

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 11-12-2012		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Oct-2009 - 30-Sep-2012	
4. TITLE AND SUBTITLE Final Technical Report: Graphene Nanostructures for Novel Spin Magnetic Device Applications			5a. CONTRACT NUMBER W911NF-09-1-0532		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS Ki Wook Kim			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES North Carolina State University Research Administration NC State University Raleigh, NC 27695 -7514			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 56125-EL.18		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT This research project theoretically exploited the unique properties of nanoscale graphene based structures for highly functional spintronic applications at room temperature. To overcome the non-magnetic nature of intrinsic graphene, two promising phenomena were explored that can introduce desired spin magnetic functionalities with electrical control. The first approach incorporates the magnetism by forming a hybrid structure with appropriate magnetic materials. The interactions between graphene electrons and magnetic ions at the interfaces result in					
15. SUBJECT TERMS graphene, topological insulator, magnetoelectric devices, spintronics					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Ki Wook Kim
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 919-515-5229

Report Title

Final Technical Report: Graphene Nanostructures for Novel Spin Magnetic Device Applications

ABSTRACT

This research project theoretically exploited the unique properties of nanoscale graphene based structures for highly functional spintronic applications at room temperature. To overcome the non-magnetic nature of intrinsic graphene, two promising phenomena were explored that can introduce desired spin magnetic functionalities with electrical control. The first approach incorporates the magnetism by forming a hybrid structure with appropriate magnetic materials. The interactions between graphene electrons and magnetic ions at the interfaces result in effective magnetic fields that can affect the characteristics of both graphene and magnetic layers. The second approach introduces the magnetic effects by utilizing non-zero magnetic moments induced at the edge states, defects, vacancies, etc. Both of these effects may be readily amenable for electrical control through the dependence on graphene electronic properties. With the development of appropriate models, the main focus of investigation was to analyze the physical properties and basic functionalization principles, particularly as the dimension of the structure shrinks, and to examine their device potential including spin magnetic switches. As an extension of the original concepts, the research project also examined spin magnetic properties of topological insulators and their potential applications; with strong spin-orbit coupling, this emerging material system with nanoscale 2D electron states offers a new opportunity in a manner analogous to the graphene based hybrid structures.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
-----------------	--------------

