Acoustic Tweezers: Manipulating Bioparticles Using Standing Surface Acoustic Waves (SSAW)

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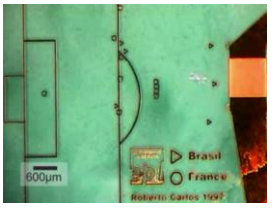
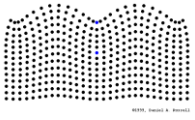
Microfluidic Soccer— a Fun Example of Acoustic Tweezers

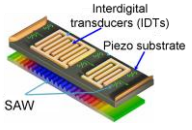
Roberto Carlos Free Kick

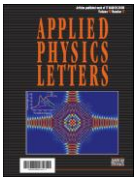


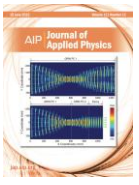
Micro fluidic version

Surface Acoustic Waves (SAW)

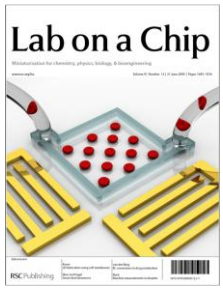








Standing Surface Acoustic Waves (SSAW)



$$F_r = -\left(\frac{\pi p_0{}^2 V_p \beta_m}{2\lambda}\right)\phi(\beta,\rho)\sin(2kx)$$

$$\phi = \frac{5\rho_p - 2\rho_m}{2\rho_p + \rho_m} - \frac{\beta_p}{\beta_m}$$

$$F_v = -6\pi\eta r v$$

J. Shi, D. Ahmed, X. Mao, S.-C. S. Lin, and T. J. Huang, *Lab Chip*, 2009, 9, 2890-32895.

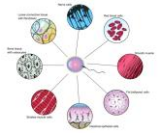
Functions of Acoustic Tweezers

- **Cell/particle patterning**
- Nanomaterial manipulation
- Single particle (cell, organism) manipulation
- Cell/particle separation
- Fluorescence-activated cell sorting (FACS)

Motivation to Pattern Cells

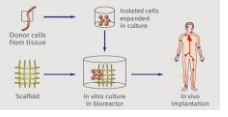
Cell Signaling and Interaction

Cell Growth and Differentiation



Drug Discovery

Tissue Engineering



http://www.weizmann.ac.il/Biological_Chemistry/scientist/Fainzilber/Introduction%20picture.jpg
http://www.griffith.edu.au/research/research-excellence/drug-discovery-infectious-diseases
http://219.221.200.61/ywxy/zbsw(E)/pic/ech12-2.jpg
http://archive.student.bmj.com/issues/08/05/education/images/view_11.jpg

Working Mechanism of SSAW-Based Cell Patterning

$$F_r = -\left(\frac{\pi p_0{}^2 V_p \beta_m}{2\lambda}\right)\phi(\beta,\rho)\sin(2kx)$$

$$\phi = \frac{5\rho_p - 2\rho_m}{2\rho_p + \rho_m} - \frac{\beta_p}{\beta_m}$$

$$F_v = -6\pi\eta r v$$

J. Shi, D. Ahmed, X. Mao, S.-C. S. Lin, and T. J. Huang, *Lab Chip*, 2009, 9, 2890-32895.

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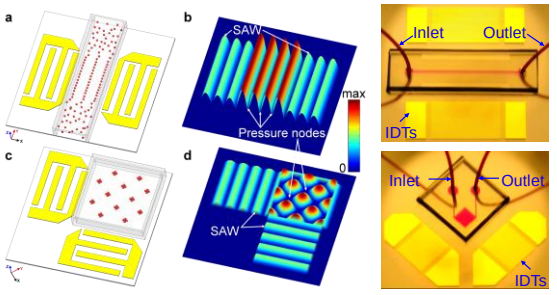
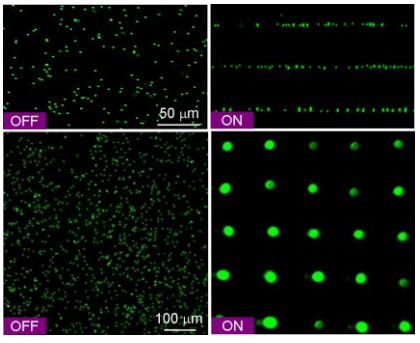
Simulation of Pressure Field and Device Fabrication



