Lawrence Friedman

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EDUCATION

1999	Ph.D.	Physics, University of California – Berkeley Advised by Daryl Chrzan Thesis: "Advances in the Theory of the Hall-Petch Relation, Dislocation Pileups and Dislocation Sources"
1995	M.A.	Physics, University of California – Berkeley
1993	B.A.	Physics, University of Chicago

PROFESSIONAL EXPERIENCE

08/2002 – Present	Assistant Professor Department of Engineering Science and Mechanics Pennsylvania State University
09/1999 – 07/2002	Postdoctoral "Metals" Fellow (Advised by Erik van der Giessen) Netherlands Institute for Metals Research, Technical University of Delft (The Netherlands), University of Groningen (The Netherlands)
06/1999 – 08/1999	Postdoctoral Student (Advised by Daryl Chrzan) Lawrence Berekeley National Laboratory, University of California – Berkeley
08/1993 – 05/1999	Graduate Research/Teaching Assistant Department of Physics and Department of Materials Science University of California – Berkeley

REFEREED JOURNAL ARTICLES[†]

1. A.L. Romasco, L.H. Friedman, L. Fang[*], R.A. Meirom, T.C. Clark, R. Polcawich, J. Pulskamp, M. Dubey, and C.L. Muhlstein, "Practical Implications of Instrument

[†] links and downloads at http://www.esm.psu.edu/wiki/research:lhf10:publications
[*] Author supervised by L. Friedman

Displacement Drift during Force-Controlled Nanoindentation," submitted to *Journal of Testing and Evaluation*.

2. A.L. Romasco, L.H. Friedman, L. Fang*, R.A. Meirom, T.C. Clark, R. Polcawich, J. Pulskamp, M. Dubey, and C.L. Muhlstein, "Deformation Behavior of Nanograined Platinum Films," submitted to *Thin Solid Films*.
3. Lei Fang*, Christopher L. Muhlstein, Amber L. Romasco, James G. Collins and Lawrence H. Friedman, "Augmented instrumented indentation using electrical contact current-voltage (I-V) curves," submitted to *Journal of Materials Research*.
4. L. H. Friedman*, "Anisotropy and Morphology of Strained III-V Heteroepitaxial Films," *Physical Review B*, in press. (arXiv:0804.2438v2 [cond-mat.mtrl-sci])
5. C. Kumar* and L. H. Friedman, "Effects of elastic heterogeneity and anisotropy on the morphology of self-assembled epitaxial quantum dots," *Journal of Applied Physics*, 104 (3):034902 (9 pages) (2008). [doi:10.1063/1.2960560]
6. L. Fang*, C. Muhlstein, J. Collins, A. Romasco, and L. Friedman, "Continuous electrical in-situ contact area measurement during instrumented indentation," *Journal or Materials Research*, 23, 2480 (2008), [doi:10.1557/JMR.2008.0298].
7. Lawrence H. Friedman, "Predicting and Understanding Order of Epitaxial Quantum Dots: Early Growth Stages," *Journal of Electronic Materials*, 36(12):1546-1554 (2007), [doi:10.1007/s11664-007-0246-x] (selected as a top paper for complimentary Open Choice program).
8. Lawrence H. Friedman, "Order of epitaxial self-assembled quantum dots: Linear analysis," *Journal of Nanophotonics*, 1(1):013513 (42 pages), 2007.
9. Lawrence H. Friedman, "Anisotropy and order of epitaxial self-assembled quantum dots," *Physical Review B*, 75(19):193302 (4 pages) (2007).
10. C. Kumar* and L. H. Friedman, "Simulation of thermal field directed self-assembly of epitaxial quantum dots," *Journal of Applied Physics*, 101(9):094903 (9 pages), 2007.
11. L. Fang* and L. H. Friedman, "Analytic treatment of metallic multilayer strength at all length scales: Influence of dislocation sources," *Acta Materialia*, 55(5):1505-1514 (2007).
12. L. H. Friedman and J. Xu, "Feasibility study for thermal-field directed self-assembly of heteroepitaxial quantum dots," *Applied Physics Letters*, 88:093105 (3 pages) (2006).
13. L. H. Friedman. "Exponent for Hall-Petch behaviour of ultra-hard multilayers," *Philosophical Magazine*, 86(11): 1443–1481 (2006).
14. L. Fang* and L. H. Friedman. "Strength of metallic multilayers at all length scales from analytic theory of discrete dislocation pileups", *Philosophical Magazine*, 85 (28): 3321-3355 (2005).

