LA-UR-97- 3073

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Title:

High-Resolution Electron Microscopy of Advanced Materials

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Submitted to:

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High-Resolution Electron Microscopy of Advanced Materials

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Abstract

This final report chronicles a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The High-Resolution Electron Microscopy Facility has doubled in size and tripled in quality since the beginning of the three-year period. The facility now includes a field-emission scanning electron microscope, a 100 kV field-emission scanning transmission electron microscope (FE-STEM), a 300 kV field-emission high-resolution transmission electron microscope (FE-HRTEM), and a 300 kV analytical transmission electron microscope. A new orientation imaging microscope is being installed. X-ray energy dispersive spectrometers for chemical analysis are available on all four microscopes; parallel electron energy loss spectrometers are operational on the FE-STEM and FE-HRTEM. These systems enable evaluation of local atomic bonding, as well as chemical composition in nanometer-scale regions. The FE-HRTEM has a point-to-point resolution of 1.6 Å, but the resolution can be pushed to its information limit of 1 Å by computer reconstruction of a focal series of images. HRTEM has been used to image the atomic structure of defects such as dislocations, grain boundaries, and interfaces in a variety of materials from superconductors and ferroelectrics to structural ceramics and intermetallics.

Background and Research Objectives

Direct imaging of atomic structures is already possible at near 1 Å spatial resolution by transmission electron microscopy (TEM); chemical analysis is also approaching atomic spatial resolution, so that labeling individual atoms is becoming a reality. Electron microscopy (EM) is a vital characterization tool for relating structure to the other three corners of the materials science and engineering tetrahedron: processing, properties, and performance. This has become increasingly true with the shrinking scale and increasing complexity of structural and electronic components. Therefore, the Electron Microscopy Facility (EMF) is a key part of the Laboratory's efforts in the broad area of materials science research. The EMF was significantly expanded in 1988 with the installation of

- two state-of-the-art transmission electron microscopes,
- a Philips CM30 analytical electron microscope (AEM), and

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- a Philips CM30st high-resolution transmission electron microscope (HRTEM) to go with the existing Camscan scanning electron microscope (SEM).

Over the years, analytical capabilities were added in the form of

- Kevex energy dispersive X-ray spectroscopy (EDS) for the AEM and SEM;
- a Gatan parallel electron energy loss spectrometer (PEELS), also for the AEM;
- a Dingley camera for orientation determination in texture analysis for the SEM; and
- various image processing, enhancement, and computing features for the HRTEM.

This was the situation at the beginning of the three-year, Laboratory Directed Research and Development (LDRD) project period. With the occupancy of the Materials Science Laboratory (MSL) at Los Alamos, we were then in a unique position to make a dramatic advance in our EM capabilities. For example, we have installed three new instruments based on field-emission (FE) electron source technology:

- a JEOL JEM3000F field-emission high resolution transmission electron microscope (FE-HRTEM),
- a VG HB-601 field-emission scanning transmission electron microscope (FE-STEM), and
- a JEOL JSM6300FXV field-emission scanning electing microscope (FE-SEM).

All three instruments are operational and performing in a spectacular fashion.

There is nothing particularly new about the FE source itself. It has stringent vacuum requirements that have tended to make it incompatible with regular EM. VG built their FEG-STEM many years ago, starting with a UHV system; the STEM performed brilliantly but was not very user-unfriendly. However, they have finally developed a new unit, the HB-601, which is reasonably friendly and, more importantly, is capable of both high-resolution imaging (by Z contrast imaging) and fine probe chemical analysis by using installed EDS and PEELS systems. The FE-SEM is fairly straightforward because of the modest voltages (30 kV) needed for an SEM; vacuum problems have been solved by having small apertures between the specimen chamber and the FE source. Resolution is approximately 15 Å at 30 kV and approximately 50 Å at 1 kV (a tremendous advantage for imaging nonconducting ceramics and polymers without the need for coating). A PGT EDS system has been added for chemical analysis.

