Multiscale Modeling and Process Optimization For Engineered Microstructural Complexity

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13. ABSTRACT
This reports on the results of the MURI project on Engineering Microstructural Complexity in Ferroelectric Devices.
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Papers published: Peer Reviewed Journals

1. V. Gavini, J. Knap, K. Bhattacharya and M. Ortiz.
   Non-Periodic Finite-Element Formulation of Orbital-Free Density Functional Theory. 

2. V. Gavini, K. Bhattacharya and M. Ortiz.

   A real-space non-local phase-field model of ferroelectric domain patterns in complex geometries. 

   Anharmonic lattice statics analysis of 180° and 90° ferroelectric domain walls in PbTiO3.

5. A. Yavari, M. Ortiz and K. Bhattacharya.
   A theory of anharmonic lattice statics for the analysis of defective crystals. 

   A model for large electrostrictive actuation in ferroelectric crystals. 

7. Y. Xiao and K. Bhattacharya.
   A continuum theory of deformable semiconducting ferroelectrics. 

8. I. Arias, S. Serebrinsky, M. Ortiz
   Cohesive model of electromechanical fatigue for ferroelectric materials and structures 

9. Q.S. Zhang, T. Cagin and W.A. Goddard, III, 
   The ferroelectric and cubic Phases in BaTiO3 ferroelectrics are also antiferroelectric, 

10. Q.S. Zhang and W. A. Goddard, III, 
   Charge and Polarization Distributions at the 90º Domain Wall in Barium Titanate
Plasmon Assisted Chemical Vapor Deposition, 

Characterization and microstructure of highly preferred oriented lead barium titanate 
thin films on MgO (100) by sol-gel process. 

Graded ferroelectric capacitors with robust temperature characteristics. 

Characterization of domain walls in BaTiO₃ using simultaneous atomic force and 
piezo-response force microscopy. 

15. J.L. Ruglovsky, J. Li, K. Bhattacharya and H.A. Atwater 
The effect of biaxial texture on the effective electromechanical constants of 
polycrystalline barium titanate and lead titanate thin films. 

16. I. Arias, S. Serebrinsky and, M. Ortiz 
A phenomenological cohesive model of ferroelectric fatigue, 

In Situ Measurements of Stress with Temperature in Thin Film PbₓBa₁₋ₓTiO₃ 

18. S.A. Serebrinsky, I. Arias, M. Ortiz 
Cohesive model of electromechanical fatigue for ferroelectric materials and structures 

Mechanical characterization of released thin films by contact loading. 

20. S. Serebrinsky and, M. Ortiz 
A hysteretic cohesive-law model of fatigue-crack nucleation 

Depletion layers and domain walls in semiconducting ferroelectric thin films. 

22. W.-D. Yang and S. M. Haile, 
Highly Preferred Oriented Lead Barium Titatante Thin Fils using Acetylacetone as 
Chelating Agent in a Sol-Gel Process, 

Domain switching in polycrystalline ferroelectric ceramics 

24. Y.B. Park. P. Nardi, X.D. Li XD and H.A. Atwater.
Nanomechanical characterization of cavity growth and rupture in hydrogen-implanted single-crystal BaTiO$_3$


25. R. T. Brewer, D. A. Boyd, M. Y. El-Naggar, S. W. Boland, Y.-B. Park, S. M. Haile, D. G. Goodwin, and H. A. Atwater,
Growth of biaxially textured Ba$_x$Pb$_{1-x}$TiO$_3$ ferroelectric thin films on amorphous Si$_3$N$_4$

A computational model of ferroelectric domains. Part I: Model formulation and domain switching.

27. W. Zhang and K. Bhattacharya.
A computational model of ferroelectric domains. Part II: Grain boundaries and defect pinning.

28. M.Y. El-Naggar, D.A. Boyd, and D.G. Goodwin
Characterization of Highly-Oriented Ferroelectric Pb$_x$Ba$_{1-x}$TiO$_3$ Thin Films Grown by MOCVD,

Multiscale study of internal stress and texture in ferroelectrics

30. Y.B. Park, J.L. Ruglovsky and H.A. Atwater
Microstructure and properties of single crystal BaTiO$_3$ thin films synthesized by ion implantation induced layer transfer

31. D. Shilo, G. Ravichandran and K. Bhattacharya
Investigation of twin-wall structure at the nanometer scale using atomic force microscopy.

