Research

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1 Scientific focus

Electrons have electric charge but also carry both intrinsic angular momentum (called "spin") and an associated magnetic moment. Unlike the scalar charge, spin is a vector-like quantity that points in a given direction, and hence the nature of its interaction with other electronic degrees of freedom is fundamentally different.

My interests within solid-state device physics mostly pertain to the flow of this spin through otherwise nonmagnetic semiconductors, where under normal circumstances there are equal numbers of spins aligned or anti-aligned along any given axis. Forcing electrons to move across carefully-controlled interfaces between appropriate materials can, however, create an imbalance of spin directions or "polarization" out of equilibrium. One motivation for this topic choice is that there are potentially several practical applications of spin-electronics where spin orientation is controlled through real or effective magnetic field coupling to the magnetic moment. My hope is that we are working toward a time when this science enables an essential technology, much as a thorough understanding of charge transport in semiconductors built throughout the middle of the 20th century led directly to the development of electronic devices and the information age we now enjoy. Thus, I have focused my research not on exotic substances but rather the same materials basis for conventional electronics (elemental semiconductors such as silicon and germanium, and more recently, 2-dimensional layers of phosphorus).

As an assistant professor of Electrical Engineering at another university, I developed techniques that ultimately enabled my group to make the first experimental demonstration of non-equilibrium spin-polarized electron transport through silicon (2007). This was a hard technical and engineering problem to solve for many reasons; even now no other groups have replicated our success because of the enormous investment in time & capital, and the multi-disciplinary expertise required for success. A panoramic photo of several multi-chambered ultra-high vacuum thin-film deposition chambers that were entirely custom-designed and built by me for this purpose are shown below inside my custom semiconductor device fabrication cleanroom in Fig. 1, and my new low-temperature device measurement lab is shown in Fig. 2.

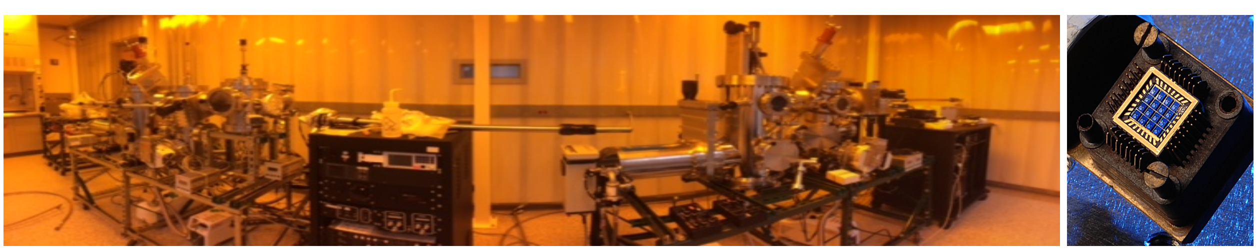


Figure 1: Custom-built ultra-high vacuum thin-film deposition chambers in Appelbaum's semiconductor device fabrication cleanroom in the Physical Sciences Complex, and an example packaged and mounted spintronic semiconductor device array fabricated using them.

Figure 2: Appelbaum's semiconductor device measurement lab in the Physical Sciences Complex.

Carving out this niche in the field has led to many unique opportunities for exploring a previously obscured but rich scientific landscape. Since my transition to the Physics department at UMD in 2009, I have exploited our prior technical accomplishments in device design and fabrication to focus on the more fundamental aspects such as the microscopic mechanisms dominating transport of spin-polarized electrons in elemental semiconductors, especially relaxation or "spin flip". Over the course of these last 6 years or so, we have had many successes in identifying these processes, especially where the crystal symmetry, electronic states' properties, and isoenergetic surface topology (and hence the nature of momentum scattering) play a major role.

2 Some context: Research style

My research described above is within the discipline of solid-state condensed-matter physics. Although this is a rather broad field, a small number of topics tend to dominate attention at any one time, with trends shifting every few years. It is often sensible to align one's research to these trends, since it maintains a sense of scholarly community and is to some degree essential in a sociological context to establish scientific consensus.

