AFRL-OSR-VA-TR-2014-0118

EPITAXIAL GRAPHENE QUANTUM ELECTRONICS

Walter De Heer
GEORGIA TECH RESEARCH CORPORATION

05/19/2014
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
11-5-2014	Final	01-JUL-2010 to 31-DEC-2013

4. TITLE AND SUBTITLE
Epitaxial Graphene Quantum Electronics

5a. CONTRACT NUMBER
FA9550-10-1-0367

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Walter A. de Heer

5d. PROJECT NUMBER
4106C15

5e. TASK NUMBER

5f. WORK UNIT NUMBER
NA

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
School of Physics, Georgia Institute of Technology. Atlanta GA 30332-0430

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RES/AFOSR/ARLINGTON, VA

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Under the NSSEFF grant, we have accomplished several of the most important experimental results in graphene to date. The epitaxial graphene route that we have pursued since 2001 has fully lived up to its expectations. As we stated in our original proposal, we hoped to duplicate the transport properties that we had observed in carbon nanotubes, 15 years ago, in graphene. In the past three years, we have achieved close to all that we proposed and more.
*We have discovered nanotube-like ballistic transport in graphene nanoribbons
* We demonstrated a novel form or transport in these ribbons, involving a single channel and we possibly may have discovered non-conventional, short-lived charge carriers (trions).
* We demonstrated one-dimensional ferromagnetism with spintronics potential.
* We have achieved the highest operational frequency in graphene transistors.

15. SUBJECT TERMS

Epitaxial graphene; quantum transport; nanoelectronics.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		3	Walter A de Heer
					19b. TELEPHONE NUMBER *(include area code)* 404 894 7880

National Security Science and Engineering Fellowship (NSSEFF)
Supported by the National Defense Education Program (NDEP)
Report – Activity through December 2013

NAME: **Walt A. de Heer** **START DATE**:July 1 2010

TITLE: Professor of Physics **END DATE:**Dec 31 2014

INSTITUTION: Georgia Institute of Technology

PROJECT TITLE: NDEP/NSSEFF - Epitaxial Graphene Quantum Electronics

Please include a current copy of your vitae with your report.

1. Peer-reviewed publications

a. In preparation	2	c. Submitted	3
b. Accepted		d. published	48

Presentations

DoD-related

a. DoD research audiences
b. General DoD audiences/events 4

Conferences/Meetings

a. Local/regional audiences	Total:	Invited:
b. National meetings	Total:13	Invited:13
c. International meetings	Total:9	Invited:9

3. Researchers supported

a. Undergraduate students 3
b. Graduate students 4
c. Post-docs 1

4. Patents

a. Filed 3
b. Received 0

5. Subsequent Funding

Have you applied for additional research funds as a result of the work you have done on your NSSEFF grant? If so, please indicate to where you made your application, the amount requested, and the status of each funding request. Add lines as needed.

Source	Amount Requested	Current Status (3/2014)
MRSEC	100 k/year	Sept 2009 –Sept. 2014
AFOSR (this grant)	300 k/year	Jul 2010 to Dec. 2013
AFOSR (renewal grant)	200 k/year	Sept. 2013-Sept. 2016
Pre-proposal to Moore Foundation	300 k/year	Requested Jan 2015-Jan. 2019
Super Seed /Michigan MRSEC	100 k/year	Requested Sept. 2014-Sept. 2017

.

For the following questions, please use as much space as necessary to answer each item. As appropriate, bullet lists are sufficient.

6. Since the start of your NSSEFF grant, what interactions have you had with the Department of Defense? *(i.e., visiting DoD facilities, collaborating with DoD, and/or bringing DoD personnel to campus or other events, etc.)* Interactions have been limited to annual AFOSR contractor meetings.

7. Since the start of your NSSEFF grant what new discoveries have you had and how might these be connected to issues that the general U.S. public might be concerned with? Please list bullet points for a general –non-scientific –audience.

Our research focuses on a new form of electronics based on graphene. This innovative direction has been pursued by my group since 2001 predating all other graphene work world wide. Graphene based electronics is now seen as one of the most promising new directions in electronics research.

*Our most important discovery is the observation of essentially resistanceless graphene "wires" that are patterned on silicon carbide. (Silicon carbide is an electronic material that has been pioneered by AFORS researcher for over 2 decades.) This discovery will fundamentally impact both graphene electronics as well as basic science. The paper has been published in Nature in Feb. 2014. In more technical terms We have discovered single channel ballistic transport in graphene nanoribbons including a variety of new phenomena. Resistances are found to be below 1 Ohm per square, 1000 times smaller than in conventional graphene. We further have discovered that ballistic channel is spin polarized and a one-dimensional ferromagnet. This is an important discovery with implications for spintronics.

* We have found that ballistic transport most likely involves non-conventional charge carriers with finite life times. We speculate that the charge carriers are not electrons, but rather particles that are composed of several electrons and holes. This extremely interesting new avenue is now under investigation and is expected to have important consequences in the realm of transport in neutral graphene.

* We have discovered essentially reflectionless tunneling across physical nanogaps cut across graphene nanoribbons. This manifestation of Klein tunneling is observed even at room temperature and will facilitate so-called ultrathin body field effect transistors, to be the at the heart of a promising ultrahigh frequency technology for digital applications. This is work in progress.s

*We have found a new form of semiconducting graphene (also on silicon carbide), consisting of a graphene layer that is covalently bonded to the silicon terminated face of silicon carbide. While this so-called buffer layer was known, its semiconducting properties were not exploited (or realized). We have produced field effect devices that use this material as the semiconductor, thereby making an important inroad to all graphene digital electronics. This work is still in progress.

.

8. Awards and honors since receiving the NSSEFF grant. Please indicate the year in which each award/honor was bestowed.

1. MRS medal for pioneering research in graphene electronics (2010)

2. Utz--Hellmuth Felcht Award for the invention of graphene based electronics (2011)

3. J. W . Beams Award for achievements in Physics (2012)

9. To what extent has the NSSEFF grant enabled DOMESTIC collaborations, discovery, innovation, new experiences, sabbaticals, and/or other professional development?

My NSSEFF grant (330 k/year for 3 years) has enabled fundamental research that has greatly contributed to the important discoveries listed above. The funding was used to support students, purchase materials and supplies, and to travel in order to present the results at national and international meetings. Undergraduate, graduate and postdoctoral students have benefitted immensely from the experience of participating in world-class pioneering research. Our most recent research is showing that epitaxial graphene nanoelectronics may be realized relatively soon. We hope to demonstrate extreme frequency transistors in the near future.

10. To what extent has the NSSEFF grant enabled INTERNATIONAL collaborations, discovery, innovation, new experiences, sabbaticals, and/or other professional development?

Some funding has been used for participation in international meetings. Several international collaborations, primarily with researchers in France (CNRS Grenoble and the Soleil synchrotron facility in Paris). Some funding was also used to support the international STEG conference series (Science and Technology of Epitaxial Graphene) that is organized by me and Dr. Claire Berger (scientific researcher in my group)

11. Photos – please submit a recent photo of yourself and, if possible, of your research group. Also, submit graphics related to your work funded by NSSEFF that are appropriate for general audiences.

(See PPT files)

12. Link to your lab's webpage: http://www.graphene.gatech.edu/

.