* Author supervised by L. Friedman

15. L. H. Friedman and L. Fang*, "Towards a full analytic treatment of the Hall-Petch behavior in multilayers: putting the pieces together." *TMS Letters*, 1(1):3-4 (2004).
16. L. H. Friedman, "Towards a full analytic treatment of the Hall–Petch behavior in multilayers: putting the pieces together," *Scripta Materialia*, 50 (6): 763-767 (2004).
17. P. A. Greaney, L. H. Friedman, and D. C. Chrzan, "Continuum simulation of dislocation dynamics: predictions for internal friction response," *Computational Materials Science*, 25(3): 387-403 (2002). (Contributing author)
18. D. Weygand, L. H. Friedman, E. van der Giessen, and A. Needleman, "Aspects of boundary-value problem solutions with three-dimensional dislocation dynamics," *Modeling and Simulation in Materials Science and Engineering*, 10 (4): 437-468 (2002). (Contributing author)
19. D. Weygand, L. H. Friedman, E. van der Giessen, and A. Needleman, "Discrete dislocation modeling in three-dimensional confined volumes," *Materials Science and Engineering A*, 309-310: 420-424 (2001). (Contributing author)
20. K. Faradjian, L. H. Friedman, and D. C. Chrzan, "Frank-Read sources within a continuum simulation," *Modelling and Simulation in Materials Science and Engineering*. 7(4): 479-494 (1999). (Equal contributions by authors)
21. L. H. Friedman and D. C. Chrzan, "Scaling theory of the Hall-Petch relation for mulitlayers," *Physical Review Letters*, 81(3): 2715-2718 (1998).
22. L. H. Friedman and D. C. Chrzan, "Continuum analysis of dislocations pile-ups: influence of sources" *Philosophical Magazine A*, 77(5): 1185-1204 (1998).

CONFERENCE PROCEEDINGS

1. L. H. Friedman, "Stochastic continuum modeling self-assembled epitaxial quantum dot formation," Proc. SPIE, Vol. 7041, 704103 (2008) [doi:10.1117/12.795615].
2. D. Weygand, L. H. Friedman, E. van der Giessen, and A. Needleman, "Dislocation dynamics modeling in confined volumes," *Advances in Mechanical Behavior, Plasticity and Damage. Proceedings of Euromat 2000* vol. 1: 293-298 (2000).
3. L. H. Friedman**,** D. Weygand, and E. van der Giessen, "Size effects and scaling in misfit dislocation formation in self-assembled quantum dots." *Technical Proceedings of the 2002 International Conference on Computational Nanoscience*, 271-274 (2002).

CONFERENCE PRESENTATION AND INVITED TALKS

1. Lawrence H. Friedman. "Stochastic Finite Temperature Continuum Modeling With Applications to Film Evolution," TMS (Metals Minerals and Materials Society) 2009 Annual Meeting, San Francisco, CA, scheduled for February, 2009. (abstract accepted).