- | | | |
|------------|-------|--|
| 08/16/2011 | 2.00 | J. Mullen, K. Borysenko, X. Li, Y. Semenov, J. Zavada, M. Nardelli, K. Kim. Electron-phonon interactions in bilayer graphene, Physical Review B, (04 2011): 0. doi: 10.1103/PhysRevB.83.161402 |
| 08/16/2011 | 7.00 | X. Li, E. A. Barry, J. M. Zavada, M. Buongiorno Nardelli, K. W. Kim. Influence of electron-electron scattering on transport characteristics in monolayer graphene, Applied Physics Letters, (08 2010): 0. doi: 10.1063/1.3483612 |
| 08/16/2011 | 6.00 | Y Chen, T Jayasekera, A Calzolari, K W Kim, M Buongiorno Nardelli. Thermoelectric properties of graphene nanoribbons, junctions and superlattices, Journal of Physics: Condensed Matter, (09 2010): 0. doi: 10.1088/0953-8984/22/37/372202 |
| 08/16/2011 | 3.00 | X. Li, E. A. Barry, J. M. Zavada, M. Buongiorno Nardelli, K. W. Kim. Surface polar phonon dominated electron transport in graphene, Applied Physics Letters, (12 2010): 0. doi: 10.1063/1.3525606 |
| 08/16/2011 | 4.00 | Y. Semenov, J. Zavada, K. Kim. Electron spin relaxation in carbon nanotubes, Physical Review B, (10 2010): 0. doi: 10.1103/PhysRevB.82.155449 |
| 12/11/2012 | 5.00 | V. A. Kochelap, K. W. Kim, V. N. Sokolov. Magnetoconcentration effect in intrinsic graphene ribbons, Applied Physics Letters, (09 2010): 112112. doi: 10.1063/1.3486124 |
| 12/11/2012 | 15.00 | Y. G. Semenov, J. M. Zavada, K. W. Kim. Graphene spin capacitor for magnetic field sensing, Applied Physics Letters, (07 2010): 13106. doi: 10.1063/1.3462297 |
| 12/11/2012 | 14.00 | Yuriy Semenov, Xiaodong Li, Ki Kim. Tunable photogalvanic effect on topological insulator surfaces via proximity interactions, Physical Review B, (11 2012): 201401. doi: 10.1103/PhysRevB.86.201401 |
| 12/11/2012 | 16.00 | Thushari Jayasekera, B. D. Kong, K. W. Kim, M. Buongiorno Nardelli. Band Engineering and Magnetic Doping of Epitaxial Graphene on SiC (0001), Physical Review Letters, (04 2010): 146801. doi: 10.1103/PhysRevLett.104.146801 |
| 12/11/2012 | 17.00 | Y. G. Semenov, J. M. Zavada, K. W. Kim. Electrically controlled magnetic switching based on graphene-magnet composite structures, Journal of Applied Physics, (03 2010): 64507. doi: 10.1063/1.3354066 |
| 12/11/2012 | 8.00 | Y. Semenov, J. Zavada, K. Kim. Weak ferromagnetism of antiferromagnetic domains in graphene with defects, Physical Review B, (10 2011): 165435. doi: 10.1103/PhysRevB.84.165435 |
| 12/11/2012 | 9.00 | K. Borysenko, M. Buongiorno Nardelli, K. Kim, X. Li. Electron transport properties of bilayer graphene, Physical Review B, (11 2011): 195453. doi: 10.1103/PhysRevB.84.195453 |
| 12/11/2012 | 10.00 | X. Li, B. D. Kong, J. M. Zavada, K. W. Kim. Strong substrate effects of Joule heating in graphene electronics, Applied Physics Letters, (12 2011): 233114. doi: 10.1063/1.3668113 |
| 12/11/2012 | 11.00 | M. Buongiorno Nardelli, R. Mao, B. D. Kong, K. W. Kim, T. Jayasekera, A. Calzolari. Phonon engineering in nanostructures: Controlling interfacial thermal resistance in multilayer-graphene/dielectric heterojunctions, Applied Physics Letters, (09 2012): 113111. doi: 10.1063/1.4752437 |
| 12/11/2012 | 12.00 | X. Duan, V. A. Stephanovich, Y. G. Semenov, K. W. Kim. Magnetic domain wall transfer via graphene mediated electrostatic control, Applied Physics Letters, (07 2012): 13103. doi: 10.1063/1.4732794 |

12/11/2012 13.00 Yuriy Semenov, Xiaopeng Duan, Ki Kim. Electrically controlled magnetization in ferromagnet-topological insulator heterostructures, Physical Review B, (10 2012): 161406. doi: 10.1103/PhysRevB.86.161406

TOTAL: 16

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
-----------------	--------------

08/16/2011	1.00	B. D. Kong, Y. G. Semenov, C. M. Krowne, K. W. Kim. Unusual magnetoresistance in a topological insulator with a single ferromagnetic barrier, Applied Physics Letters, (06 2011): 243112. doi: 10.1063/1.3600330
------------	------	--

TOTAL: 1

Number of Papers published in non peer-reviewed journals:

(c) Presentations

E. A. Barry, J. T. Mullen, K. Borysenko, T. Jayasekera, B. Kong, K. W. Kim, and M. Buongiorno Nardelli, "First Principles Analysis of Electron-Phonon Scattering Rates in Graphene and Their Influence on Electronic Transport," presented at the Army Research laboratory Workshop on Graphene Electronics (August, 2009. Adelphi, Maryland).