32. M. A. Gallivan and R. M. Murray
Reduction and Identification Methods for Nonhomogeneous Markovian Control Systems, with Applications to Thin Film Deposition,

33. M. A. Gallivan, D. G. Goodwin, R. M. Murray
Effective Transition Rates for Epitaxial Growth Using Fast Modulation
*Physical Review B*, **70**: art. no. 045409, 2004

34. S.W. Boland, S.C. Pillai, W.D. Yang, S.M. Haile
Preparation of (Pb, Ba)TiO$_3$ Powders and Highly Oriented Thin Films by a Sol-Gel Process

35. S.C. Pillai, S.W. Boland, S.M. Haile
Low Temperature Crystallization of Sol-Gel Processed Pb0.5Ba0.5TiO3

36. K. Bhattacharya and G. Ravichandran
Ferroelectric perovskites for electromechanical actuation
37. R.T. Brewer, H.A. Atwater, J.R. Groves and P.N. Arendt
Reflection high-energy electron diffraction analysis of polycrystalline MgO films with grain size and orientation distributions,
38. R. C. Rogan, E. Üstündag, B. Clausen and M. R. Daymond
Texture and Strain Analysis of the Ferroelastic Behavior of Pb(Zr,Ti)O3 by In-Situ Neutron Diffraction,
39. R. C. Rogan, N. Tamura, G. A. Swift and E. Üstündag
Direct Measurement of Triaxial Strain Fields around Ferroelectric Domains Using X-Ray Microdiffraction,
40. J.W. Hartman, R.T. Brewer, H.A. Atwater
Reflection high-energy electron diffraction analysis of polycrystalline films with grain size and orientation distributions,
41. B. Clausen, R. C. Rogan, E. Üstündag, M. R. Daymond and V. Knoblauch
Ferroelastic Behavior of PZT-Based Ferroelectric Ceramics,
42. R. T. Brewer, H. A. Atwater
Rapid biaxial texture development during nucleation of MgO thin films during ion beam-assisted deposition
Rheed in-plane rocking curve analysis of biaxially-textured polycrystalline MgO films on amorhous substrates grown by ion beam-assisted deposition.
44. M. Uludogan, T. Çagin, A. Strachan, W. A. Goddard, III
Ab initio studies of pressure induced transitions in BaO.

Papers published: Peer Reviewed Conference Proceedings

3. S. W. Boland, and S. M. Haile, “Comparison of Titanium Precursors in the Sol-gel Synthesis of Pb0.5Ba0.5TiO3 Powders and Thin Films” in Ferroelectric Thin Films XII, Editors D. Kaufman, S. Hoffmann-Eifert, H. Funakubo, V. Joshi, A. I.


Papers published non-peer
None

Papers Presented

1. K. Bhattacharya gives invited presentation at the “MEMS reliability workshop” at ARL Adelphi.


29. Olga Kowalewsky, J. Knap, M. Ortiz, “Complex Lattice Quasicontinuum Theory and Its Application to Ferroelectrics” Technical University Dresden, Germany, April 2004
30. S. Boland (invited oral) presented "Oriented Ferroelectric Thin Films on Soluble Substrates" at the International Materials Research Congress; Cancun, Mexico 2004
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44. R. Rogan, Ferroelastic Behavior of PZT-Based Ferroelectric Ceramics, 6th European Conference on Residual Stress, Portugal; July 2002.
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54. K. Bhattacharya, Applications of Active Materials to Microactuation, First Congress on Artificial Muscles, Albuquerque, December 02.
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64. R.T. Brewer, D.A. Boyd, M. El-Naggar, S.W. Boland, S.M. Haile, D.G. Goodwin and H.A. Atwater, Ion-Beam Assisted Deposition of Biaxially Textured MgO on Amorphous Si3N4 for Heteroepitaxy of Biaxially Textured BaXPb1-XTiO3 204th Meeting of the Electrochemical Society; Orlando, FL October 2003.
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69. R.T. Brewer, D.A. Boyd, M. El-Naggar, S.W. Boland, S.M. Haile, D.G. Goodwin and H.A. Atwater, Ion-Beam Assisted Deposition of Biaxially Textured MgO on Amorphous Si3N4 for Heteroepitaxy of Biaxially Textured BaXPb1-XTiO3 204th Meeting of the Electrochemical Society; Orlando, FL October 2003.
presentation at Fall 2002 MRS meeting, in *Ferroelectric Thin Films XI*, Boston, 2-5 December 2002.