J. Shi, D. Ahmed, X. Mao, S.-C. S. Lin, and T. J. Huang, *Lab Chip*, 2009, 9, 2890-32895.

PSU BioNEMS Laboratory

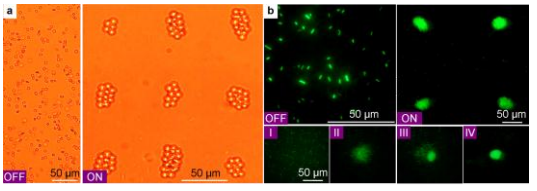
Patterning of Fluorescent Beads



J. Shi, D. Ahmed, X. Mao, S.-C. S. Lin, and T. J. Huang, *Lab Chip*, 2009, 9, 2890-32895.

PSU BioNEMS Laboratory

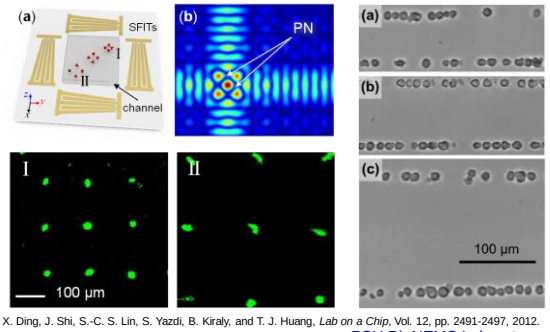
Patterning of Bovine Red Blood Cells and E. coli Cells



J. Shi, D. Ahmed, X. Mao, S.-C. S. Lin, and T. J. Huang, *Lab Chip*, 2009, 9, 2890-32895.

PSU BioNEMS Laboratory

Tunable Cell Patterning



X. Ding, J. Shi, S.-C. S. Lin, S. Yazdi, B. Kiraly, and T. J. Huang, *Lab on a Chip*, Vol. 12, pp. 2491-2497, 2012.

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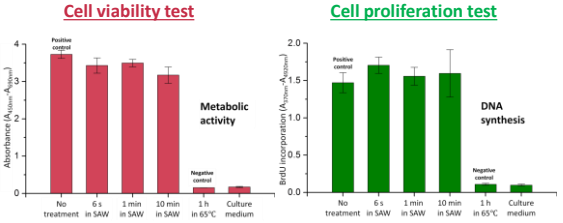
Cell Viability and Proliferation Tests



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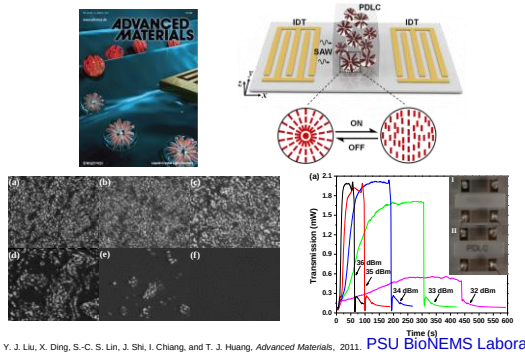
Functions of Acoustic Tweezers

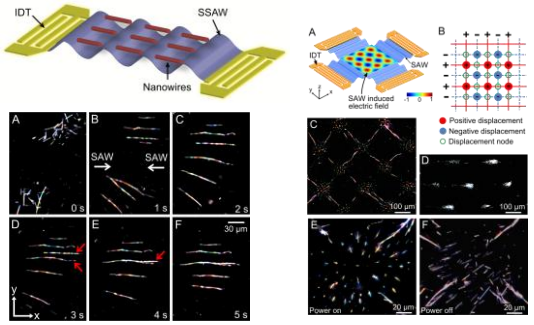
- Cell/particle patterning
- **Nanomaterial manipulation**
- Single particle (cell, organism) manipulation
- Cell/particle separation
- Fluorescence-activated cell sorting (FACS)

SAW-Driven Light Shutters using Polymer-Dispersed Liquid Crystals (PDLC)



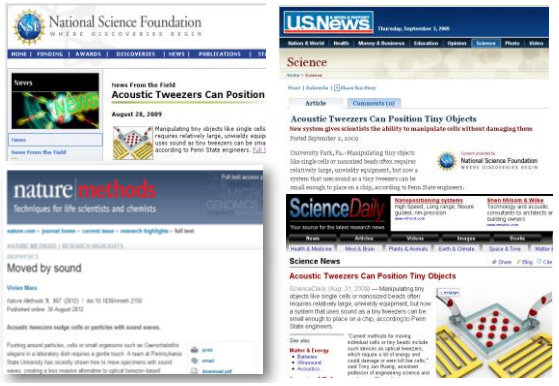
Y. J. Liu, X. Ding, S.-C. S. Lin, J. Shi, I. Chiang, and T. J. Huang, *Advanced Materials*, 2011.