B. D. Kong, T. Jayasekera, K. W. Kim, and M. Buongiorno Nardelli, "Band Engineering and Magnetic Doping of Epitaxial Graphene on SiC," presented at the March Meeting of the American Physical Society (March, 2010, Portland, Oregon), Bull. Am. Phys. Soc. 55, H22.00005 (2010).

Y. F. Chen, T. Jayasekera, B. D. Kong, K. W. Kim, and M. Buongiorno Nardelli, "Thermal Transport in Graphitic Nanostructures: Analytic Force Constants and First Principles Calculations," presented at the March Meeting of the American Physical Society (March, 2010, Portland, Oregon), Bull. Am. Phys. Soc. 55, P21.00010 (2010).

Y. G. Semenov, J. M. Zavada, K. W. Kim, "Electron Spin Relaxation in Carbon Nanotubes: Dyakonov-Perel Mechanism," presented at the March Meeting of the American Physical Society (March, 2010, Portland, Oregon), Bull. Am. Phys. Soc. 55, V35.00013 (2010).

T. Jayasekera, B. D. Kong, K. W. Kim, and M. Buongiorno Nardelli, "Band Engineering and Magnetic Doping of Epitaxial Graphene on SiC (0001)," presented at 2010 Graphene Week (April, 2010, College Park, Maryland).

E. A. Barry, X. Li, J. M. Zavada, M. Buongiorno Nardelli, and K. W. Kim, "Influence of Electron-Electron Scattering and Substrate Effects on the Transport Properties of Monolayer Graphene," presented at 2010 Graphene Week (April, 2010, College Park, Maryland).

Y. G. Semenov, J. M. Zavada, and K. W. Kim, "Electron Spin Relaxation in Carbon Nanotubes," presented at the Third International World University Network (WUN) Conference on Spintronic Materials and Devices (Urbana, Illinois, June, 2010).

Y. G. Semenov, J. M. Zavada, and K. W. Kim, "Efficient Electron Spin Relaxation via Dyakonov-Perel Type Mechanism in Carbon Nanotubes," presented at the 55th Magnetism and Magnetic Materials Conference (November, 2010, Atlanta, Georgia).

Y. G. Semenov, J. M. Zavada, and K. W. Kim, "Magnetic Correlation in Graphene with Vacancies," presented at the 55th Magnetism and Magnetic Materials Conference (November, 2010, Atlanta, Georgia).

K. M. Borysenko, J. T. Mullen, X. Li, Y. G. Semenov, J. M. Zavada, M. Buongiorno Nardelli, and K. W. Kim, "Electron Transport Properties of Bilayer Graphene," presented at the March Meeting of the American Physical Society (March, 2011, Dallas, Texas), Bull. Am. Phys. Soc. 56, Q37.00010 (2011).

Y. G. Semenov, J. M. Zavada, K. Borysenko, and K. W. Kim, "Effects of Magnetic Correlation of Localized Spins in Graphene," presented at the March Meeting of the American Physical Society (March, 2011, Dallas, Texas), Bull. Am. Phys. Soc. 56, K1.00173 (2011).

T. Jayasekera, S. Xu, K. W. Kim, and M. Buongiorno Nardelli, "Electronic Properties of the Graphene/SiC (000) Interface: a First Principles Study," presented at the March Meeting of the American Physical Society (March, 2011, Dallas, Texas), Bull. Am. Phys. Soc. 56, P36.00001 (2011).

X. Duan, V. A. Stephanovich, Y. G. Semenov, and K. W. Kim, "Currentless Domain Wall Motion along Biased Ferromagnet/Semiconductor Heterostructures," presented at the 56th Magnetism and Magnetic Materials Conference (November, 2011, Scottsdale, Arizona).

Y. G. Semenov and K. W. Kim, "Magnetoelectric Effect in Topological Insulator/Magnetic Layer Nanostructure," presented at the March Meeting of the American Physical Society (March, 2012, Boston, Mass.), Bull. Am. Phys. Soc. 57, V37.00003 (2012).

