ROUTING AND ACTION

MEMORANDUM

ROUTING

TO:(1) Electronics Division (Qiu, Joe)

Report is available for review

(2) Proposal Files Report No.: -II Proposal Number: 66414-EL-II.3

DESCRIPTION OF MATERIAL

CONTRACT OR GRANT NUMBER: W911NF-14-1-0572

INSTITUTION: Purdue University

PRINCIPAL INVESTIGATOR: Peide Ye

TYPE REPORT: Final Report

DATE RECEIVED: 11/19/15 4:59PM

PERIOD COVERED: 9/1/14 12:00AM through 5/31/15 12:00AM

TITLE: Final Report: Ballistic Phosphorene Transistor

ACTION TAKEN BY DIVISION

(x) Report has been reviewed for technical sufficiency and IS [x] IS NOT [ ] satisfactory.

(x) Material has been given an OPSEC review and it has been determined to be non sensitive and, except for manuscripts and progress reports, suitable for public release.

(x) Perfomance of the research effort was accomplished in a satisfactory manner and all other technical requirements have been fulfilled.

(x) Based upon my knowledge of the research project, I agree with the patent information disclosed.

Approved by SSL\JOE.QIU on 2/1/16 11:15AM

ARO FORM 36-E

REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
19-11-2015	Final Report	1-Sep-2014 - 31-May-2015

4. TITLE AND SUBTITLE
Final Report: Ballistic Phosphorene Transistor

5a. CONTRACT NUMBER
W911NF-14-1-0572

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Peide Ye

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Purdue University
Sponsored Program Services
155 S. Grant Street
West Lafayette, IN 47907 -2114

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)
66414-EL-II.3

12. DISTRIBUTION AVAILIBILITY 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 contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
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15. SUBJECT TERMS
Black Phosphorus, Phosphorene, FET

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Peide Ye
					19b. TELEPHONE NUMBER
					765-494-7611

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Ballistic Phosphorene Transistor

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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>

TOTAL:

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>

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

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
11/19/2015	1.00	Yexin Deng, Nathan J. Conrad, Zhe Luo, Han Liu, Xianfan Xu, Peide D. Ye. Towards High-Performance Two-Dimensional Black Phosphorus Optoelectronic Devices: the Role of Metal Contacts, IEDM[object Object] (12 2014)
11/19/2015	2.00	Han Liu, Yuchen Du, Yexin Deng and Peide D. Ye. Semiconducting black phosphorus: synthesis, transport properties and electronic applications, Chemical Society Review (07 2014)

TOTAL: **2**

Number of Manuscripts:

Books

Received   Book

TOTAL:

Received   Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yexin Deng	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Peide Ye	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Adam Charnas	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

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: 1.00

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:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

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

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This is the final report for ARO Grant No. W911NF-14-1-0572 entitled “Ballistic Phosphorene Transistor” as a STIP award for the period 09/1/2014 through 5/31/2015. The ARO program director responsible for the grant is Dr. Joe Qiu. The PI is Prof. Peide Ye of Purdue University. The objective of this project is to explore phosphorene, a name we coined for a 2D atomic layer of black phosphorus (BP), which, unlike graphene, can have an inherent and direct bandgap on the order of 1 eV and, unlike MoS2 or other transition-metal dichalcogenides (TMDs) with strong d-orbital coupling, can have carrier mobility on the order of 104 cm2/Vs. Thus, phosphorene can potentially overcome the challenges of all other 2D materials for ultra-scaled thin-body low-power transistor applications thereby transforming the electronics industry. Even more, phosphorene and few-layer phosphorene has very unique anisotropic transport properties which we have also first explored in transport. [1,2] In FY15, Professor Ye’s team investigated unique transport property and explore its potential applications in field-effect transistor at ballistic limit down to 15 nm channel region. His team studied the channel length scaling of ultra-thin phosphorene field-effect transistors (FETs), and discuss a scheme for using various contact metals to change transistor characteristics. Through studying transistor behaviors with various channel lengths, the contact resistance can be extracted from the transfer length method (TLM). With different contact metals, we find out that the metal/BP interface has different Schottky barrier, leading to a significant difference in contact resistance, which is quite different from previous studies of transition metal dichalcogenides (TMDs) such as MoS2 where Fermi-level is strongly pinned near conduction band edge at metal/MoS2 interface. The nature of BP transistors are Schottky barrier FETs, where the on and off states are controlled by tuning the Schottky barriers at the two contacts. His team also observed the ambipolar characteristics of BP transistors with enhanced n-type drain current and demonstrate that the p-type carriers can be easily shifted to n-type or vice versus by controlling the gate bias and drain bias as illustrated in Figure 1, showing the potential to realize BP CMOS logic circuits.[2] Due to the dominant contact resistance, the drain current of BP FETs doesn’t increase dramatically even with channel length down to 15nm. His team is working toward to develop an effective doping scheme on BP and phosphorene to significantly reduce the contact resistance and realize low-resistive ohmic contact ballistic transistors on BP and phosphorene.

