

The following reverse chronologically ordered list of **Public RElations BYTEs (PURE BYTEs)** are summaries in 200 words or less describing selected published works in layman's terms using a title that attempts to entice the attention of even the most casual reader. A PURE BYTE is essentially an abstract for a non-technical audience, and like a sound bite, is intended to be brief, catchy and informative.

### **PURE BYTE #11**

Abstract and Title for non-scientific audience\*

#### **Charge density waves make their debut at buried metal/semiconductor interfaces**

Charge density waves (CDWs) in crystalline solids manifest themselves as periodic modulations of conduction electron densities associated with underlying atomic lattice distortions. In this paper we find that in addition to well-known bulk transport and surface sensitive techniques, CDWs can also be detected at planar interfaces between a CDW-harboring metal and common semiconductors such as GaAs. The metal/semiconductor interface (aka Schottky junction) provides an asymmetric barrier to the flow of electrons and is ubiquitous and well understood in semiconductor technology. If a CDW transition occurs in the metal, then the charge distribution and electronic energy levels at the barrier/interface are strongly affected. These CDW phase transitions induce changes in bulk electronic properties which are uniquely manifested at the interface by temperature-dependent energy parameters describing the barrier and which can be easily extracted from electrical measurements. Since interface phenomena are at the heart of most electronic applications, we anticipate that our understanding of asymmetric metal/semiconductor barriers between exotic layered materials (such as the ones studied here) and conventional semiconductors will improve scientific understanding and impact future technological applications of novel heterogeneous interfaces.

\* "Van der Waals Schottky barriers as interface probes of the correlation between chemical potential shifts and charge density wave formation in 1T-TiSe<sub>2</sub> and 2H-NbSe<sub>2</sub>", Ang J. Li, Xiaochen Zhu, Daniel Rhodes, Christopher C. Samouche, Luis Balicas and Arthur F. Hebard, Phys. Rev. B **96**, 125301 (2017).

### **PURE BYTE #10 (Abstract and Title for non-scientific audience)**

Abstract and Title for non-scientific audience\*

#### **Straining to enhance magnetoelectric coupling.**

Magnetoelectric coupling, the induction of electric (magnetic) polarization via magnetic (electric) fields, is important due to both its complex physical origins and potential technological applications. This paper reports on a surprisingly large linear magnetoelectric coupling between magnetic and electric dipoles that are simultaneously present (i.e., multiferroic) in pulse-laser deposited thin films of BiMnO<sub>3</sub>. Our observations are particularly perplexing because bulk crystalline BiMnO<sub>3</sub>, the only transition-metal perovskite oxide that is both strongly ferromagnetic and insulating, has been shown by experiment and theory to be centrosymmetric, thus preserving an intrinsic structural symmetry that does not allow electric dipoles (hence ferroelectricity) to be present. To resolve this question of why multiferroic behavior occurs in thin-film but not bulk BiMnO<sub>3</sub>, we find that substrate-induced strain

together with “hidden” antiferromagnetic ordering of the magnetic dipoles combine to break centrosymmetric symmetry and give rise to ferroelectric behavior with surprisingly large magnetoelectric coupling. Our study based on straightforward thermodynamics opens a new perspective on maximizing the magnetoelectric coefficient in the design of novel multiferroics that increases physical understanding and might eventually have practical application.

\* “Proximate transition temperatures amplify linear magnetoelectric coupling in strain-disordered multiferroic BiMnO<sub>3</sub>” Patrick R. Mickel, Hyoungjeen Jeon, Pradeep Kumar, Amlan Biswas, and Arthur F. Hebard, Phys. Rev. B 93,1342059 (2016).

### **PURE BYTE #9 (based on Editor’s Selection of accompanying article)**

Abstract and title for non-scientific audience\*

#### **Electron motion in antiferromagnets is different than in ferromagnets**

In contrast to ferromagnets in which the magnetic moments of all the atoms/electrons are oriented in the same direction, the magnetic moments of neighboring atoms/electrons in an antiferromagnetic align in opposite directions to cancel the total magnetization. This paper provides an experimental description and theoretical explanation of how disorder affects electronic transport in antiferromagnetic thin films. The authors find a quantum correction to the conductivity which survives to high disorder strength because of a high rate of inelastic scattering of electrons off of gapped antiferromagnetic spin waves. The data provide first-time estimates of the spin-wave energy gap and exchange energy derived solely from transport measurements. The focus on the unexplored effect of antiferromagnetism on electronic transport provides new perspectives on the role of electronic transport and spin alignment in disordered magnetic systems.

\*“Transport measurements of the spin-wave parameters of thin Mn films”, S. Buvaev, S. Ghosh, K. Muttalib, P. Wölfle, and A. Hebard, Phys. Rev. B 90, 214429 (2014).