R. Mao, B. D. Kong, T. Jayasekera, M. Buongiorno Nardelli, "Nanoscale Thermal Transport in Graphene Interfaces," presented at the March Meeting of the American Physical Society (February, 2012, Boston, Mass.), Bull. Am. Phys. Soc. 57, B6.00001 (2012).

X. Duan, V. A. Stephanovich, Y. G. Semenov, H. Fangohr, M. Franchin, and K. W. Kim, "Electric Field Driven Domain Wall Transfer in Hybrid Structures," presented at the 70th Annual Device Research Conference (June, 2012, University Park, Pennsylvania).

Number of Presentations: 16.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received

Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received

Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received

Paper

TOTAL:

Number of Manuscripts:

Books

Received

Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Xiaodong Li	0.15	
Xiaopeng Duan	0.15	
FTE Equivalent:	0.30	
Total Number:	2	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Yuriy Semenov	0.50
FTE Equivalent:	0.50
Total Number:	1

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Ki Wook Kim	0.07	
FTE Equivalent:	0.07	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:.....	0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Scientific Progress and Accomplishments

This research project pursued theoretical understanding of magnetic correlation in both the graphene and the newly emerging topological insulator based structures for potential device applications. Highlights include new device concepts for low-power magnetic switch with all electrical control, electrically modulated domain wall transfer, sensitive room-temperature detection of magnetic fields and THz/far-IR radiation, as well as an unusual giant magnetoresistive effect with a single magnetic barrier.

- We explored electrically controlled magnetic correlation in graphene based composite structures for potential device applications. Prompted by recent studies of the Kondo effect in graphene that illustrated a strong influence of localized spin moments (associated with vacancies) through their interaction with the itinerant electrons, we investigated the role of carrier-impurity exchange interaction in formation of magnetic phase states of graphene with vacancies and modification in graphene-based composite structures. Our theoretical analysis based on a mean field model showed that the electronic free energy in graphene is indeed modified by the exchange interaction with localized spin moments. The calculation further revealed that at low temperatures a phase transition to antiferromagnetic (AF) ordering of the magnetization occurs, which in turn lead to a band gap opening between the conduction and valence bands. The AF phase transfer also has a significant impact on magnetic properties of graphene based composite structures. In a sandwich configuration (i.e., graphene placed in the middle), graphene is found to mediate the exchange bias field between two adjacent ferromagnetic (FM) layers. Accordingly, the exchange bias field can be altered and even reversed by modulating electronic properties of graphene. Our preliminary results thus far demonstrated that a sufficiently large vacancy concentration induces antiparallel alignment of two FM magnetizations, while the direction of the exchange bias field flips at low concentrations favoring parallel alignment. At the same time, it was shown that a high electron density can drastically enhance the strength of the effective magnetic field. As the electron density in graphene can be manipulated electrically, the observed phenomenon may be utilized for electrically controlled magnetization reversal.
- We proposed and theoretically analyzed a new scheme for electrically controlled magnetic domain wall transfer in graphene-ferromagnet composite structures for magnetoelectronic device applications. Unlike the conventional approach based on spin-momentum transfer, the proposed concept takes advantage of the proximity exchange interaction between graphene electrons and magnetic ions in a ferromagnetic layer and the fact that the resulting “effective magnetic field” can be manipulated by merely modulating the electron density in graphene (i.e., no current flow/low power). Figure 1 shows the structure under consideration. It consists of monolayer graphene and a thin ferromagnetic insulator (FMI) on top. Then, two ferromagnetic metallic

