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AFOSR FINAL REPORT
February 28, 2011

To: <http://afosr.techreport.sgizmo.com>
Subject: Annual Progress Report to Dr. Michael Berman
From: Professor Ahmed Zewail, Caltech

Contract/Grant Title: Imaging Surfaces and Nanostructures
Contract/Grant #: FA9550-07-01-0484
Reporting Period: 1 June 2007 to 30 November 2010

Publications of this research are reported in *Science*, *JACS*, *JPC*, *ChemPhysChem*, *PNAS*, *Nano Lett.*, and *PCCP*. Developmentally, we have advanced ultrafast electron microscopy (and diffraction) to a new level. The electron pulses typically have an energy of 30 keV for diffraction and 100-200 keV for microscopy, corresponding to speeds of 33-70% of the speed of light. Recently, we introduced the concept of tilted optical pulses into diffraction and imaging techniques and demonstrated the methodology experimentally. In a separate contribution, we provided a novel approach for reaching the attosecond time domain. Such attosecond electron pulses are significantly shorter than those achievable with extreme UV light sources near 25 nm (-50 eV) and have the potential for applications in the visualization of ultrafast electron dynamics.

For the applications of UEM (and diffraction), we successfully reported the direct imaging, atomic-scale, of molecular nanocrystals, the phase transition in metal-insulator transitions, the embryonic crystallization following extreme melting, and the discovery of nanogating in quasi-1D materials. We also reported on the theoretical foundation for the phenomena, and research continues in these new directions. Recent highlights are published in *Science*, *Ann. Rev. Phys. Chem.*, and *Phys. Chem. Chem. Phys.* as overviews and reviews (example attached).

Recently, we reported on martensitic phase transformation in iron and two new techniques: convergent beam ultrafast electron diffraction for nano-scale structures and near-field ultrafast electron microscopy for plasmonics. A perspective of the recent developments was published last year as an invited review (see #15 below).

Archival publications (published) during reporting period:

- 1) P. Baum, D.-S. Yang, and A. H. Zewail, "4D Visualization of Transitional Structures in Phase Transformations by Electron Diffraction," *Science* **318**, 788 (2007); see also the Perspective by Andrea Cavalleri, *ibid.* p. 755.
- 2) H. S. Park, J. S. Baskin, O-H. Kwon, and A. H. Zewail, "Atomic-Scale Imaging in Real and Energy Space Developed in Ultrafast Electron Microscopy," *Nano Lett.* **7**, 2545 (2007).
- 3) V. A. Lobastov, J. Weissenrieder, J. Tang, and A. H. Zewail, "Ultrafast Electron Microscopy (UEM): 4D Imaging and Diffraction of Nanostructures during Phase Transitions," *Nano Lett.* **7**, 2552 (2007).
- 4) D. J. Flannigan, V. A. Lobastov, and A. H. Zewail, "Controlled Nanoscale Mechanical Phenomena Discovered with Ultrafast Electron Microscopy," *Angew. Chem. Int. Ed.* **46**, 9206 (2007).

- 5) P. Baum and A. H. Zewail, "Attosecond Electron Pulses for 4D Diffraction and Microscopy," *Proc. Natl. Acad. Sci.* **104**, 18409 (2007).
- 6) I-R. Lee, L. Banares, and A. H. Zewail, "Direct Observation of the Primary Isomerization Dynamics of Stilbene Anion Radical," *J. Am. Chem. Soc.*, **130(21)**, 6708 (2008).
- 7) D. Shorokhov and A. H. Zewail, "4D Electron Imaging: Principles and Perspectives," *Phys. Chem. Chem. Phys.* **10**, 2879 (2008).
- 8) A. Gahlmann, S. T. Park, and A. H. Zewail, "Ultrashort Electron Pulses for Diffraction, Crystallography and Microscopy: Theoretical and Experimental Resolutions," *Phys. Chem. Chem. Phys.* **10**, 2894 (2008).
- 9) F. Carbone, P. Baum, P. Rudolf, and A. H. Zewail, "Structural Pre-ablation Dynamics of Graphite Observed by Ultrafast Electron Crystallography," *Phys. Rev. Lett.* **100**, 035501 (2008).
- 10) P. Baum and A. H. Zewail, "Femtosecond Diffraction with Chirped Electron Pulses," *Chem. Phys. Lett.* **462**, 14 (2008).
- 11) B. Barwick, H. S. Park, O-H. Kwon, J. S. Baskin, and A. H. Zewail, "4D Imaging of Transient Structures and Morphologies in Ultrafast Electron Microscopy," *Science* **322**, 1227 (2008).
- 12) H. S. Park, O-H. Kwon, J. S. Baskin, B. Barwick, and A. H. Zewail, "Direct Observation of Martensitic Phase-Transformation Dynamics in Iron by 4D Single-Pulse Electron Microscopy," *Nano Lett.* **9**, 3954 (2009).
- 13) A. Yurtsever and A. H. Zewail, "4D Nanoscale Diffraction Observed by Convergent-Beam Ultrafast Electron Microscopy," *Science* **326**, 708 (2009).
- 14) B. Barwick, D. J. Flannigan, and A. H. Zewail, "Photon Induced Near-Field Electron Microscopy," *Nature* **462**, 902 (2009).
- 15) A. H. Zewail, "4D Electron Microscopy," *Science (Review)* **328**, 187 (2010).
- 16) A. H. Zewail, "Filming the Invisible in 4D," *Sci. Am.*, **303**, 74 (2010).