**Books**
None

**Honors**
1. M. Ortiz is elected Fellow of the American Academy of Arts and Sciences, 2007.
2. G. Ravichandran awarded Doctor Honoris Caua (Dhc) by the Paul Verlaine University, 2006
3. G. Ravichandran has been named Goode Professor of Aeronautics and Mechanical Engineering, 2006.
4. K. Bhattacharyya has been named Midwest Mechanics Lecturer, 2006-2007.
7. R. Zhang received the Coles Award for most innovative experimental design by a doctoral candidate, 2005.
8. G. Ravichandran has been awarded the Lazan Award of the Society of Experimental Mechanics.
10. M. Ortiz has been granted the Humboldt Research Award for Senior U.S. Scientists, 2002.
11. Stacey Boland received the Intel Graduate Student Fellowship, 2004-05
12. Stacey Boland received a PEO Scholar Award, 2005
13. Melody Grubbs received a Melon Minority Fellowship, 2005
14. Jennifer Ruglofsky received the Applied Materials Fellowship, 2004-05
15. Mohammed El-Naggar received the Applied Materials Fellowship, 2004-05
16. S.M. Haile presented the MSE DOW Lecture at Northwestern University, 2005
17. G. Ravichandran appointed as the John E. Goode, Jr. Professor of Aeronautics and Mechanical Engineering, 2005
Patents
   Ferroelectric nanophotonic materials and devices.
2. L.F. Greengard, M. Brongersma, D.A. Boyd.
   Method and system for forming a film of material using plasmon assisted chemical reactions.
   Electromagnetic control of chemical catalysis.
   Method and apparatus for measuring the mechanical response of micro-electromechanical systems. Filed, 2005.

Scientific Progress

*Quasi-continuum orbital-free density-functional theory: A route to multi-million atom non-periodic DFT calculation*

- Density functional theory has provided insights into various materials properties in the recent decade. However, the computational complexity of this approach has made other aspect, especially those involving defects, beyond reach. We have developed a
method that enables the study of a multi-million atom cluster using orbital free density functional theory with no spurious physics or restrictions on geometry. The key idea is a systematic means of adaptive coarse-graining retaining full resolution where it is necessary and coarsening with no patches, assumptions or structure. We demonstrate the method, its accuracy under modest computational cost and the physical insights it offers using a multi-million cluster of aluminum containing a single defect.

Synthesis of textured electrode and ferroelectric films using sol-gel

- Synthesized out-of-plane oriented LaNiO₃ conducting oxide electrodes on a variety of substrates [Si(111), Si(100), Si₃N₄, Ti/Si, Pt/Ti/SiO₂/Si, SiO₂/Si, and SiO₂] by chemical solution deposition (CSD) methods. Sheet resistance shown to be sufficient for electrode applications, ~ 50 Ω/square under ambient conditions. Demonstrated that texturing occurs by a classic mechanism in which grains exposing low energy, slow-growing surfaces eventually dominate the film. Absence of in-plane orientation revealed by X-ray diffraction pole figure analysis.
- Deposited oriented BaₓPb₁₋ₓTiO₃ and PZT on oriented LaNiO₃ conducting oxide electrodes by CSD. Demonstrated robustness of LaNiO₃ as a CSD substrate as compared to MgO for the deposition of BaₓPb₁₋ₓTiO₃ as a result of the lower sensitivity of LaNiO₃ to atmospheric moisture. BaₓPb₁₋ₓTiO₃ crystallization temperature reduced to 450°C.
- Carried out extensive surveys of alternate chemical systems (alternate precursors and solvents) to enhance in-plane orientation of LaNiO₃ attainable by CSD. Some promising systems have emerged, but as yet none provide sufficient bi-axial orientation. Exploration of CSD parameter space continues.