The FE-HRTEM has been the most difficult to develop because of the higher voltages involved (300 kV). The impetus to finding a solution was provided by the Brite Euram project in the late eighties, whereby Philips cooperated with several European universities (Delft, Tübingen, and Antwerp), with later involvement from AT&T Bell Labs. The critical components of the project are the FE source itself, the special stable specimen stage, the ultra-high-resolution objective pole-piece, and the image retrieval system. JEOL

and Hitachi developed their own instruments, and after a competitive bidding process we opted for the JEOL design. This turned out to be a felicitous decision because Philips delivered the Antwerp machine two years later and are still having problems with the high-resolution objective lens. The upshot is that 1 Å microscopy is at hand and that Los Alamos has jumped to the forefront of this exciting new development.

The FE source is a key component in all these new instruments. The importance of field emission is that it provides a much brighter source, a smaller virtual source, a smaller intense probe, and a coherent beam of electrons for holography and high-resolution applications. These instruments have provided a quantum jump in our capabilities for atomic-level structural and chemical analysis of features such as grain boundaries, interfaces, and dislocations in advanced materials. It is our intention to develop these facilities to their fullest extent for the characterization of defects in materials such as ceramics, intermetallics, composites, superconductors, and electronic materials.

Importance to LANL's Science and Technology Base and National R&D Needs

The new instruments for the EMF have enormous potential for impact on various existing and future materials science activities at Los Alamos. The facility is the equal of or better than any other in the world, including at any other national laboratory. We will be able to image with 1 Å structural resolution and perform chemical analysis and imaging at the 5-10 Å level. The objective of this research is to establish a world-class EMF. This is not simply a matter of making the new instruments available and training new operators. It is also necessary to develop new techniques and to optimize procedures that are at the cutting edge of EM instrumentation. For the FE-HRTEM, we propose to develop image-processing and image-computation systems to realize the true atomic-scale capabilities of the microscope. For the FE-STEM, we plan to utilize very high vacuum capabilities to optimize the analytical capabilities at the 5-10 Å level, as well as to optimize the so-called Z contrast method to image atomic planes in materials such as superconductors. For the FE-SEM, surface imaging at the 10 Å level will be taken advantage of, as well as its superior X-ray analytical capabilities. Applications will cover the full range of materials problems associated with the Los Alamos Center for Materials Science (CMS) competency development in advanced materials and processing. As such, the facility is of enormous importance to the Laboratory's science and technology base and national R&D needs in the full range of materials science research, both in the defense and energy research arenas.

Scientific Approach and Accomplishments

The FE-SEM, FE-STEM, and FE-HRTEM are all fully operational in the MSL. The existing HRTEM has been traded in for a new orientation imaging microscope, which is basically an SEM with a Dingley camera such that grains in textured materials can be automatically oriented and displayed in color according to closely matched orientations. The AEM has been moved to the EMF in the MSL. We have installed new or upgraded EDS systems for the various SEMs and TEMs; these are being networked via Ethernet. Networking in a practical way has been talked about for years but only now has become the norm. The EDS systems are all now based on workstations or PCs or MACs; therefore, networking the EDS systems, the central computer system, and individual computer systems has become a reality. In fact, for the JEOL JSM-6300FXV, which has digitized image storage and processing, printing is achieved on a dye-sublimation printer and film has been totally eliminated. Networking has become routine for down- and up-loading images, as has remote operation. This also has now been achieved with the JEOL JEM-3000F FE-HRTEM, which has a Gatan multi-scan ccd camera and associated image processing software on a Macintosh. Auto-tuning software has also been installed such that the computer on the microscope can be accessed and automatic stigmation and voltage centering can be achieved with a suitable amorphous image (via fast Fourier transform operations).

We have completely upgraded the old PEELS to Digi-PEELS and have transferred it over to the FE-HRTEM to take advantage of its superior fine-probe capability and its superior energy spread. A separate PEELS has been installed on the FEG-STEM, where there are no contamination problems in the high vacuum and the energy stability is potentially even better (the zero loss peak is presently wider than it should be because of a small voltage fluctuation problem that has to be cured). It is important to appreciate that the generally accepted resolution in a HRTEM is determined by the spherical aberration coefficient, C_s , of the objective lens; the best C_s available for a 300 kV microscope is ~ 0.7 mm, giving a resolution of ~ 1.7 Å. However, for a FE source, the beam is highly coherent and there is information in the diffracted beams out to approximately 1 Å. The phase of this information (contrast transfer function, or CTF) is oscillating rapidly in this region, making interpretation difficult; however, computing techniques are being developed to extract meaningful information out to the 1 Å level. One method is to take a focal series around the so-called Lichte focus, where the CTF is oscillating at a minimal rate; computer programs have been developed by the Antwerp group (Van Dyck, et al.) to take a focal series of 20 digitized micrographs and extract a map of the projected potential, which

represents the atomic positions. There is also a joint project between Michael O'Keefe at Lawrence Berkeley National Laboratory and Ondrej Krivanek at Gatan to design an improved program along the same lines. The interest will be to use this for atomic distributions around dislocations, interfaces, and other defects.