### **PURE BYTE #8 (based on an APS News release)**

Abstract and title for non-scientific audience\*

#### **Writing Graphene Circuitry with Ion “Pens”**

Silicon carbide (SiC) comprises both silicon and carbon, but at high temperatures (around 1300 degrees Celsius) silicon atoms will vaporize off the surface, leaving the carbon atoms to grow into sheets of pure graphene. Researchers had previously used this thermal decomposition technique to create large sheets of graphene, which were then etched to make the patterns required for devices. The etching process, however, can introduce defects or chemical contaminants that reduce graphene’s prized electron mobility. We have found that implanting silicon or gold ions in SiC lowers the temperature at which graphene forms by approximately 100 degrees Celsius. Thus by using a narrowly focused

ion beam to implant ions only where graphene layers are desired, and then heating the SiC to 1200 degrees Celsius thin lines of graphene with nanoscale dimensions (~20 nm width) have been patterned. Selective graphene growth at even lower temperatures may be possible.

\* “Drawing graphene nanoribbons on SiC by ion implantation”, S. Tongay, M. Lemaitre, J. Fridmann, A.F. Hebard, B.P. Gila, and B.R. Appleton, Applied Physics Letters 100, 073501 (2012).

## **PURE BYTE #7**

Abstract and title for non-scientific audience\*

### **Polymer coating gives graphene solar cells highest efficiency yet**

Graphene and silicon, when they come together, form what is called a Schottky junction — a one-way street for electrons that when illuminated with light, acts as the power conversion zone for an entire class of solar cells. Schottky junctions are commonly formed by layering a metal on top of a semiconductor. In following up on previous work (2010) that graphene, a semi-metal, makes a suitable substitute for metal in creating Schottky junctions, we have over coated the graphene with a transparent polymer (trifluoromethanesulfonyl-amide) film which makes the graphene film more conductive and simultaneously increases the electric field potential inside the cell. These effects combine to give a record-breaking power conversion efficiency approaching 9% for graphene solar cells.

\* “High Efficiency Graphene Solar Cells by Chemical Doping”, Xiaochang Miao, Sefaattin Tongay, Maureen K. Petterson, Kara Berke, Andrew G. Rinzler, Bill R. Appleton and Arthur F. Hebard, *Nano Lett.* 12 (6), 2745–2750 (2012).

## **PURE BYTE #6 (Appears as popular summary to cited paper)**

Abstract and title for non-scientific audience\*

### **Rectification at Graphene-Semiconductor Interfaces: Zero-Gap Semiconductor-Based Diodes**

When a metal and a semiconductor are appropriately chosen and put in contact, their interface behaves as a rectification barrier to electric current—the so-called Schottky barrier that allows a current to flow easily in one direction, but not in the other. This concept is a classical and commonplace one in semiconductor electronics. In contrast, monolayer graphene, a one-atom-thick sheet of carbon atoms arranged in a honeycomb-like lattice, is a very new form of material. Mechanically robust, thermally stable, electrically conducting like a semimetal, and impermeable even to the smallest gas atoms, graphene has become a launch pad for materials engineering and innovative electronics. In this experimental paper, we give the classical concept of metal/semiconductor Schottky barriers a new take by replacing the normal metal with monolayer graphene.

\* “Rectification at Graphene-Semiconductor Interfaces: Zero-Gap Semiconductor Based Diodes”, S. Tongay, M. Lemaitre, X. Miao, B. Gila, B. R. Appleton, and A. F. Hebard, *Phys. Rev. X* 2, 011002 (2012).

## PURE BYTE #5

Abstract and title for non-scientific audience\*

### Quantum tunneling in a nanowire.

In this paper, we reveal that magnetic tunnel junctions form spontaneously in manganite nanowires. A magnetic tunnel junction consists of two closely-spaced magnetic metals separated by a thin insulator. The probability that an electron will quantum mechanically tunnel through the insulator depends on the spin of the tunneling electron and the metal it is tunneling into. The resistance associated with the tunneling electrons thus depends on the spin of the electrons in each metal, and can be controlled by externally applying a magnetic field. This concept is used extensively in modern random access memories where magnetic tunnel junctions are prepared by separately depositing each metal and insulator layer. The manganite  $(\text{La,Pr,Ca})\text{MnO}_3$  naturally breaks up into microscopic insulating and ferromagnetic metallic regions within a certain temperature range. Within this temperature window, alternating insulating and metallic regions self-organize in the nanowires and are essentially microscopic analogs of magnetic tunnel junctions. This experiment reveals an intrinsic phenomenon previously unrecognized in manganites---one that has implications for technological applications if similar effects can be measured at room temperature.

\* “Tunneling magnetoresistance in  $(\text{La,Pr,Ca})\text{MnO}_3$  nanobridges”, G. Singh-Bhalla, A. Biswas and A. F. Hebard, *Phys. Rev.* **B 80**, 144410(2009) (selected as Editor’s choice).