* Author supervised by L. Friedman

2. Lawrence H. Friedman. "Surface Energy Effects on the Self-Assembly of Epitaxial Quantum Dots," Photonics West (SPIE), San Jose, CA, scheduled for January 2009. (**invited speaker**)
3. L. Fang, C. Muhlstein, J. Collins, A. Romasco, and L. Friedman. "An electrical technique to measure *in-situ* contact area during instrumented indentation and its application of characterizing materials that pile-up," SES2008 (2008 Society of Engineering Science Annual Technical Meeting), Urbana-Champaign, IL, October 2008. (abstract accepted)
4. Lawrence H. Friedman. "Practical Finite Temperature Continuum Modeling With Applications to Film Evolution," SES2008 (2008 Society of Engineering Science Annual Technical Meeting), Urbana-Champaign, IL, October 2008. (abstract accepted)
5. L. Fang, C. Muhlstein, J. Collins, A. Romasco, and L. Friedman, "Continuous electrical in-situ contact area measurement during instrumented indentation," MS&T08 (Materials Science & Technology 2008 Conference and Exhibit), Pittsburgh, PA, October 2008. (abstract accepted)
6. L. H. Friedman, "Stochastic continuum modeling self-assembled epitaxial quantum dot formation," SPIE Symposium on NanoScience + Engineering, Optics & Photonics Meeting, San Diego, CA, August 13, 2008. (**invited speaker**)
7. L. H. Friedman, "Faceting and Surface Energy Effects on the Self-Assembly of Epitaxial Quantum Dots," TMS (The Minerals, Metals and Materials Society) 2008 Annual Meeting, New Orleans, LA, March 11, 2008.
8. C. Kumar and L. H. Friedman, "Effect of Elastic Inhomogeneity and Anisotropy on the Order of Epitaxial Quantum Dots" APS (American Physical Society) March Meeting 2007, New Orelans, LA, March 10, 2008
9. L. H. Friedman, "Dislocation Pileups and Strength of Multilayers," Plasticity 2008, Kailua-Kona, Island of Hawaii, Feb., 2008. (**invited speaker**)
10. L. H. Friedman, "Morphology and Ordering of III-V Epitaxial Self-Assembled Quantum Dots," MRS (Materials Research Society) Fall 2007 Meeting, Boston, MA, November 27, 2006.
11. Lawrence H. Friedman, "Predicting and Understanding Order of Epitaxial Quantum Dots: Early Growth Stages," Nanoscience Group Seminar, Department of Physics, University of Arkansas, Fayetteville, AR. May 22, 2007. (**invited speaker**)
12. L. H. Friedman, "Predicting and Understanding Order of Heteroepitaxial Quantum Dots," SIMC-XIV (14th Semiconducting and Insulating Materials Conference), Fayeteville, AR, May 16, 2007.
13. L. H. Friedman, "Predicting and understanding order of heteroepitaxial quantum dots: early growth stages," TMS (The Minerals, Metals and Materials Society) 2007 Annual Meeting, Orlando, FL, February 25, 2007.

14. L. H. Friedman, "Order, randomness and fluctuations in heteroepitaxial quantum dot growth," MRS (Materials Research Society) Fall 2006 Meeting, Boston, MA, November 29, 2006.
15. L. H. Friedman, "Origins of order and disorder in self-assembled epitaxial quantum dots," NANOMEC-06 Materials Science And Materials: Mechanics At The Nanoscale, Bari, Italy, November 23, 2006. (invited speaker)
16. C. Kumar and L. H. Friedman, "Simulation of thermal-field directed self-assembly of epitaxial quantum dots," Materials Science and Technology 2006 Conference, Cincinnati, OH, October 19, 2006.
17. Lawrence H. Friedman, "Order, Randomness and Fluctuations in Heteroepitaxial Quantum Dot Growth," Comutational and Applied Mathematics Colloquium, Department of Mathematics, Penn State University, September 29, 2006. (invited speaker)
18. L. H. Friedman, "Crystal anisotropy and order of epitaxial self-assembled quantum dots," 43rd Annual Technical Meeting of the Society of Engineering Science, University Park, PA, August 14, 2006.
19. C. Kumar and L.H. Friedman, "Simulation of Thermal-Field Directed Self-Assembly of Epitaxial Quantum Dots," 43rd Annual Technical Meeting of the Society of Engineering Science, University Park, PA, August 14, 2006.
20. C. Kumar and L. H. Friedman**,** "Simulation of thermal-field directed self-assembly of epitaxial quantum dots," TMS (The Minerals, Metals and Materials Society) 2006 Electronic Materials Conference, University Park, PA, June 28, 2006.
21. L. H. Friedman and J. Xu, "Feasibility study of directed self-assembly of semiconductor quantum dots," 2006 NSTI Nanotechnology Conference and Trade Show, Boston, MA, May 9, 2006.
22. L. H. Friedman and J. Xu, "Feasibility study of directed self-assembly of semiconductor quantum dots," (poster), APS (American Physical Society) March Meeting 2006, Baltimore, MD, March 15 2006.
23. L. Fang and L. H. Friedman, "Analytic treatment of metallic multilayer strength at all length scales," APS (American Physical society) March Meeting 2006, Baltimore, MD, March 14, 2006.
24. L. Fang and L. H. Friedman, "Analytic treatment of metallic multilayer strength at all length scales," 2006 TMS Annual Meeting, San Antonio, TX, March 14, 2006 .
25. L. Fang and Lawrence H. Friedman, "Analytic treatment of metallic multilayer strength at all length scales," 2005 MRS Fall Meeting, Boston, MA, Dec. 2, 2005.
26. L. Fang and L. H. Friedman, "Strength of metallic multilayers at all length scales via a dislocation-based model," Annual Meeting of the Minerals, Metals and Materials Society (TMS), San Francisco, CA, February 14, 2005.
27. L. H. Friedman and L. Fang, "Towards a full analytic treatment of the Hall-Petch behavior in multilayers: *putting the pieces together*," Annual Meeting of the Minerals, Metals and Materials Society (TMS), Charlotte, NC, March 15, 2004.

