santa Barbara. From 2005 to 2008, he was a visiting scientist at Max Planck Institute for Solid State Research. In 2008, he joined the IoP, CAS. His current interests include semiconductor spintronics, mesoscale and nanoscale physics.

Peng Xiong is a professor of physics at the Florida State University (FSU). He received his B.Sc. from University of Science and Technology of China in 1987, and Ph.D from Brown University in 1993. He then spent the next four years as a postdoctoral fellow at the University of California at San Diego. He joined the faculty of FSU in 1997, and became a full professor in 2007. His current research interest includes superconductivity in low-dimensional systems and heterostructures, semiconductor and molecular spintronics, correlated electron physics, and organic/solid-state hybrid nanostructures.