## **PURE BYTE #4**

Abstract and title for non-scientific audience\*

### **Electrons in magnetic films feel their spin at the quantum dance!**

Condensed matter physicists have for a long time been intrigued by the manner in which electrons in metals assume a quantum wave-like character as the temperature is lowered. In this paper we find that the interactions between electrons in thin films of the magnetic metal gadolinium are strongly affected by the presence of their own aligned spins which in turn are responsible for the magnetism. The modified electron-electron interactions localize the electrons, thus compromising their ability to move with ease through the metal as the temperature is lowered. The non-classical quantum corrections to the electrical conductivity arise because electrons, which carry both spin and charge, are schizophrenic - having either particle or wave-like character traits. The quantum character of the electrons enables them to be simultaneously at many places in a dance coordinated by the wave-like character of their spin alignments. The signature linear temperature of the conductivity confirms theoretical predictions and is unique to systems which are both metallic and magnetic with spontaneously aligned spins.

\* “Spin-wave-mediated quantum corrections to the conductivity of thin ferromagnetic films of gadolinium”, Rajiv Misra, Arthur F. Hebard, Khandker A. Muttalib and Peter Wölfle, Physical Review B 79, (2009) (selected as Editor’s choice).

## **PURE BYTE #3**

Abstract and title for non-scientific audience\*

### **Building new walls on a magnetic landscape**

To reduce magnetostatic energy, a ferromagnetic metal such as iron forms domains of aligned spins separated by domain walls. The domain walls are metallic regions, typically one micron in width, which manifest gradual changes in spin orientation to accommodate the transition between misaligned spins of neighboring domains. In ferromagnetic manganites, the domain walls can comprise an insulating phase which coexists with the metallic magnetic phase. Our measurements on sub-micron width manganite constrictions show that these insulating domain walls have record-high resistances and can be as thin as a few atomic layers, thus allowing quantum-mechanical tunneling of spin-aligned electrons between adjacent antiparallel domains.

\* “Intrinsic Tunneling in Phase Separated Manganites”, G. Singh-Bhalla, S. Selcuk, T. Dhakal, A. Biswas, A.F.Hebard, Physical Review Letters **102**, 077205 (2009).

## PURE BYTE #2

Abstract and title for non-scientific audience\*

### **Electrons in ferromagnets invited to the quantum dance!**

Condensed matter physicists have for a long time been intrigued by the manner in which electrons in metals assume a quantum wave-like character as the temperature is lowered. This character trait becomes manifest when electrons remember their travels and interfere with themselves, much like water waves building up in amplitude when suitably channeled. The resulting tendency of the electrons to stay in one place, or equivalently to be “localized”, causes an increase in electrical resistance that has a non-classical quantum origin. This signature quantum resistance is easily observed in ordinary metals but is not expected to be present in magnetic metals (i.e., ferromagnets) such as iron, since intrinsic magnetic fields severely compromise the ability of the electrons to self interfere. Contrary to these expectations, this paper shows that electrons in ferromagnets can behave much like their brethren in ordinary metals and execute a dance in which they revisit their former coordinates and self interfere. In the experiment, atomically thin films of iron are fabricated and then measured at low temperature and high magnetic field without being exposed to harmful air oxidation. Theoretical analysis takes into account electron-electron interactions and explains the observed localization behavior.

\* “Weak localization correction to the anomalous Hall effect in polycrystalline Fe films” , P. Mitra, R. Misra, A.F. Hebard, K. A. Muttalib and P. Woelfle, Phys. Rev. Lett. **99**, 046804 (2007).

## **PURE BYTE #1**

Abstract and title for non-scientific audience\*

### **Anisotropy in thin films: A new direction!**

Conventional electrical measurements of conducting thin films fabricated on insulating substrates are only sensitive to in-plane currents that are forced to flow parallel to the film interfaces. Accordingly, there is a critical lack of information about perpendicular electrical transport in strongly correlated electronic materials, such as manganites and high-Tc superconductors, which have anisotropic (direction-dependent) properties due to atomic layering and/or substrate-induced strain. We show that incorporation of an anisotropic manganite film as the base layer of a three-layer capacitor configuration allows simultaneous measurement of electrical transport in both perpendicular and parallel directions. This unconventional technique advantageously employs the simultaneous measurement of dc resistance to extract the in-plane properties and ac capacitance to extract the out-of-plane properties. The information uncovered confirms separate anisotropic percolation transitions that reflect temperature and magnetic field dependent competition between insulating and metallic magnetic phases of the manganite film. In addition, we find a very striking length scale invariance in the distribution of the insulating and metallic phases.

\* “Colossal magnetocapacitance and scale-invariant dielectric response in phase-separated manganites”, Ryan P. Rairigh, Guneeta Singh-Bhalla, Sefaatin Tongay, Tara Dhakal, Amlan Biswas and Arthur F. Hebard, Nature Physics 3, 551 (2007).