28. Lawrence H. Friedman, "The Hall-Petch Behavior of Multilayer Coatings," Seminar, Dept. of Engineering Science and Mechanics, Penn State University, October 8, 2003. (invited speaker)
29. Lawrence H. Friedman, "Applications of Crystal Microplasticity: Modeling and Theory," Department of Engineering Science and Mechanics, Penn State University, January 22, 2003. (invited speaker)
30. L. H. Friedman. "Analytic prediction of Hall-Petch exponent in multilayer coatings," Materials Research Society Fall Meeting, Boston, MA, December 2, 2002.
31. L. H. Friedman, D. Weygand, and E. van der Giessen, "Size effects and scaling in misfit dislocation formation in self-assembled quantum dots," International Conference on Computational Nanoscience, San Juan, Puerto Rico, 2002.
32. Lawrence H. Friedman, D. M. Weygand, and E. van der Giessen, "Size Effects and Scaling in Misfit Dislocation Formation in Self-Assembled Quantum Dots," MRS (Materials Research Society) Fall Meeting, Boston, MA, 2002.
33. L. H. Friedman, D. M. Weygand, and E. van der Giessen, "3D simulation of misfit dislocations in epitaxial quantum dots," Bond voor Materialkennis Materials Research, Veldhoven, The Netherlands, 2001.
34. Lawrence H. Friedman, "Scaling Theory of Hall-Petch Relation for Metallic Multilayers," Department of Mechanical Engineering, Yale University, March 23, 2001. (invited speaker)
35. Lawrence H. Friedman, D. M. Weygand, and E. van der Giessen, "Three-dimensional simulation of misfit dislocations in islands in strained epitaxial systems." 37th Annual Technical Meeting of SES (Society of Engineering Science, Columbus, SC, 2000.
36. Lawrence H. Friedman, "Scaling Theory of Hall-Petch Relation for Metallic Multilayers," Max Planck Institute for Metallurgy (Stuttgart, Germany), July, 13, 2000. (invited speaker)
37. L. H. Friedman and D. C. Chrzan, "Scaling theory of dislocation pileups and the Hall-Petch relation," Materials Research Society Fall Meeting, Boston, MA, 1998.
38. L. H. Friedman and D. C. Chrzan, "Generalization of the Hall-Petch relation to elastically inhomogeneous materials," American Physical Society March Meeting, Los Angeles, CA, 1998.
39. L. H. Friedman and D. C. Chrzan, "Influence of Frank-Read sources on the Hall-Petch relation: a continuum analysis." Materials Research Society Spring Meeting, San Francisco, CA, 1997.
40. Lawrence H. Friedman and D. C. Chrzan, "Influence of Frank-Read sources on the Hall-Petch relation: a continuum analysis," 1997, American Physical Society March Meeting, Kansas City, MO, 1997.

PROFESSIONAL ASSOCIATIONS AND ACTIVITIES

- The Minerals, Metals and Materials Society (TMS), 2004 – present.
- American Society of Mechanical Engineers (ASME), 2004 – present.
- Society of Engineering Science (SES), 2001 – present.
- American Physical Society, 1998 – present.
- Materials Research Society, 1998 – present.
- Reviewer for *Acta Materialia, European Journal of Mechanics, Journal of Materials Science, Philosophical Magazine, Scripta Materialia, Thin Solid Films*.
- Proposal Reviewer for National Science Foundation, Air Force Office of Scientific Research.
- Chair-elect (3/2009 – 3/2011) / Vice-chair (3/2007 – 3/2009) / Member (2004 – present) of TMS (The Minerals, Metals and Materials Society) Nanomechanical Material Behavior Committee.
- Organizing Committee Member, SES 2006 conference (Society of Engineering Science), University Park, PA, August 2006.
- Symposium organizer, "Pushing Mechanics to the Nanoscale Limit," at SES 2006 (Society of Engineering Science) meeting, University Park, PA August 2006.
- Organizer, "Tutorial on Nanomechanical Characterization", TMS (The Minerals, Metals and Materials Society) 2008 Annual Meeting.
- Session Chair, "Theory of Self-Assembly" at MRS (Materials Research Society) Fall 2006 Meeting, Boston, MA, 11/30/06; Plenary Lecture of SES (Society of Engineering Science) 2006 Meeting, University, Park, PA, 8/15/06; General Topics Session of SES 2002 (Society of Engineering Science) meeting, University Park, PA (10/15/02 and 10/16/02).