My own approach to research has nevertheless always been to pursue topics where I can make a *unique* contribution to the field, regardless of trends. I am generally not interested in the obvious next steps that others will do in droves – applying the same set of tools to the same problems as everyone else – once a hot new subject attracts attention.

As an experimentalist, my lab builds arrays of complicated semiconductor devices from bare commodity wafers using unconventional techniques enabled by fabrication equipment I designed and custom-built. This work is very demanding and it takes new lab members many months to make progress even just to reproduce known results obtained by previous students and postdocs. We subsequently perform all the low-temperature measurements on these fragile devices.

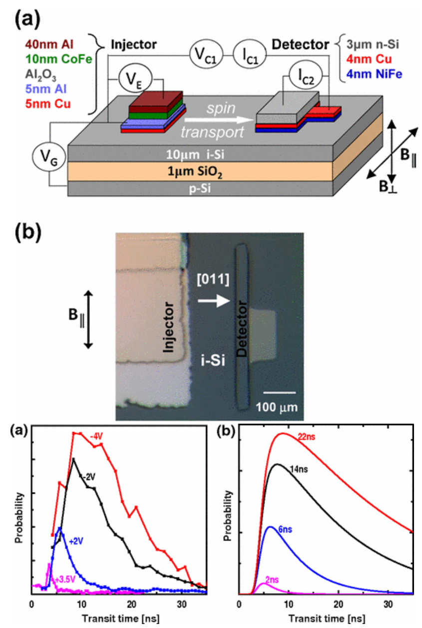
Although we have collaborated with theorists on a few occasions, I have a more holistic approach than most experimentalists. I especially enjoy demonstrating the relevance of theory in numerical computer simulations to uncover the physical mechanisms responsible for the phenomena observed in our data. By doing essentially everything necessary ourselves, we strive to gain a complete understanding of our subject. Consequently, our papers have relatively few authors (I usually place my name last in the authorship list), and I agonize over the choice of every sentence.

This research style applied to technically difficult topics both limits the production rate for journal papers and makes our expertise difficult to acquire by other groups, resulting in an only modest citation count (and so-called "h-index"). It also suppresses the kind of collateral authorship found in the records of some researchers with many external collaborators where the intellectual contribution requirements for inclusion are minimal. However, my goal is to maintain a creative, unique approach and exploit strengths distinct to my group and personal sense of scientific aesthetic. I maintain the conviction that numerically quantifiable citation "impact" cannot be the sole motivating factor for truly long-lasting science.

3 Research Highlights

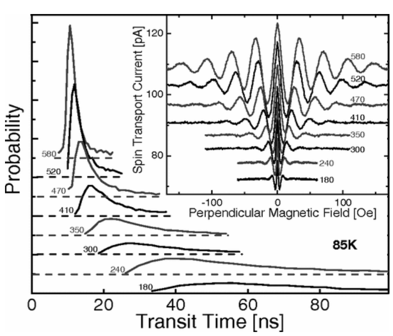
Below, I describe one significant paper from each year since joining UMD as associate professor in 2009:

2009. Hyuk-Jae Jang and Ian Appelbaum, "Spin Polarized Electron Transport near the Si/SiO_2 Interface", *Phys. Rev. Lett.* **103**, 117202 (2009). [45 citations]:



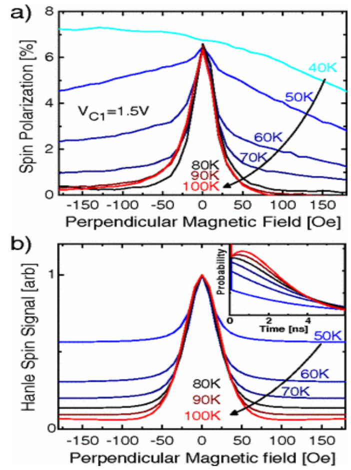
As spin-polarized electrons are attracted to the oxide interface by an electrostatic gate, we observed a paradox: spin transit times between injector and detector *de*creases and spin coherence as measured by Larmor precession fringes *in*creases, despite a reduction in total spin polarization. We explained this behavior (which is in contrast with the expected exponential depolarization seen in bulk transport devices) using a transform method to recover the empirical spin current transit-time distribution and a simple two-stage drift-diffusion model. We identified strong interface-induced spin depolarization (reducing the spin lifetime by over 2 orders of magnitude from its bulk transport value) as the consistent cause of these phenomena, and resolved the paradox. This was followed up with extensive finite-differences modeling in Jing Li and Ian Appelbaum, "Modeling spin transport in electrostatically-gated lateral-channel silicon devices: Role of interfacial spin relaxation", *Phys. Rev. B* **84**, 165318 (2011)[33 citations] and further experiments in Jing Li and Ian Appelbaum, "Lateral spin transport through bulk silicon", *Appl. Phys. Lett.* **100**, 162408 (2012) [19 citations]. Through an international collaboration, we have begun to apply resonant microwave techniques to identify the microscopic mechanism for this relaxation pathway, already showing that resonant microwave irradiation can be used to induce spin rotation of spin-polarized electrons as they travel across a silicon channel. [C. Lo, J. Li, I. Appelbaum, and J.J.L. Morton, "Microwave manipulation of electrically injected spin polarized electrons in silicon", *Phys. Rev. Applied* **1**, 014006 (2014).]

2010. Biqin Huang and Ian Appelbaum, "The Larmor clock and anomalous spin dephasing in silicon", *Phys. Rev. B Rapid Comm.* **82**, 241202(R) (2010). ("Editor's Suggestion") [25 citations]:



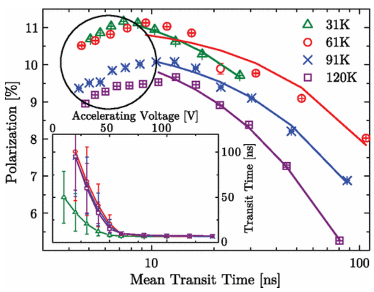
Here we showed that measurement of coherent spin precession in a controllable magnetic field can be transformed into an empirical spin transit time distribution with sub-nanosecond resolution, without the need for time-of-flight methods. A spin analogue of the classic Haynes-Shockley experiment (for minority charge carriers) is then possible. Analysis of these transport-time distributions from long-distance silicon channels revealed a spin diffusion coefficient inconsistent with the Einstein relation that relates diffusivity to mobility, as expected for non-conserved quantities like spin.

2011. Yuan Lu, Jing Li, and Ian Appelbaum, "Spin-Polarized Transient Electron Trapping in Phosphorus-doped Silicon", *Phys. Rev. Lett.* **106**, 217202 (2011). [17 citations]:



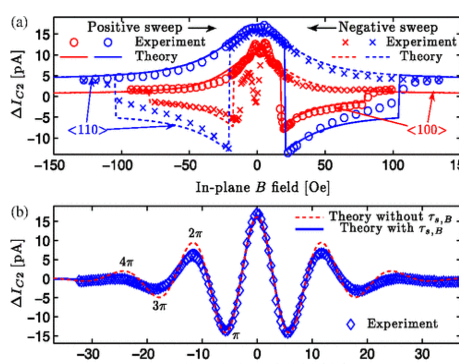
Using the Larmor clock analysis described above to examine transport data from silicon with intentional donor impurities, we observed evidence for two distinct transport pathways: (i) short time scales (≈50 ps) due to purely conduction-band transport from injector to detector and (ii) long time scales (≈1 ns) originating from delays associated with capture or reemission in shallow impurity traps. The origin of this phenomenon, examined via temperature, voltage, and electron density dependence measurements, was established by means of a comparison to a numerical model inspired by probabilistic queuing theory, and is shown to reveal the participation of metastable excited states in the phosphorus-impurity spectrum. This work then inspired ongoing research (funded by ONR) into radiative emission from impurity level transitions and the manipulation of spin selection rules for controllable THz sources.