During this project, we have presented our research results in top 2D conferences and also published in top nanoelectronics journals as listed following.
Invited Conference Presentations:

1. Peide Ye, “Graphene and other 2D materials for high frequency devices,” IEEE MTT-S IMS2014 (International Microwave Symposium), Tampa Bay, USA, June 1-6, 2014.

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8. Peide Ye, “Device Technology at 7nm and Beyond,” 2014 IEEE International Electron Devices Meeting (IEDM 2014), San Francisco, USA, December 15-17, 2014. (Short Course)

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2. Yexin Deng, Zhe Luo, Nathan J. Conrad, Han Liu, Yongji Gong, Sina Najmaei, Pulickel M. Ajayan, Jun Lou, Xianfan Xu and Peide D. Ye, Black Phosphorus-Monolayer MoS2 van der Waals Heterojunction p-n Diode, ACS Nano Vol. 8, No. 8, 8292-8299, 2014.

3. Yuchen Du, Lingming Yang, Han Liu, and Peide D. Ye, Contact research strategy for emerging molybdenum disulfide and other two-dimensional field-effect transistors, APL Materials 2, 092510, 2104.

4. Yuchen Du, Han Liu, Yexin Deng, and Peide D. Ye, Device Perspective for Black Phosphorus Field-Effect Transistors: Contact Resistance, Ambipolar Behavior, and Scaling, ACS Nano Vol.8, No.10, 10035-10042, 2014.

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Technology Transfer

Ballistic Phosphorene Transistor

Professor Peide D. Ye, Purdue University, STIP Award

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[1] H. Liu, A. T. Neal, Z. Zhu, D. Tomanek, and P. D. Ye, ACS Nano **8**, 4033-4041, 2014.
[2] Z. Luo, J. Massen, Y. Deng, Y. Du, R. Garrelts, M.S. Lundstrom, P.D. Ye, X. Xu, Nature Comm. 2015 DI:10.1038/ncomms9572
[3] Y. Du, H. Liu, Y. Deng, and P.D. Ye, ACS Nano **8**, 10035-10042, 2014.

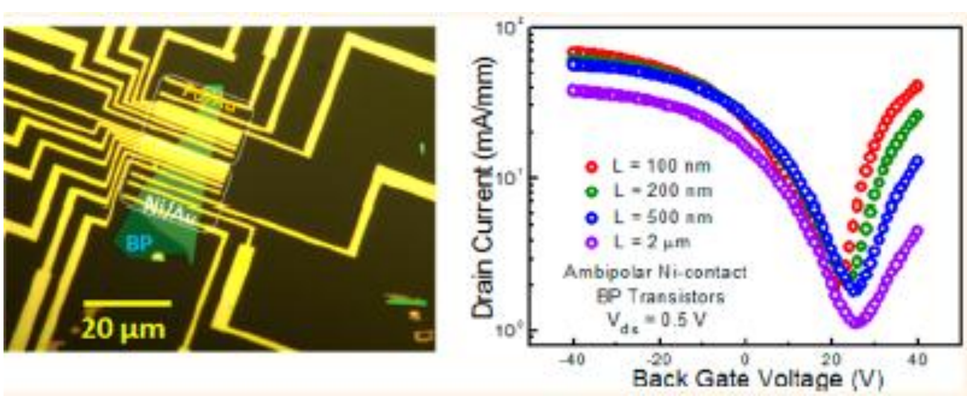

Figure 1: (left) Optical image of the ultra-thin BP FETs with Ni/Au and Pd/Au contacts on the same BP flake. (right) *I-V* transfer characteristic of Ni contact BP FETs with channel length from 2 μm to 100 nm.

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5. Han Liu, Yuchen Du, Yexin Deng, and Peide D. Ye, Semiconducting Black Phosphorus: Synthesis, Transport Properties and Electronic Applications, Chemical Society Review 2015, 44, 2732, DOI:10.1039/c4cs00257a