HONORS

- Invited Speaker, SPIE International Symposium on Integrated Optoelectronic Devices 2009, Quantum Dots, Particles, and Nanoclusters VI, San Jose, CA, scheduled for January 2009.
- Invited Speaker, SPIE Symposium on NanoScience + Engineering, San Diego, CA, scheduled for August 2008.
- Invited Speaker, PLASTICITY 2008, Kailua-Kona, Island of Hawaii, Feb. 2008.
- Invited Speaker, NANOMECH-06, Bari, Italy, November 2006.
- Materials Research Society Graduate Student Silver Medal Award, December, 1998.

RESEARCH GRANTS

1. 1/1/06 – 12/31/08, "Electronanoindentation: fundamental investigations and applications to piezoelectric thin films," awarded by National Science Foundation, Civil and Mechanical Systems Program (CMS), $280,000 (candidate's share = 50%), Candidate is P.I.

2. 7/01/03 – 6/30/05, "Nanostructured Protective Coatings Against Wear," funded by Air Force Research Laboratory." Total project is $833,000 (candidate's share = 0.9%). Candidate was subcontracted researcher.

STUDENT THESES SUPERVISED / IN PROGRESS

- Lei Fang, M. S. Engineering Mechanics, 12/05.
- Kedar Shah B. S. Engineering Science, 5/06.
- Lei Fang, Ph.D. Engineering Science and Mechanics (in progress), expected graduation: 12/08.
- Chandan Kumar, Ph.D. Engineering Science and Mechanics (in progress), expected graduation: 5/09.

COURSES TAUGHT AT PENN STATE UNIVERSITY

- Nanomechanics (Graduate, created by L. H. Friedman) http://www.esm.psu.edu/wiki/_media/research:lhf10:syllabus.pdf
- Finite Element Analysis (Graduate)
- Engineering Mechanics: Dynamics (Undergraduate)
- Equilibrium Mechanics (Undergraduate Honors)
- Mechanical Response of Engineering Materials (Undergraduate)

SOFTWARE DEVELOPED FOR RESEACH AND TEACHING

- Stochastic Simulations of Self-Assembled Epitaxial Quantum Dot Growth – Mathematica based simulation of epitaxial quantum dot formation. Features include linear and nonlinear evolution, stochastic initial conditions and stochastic surface diffusion using an adaptive stochastic Euler algorithm and random material deposition.
- Simple Examples of Stochastic Differential Equations – Mathematica based simulations of simple stochastic differential equations.
- Nanomechanics demo suite – Mathematica based calculations and simulations to aid in instruction of Graduate Nanomechanics
- Plane-Stress FEA Program – to aid in instruction of Graduate Finite Element Analysis
- Pileup Engine – Mathematica based simulation for calculating scaling exponent for Hall-Petch Behavior of Multilayers and plotting related elastic fields.
- 3D Dislocation Dynamics - Finite Element Method Simulation – Developed by D. M. Weygand, L. H. Friedman, E. van der Giessen and A. Needleman. Discrete 3D dislocation dynamics simulation coupled to finite element method to impose boundary conditions.
- 3D dislocations Dynamics Simulation – Developed by L. H. Friedman, A.K. Faradjian, P.A. Greaney and D. C. Chrzan.

- 2D Dislocation Pileup Simulator – Determines the yield stress of bilayers and trilayers based on microscopic and elastic parameters by simulating quasistatic formation of dislocation pileups.
- Sliding Wheels – Developed by L. H. Friedman and D. C. Chrzan. Simulates 2D system with local rotations and frictional dissipation as a toy model of microscopic rotations during mechanical deformation.