2012. Jing Li, Lan Qing, Hanan Dery, and Ian Appelbaum, "Field-induced negative differential spin lifetime in silicon", *Phys. Rev. Lett.* **108**, 157201 (2012). [28 citations]:



In this work detailing the analysis of spin-transport measurements in high electric fields, we showed that the electric-field-induced thermal asymmetry between the electron and lattice systems in pure silicon substantially impacts the identity of the dominant spin relaxation mechanism. Comparison of empirical results from long-distance spin transport devices with detailed Monte Carlo simulations confirms a strong spin depolarization beyond what is expected from the standard Elliott-Yafet theory even at low temperatures. The enhanced spin-flip mechanism is attributed to phonon emission processes during which electrons are scattered between conduction band valleys that reside on different crystal axes. This leads to anomalous behavior, where (beyond a critical field) reduction of the transit time between spin-injector and spin-detector is accompanied by a counterintuitive reduction in spin polarization and an apparently "negative" spin lifetime.

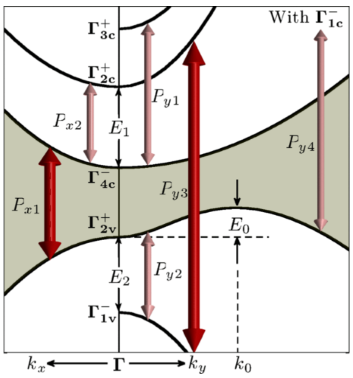
2013. Pengke Li, Jing Li, Lan Qing, Hanan Dery, and Ian Appelbaum, "Anisotropy-driven spin relaxation in germanium", *Phys. Rev. Lett.* **111**, 257204 (2013). ("Editor's Suggestion")[18 citations]:



We demonstrated an extraordinary mechanism in centrosymmetric diamond-lattice germanium which is reminiscent of the Dyakonov-Perel spin relaxation process that dominates in noncentrosymmetric semiconductor crystal lattices. In that well-known case, broken spatial inversion symmetry allows spin-orbit interaction to cause a momentum-dependent spin splitting; intravalley scattering during spin precession about this random effective magnetic field leads to depolarization. By straightforwardly showing the suppression of spin polarization with a longitudinal magnetic field in germanium spin-transport devices, we identify an analogous spin relaxation pathway caused by the presence of an additional random field whose origin is rooted instead in the broken time reversal symmetry, and intervalley scattering allows g-factor anisotropy to drive its fluctuation between four different orientations.

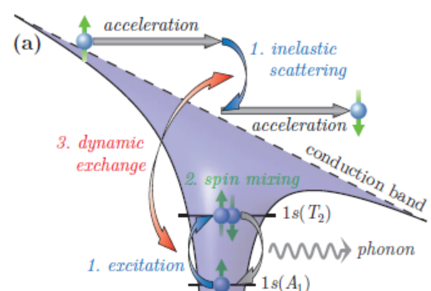
This is the first experimental result in the field that fully demonstrates the sensitivity of spin transport to band structure topology and symmetry through the spin-orbit interaction.

2014. P. Li and I. Appelbaum, "Electrons and holes in phosphorene", *Phys. Rev. B* **90**, 115439 (2014) ("Editor's Suggestion")[29 citations]:



Despite its low atomic number and inversion symmetry, recent electronic measurements demonstrate that (group-IV) graphene has a greatly disappointing and temperature-insensitive spin lifetime, corroborated by theory showing strong coupling to flexural (out-of-plane) phonons that cannot be effectively suppressed due to quadratic dispersion and therefore an energy-indpendent density of states. There exists a class of graphene-like 2-dimensional semiconductors formed from elemental group-IV OR group V atoms, some of which may be immune to this deleterious coupling. Only one is known to mechanically exfoliate like graphene: phosphorene (monolayer black phosphorus). Using group theory, we analyzed the symmetry of its electronic bandstructure including spin-orbit interaction close to the insulating gap edge with special interest in the spin-transport properties. Importantly, we discovered that the unique anisotropy of the valence band vastly suppresses spin relaxation due to flexural phonons for polarization along a specific in-plane direction. This result allowed us to predict a spin lifetime comparable to bulk Si, vastly greater than graphene. I am actively in search of funding to extend this theory work to the realm of experiment so that we can test this prediction.