SSAW-Driven Tunable Nanowire Patterning



Y. C. Chen, et al, *ACS Nano*, 2013.

Acoustic Tweezers? Not Yet!



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- **Single particle (cell, organism) manipulation**
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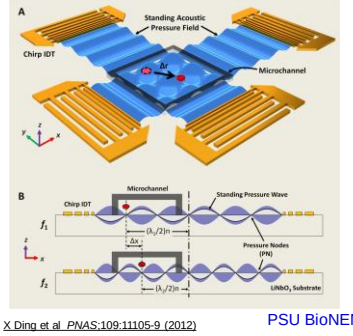
Working Mechanism of SAW-Based Single Particle Manipulation

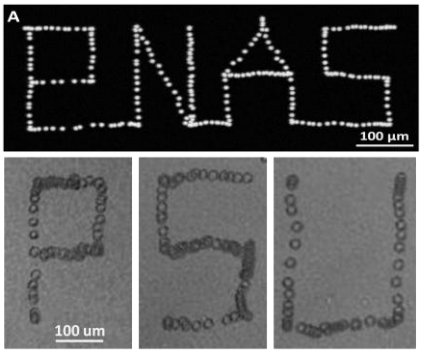


X Ding et al *PNAS*;109:11105-9 (2012)

Single Particle Manipulation

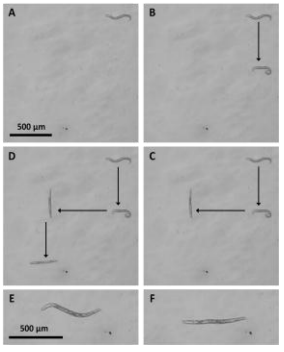
X Ding et al *PNAS*;109:11105-9 (2012)

Single Cell Manipulation



X Ding et al *PNAS*;109:11105-9 (2012)

On-Chip Manipulation of Single Organism (*C.* Elegans)



X Ding et al *PNAS*;109:11105-9 (2012)

Functions of Acoustic Tweezers

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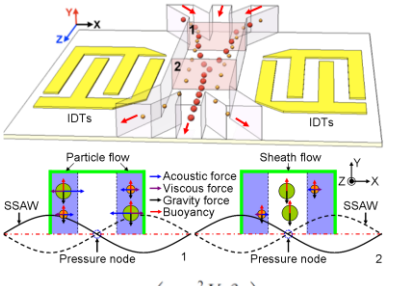
- Fluorescence-activated cell sorting (FACS)

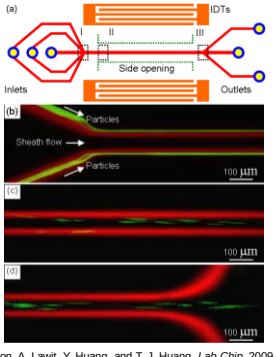
Particle Separation via Acoustic Tweezers



$$F_r = -\left(\frac{\pi p_0^{\,2} V_p \beta_m}{2\lambda}\right)\phi(\beta,\rho)\sin(2kx)$$

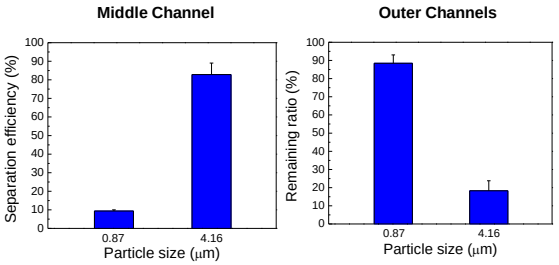
J. Shi,* H. Huang,* Z. Stratton, A. Lawit, Y. Huang, and T. J. Huang, *Lab Chip*, 2009, 9, 3354-3359

Experimental Results



J. Shi,* H. Huang,* Z. Stratton, A. Lawit, Y. Huang, and T. J. Huang, *Lab Chip*, 2009, 9, 3354-3359

Separation Efficiency Analysis



A few slides are deleted here since they are unpublished.

