REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
09-01-2015	Final Report	1-Oct-2011 - 30-Sep-2014

4. TITLE AND SUBTITLE
Final Report: Flexoelectricity in PZT Nanoribbons and Biomembranes

5a. CONTRACT NUMBER
W911NF-11-1-0494

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Prashant K Purohit

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Pennsylvania
Office of Research Services
3451 Walnut Street, Suite P-221
Philadelphia, PA 19104 -6205

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)
60735-EG.9

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
The objective of this grant was to study flexoelectric phenomena in solids and in biomembranes. Over a three year period funds from this grant were used to accomplish several projects that form a large part of the PhD thesis of Mr. Sheng Mao. In the first project we formulated the governing equations for a flexolelectric solid undergoing small deformations. These governing equations were used to solve for the stress, displacement and polarization fields in

15. SUBJECT TERMS
flexoelectricity, biomembranes, defects, fluctuations

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			PRASHANT PUROHIT
UU	UU	UU	UU		19b. TELEPHONE NUMBER 215-898-3870

Report Title

Final Report: Flexoelectricity in PZT Nanoribbons and Biomembranes

ABSTRACT

The objective of this grant was to study flexoelectric phenomena in solids and in biomembranes. Over a three year period funds from this grant were used to accomplish several projects that form a large part of the PhD thesis of Mr. Sheng Mao. In the first project we formulated the governing equations for a flexolelectric solid undergoing small deformations. These governing equations were used to solve for the stress, displacement and polarization fields in several one and two-dimensional electromechanical problems. A key highlight of this paper was a flexoelectric reciprocal theorem. We used the formulation in this paper to solve for the electrical and mechanical fields around point defects,dislocations and cracks in flexoelectric solids. We confirmed the important roleof flexoelectricity in the immediate vicinity of defects due to the existence of large strain gradients. A key highlight of this paper was that we showed thatflexoelectricity is the most likely mechanism behind electromagnetic radiationfrom moving dislocations and cracks in ice. We also collaborated with Michael McAlpine in Princeton on several projects. We studied the electromechanical response of neuronal cells, energy harvesting using pyro-para-electricity and a new way of producing PZT nanoribbons for energy harvesters.

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
08/20/2014	1.00	Tal Kramer, Thanh D. Nguyen, Nikhil Deshmukh, Prashant K. Purohit, Michael J. Berry, Michael C. McAlpine, John M. Nagarah. Piezoelectric nanoribbons for monitoring cellular deformations, Nature Nanotechnology, (09 2012): 587. doi: 10.1038/nnano.2012.112
TOTAL:	**1**	

Number of Papers published in peer-reviewed journals:

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

Received		Paper
01/09/2015	7.00	Huai-an Chin, Sheng Mao, Chiao-Ti Huang, Kwaku K. Ohemeng, Sigurd Wagner, Prashant Purohit, Michael McAlpine. Pyro-paraelectricity, Extreme Mechanics Letters, (01 2015): 0. doi:
01/09/2015	8.00	Thanh Nguyen, Sheng Mao, Yao-Wen Yeh, Prashant Purohit, Michael McAlpine. Nanoscale flexoelectricity, ADVANCED MATERIALS, (02 2013): 946. doi:
TOTAL:	**2**	

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 10.00

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
08/20/2014	4.00	Prashant_Purohit. Tension dependent growth and retraction of neurites, IUTAM symposium on soft active materials. 15-MAY-14, . : ,
TOTAL:	**1**	

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

(d) Manuscripts

Received		Paper
01/09/2015	6.00	Prashant Purohit, Sheng Mao. Defects in flexoelectric solids, Journal of the Mechanics and Physics of Solids (11 2014)
08/20/2014	2.00	Sheng_Mao, Prashant_Purohit. Insights into flexoelectric solids from strain gradient elasticity, Journal of Applied Mechanics (03 2014)
08/20/2014	3.00	Kellye_Cung, Booyeon_Han, Thanh_Nguyen, Sheng_Mao, Yao-Wen_Yeh, Shiyou_Xu, Rajesh_Naik, Gerald_Poirier, Nan_Yao, Prashant_Purohit, Michael_McAlpine. Biotemplated synthesis of PZT nanowires, Nano Letters (11 2013)
08/20/2014	5.00	Thanh_Nguyen, Ian_Hogue, Kellye_Cung, Prashant_Purohit, Michael_McAlpine. Tension induced neurite growth in microfluidic channels, Lab on a Chip (07 2013)
TOTAL:	**4**	

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Sheng Mao	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
Prashant K Purohit	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
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

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

The objective of this grant was to study flexoelectric phenomena in solids and in biomembranes. Over a three year period funds from this grant were used to accomplish several projects that form a large part of the PhD thesis of Mr. Sheng Mao. In the first project we formulated the governing equations for a flexolelectric solid undergoing small deformations. These governing equations were used to solve for the stress, displacement and polarization fields in several one and two-dimensional electromechanical problems. A key highlight of this paper was a flexoelectric reciprocal theorem. We used the formulation in this paper to solve for the electrical and mechanical fields around point defects, dislocations and cracks in flexoelectric solids. We confirmed the important role of flexoelectricity in the immediate vicinity of defects due to the existence of large strain gradients. As a highlight of this paper we showed that flexoelectricity is the most likely mechanism behind electromagnetic radiation from moving dislocations and cracks in ice.

Funds from this grant also supported our collaboration with Michael McAlpine at Princeton University. We collaborated on several projects. In the first project we studied the electromechanical response of neurons. We showed that changing the potential difference across the neuronal membrane causes mechanical deformations that can be detected by PZT nanoribbons. In a second project we studied the force dependent growth of neurons in micro-fluidic channels. We wrote a model based on the polymerization of microtubules that could accurately capture the force dependent growth of the neuron. In a third project we showed how bio-templated PZT nanowires could be used to produce currents when subjected to cyclic deformations. Our contribution to this paper was an electromechanical model describing the current generation. In a fourth collaboration we showed that when a BST thin film is subjected to cyclic temperature changes then it can produce current due to flexo-electricity. Our contribution to this paper was to write a model for the coupling of the large strain gradient in the thin films to the charge separation accross it, and an analysis of the convective, conductive and radiateive heat transfer that causes the transient heating and cooling of the film resulting in the flow of electrical charges. We also wrote a review paper in Advanced Materials summarizing nanoscale flexoelectricity.

Technology Transfer