Synthesis of textured electrode and ferroelectric films using pulsed laser deposition

- Synthesized biaxially textured films BaₓPb₁₋ₓTiO₃ with SrRuO₃ electrodes. As grown films are oxygen-deficient with poor properties, and thus are oxygenated by annealing in an oxygen rich atmosphere. The films have been demonstrated to have biaxial texture, excellent ferroelectric and switching behavior under piezo-force microscopy (PFM) and good optical quality.

Fabrication and testing of ferroelectric bridges and cantilevers

- Fabricated a series of bridge like test-structures with various controls:
  - PT/Au/SiO₂ using MOCVD
  - PT/Au/SiO₂ using PLD (unfortunately gave wrong phase)
  - PT/MgO/SiO₂ using MOCVD (good quality but no bottom electrode)
  - PT/SRO/MgO/SiO₂ using PLD
- The bridges are tested using a variety of means
  - Force-displacement-voltage testing using the electromechanical test-bed. The mechanical tests are extremely repeatable, and allow us to extract residual stress and elastic modulus.
  - Cracking behavior using the electromechanical test-bed.
  - Cathodoluminescence measurements on films to explore microstructure (new application of this technique)
• PFM
• The role of texture in enhancing piezoelectric response demonstrated

**Plasmon Assisted Chemical Vapor Deposition**

- We introduce a new chemical vapor deposition (CVD) process that can be used to selectively deposit materials of many different types. The technique makes use of the plasmon resonance in nanoscale metal structures to produce the local heating necessary to initiate deposition when illuminated by a focused low-power laser. We demonstrate the technique, which we refer to as plasmon-assisted CVD (PACVD), by patterning the spatial deposition of PbO and TiO2 on glass substrates coated with a dispersion of 23 nm gold particles. The morphology of both oxide deposits is consistent with local laser-induced heating of the gold particles by more than 150 °C. We show that temperature rises of this magnitude are consistent, considering the heat loss mechanisms. The technique is general and can be used to spatially control the deposition of virtually any material for which a CVD process exists.

**Fundamental studies of ferroelectric materials**

- Study the Variation of Phonon distortion to understand diffuse scattering, and found that it is related to a TO-TA transformation during the symmetry reduction from Pm3m to I-43m. The TA modes in I-43m are anisotropic and always softer than TO modes, leading to observed diffuse X-ray scattering.
- Developed the PQEq force field based on QM calculations for BaTiO3, which enabled us to extend first principles based calculations to over 5000 atoms. This allowed us to determine the equilibrium structure of the 90° domain walls for periodic cells with lengths up to 74 nm (5120 atoms). We find that the domain wall has a width of 21 nm consisting of a dramatic switch in polarization over a 5 nm central layer surrounded by two transition layers each 8 nm wide. The central 5nm layer consists of a 2 nm sublayer with overshooting polarizations and a 3 nm sublayer with reversed polarization. This structure explains the discrepancies in interpreting previous experimental and theoretical analyses of the domain width and provides a great deal of detailed information about distortions, charges, and electric field that we believe of great interest to workers in the field. In particular we find that long-range interactions are crucial in stabilizing the domain wall.
- Anharmonic lattice statics calculations show that a periodic array of oxygen vacancies on a 180-degrees domain wall make its thickness double. This is the first quantitative calculation that shows domain wall broadening due to oxygen vacancies. This is in agreement with recent experimental studies by Shilo et al. (2004).

**Theoretical models of electromechanical fatigue**

- Developed a cohesive model for electromechanical fatigue and provided a thorough comparison with experimental data. The local hysteretic cohesive model was embedded into a simple slab geometry, and we considered the variation of a number of system parameters, to wit, number of applied cycles, nominal field amplitude, slab thickness and applied field frequency. In particular, we concluded that the exhaustion of the effective applied field due to the degrading cohesive interfaces, which is responsible for the size effect, also leads to a decrease in the amount of switching
with increasing field frequency. This is in line with several reported experimental data.