The techniques developed for high-resolution structural and chemical imaging have been applied to a variety of problems in the areas of advanced materials and processing. The applications have involved dislocations, grain boundaries, interfaces, and other defects in ceramics, intermetallics, composites, multilayers, superconductors, and electronic materials. We have found it valuable to maintain close interaction with the materials modeling community. This has been particularly true for the assessment of atomic arrangements around defects in which the observations have been compared with calculations and used to feed back information for improved interatomic potentials. Examples of applications are found in the publications list given below.

Publications

1. M. M. Chadwick, J. J. Petrovic, S. C. Danforth, and T. E. Mitchell, "Topotactic Growth of Si_2ON_2 on SiC ," *Acta Metall. Mater.* **41**, 375-386 (1993).
2. Unal, J. J. Petrovic, and T. E. Mitchell, "Mechanical Properties of Hot Isostatically Pressed Si_3N_4 and $\text{Si}_3\text{N}_4/\text{SiC}$ Composites," *J. Mater. Res.* **8**, 626-634 (1993).
3. H. Suematsu, J. J. Petrovic, and T. E. Mitchell, "Deformation and Toughness of α -Silicon Nitride Single Crystals," in *Silicon Nitride Ceramics Scientific and Technological Advances*, I-Wei Chen, P. F. Becher, M. Mitomo, G. Petzow, and T-S Yen, eds., Mat. Res. Soc. Symp. Proc. Vol. 287, 449-454 (1993).
4. I. E. Reimanis, J. J. Petrovic, H. Suematsu, T. E. Mitchell, and O. S. Leung, "The Mechanical Properties of a Novel Si_3N_4 - Amorphous Si_3N_4 Composite," in *Silicon Nitride Ceramics Scientific and Technological Advances*, I-Wei Chen, P. F. Becher, M. Mitomo, G. Petzow, and T-S Yen, eds., Mat. Res. Soc. Symp. Proc. Vol. 287, 499-504 (1993).
5. S. A. Maloy, J. J. Petrovic, and T. E. Mitchell, "Dislocation Decomposition and Dissociation in Molybdenum Disilicide," Proc. 51st Annual Meeting, Microscopy Society of America, G. W. Bailey and C. L. Rieder, eds., San Francisco Press, 912-913 (1993).
6. H. Suematsu, J. J. Petrovic, and T. E. Mitchell, "Stacking Faults in Deformed α -Silicon Nitride Single Crystals," Proc. 51st Annual Meeting, Microscopy Society of America, G. W. Bailey and C. L. Rieder, eds., San Francisco Press, 916-917 (1993).
7. S. A. Maloy, T. E. Mitchell, J. J. Lewandowski, and A. H. Heuer, " $\{103\}<331>$ Slip in MoSi_2 ," *Phil. Mag. Lett.* **67**, 313-321 (1993).