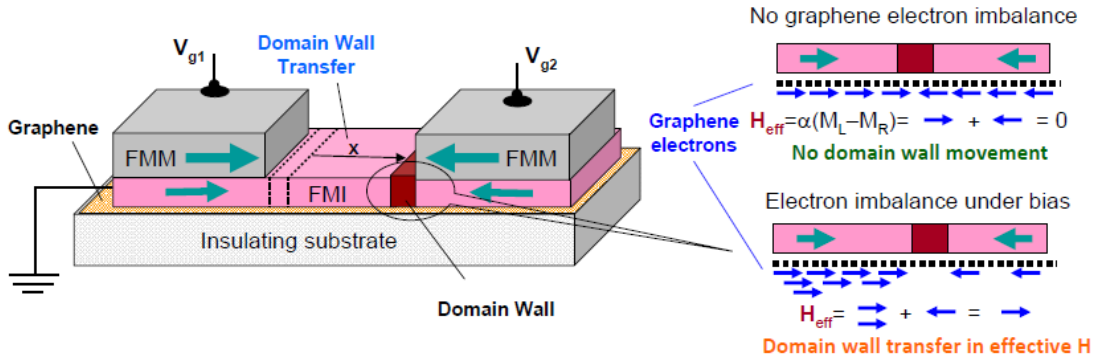


Figure 1: Schematic illustration of domain wall transfer in the proposed graphene-ferromagnet structure. The imbalance in the graphene electron density (thus, net electron spin polarization) can cause an effective magnetic field in the ferromagnetic insulator layer (FMI) in contact via the exchange interaction. Hence, the domain wall can be moved toward the desired direction by controlling the gate biases, V_{g1} and V_{g2} .

(FMM) gates are formed with opposite magnetization directions. Magnetization of the FMI regions (i.e., domains) under the gate is determined by that of the respective FMM. Hence, a domain wall is formed in the middle region. Electrical biases applied to the gate can vary the electronic density in the corresponding area of graphene. At zero (or identical) bias, both magnetic domains (with opposite magnetization) contribute equally to the spin polarization of graphene electrons in the middle region, negating each other. On the other hand, net polarization can be achieved when an imbalance in the electron density occurs (i.e., via uneven gate biases). This nonzero spin polarization acts like an effective magnetic field H_{eff} in the ungated region of FMI, pushing the domain wall in the desired direction. A preliminary estimate shows that H_{eff} of approx. 1000 oe is attainable for the bias of $\mu_L - \mu_R = 200$ meV (between two gated regions in graphene) and the FMI thickness of 1 nm, sufficiently large for realistic application. More detailed calculations are currently under way for accurate evaluation of the performance under realistic device conditions.

- We proposed and theoretically analyzed a graphene-based spin capacitor and its potential application to sensitive magnetic field detection at room temperature. The main characteristic feature of the proposed device is essentially similar to a spin FET using graphene ribbon as the channel but has only one ferromagnetic (FM) terminal (say, source or drain). Thus, it forms a capacitor between the gate and FM S/D contacts, which stores not only the electric charge under an appropriate electrical bias but also spin polarization of those electrons (injected from the FM S/M) and their time evolution. Unlike the electric charge, spin polarization changes as a function of time due to spin precession in a magnetic field and decoherence. As soon as the sign of the gate bias is reversed, the electrons leave the capacitor with rotated and reduced spin polarization which, combined with the fixed magnetization of the FM S/D, can be detected electrically via the terminal current. Since the degree of rotation and decay is determined by the duration of electron spin exposure to the magnetic field as well as the strength and orientation of magnetic field in reference to the injected electron spin polarization, a series of measurements with differing detector orientation and exposure time can determine the strength and direction of the external (i.e., target) magnetic field. The proposed device provides a significant advantage over the schemes based on transient two-terminal measurement as the output signal is immune from the spin dephasing originating from the dispersion in transit time. Assuming the frequency measurement error of the order of a few per cent and the electron spin relaxation time of 100 ns at 300 K (a conservative choice), this device is capable of detecting magnetic fields in the 10 mOe (i.e., 0.01 Oe) range at the ambient temperature without involving any cooling or special equipment.
- We investigated transverse redistributions of the electrons and holes in intrinsic graphene ribbons under the influence of crossed electric and magnetic fields, i.e., the magnetoconcentration effect. Specifically, we examined a monolayer graphene ribbon in the xy plane confined by the width W in the y direction; the electric $\mathbf{E}$ and magnetic $\mathbf{H}$ fields were applied along the x and z axes, respectively. The magnetic field was considered to be classically strong, i.e., it does not lead to the formation of Landau levels. When the ribbon width exceeds the electron hole de Broglie wavelength, quantization of the electron and hole energy spectrum is not essential and can be disregarded. The ribbon length in the x direction was assumed to provide the longest dimension allowing a 1D treatment of the problem, with the inhomogeneity along the y axis. The nonequilibrium inhomogeneous redistribution of carriers under the influence of the fields was obtained by solving the Boltzmann kinetic equation within the local quasiequilibrium approximation. The calculation illustrates that an effective control of the carriers can be achieved from deep depletion to accumulation modes depending on the properties of the ribbon edges, provided electron-hole recombination/generation rates at the edges are different from those inside the ribbon. The current-voltage characteristics reflect the behavior of the carrier redistributions across the ribbon. Accordingly, interesting effects such as population inversion (accumulation