Functions of Acoustic Tweezers

- Cell/particle patterning
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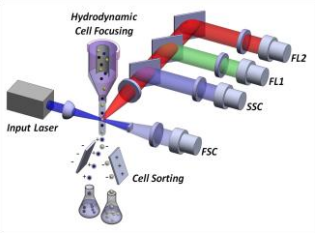
- **Fluorescence-activated cell sorting (FACS)**

Fluorescence-Activated Cell Sorting (FACS)

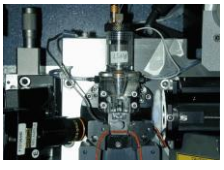


**** 3D focusing of cells*** **** Multi-parametric optical detection*** **** Cell sorting***

Applications

Biomedical Research (Cell/Molecular biology, immunology, genetics, stem cell sorting, *etc*)
Clinical Diagnosis and Therapeutics (HIV diagnosis and staging, leukemia diagnosis, etc)

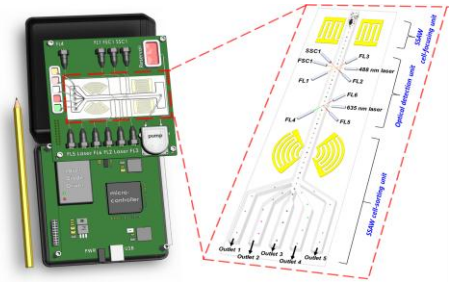
Drawbacks of Conventional FACS



- High equipment cost (~$500,000)
- Large size
- High maintenance (average maintenance cost: $30,000 per year)
- Significant biosafety concerns
- Reduced cell viability and other functions
- Inability to accurately analyze or sort cells in small sample sizes

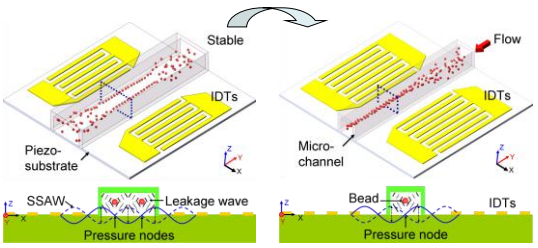
www.ottawagenomecenter.ca/services/flowcytometry/
http://www.rpciflow.org/news_events/movies.htm

Our Solution: Standing SAW (SSAW) Based FACS



1) significantly improved biocompatibility; 2) significantly improved biosafety; 3) unprecedented ability to perform multi-parametric cell analysis and sorting with small cell sample sizes; and 4) low cost, small size, and low maintenance

From Patterning to Focusing

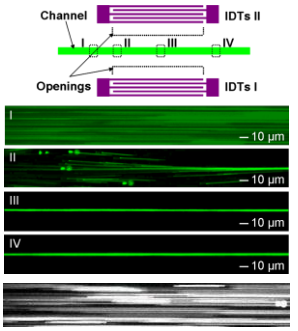


1D patterning in a stable channel

Focusing in a dynamic flowing channel

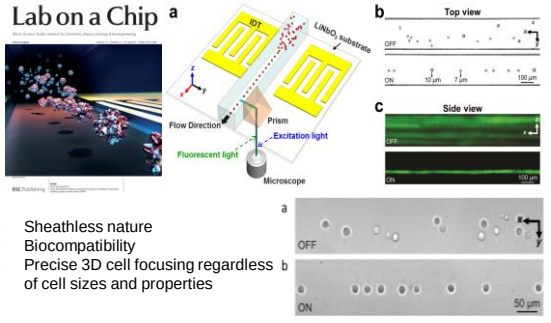
J. Shi, S. Yazdi, S.-C. S. Lin, X. Ding, I-K Chiang, K. Sharp, and T. J. Huang, *Lab on a Chip*, 2011, **11**, 2319-2324.