8. E. A. Mathez, J. D. Blacic, C. Maggiore, and T. E. Mitchell, "The Determination of Oxygen Content of Diamond by Microactivation," *American Mineralogist* **78**, 753-761 (1993).
9. A. H. Carim and T. E. Mitchell, "90° Boundaries and Associated Interfacial and Stand-off Dislocations in YBa₂Cu₃O_{7-δ}," *Ultramicroscopy* **51**, 228-238 (1993).
10. H. Suematsu, J. J. Petrovic, T. E. Mitchell, and T. Yano, "Interfacial Structure of Si₃N₄ brazed with a Ag-Cu-Ti alloy," *Ceram. Trans.* **35**, 59-68 (1993).
11. H. Kung, M. Nastasi, T. R. Jervis, K. M. Hubbard, R. M. Messner, T. E. Mitchell, and J. D. Embury, "The Structure and Mechanical Properties of Ru-Cu and Ru-Ti Nanolayer Composites," in *Thin Films: Stresses and Mechanical Properties IV*, P. H. Townsend, T. P. Weihs, J. E. Sanchez, and P. Borgesen, eds., Mater. Res. Soc. Proc., Vol. 308, 747-752 (1993).
12. T. E. Mitchell and S. A. Maloy, "Plastic Anisotropy in MoSi₂ Single Crystals," in "Critical Issues in the Development of High Temperature Structural Materials", N. S. Stoloff, D. J. Duquette and A. F. Giamei, eds., The Minerals, Metals and Materials Society, 279-290 (1993).
13. T. E. Mitchell, "Phase Transformations in Superconducting and Non-Superconducting Perovskites," in Proc. *International Conference on Phase Transformations*. (ICOMAT-92), C. M. Wayman and J. Perkins, eds., Monterey Inst. for Advanced Studies, 725-730 (1993).
14. K. P. D. Lagerlof, A. H. Heuer, J. Castaing, J. P. Riviere, and T. E. Mitchell, "Slip and Twinning in Sapphire (α-Al₂O₃)," *J. Amer. Ceram. Soc.* **77**, 385-397 (1994).
15. H. Kung, T. R. Jervis, J.-P. Hirvonen, M. Nastasi, and T. E. Mitchell, "Characterization of Structure and Mechanical Properties of MoSi₂-SiC Nanolayer Composites," in *High Temperature Silicides and Refractory Alloys*, C. L. Bryant, J. J. Petrovic, B. P. Bewlay, A. K. Vasudevan, and H. A. Lipsitt, eds., Mater. Res. Soc. Vol. **322**, 27-32 (1994).
16. S. A. Maloy, T. E. Mitchell, and J. J. Petrovic, "The Temperature and Strain Rate Dependence of the Flow Stress in MoSi₂ Single Crystals," in *High Temperature Silicides and Refractory Alloys*, C. L. Bryant, J. J. Petrovic, B. P. Bewlay, A. K. Vasudevan, and H. A. Lipsitt, eds., Mater. Res. Soc. Vol. **322**, 21-26 (1994).
17. P. Tiwari, X. D. Wu, M. Q. Lee, S. R. Foltyn, M. Q. Lee, I. H. Campbell, R. C. Dye, R. E. Muenchausen, J. F. Smith, and T. E. Mitchell, "Study of Low Resistivity Oxides on Pt/MgO," *Phil. Mag. B* **69**, 1101-1110 (1994).
18. T. E. Mitchell and S. A. Maloy, "Structure of Dislocations in MoSi₂," in *Electron Microscopy 1994*, Proc. 13th International Congress on Electron Microscopy, B. Jouffrey and C. Colliex, eds., Les Edition de Physiques, Les Ulis, Vol. 2A, 89-90 (1994).