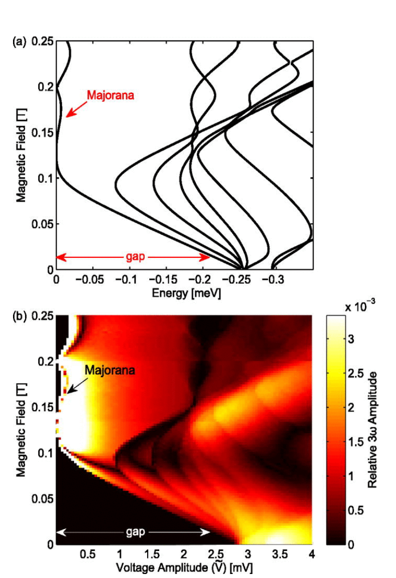
2015. L. Qing, J. Li, I. Appelbaum, and H. Dery, "Spin relaxation via exchange with donor impurity-bound electrons", *Phys. Rev. B Rapid Comm.* **91**, 241405(R) (2015):

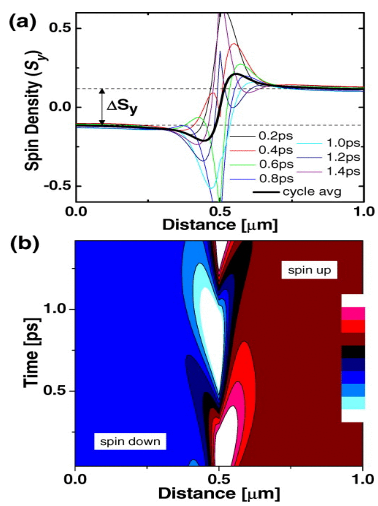


At low temperatures, electrons in semiconductors are bound to shallow donor impurity ions, neutralizing their charge in equilibrium. Inelastic scattering of other externally-injected conduction electrons accelerated by electric fields can excite transitions within the manifold of these localized states. Promotion of the bound electron into highly spin-orbit-mixed excited states drives a strong spin relaxation of the conduction electrons via dynamic exchange interactions, reminiscent of the Bir-Aronov-Pikus process where exchange occurs with valence band hole states. Through low-temperature experiments with silicon spin transport devices and complementary theory incorporating a master rate-equation approach using Fermi's golden rule, we revealed the consequences of this previously unknown spin depolarization mechanism both below and above the impact ionization threshold and into the "deep inelastic" regime.

4 Broader Interests

Majorana modes in 1D spin-orbit coupled superconductors: During Spring 2013, I spent 3 days a week at Harvard under the gracious hospitality of Prof. Amir Yacoby as a "Visiting Scholar", primarily on numerical modeling of spin-orbit-coupled superconductor materials and detection schemes for observing the predicted Majorana fermion in these systems. This resulted in two papers, one describing a novel technique (Ian Appelbaum, "Tunnel conductance spectroscopy via harmonic generation in a hybrid capacitor device", *Appl. Phys. Lett.* **103**, 122604 (2013) [15 citations]), and a funded proposal (NSF-DMR unsolicited) to carry out its experimental realization using materials from epitaxial-growth collaborators at Adelphi Army Research Labs. The other makes use of electrostatic detection of Majorana modes: G. Ben-Shach, A. Haim, I. Appelbaum, Y. Oreg, A. Yacoby and B.I. Halperin, "Detecting Majoranas in 1D wires by charge sensing", *Phys. Rev. B* **91**, 045403 (2015) [7 citations].