Experimental Results on 2D Focusing



J. Shi, X. Mao, D. Ahmed, A. Colletti, and T. J. Huang, *Lab on a Chip*, 2008, **8**, 221–223.

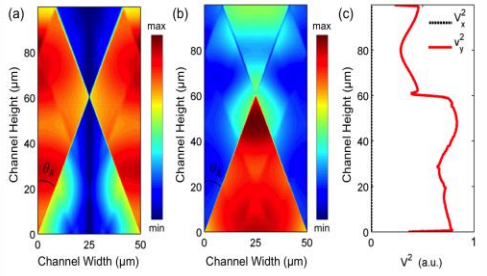
Focusing in Vertical Direction (Experimental Observation)



- Sheathless nature
- Biocompatibility
- Precise 3D cell focusing regardless of cell sizes and properties

J. Shi, S. Yazdi, S.-C. S. Lin, X. Ding, I-K Chiang, K. Sharp, and T. J. Huang, *Lab on a Chip*, 2011, **11**, 2319-2324.

Focusing in Vertical Direction (Theoretical Analysis)



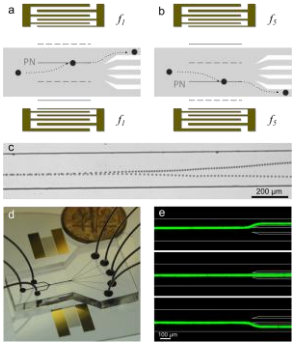
Computational Results: focal point is **46 μm** above the bottom of the channel
Experimental Results: focal point is **42 μm** above the bottom of the channel

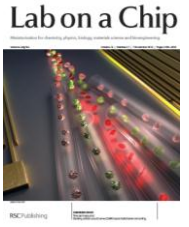
J. Shi, S. Yazdi, S.-C. S. Lin, X. Ding, I-K Chiang, K. Sharp, and T. J. Huang, *Lab on a Chip*, 2011, **11**, 2319-2324.

Device Characterization

A few slides are deleted here since they are unpublished.

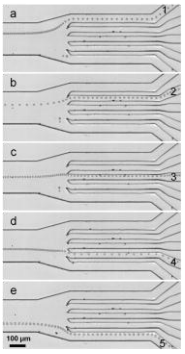
SSAW-Based Multi-Channel Cell Sorting





X. Ding, et al, *Lab on a Chip*, Vol.12, pp. 4228–4231, 2012.

SSAW-Based Multi-Channel Cell Sorting



X. Ding, et al, *Lab on a Chip*, Vol.12, pp. 4228–4231, 2012.

Summary

Functions of Acoustic Tweezers:

- Cell/particle patterning
- Nanomaterial manipulation
- Single particle (cell, organism) manipulation
- Cell/particle separation
- Fluorescence-activated cell sorting (FACS)

Advantages of Acoustic Tweezers:

- Low power intensity —10,000,000 times lower than optical tweezers
- Non-invasive—clean and safe
- Versatility —Applicable to all kinds of bioparticles
- Easy fabrication—low cost
- Conpact device

Biomedical Nano-Electro-Mechanical-Systems (BioNEMS)

—Multi-Physics of Micro/Nano Systems

Multidisciplinary:

Biology
Bioengineering
Chemical engineering
Electrical engineering
Engineering science
Materials science
Mechanical engineering
Physics

Student Awards *(from University to National to International Levels)*:

- ✓ 2009 & 2010 Penn State Alumni Association Dissertation Awards
- ✓ 2009-2013 Rustum and Della Roy Innovation in Materials Research Awards
- ✓ 2010 Fulbright Scholarship
- ✓ 2011 NSF Graduate Fellowship
- ✓ 2011 NASA Research Fellowship
- ✓ 2009 Materials Research Society (MRS) Silver Medal
- ✓ 2008 American Academy of Mechanics (AAM) Founder's Prize
- ✓ 2008 KAUST Scholar Award (world-wide selection)