19. H. Kung, T. R. Jervis, J-P Hirvonen, M. Nastasi, T. E. Mitchell, and J.D. Embury, "Phase Transformation and Layer Evolution in Molybdenum Disilicide-Silicon Carbide Nanolayered Coatings," Proceedings, 52nd Annual Meeting, Microscopy Society of America, G. W. Bailey and A. J. Garratt-Reed, eds., San Francisco Press, 538-539 (1994).
20. D. S. Zhou and T. E. Mitchell, "Grown-in Defects in CVD α -Si₃N₄," Proceedings, 52nd Annual Meeting, Microscopy Society of America, G. W. Bailey and A. J. Garratt-Reed, eds., San Francisco Press, 640-641 (1994).
21. F. Chu, D. P. Pope, D. S. Zhou, and T. E. Mitchell, "Morphology of $\Sigma 3\{<110>/70.53^\circ\}$ Grain Boundaries in a C15 Intermetallic Compound," Proceedings, 52nd Annual Meeting, Microscopy Society of America, G. W. Bailey and A. J. Garratt-Reed, eds., San Francisco Press, 684-685 (1994).
22. O. Unal, T. E. Mitchell, and A. H. Heuer, "Microstructures of Y₂O₃-Stabilized ZrO₂ Electron Beam-Physical Vapor Deposition Coatings on Ni-Base Superalloys," *J. Amer. Ceram. Soc.* **77**, 984-992 (1994).
23. F. Chu, M. Lei, A. Migliori, S. P. Chen, and T. E. Mitchell, "Anomalous Elastic Properties in a C16 Laves Compound," *Phil. Mag. B* **70**, 867-880 (1994).
24. F. Chu, M. Sob, R. Siegl, T. E. Mitchell, D. P. Pope, and S. P. Chen, "Total Energy and Electronic Structure Calculations of C15 Laves Phase Compounds MV₂ (M = Zr, Hf and Ta): Elastic Properties," *Phil. Mag. B* **70**, 881-892 (1994).
25. T. R. C. Fernandez, W. E. Lee, and T. E. Mitchell, "Microstructural Aspects of the Reduction of Zimbabwe Chromite to High Carbon Ferrochromium," *Trans. Instn. Min. Metall.* **103**, C177-C187 (1994).
26. I. E. Reimanis, J. J. Petrovic, and T. E. Mitchell, "The Fracture Behavior of Single Crystal Y₃Al₅O₁₂," *J. Non-Crystalline Solids* **177**, 67-73 (1994).
27. P. Tiwari, X. D. Wu, S. R. Foltyn, Q. X. Jia, I. H. Campbell, P. A. Arendt, R. E. Muenchhausen, T. E. Mitchell, and J. Narayan, "Synthesis of Epitaxial Pt on (100)Si using TiN Buffer Layer by Pulsed Layer Deposition," *Appl. Phys. Lett.* **65**, 2693-2695 (1994).
28. I. E. Reimanis, J. J. Petrovic, H. Suematsu, and T. E. Mitchell, "The Mechanical Properties of Single Crystal α -Si₃N₄," in *Silicon Based Structural Ceramics*, Ceramic Trans. Vol. **42**, B. W. Sheldon and S. C. Danforth, eds., American Ceramic Society, 229-236 (1995).
29. I. E. Reimanis, J. J. Petrovic, H. Suematsu, and T. E. Mitchell, "The Fracture Behavior of a CVD Crystalline Si₃N₄/Amorphous Si₃N₄ Composite," in *Silicon Based Structural Ceramics*, Ceramic Trans. Vol. **42**, B. W. Sheldon and S. C. Danforth, eds., American Ceramic Society, 277-283 (1995).
30. S. A. Maloy, T. E. Mitchell, and A. H. Heuer, "High Temperature Plastic Anisotropy in MoSi₂ Single Crystals," *Acta Met. Mater.* **43**, 657-668 (1995).

