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Spin-Orbit-Enhanced Functionality in LaAlO3/SrTiO3 Nanostructures

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Final Report

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The overarching goal of the proposed research has been to develop a fundamental understanding of conductive nanostructures at oxide interfaces, and in particular to explore the role of spin-orbit interactions. We have used a variety of methods to work toward this goal, including the use of DC-GHz transport and optical techniques as well as exploration of alternative growth methods. Below we focus on several key results that are representative of our findings.

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G. Jnawali, L. Chen, M. Huang, H. Lee, S. Ryu, J. P. Podkaminer, C.-B. Eom, P. Irvin, and J. Levy, "Photoconductive response of a single Au nanorod coupled to $LaAlO_3/SrTiO_3$ nanowires," Applied Physics Letters **106**, 211101 (2015). http://dx.doi.org/10.1063/1.4921750

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Y. Ma, M. Huang, S. Ryu, C. W. Bark, C.-B. Eom, P. Irvin, and J. Levy, "Broadband Terahertz generation and detection at 10 nm scale," Nano Letters **13**, 2884 (2013). http://dx.doi.org/10.1021/nl401219v

P. Irvin, M. Huang, F. J. Wong, T. D. Sanders, Y. Suzuki, and J. Levy, "Gigahertz-frequency operation of a $LaAlO_3/SrTiO_3$-based nanotransistor," Applied Physics Letters **102**, 103113 (2013). http://dx.doi.org/10.1063/1.4795725

Presentations

Ultrafast Optical Response of Graphene/LaAlO3/SrTiO3 Nanostructures. Chen, Lu; Jnawali, Giriraj; Huang, Mengchen; Hsu, Jen-Feng; Bi, Feng; Lee, Hyungwoo; Ryu, Sangwoo; Eom, Chang-Beom; D'Urso, Brian; Irvin, Patrick; Levy, Jeremy. APS March Meeting 2015, abstract #L13.001

Electric field effects in graphene-complex-oxide heterostructures. Jnawali, Giriraj; Huang, Mengchen; Hsu, Jen-Feng; Bi, Feng; Chen, Lu; Zhou, Rongpu; Lee, Hyungwoo; Ryu, Sangwoo; Eom, Chang-Beom; Irvin, Patrick; D'Urso, Brian; Levy, Jeremy. APS March Meeting 2015, abstract #S16.011

Anisotropic superconducting properties of nanowires at the LaAlO3/SrTiO3 (110) interface. Irvin, Patrick; Huang, Mengcheng; Annadi, Anil; Cheng, Guanglei; Levy, Jeremy; Gopinadhan, Kalon; Venkatesan, Thirumalai; Ariando, Ariando. APS March Meeting 2015, abstract #L13.009

Quantized conductance through quantum point contacts in LaAlO3/SrTiO3 nanowires. Annadi, Anil; Lu, Shicheng; Cheng, Guanglei; Tomczyk, Michelle; Huang, Mengchen; Lee, Hyungwoo; Ryu, Sangwoo; Eom, Chang-Beom; Irvin, Patrick; Levy, Jeremy. APS March Meeting 2015, abstract #L13.007

Quantized conductance through reconfigurable 1D channels. Lu, Shicheng; Annadi, Anil; Cheng, Guanglei; Tomczyk, Michelle; Huang, Mengchen; Lee, Hyungwoo; Ryu, Sangwoo; Eom, Chang-Beom; Irvin, Patrick; Levy, Jeremy. APS March Meeting 2015, abstract #M26.014

THz investigations of graphene-complex-oxide heterostructures. Jnawali, Giriraj; Chen, Lu; Irvin, Patrick; Levy, Jeremy; Ryu, Sangwoo; Eom, Chang-Beom; Ghahari, Fereshte; Ravichandran, Jayakanth; Kim, Philip. APS March Meeting 2014, abstract #Y45.00013

Broadband THz Spectroscopy of Single Nanoscale Objects. Lu Chen, Giriraj Jnawali, Mengchen Huang, Patrick Irvin, Sangwoo Ryu, Chang-Beom Eom, Jeremy Levy. APS March Meeting 2014, abstract #T44.00008