Awards Received by Huang's Graduate Students

Brian Kiraly, NASA Space Technology Research Fellowships (2011)
Brian Kiraly, NSF Graduate Research Fellowship (2011)
Steven Lin, Rustum and Della Roy Innovation in Materials Research Award, The Pennsylvania State University (2011)
Xiaoyun Ding, Innovation Award in Presentation Competition at the ESM Today Graduate Research Symposium (2011)
Bala Krishna Juluri, First-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2011)
Ahmad Ahsan Nawaz, Second-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2011)
Shahrzad Yazdi, Third-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2011)
Michael Lapsley, Third-Place Prize in Presentation Competition at the ESM Today Graduate Research Symposium (2011)
Daniel Ahmed, Third-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2010)
Yuebing Zheng, Penn State Alumni Association Dissertation Award (2010)
Jinjie Shi, Rustum and Della Roy Innovation in Materials Research Award, The Pennsylvania State University (2010)
Bala Krishna Juluri, Rustum and Della Roy Innovation in Materials Research Award, The Pennsylvania State University (2010)
Michael Lapsley, NASA Space Grant Consortium Fellowship, National Aeronautics and Space Administration (NASA) (2010)
Steven Lin, Theodore Holden Thomas, Jr. Memorial Scholarship, The Pennsylvania State University (2010)
Steven Lin, Student Paper Competition Award, 2010 IEEE International Ultrasonics Symposium
Steven Lin, Theodore Holden Thomas, Jr. Memorial Scholarship, The Pennsylvania State University (2010)
Xiaole Mao, Vilforth Graduate Scholarship, The Pennsylvania State University (2010)
Qingzhen Hao, David C. Duncan Graduate Fellowship, The Pennsylvania State University (2010)
Ahmad Ahsan Nawaz, Fulbright Scholarship, Fulbright Foundation (2010)
Bala Krishna Juluri, Dr. Paul A. Lester Memorial Award, The Pennsylvania State University (2010)
Xiaole Mao, Innovation Award in Presentation Competition at the ESM Today Graduate Research Symposium (2010)
Michael Lapsley, Second-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2010)
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Daniel Ahmed, Third-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2010)
Mengqian Lu, Third-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2010)
Yuebing Zheng, Rustum and Della Roy Innovation in Materials Research Award, The Pennsylvania State University (2009)
Yuebing Zheng, MRS Graduate Student Award, Materials Research Society (MRS) (2009)
Yuebing Zheng, Rustum and Della Roy Innovation in Materials Research Award, The Pennsylvania State University (2009)
Jinjie Shi, Penn State Alumni Association Dissertation Award (2009)
Jinjie Shi, the Sabih and Guler Hayek Graduate Scholarship in Engineering Science and Mechanics (2009)
Bala Krishna Juluri, the Sabih and Guler Hayek Graduate Scholarship in Engineering Science and Mechanics (2009)
Zackary Stratton, The P.B. Breneman Best Design in Research, The Pennsylvania State University (2009)
Daniel Ahmed, Grand Prize in Poster Competition at the ESM Today Graduate Research Symposium (2009)
Jinjie Shi, Second-Place Prize in Poster Competition at the ESM Today Graduate Research Symposium (2009)
Steven Lin, Second-Place Prize in Paper Competition at the ESM Today Graduate Research Symposium (2009)
Michael Lapsley, Third-Place Prize in Presentation Competition at the ESM Today Graduate Research Symposium (2009)
Yuebing Zheng, Honorary Mention in Poster Competition at the ESM Today Graduate Research Symposium (2009)
Yuebing Zheng, American Academy of Mechanics (AAM) Founder's Prize and Grant (2008)
Jinjie Shi, the Sabih and Guler Hayek Graduate Scholarship in Engineering Science and Mechanics (2008)
Michael Lapsley, Harry G. Miller Fellowship in Engineering (2008)
Yuebing Zheng, King Abdullah Scholar Award, King Abdullah University of Science and Technology (2008)
Jinjie Shi, Grand Prize in Paper Competition at the ESM Today Graduate Research Symposium (2008)
Xiaole Mao, Innovation Award in Paper Competition at the ESM Today Graduate Research Symposium (2008)
Yuebing Zheng, First-Place Prize in Paper Competition at the ESM Today Graduate Research Symposium (2008)
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Steven Lin, PSU College of Engineering Fellowship (2007)
John Waldeisen, Outstanding Engineering Science Senior Thesis Award (2007)
Bala Krishna Juluri, PSU College of Engineering Fellowship (2006)

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Penn State BioNEMS Lab (the Huang Group)

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Ph.D. students:
Xiaole Mao, Jinjie Shi, Yuebing Zheng, Steven Lin, Bala Krishna Juluri, Mengqian Lu, Qingzhen Hao, Michael Lapsley, Xiaoyun Ding, Yanhui Zhao, Hua Huang, Bingxin Zhang, Zhangming Mao, Ahmad Ahsan Nawaz, Brian Kiraly, Yuliang Xie, Daniel Ahmed, Sixing Li, Feng Guo, Keith Chan, Yu-Chao Chen, Chandraprakash Chindam, Po-Hsun Huang, Nitesh Nama

Funding Support

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