31. F. Chu, T. E. Mitchell, S. P. Chen, M. Sob, R. Siegl, and D. P. Pope, "Experimental and Theoretical Studies on the C15 Intermetallic Compounds MV_2 ($M=Zr, Hf$ and Ta): Elasticity and Phase Stability," in *High Temperature Ordered Intermetallic Alloys VI*, J. A. Horton, I. Baker, S. Hanada, R. D. Noebe, and D. S. Schwartz, eds., Materials Research Society, Vol. 364, 1389-1394 (1995).
32. F. Chu, D. J. Thoma, Y. He, T. E. Mitchell, S. P. Chen, and J. H. Perepezko, "Theoretical and Experimental Studies on the C15 Intermetallic Compound $NbCr_2$," in *High Temperature Ordered Intermetallic Alloys VI*, J. A. Horton, I. Baker, S. Hanada, R. D. Noebe, and D. S. Schwartz, eds., Materials Research Society, Vol. 364, 1389-1394 (1995).
33. F. Chu, M. Lei, S. A. Maloy, T. E. Mitchell, A. Migliori, and J. Garrett, "Single Crystal Elastic Constants of $C40 NbSi_2$," *Phil. Mag. B* 71, 373-382 (1995).
34. T. E. Mitchell, M. Nastasi, T. R. Jarvis, and H. Kung, "Synthesis, Structure and Mechanical Properties of Nanolayered Composites of Mo , $MoSi_2$, $MoSi_2N_x$ and SiC ," in *Novel Techniques in Synthesis and Processing of Advanced Materials*, J. Singh and S. Copley, eds., TMS, Warrendale, PA, 271-281 (1995).
35. H. Kung, T. R. Jarvis, J.-P. Hirvonen, J. D. Embury, T. E. Mitchell, and M. Nastasi, "Structure and Mechanical Properties of $MoSi_2$ - SiC Nanolayer Composites," *Phil. Mag. A* 71, 759-779 (1995).
36. P. Tiwari, X. D. Wu, S. R. Foltyn, R. E. Muenchausen, P. A. Arendt, I. H. Campbell, Q. X. Jia, D. E. Peterson, T. E. Mitchell, D. Face, and D. B. Laubacher, "High-quality Epitaxial YBCO Thin Films Directly on $LiNbO_3$," *Phil. Mag. B* 71, 903-912 (1995).
37. H. Kung, T. R. Jarvis, J.-P. Hirvonen, T. E. Mitchell, and M. Nastasi, "High Temperature Structural Stability of $MoSi_2$ -Based Nanolayer Composites," *J. Vac. Sci. Tech. A* 13, 1126-1129 (1995).
38. T. Yano, M. Ikari, T. Iseki, E. H. Farnum, F. W. Clinard, Jr., and T. E. Mitchell, "Effect of Neutron Irradiation on Knoop Hardness Anisotropy in $MgO.3Al_2O_3$ Single Crystal," *J. Amer. Ceram. Soc.* 78 (6), 1469-74 (1995).
39. S. A. Maloy, S-Q Xiao, A. H. Heuer, and J. Garrett, "Precipitation of Mo_5Si_3 in $MoSi_2$," *J. Mater. Res.* 8(5), 1079-1085, (1993).
40. D.P. Butt, S. A. Maloy, H. Kung, D. A. Korzekwa, and J. J. Petrovic, "Creep Behavior of $MoSi_2$ - SiC Composites," *Mat. Res. Soc. Symp. Proc.*, Vol. 322, 197-202 (1994).
41. S. A. Maloy, G. T. Gray III, and R. Darolia, "High Strain Rate Deformation of $NiAl$," *Mat. Sci. and Engrg.* vol. A192/193, pp. 249-254 (1995).
42. S. A. Maloy and G. T. Gray, III, "The Temperature and Strain Rate Dependence of the Flow Stress of Single Crystal $NiAl$ Deformed along $\langle 110 \rangle$," *Mat. Res. Soc. Symp. Proc.*, vol. 364, pp. 549-554, (1995).

43. S-Q. Xiao, S. A. Maloy, A. H. Heuer, and U. Dahmen, "Morphology and Interface Structure of Mo₅Si₃ Precipitates in MoSi₂," *Phil. Mag A* **72**[4], pp. 997-1013, (1995).
44. S. A. Maloy, G. T. Gray, III, "High Strain Rate Deformation of Ti-48Al-2Nb-2Cr in the Duplex Morphology" in *Gamma Titanium Aluminides*, ed. by Y-W Kim, R. Wagner, and M. Yamaguchi, TMS, Warrendale, PA, pp. 307-314 (1995).
45. D. P. Butt, D. A. Korzekwa, S. A. Maloy, H. Kung, and J. J. Petrovic, "Impression Creep Behavior of SiC particle-MoSi₂ Composites," *J. Mat. Res.* **11**[6], p. 1, (1996).
46. S. A. Maloy and G. T. Gray, III, "High Strain Rate Deformation of Ti-48Al-2Nb-2Cr," *Acta Materialia* **44**[5], pp. 1741-1756, (1996).
47. Q. X. Jia, X. D. Wu, S. R. Foltyn, D. Reagor, M. Hawley, K. N. Springer, P. Tiwari, C. Mombourquette, R. J. Houlton, I. H. Campbell, H. Kung, T. E. Mitchell, and D. E. Peterson, "Fabrication and Characterization of High Temperature Superconductor Josephson Junctions with A Novel Design," *IEEE Trans. Appl. Supercond.* **5**, 2103-2106 (1995).
48. M. Yan, S. P. Chen, T. E. Mitchell, D. H. Gray, S. Yyas, and R. W. Grimes, "Atomistic Study of Energy and Structure of Surfaces in NiO," *Phil. Mag. A* **72**, 121-138 (1995).
49. D. S. Zhou, Q. X. Jia, X. D. Wu, and T. E. Mitchell, "TEM Investigation of the YSZ-on-Insulator Structure," *Proc. Microscopy and Microanalysis 1995*, G. W. Bailey, M. H. Ellisman, R. A. Hennigar, and N. J. Zaluzec, eds., New York, Jones and Begell Publishing, 472-473 (1995).
50. C. L. Chen, S. G. Song, T. E. Mitchell, G. T. Gray, III, and T. T. Tsong, "Direct Observation of Mechanical Twinning in Pure Iridium," *Proc. Microscopy and Microanalysis 1995*, G. W. Bailey, M. H. Ellisman, R. A. Hennigar, and N. J. Zaluzec, eds., New York, Jones and Begell Publishing, 522-523 (1995).
51. F. Chu and T. E. Mitchell, "TEM Investigation of the Low Temperature Phase of HfV₂," *Proc. Microscopy and Microanalysis 1995*, G. W. Bailey, M. H. Ellisman, R. A. Hennigar, and N. J. Zaluzec, eds., New York, Jones and Begell Publishing, 252-253 (1995).
52. H. Kung, T. R. Jervis, J. -P. Hirvonen, T. E. Mitchell, and M. Nastasi, "The Influence of Nitrogen on the Stability of Nanophase Molybdenum Disulfide," *Proc. Microscopy and Microanalysis 1995*, G. W. Bailey, M. H. Ellisman, R. A. Hennigar, and N. J. Zaluzec, eds., New York, Jones and Begell Publishing, 190-191 (1995).
53. F. Chu, Y. He, D. J. Thoma, and T. E. Mitchell, "Elastic Constants of the C15 Laves Phase Compound NbCr₂," *Scripta Met. Metall.* **33**, 1295-1300 (1995).
54. F. Chu, A. H. Ormeci, T. E. Mitchell, J. M. Willis, D. J. Thoma, R. C. Albers, and S. P. Chen, "Stacking Fault Energy of the NbCr₂ Laves Phase," *Phil. Mag. Lett.* **72**, 147-153 (1995).