Broadband THz Generation and Detection at 10 nm Scale. Yanjun Ma , Mengchen Huang , Jeremy Levy, Sangwoo Ryu, Chung Wung Bark, Chang-Beom Eom. APS March Meeting 2013, abstract #C12.00010

Ultrafast photoresponse of oxide nanostructures. Lu Chen , Yanjun Ma , Mengchen Huang , Sangwoo Ryu , Chung Wung Bark , Chang-Beom Eom , Jeremy Levy. APS March Meeting 2013, abstract #C12.00002

Major Accomplishments

The overarching goal of the proposed research has been to develop a fundamental understanding of conductive nanostructures at oxide interfaces, and in particular to explore the role of spin-orbit interactions. We have used a variety of methods to work toward this goal, including the use of DC-GHz transport and optical techniques as well as exploration of alternative growth methods. Below we focus on several key results that are representative of our findings.

Spin-orbit effects in 1D/2D nanostructures

The role of spin-orbit interactions depends crucially on the dimensionality of the system. The $LaAlO_3/SrTiO_3$ interface is already intrinsically two-dimensional; however, we utilize a conductive-AFM lithography technique to produce conductive nanostructures on the scale of 10 nm and smaller. Figure 1 (top) shows an illustration of a structure that was designed to explore the role of dimensionality on spin-orbit interactions. The device has five leads, two of which are used to source current (along the horizontal), and three of which are used to measure voltage drops along two channels, one of which is quasi-1D and the other of which is much wider. The 1D segment has a width *w*~10 nm, as measured by nanowire erasure experiments. The 2D segment is created by raster-scanning a rectangular area that is 200 nm wide. Transport experiments are performed as a function of a plane-perpendicular magnetic field up to 50 kOe, and as a function of an applied back gate voltage V_{back}. We observe a clear crossover from 2D weak antilocalization to a 1D suppression of this effect due to depletion from V_{back} in the 2D channel. At the most negative back gate voltage, the 1D and 2D magnetotransport results look almost identical, while there is clear weak antilocalization for the 2D system at positive back gate voltages. These results are being compared with tight-binding calculations to provide a quantitative estimate for the spin-orbit interactions in this system.