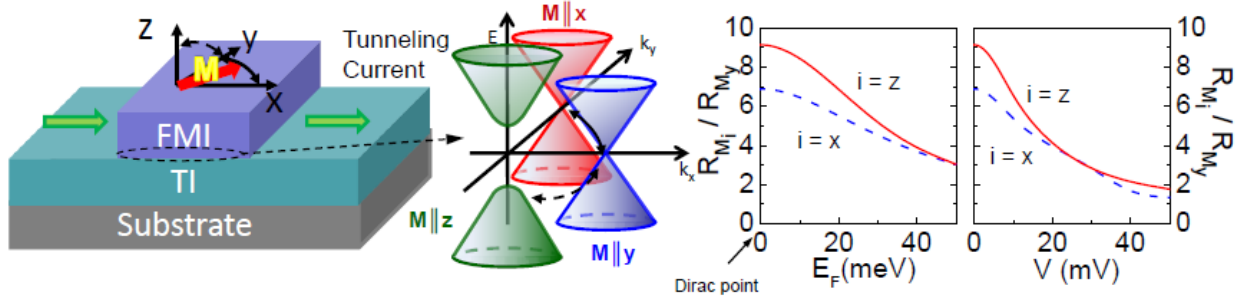


Figure 2: (Left) Schematic illustration of the proposed TI/FMI system. (Middle) Rotation of the magnetization direction around the x ($\mathbf{M}||y \leftrightarrow \mathbf{M}||z$) or the z ($\mathbf{M}||y \leftrightarrow \mathbf{M}||x$) axes leads to modification in the bandstructure of the TI surface states (i.e., the tunneling barrier). (Right) Relative ratio of surface resistance as a function of Fermi energy and gate bias when the magnetization rotates 90° ($\mathbf{M}||y \rightarrow \mathbf{M}||\{x,z\}$). The solid lines represent the values of $R_{M||z}/R_{M||y}$, while the dashed lines show those of $R_{M||x}/R_{M||y}$. A 30-nm FMI strip is considered at room temperature along with the exchange energy of 40 meV at the TI/FMI interface. Apparently, the surface channel resistance can change by nearly an order of magnitude through magnetization rotation.

mode) and induced transparency (depletion mode) may be achieved with potential implication to THz device applications.