Topological Insulators: I developed a numerical model predicting a unique signature of dielectric insulator surface states on the polarized resonant electromagnetic transmission spectrum, I. Appelbaum, "Cross-Polarized Microwave Surface-State Anti-Resonance", *J. Appl. Phys.* **116**, 064903 (2014). This work is potentially relevant to the search for novel topological insulators, a presently active topic in the field with which I have several prior contributions: Ian Appelbaum, H.D. Drew, and M.S. Fuhrer, "Proposal for a topological spin rectifier", *Appl. Phys. Lett.* **98**, 023103 (2011) [24 citations] and C. Ojeda-Aristizabal, M. S. Fuhrer, N. P. Butch, J. Paglione, and Ian Appelbaum, "Towards spin injection from silicon into topological insulators: Schottky barrier between Si and Bi_2Se_3", *Appl. Phys. Lett.* **101**, 023102 (2012) [12 citations].

5 Current and Future directions

Several important topics in semiconductor spintronics supported in part by existing funded projects:

- Recently, we have obtained initial results on THz emission from doped Si devices (see 2011 paper above), motivating our present work on utilizing spectroscopically-isolated impurity-level transition lines to produce controllably circularly-polarized radiation resulting from the spin selection rules. This is a major standing problem in the field, relevant to e.g. chiral molecule analysis.

- Breaking discrete rotational symmetry with uniaxial strain: Spin relaxation in indirect-bandgap centrosymmetric semiconductors is dominated by electron-phonon-mediated intervalley scattering. Lattice distortion caused by mechanical stress breaks the valley degeneracy and suppresses this scattering, which should lead to massively enhanced spin lifetimes. Our tunnel junction injectors can easily withstand the necessary strain and we have developed the necessary device fabrication and built a low-temperature strain vise probe with custom contact geometry.

- Electron spin resonance: In addition to collaboration with Morton's lab as described above (see 2009 Highlight), we are also building our own low-temperature ESR system to explore resonance identification of paramagnetic centers, and provide additional evidence of e.g. strain-induced spin lifetime enhancement in Si and Ge.

- Inelastic electron tunneling spectroscopy: We have used this technique to identify extrinsic contributions to a magnetoresistance phenomenon that has captured the attention of the spintronics community since it mimics spin detection: H. Tinkey, P. Li, and I. Appelbaum, "Inelastic electron tunneling spectroscopy of local "spin accumulation" devices", *Appl. Phys. Lett.* **104**, 232410 (2014) [15 citations]. I have also developed a rigorously self-consistent method for simulating true spin-accumulation magnetoresistance: I. Appelbaum, H. N. Tinkey, and P. Li, "Self-consistent model of spin accumulation magnetoresistance in ferromagnet-insulator-semiconductor tunnel junctions", *Phys. Rev. B* **90**, 220402(R) (2014) [3 citations].

- Alternative spin detection schemes: Only two electrical spin detection methods have ever been demonstrated for use with semiconductors. Both use a ferromagnetic metal contact, either in open-circuit voltage detection (as pioneered by Johnson and Silsbee, originally with Al in 1985, and applied to GaAs by Crowell's group in 2007) or in closed-circuit current detection exploiting spin-dependent inelastic scattering (as developed and extensively used by my group). Each has its own disadvantages; the former is not applicable to nondegenerate semiconductors, and the latter suffers from small signal levels. To enable a spin-polarized electronic interconnect that circumvents technology constraints on metallic interconnects affecting packing density (due to capacitive cross-talk) or modulation speed (due to RC time delay), we developed a hybrid device design with benefits of both approaches, describing and modeling it in Bryan Hemingway and Ian Appelbaum, "A Differential Spin Detection Scheme", *J. Appl. Phys.* **114**, 093907 (2013). Ongoing fabrication and measurement to benchmark the proposed technique under current DTRA funding.