Modeling of Compositionally-Graded Ferroelectrics.
- In preparation for experimental studies on the growth and dielectric properties of graded Ba$_x$Sr$_{1-x}$TiO$_3$ thin films, we developed a continuum model that accounts for the spatial variation in properties and the long-range electrostatic interactions in functionally graded ferroelectrics, with an emphasis on the dielectric behavior. Two geometries are emphasized as case studies; parallel electrode and interdigitated electrode configurations. In both cases, we look for solutions of the polarization nominally aligned with the applied electric field, and compute the temperature-dependent dielectric response. We find that the parallel electrodes configuration results in a strong temperature-dependence of the dielectric constant, due to the strong electrostatic interactions between the different layers. On the other hand, interdigitated electrodes lead to a parallel capacitance geometry that results in a broad phase transition with temperature, as is desired for tunable filter applications.

Phase-field modeling of ferroelectric devices.
- Developed a phase field approach that can study domain patterns and domain evolution in complex geometries with no a priori assumption on geometry, electrode arrangement and dielectric properties. While modern devices utilize domain switching in complex geometries and electrode arrangements, current models of domain evolution make assumptions like periodicity and complete shielding. Our work overcomes these restrictions. The key idea is a boundary element method to resolve the electrostatic fields. We use the method to examining the closure domains that form at a free surface, domain switching under cyclic electric field in a device with interdigitated electrodes and domain switching at a notch.

Contacts with DoD personnel.
1. Melanie Cole from ARL has spent a sabbatical at Caltech collaborating with David Goodwin, David Boyd, Kaushik Bhattacharya and others in the MURI group. She is developing a MOCVD system modeled after the system developed in the Goodwin lab at Caltech. Further, the theoretical work on graded BST films is the basis of an experimental effort on her part to synthesize graded BST films via MOCVD in collaboration with Goodwin and Boyd. In addition, Melanie Cole has explored the possibility of incorporating oriented LaNiO$_3$ electrodes developed by Stacey Boland and Melody Grubbs (Haile group) in BST based thin-film devices.
2. K. Bhattacharya gives invited presentation at the “MEMS reliability workshop” at ARL Adelphi.
4. Dr. Melanie Cole visited Caltech on July 15, 2004, presented a very well-attended seminar and held discussions with various MURI team members.
5. Joint ARL-Caltech workshop in Army Research Lab, Adelphi MD organized by Drs. Madan Dubey, ARL and G. Ravichandran, Caltech. Speakers included John Prater and William Lampert, ARO; Harry Atwater, Sossina Haile, David Goodwin, Ersan Ustundag, Guruswami Ravichandran, Tahir Cagin, Kaushik Bhattacharya, Caltech; Peter Chung, Frank Crowne, Melanie Cole, John Demaree, Eric Ngo, ARL; David Singh, NRL; and attendees included G. Ravichandran, Caltech; Jeff Pulskamp, Luke Currano, ARL; David A. Boyd, Santiago A. Serebrinsky, Jennifer Ruglovsky, Robert Rogan, Caltech; Eric Ngo, Eugene Zakar, Madan Dubey, Alma Wickenden, Frank Crowne, ARL; Stacey W. Boland, Caltech; Derek Demaree, Daniel Potrepka, Gary Hirsch, Peter W. Chung, Raju Namburu, Steven Tidrow, Roland Polcawich, ARL; Tahir Cagin, Sossina Haile, David Goodwin, Kaushik Bhattacharya, Harry Atwater, Caltech; Bill Lampert, John Prater, ARO; Qingsong Zhang, Caltech; Melanie Cole, ARL; David Singh, NRL. The workshop included both talks as well as informal discussion brainstorming session. Three concrete areas of collaboration emerged and are progressing. December 4, 2003.


7. David A. Boyd interacts with Dr. Alma Wickenden (ARL) for development and fabrication of PBT microstructures, 2003-04.


11. S. Boland, graduate student, visited Army Research Lab, Adelphi MD September 10-14, 2001 for a week-long working visit with A. Wickenden.

