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

Report is available for review

(2) Proposal Files   Report No.:   -II

Proposal Number: 66414-EL-II.3

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) Performance 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
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 10^4 cm^2/Vs. Thus, phosphorene can potentially...
Final Report: Ballistic Phosphorene Transistor

ABSTRACT

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 versa 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.

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)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

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

Received Paper

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 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)

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Patents Submitted

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### Names of Faculty Supported

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**FTE Equivalent:** 0.05

**Total Number:** 1

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### 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

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**FTE Equivalent:**

**Total Number:**

**Sub Contractors (DD882):**
Scientific Progress
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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:


Conference Presentations:


Journal Publications:


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.


Ballistic Phosphorene Transistor
Professor Peide D. Ye, Purdue University, STIP Award

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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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