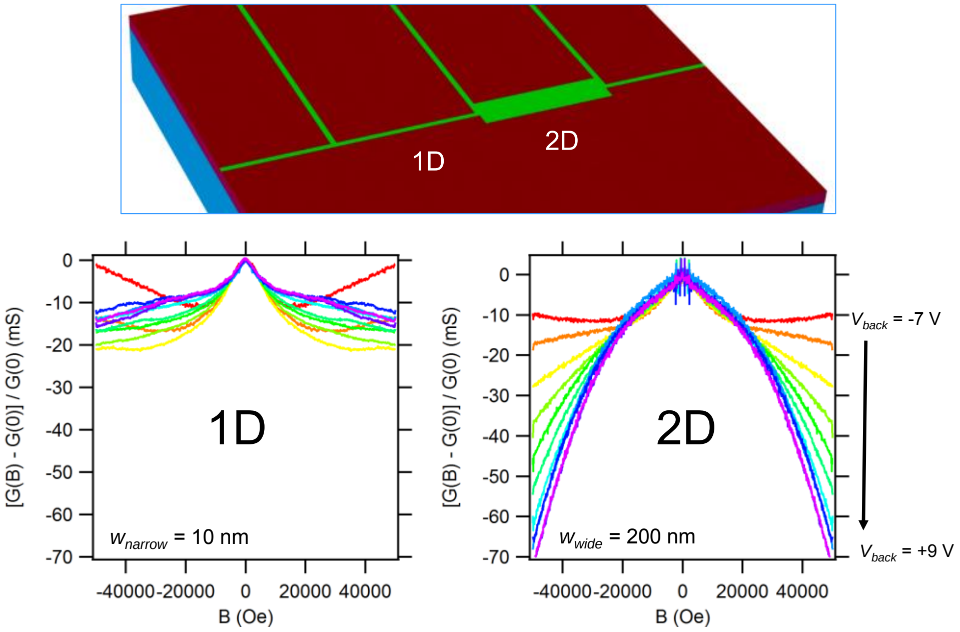
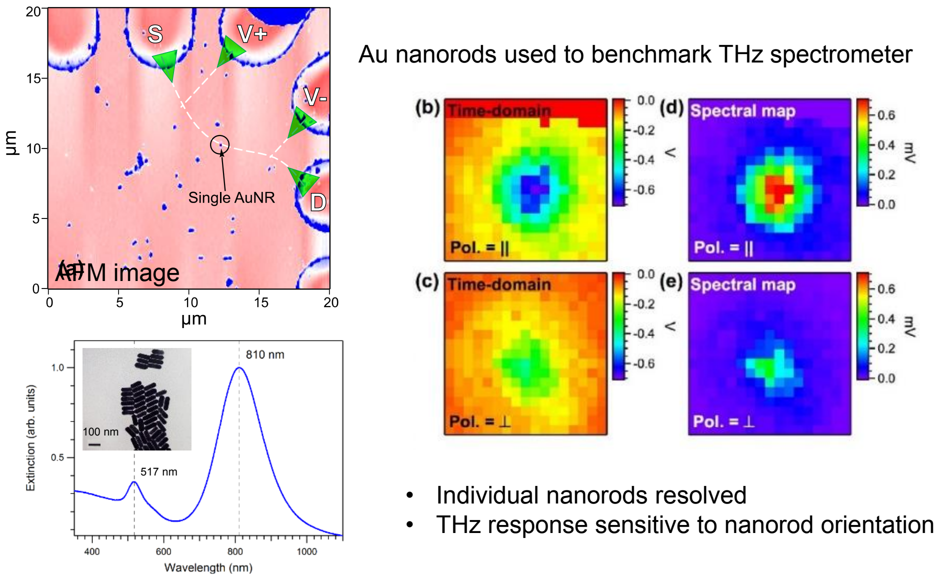


Figure 1. 1D/2D Crossover of Spin-Orbit Coupling in $LaAlO_3/SrTiO_3$ Heterostructures

THz spectroscopy of nanoparticles

We have pursued the development and use of ultrafast optical techniques to probe the interactions of conductive nanostructures at THz frequencies {Jnawali, 2015 #2999}. Figure 2 (top left) shows an AFM image of a LAO/STO canvas on which single Au nanorods (AuNRs) have been dispersed. These nanorods have plasmonic resonances that locally enhance the optical fields excited by near-infrared pulsed laser illumination. In this particular experiment, a single AuNR is identified by AFM and placed as a nanojunction. The full nanowire topology is indicated by white dashed lines, and the green triangular-shaped regions represent areas where electrical contact to interface is maximized. The use of four terminals allows for an enhancement of optically induced electrical signals. The plasmonic resonance for these AuNRs is shown directly below: a 100 nm-wide plasmonic resonance, centered around 810 nm, exists for these structures collectively. Using our time-resolved microscopy technique, we can focus on this single AuNR and measure the photoconductive response as a function of position and polarization. The results are shown in Figure 2(b-e), in which there is significant polarization contrast due to the aspect ratio of the AuNR, and the spectral response shows a similar selectivity. THz spectroscopy can in principle be applied to any molecular-scale object placed on the LAO/STO canvas. Alternately, this technique can be used to probe the far-infrared response of LAO/STO, an energy range that is difficult to access using other techniques but is important for understanding spin-orbit couplings (whose energies are also on a similar scale).


Au nanorods used to benchmark THz spectrometer

- Individual nanorods resolved
- THz response sensitive to nanorod orientation

Figure 2. Platform for molecular-scale THz spectroscopy.