- We extended the investigation of the proximity exchange interaction with ferromagnetic materials to another 2D electronic system, namely the surface states of a 3D topological insulator (TI). One crucial property of TIs is the very strong spin-orbit coupling that leads to the intimately intertwined magnetic interactions and electron orbital motions. Consequently, the focus was to exploit the feasibility of current control via spin magnetic effects. The test structure has a single FMI layer of finite width placed on a TI, whose magnetization orientation can be varied in reference to the incident current (see Fig. 2). Accordingly, the FMI layer in this design was envisioned to play the role of a tunnel barrier with a controlling knob (analogous to the gate). A theoretical analysis based on a tight-binding effective Hamiltonian demonstrated that a single ferromagnetic barrier with variable magnetization can indeed modulate the electrical current on the surface of a TI. Numerical estimates suggest that the channel resistance change of a few hundred percent may be achieved even at room temperature in the ballistic tunnel transport regime. The key condition is sufficient exchange coupling at the TI/FMI interface (> 20 meV), which appears practically attainable in the current technology. The induced change in the channel resistance as a function of the magnetization direction is expected to find realistic applications in both memory and logic devices.
- We applied the magneto-electric phenomena of TI surface states to the prediction/discovery of a linear photo-galvanic effect (PGE) at the TI/FMI interface [Fig. 3(a)]. Theoretical analysis indicates that dc flow of photo-excited carriers can be achieved by asymmetric TI surface band distortion under the influence of both symmetry-breaking proximate exchange interaction and spin-independent parabolicity of the dispersion law [Fig. 3(b,c)]. Subsequent momentum-space imbalance in the generation of electron/hole pairs (with opposite group velocities) results in net photocurrent whose direction is also controlled by the chemical potential. The proposed PGE correlates with light absorption in a wide frequency range (from a few meV to hundreds of meV) and possesses a pronounced resonant response to the photon energy about two times the TI chemical potential shift from the Dirac point – thus, tunable by an electrical gate bias (Fig. 4). Moreover, it is invariant to the sign of light circular polarization (i.e., no polarized radiation necessary). The exceptionally strong peak photocurrent of the order of tens of $\mu\text{A}/\text{cm}$ may be achieved with the illumination power of $1 \text{ W}/\text{cm}^2$ in the THz range (estimate based on Bi_2Se_3 ; see Fig. 4). The proposed TI/FMI structures may have significant advantages over the conventional devices in the detection of long-wavelength photons beyond the thermal noise limit.

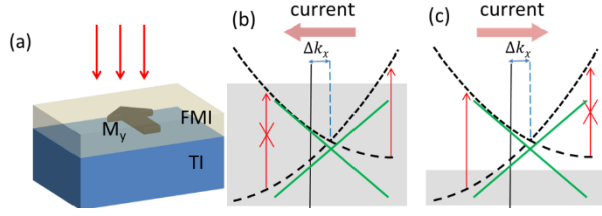


Figure 3: Schematic illustration of proposed PGE. (a) TI/FMI hybrid structure. The red arrows indicate the incident IR radiation; the block arrow denotes the magnetization direction. (b,c) Photocurrent generation in n-type and p-type TIs, respectively. The solid lines illustrate only the proximity effect on the TI surface band structure (i.e., the displacement of Δk_x). The dashed lines show the same bands when the quadratic term is also included. The shaded area denotes the filled electronic states.

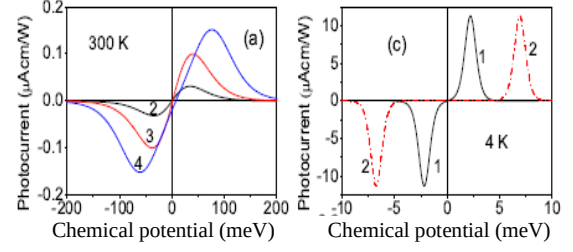


Figure 4: Photocurrent density calculated at (a) 300 K and (c) 4 K versus the chemical potential with different excitation energies: 4.4 meV, 13.7 meV, 50 meV, and 135 meV for curves 1, 2, 3 and 4, respectively. All calculations assume the relaxation time of 1 ps and the proximate exchange energy of 40 meV along with material parameters of Bi_2Se_3 .