12. A. Wickenden (ARL) visited Caltech during the week of July 8, 2002 for collaborative research projects with the PIs and co-PIs.


15. R.M. Murray has joined the Air Force Scientific Advisory Board.

Faculty and Senior Researchers

Grad Students

**Post Doctorates**
Y. Xiao, Y-B. Park, Q.S. Zhang, D.A. Boyd, S. Serebrinsky, I. Arias, R. Zhang, R. Kunnath, W. Zhang, A. Strachan, S. Pillai, W-D Yang,

**Master Degrees**
S. Boland, M. Dicken, K. Diest, M. El-Naggar, S. Boland, G. Sukul, O. Schneider, A. Yavari, V. Gavini, R. Zhang

**Under Graduates**
M. Grubbs, J. Messenger, R. Abraham, A. Subramaniam, S. Gao, K. Hammond

**Doctorate Degrees**
Multiscale Modeling and Process Optimization for Engineered Microstructural Complexity

ABSTRACT
This reports on the results of the MURI project on Engineering Microstructural Complexity in Ferroelectric Devices

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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

Number of Papers published in peer-reviewed journals: 4.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)
None.

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations
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Number of Presentations: 78.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):
None.

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

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


Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 4

(d) Manuscripts

None.

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

<table>
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<th>NAME</th>
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<tr>
<td>K. Dayal</td>
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FTE Equivalent: 24.50

Total Number: 25

Names of Post Doctorates
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**FTE Equivalent:** 10.80

**Total Number:** 12

### Names of Faculty Supported

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<td>Harry Atwater</td>
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<td>William Goddard</td>
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<td>David Goodwin</td>
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<td>Sossina Haile</td>
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**FTE Equivalent:** 0.71

**Total Number:** 9

### Names of Under Graduate students supported

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<td>R. Abraham</td>
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**FTE Equivalent:** 6.00

**Total Number:** 6
**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: 6.00
- The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: 6.00
- 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: 6.00
- Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 6.00
- 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

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**Names of Personnel receiving masters degrees**

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<tr>
<td>S. Boland</td>
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<td>M. Dicken</td>
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<td>K. Diest</td>
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<td>M. El-Naggar</td>
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<td>R. Zhang</td>
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**Total Number:** 9

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**Names of personnel receiving PHDs**

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<tr>
<td>Y. Xiao</td>
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**Total Number:** 14

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**Names of other research staff**
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<td>T. Cagin</td>
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**FTE Equivalent:** 2.00

**Total Number:** 2

Sub Contractors (DD882)

Inventions (DD882)
5 Electromagnetic control of chemical catalysis

Patent Filed in US? (5d-1) Y
Patent Filed in Foreign Countries? (5d-2) N
Was the assignment forwarded to the contracting officer? (5e) Y
Foreign Countries of application (5g-2):

5a: D.A. Boyd
5f-1a: California Institute of Technology
5f-c: 1200 E. California Blvd
   Pasadena CA 91125

5a: L.F. Greengard
5f-1a: New York University
5f-c: 70 Washington Square South, 12S
   New York NY 10012

5a: M. Brongersma
5f-1a: Stanford University
5f-c:
   Stanford CA 94305

5 Ferroelectric nanophotonic materials and devices

Patent Filed in US? (5d-1) Y
Patent Filed in Foreign Countries? (5d-2) N
Was the assignment forwarded to the contracting officer? (5e) Y
Foreign Countries of application (5g-2):

5a: H.A. Atwater
5f-1a: California Institute of Technology
5f-c: 1200 E. California Blvd
   Pasadena CA 91125

5a: K. Bhattacharya
5f-1a: California Institute of Technology
5f-c: 1200 E. California Blvd
   Pasadena CA 91125

5a: K. Dayal
5f-1a: California Institute of Technology
5f-c: 1200 E. California Blvd
   Pasadena CA 91125

5a: M. Dicken
5f-1a: California Institute of Technology
5f-c: 1200 E. California Blvd
   Pasadena CA 91125
Method and apparatus for measuring the mechanical response of micro-electro-mechanical systems

Method and system for forming a film of material using plasmon assisted chemical reactions