Broadband Terahertz generation and detection at 10 nm scale

Terahertz (0.1–30 THz) radiation reveals a wealth of information that is relevant for material, biological, and medical sciences with applications that span chemical sensing, high-speed electronics, and coherent control of semiconductor quantum bits. We have reported {Irvin, 2013 #1245} both generation and detection of broadband terahertz field from 10 nm scale oxide nanojunctions. Frequency components of ultrafast optical radiation are mixed at these nanojunctions, producing broadband THz emission. These same devices detect THz electric fields with comparable spatial resolution. This unprecedented control, on a scale of 4 orders of magnitude smaller than the diffraction limit, creates a pathway toward THz-bandwidth spectroscopy and control of individual nanoparticles and molecules.

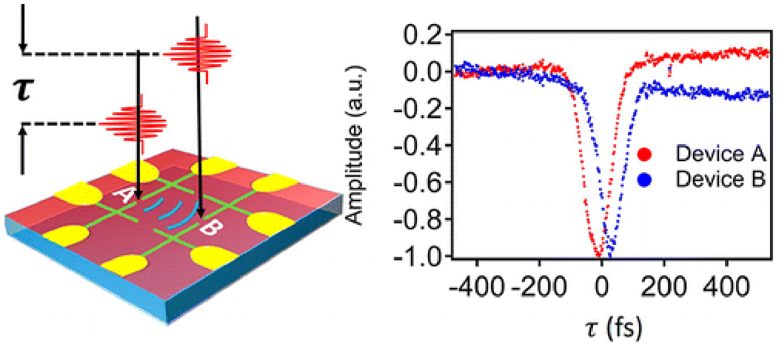
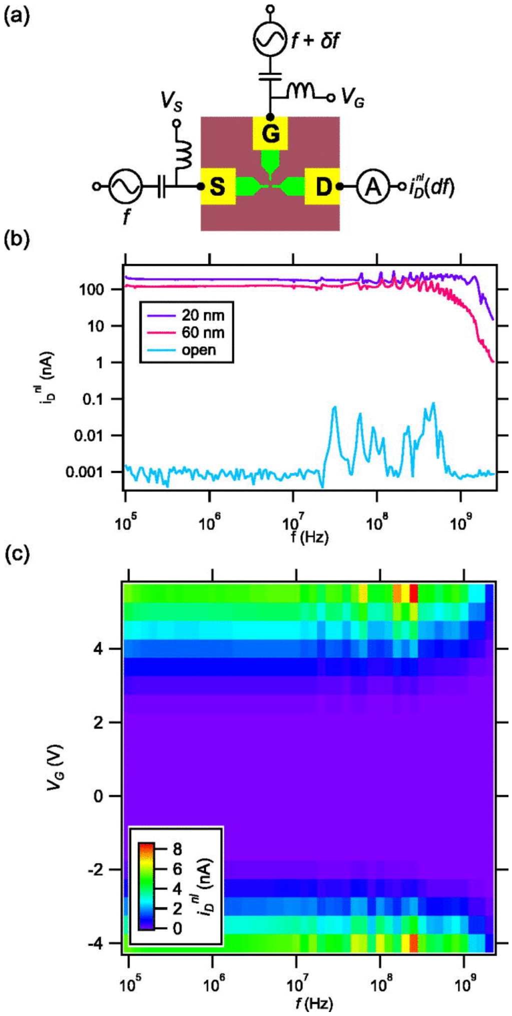


Figure 3. Nanometer-scale generation and detection of broadband THz emission.

Gigahertz-frequency operation of a $LaAlO_3/SrTiO_3$-based nanotransistor



Nanoscale control of the metal-insulator transition of the $LaAlO_3/SrTiO_3$ interface with a conductive-atomic force microscope (c-AFM) technique has enabled a variety of electrical and photonic device concepts. While previous devices have demonstrated sub-10 nm critical features, information processing applications also require high operating speeds. We have shown that a “sketched” nanoscale transistor (“SketchFET”) can operate at frequencies in excess of 2 GHz. The combination of high speed and high conductance with a small footprint make these devices and this platform attractive for sub-10 nm computing and storage architectures.

Figure 4. GHz-frequency operation of SketchFET transistor.

1.

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Abstract

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