55. D. S. Zhou, C. L. Chen, T. E. Mitchell, L. B. Hackenberger, and R. Messier, "Thin Films of Cubic Boron Nitride on Silicon," *Phil. Mag. Lett.* **72**, 163-166 (1995).
56. I. E. Reimanis, M. E. Hawley, T. E. Mitchell, and D. S. Zhou, "The Fracture Characteristics of Czochralski-grown $Y_3Al_5O_{12}$," *J. Amer. Ceram. Soc.* **78**, 2282-2286 (1995).
57. D. S. Zhou and T. E. Mitchell, "Dislocations in as-Grown CVD α -Silicon Nitride," *J. Amer. Ceram. Soc.* **78**, 3133-3136 (1995).
58. D. S. Zhou and T. E. Mitchell, "Rotation Domains in α -Silicon Nitride," *Phil. Mag. A* **72**, 1131-1140 (1995).
59. F. Chu, S. P. Chen, T. E. Mitchell, D. P. Pope, and C. T. Liu, "C15 Intermetallic Compounds HfV_2+Nb ," Proc. Second IUMRS Int. Conf. in Asia, C.-M. Wang, T.-P. Perng, and J.-Y. Hsu, eds., MRS-Taiwan, Chutung, pp. 397-402 (1995).
60. Q. X. Jia, X. D. Wu, D. S. Zhou, S. R. Foltyn, P. Tiwari, D. E. Peterson, and T. E. Mitchell, "Deposition of Epitaxial YSZ on Single-Crystal Si and Subsequent Growth of an Amorphous SiO_2 Interlayer," *Phil. Mag. Lett.* **72**, 385-391 (1995).
61. Q. X. Jia, D. S. Zhou, X. D. Wu, S. R. Foltyn, P. Tiwari, and T. E. Mitchell, "Characterization of $Ba_{0.5}Sr_{0.5}TiO_3$ Thin Film Capacitors Produced by Pulsed Laser Deposition," *Integrated Ferroelectrics* **10**, 73-79 (1995).
62. D. S. Zhou and T. E. Mitchell, "Atomic Structures of a Stacking Fault and a Domain Boundary in α -Silicon Nitride," *J. Microsc. Soc. Amer.* **1**, 263-266 (1995).
63. P. Tiwari, X. D. Wu, S. R. Foltyn, I. H. Campbell, and T. E. Mitchell, "Synthesis of Low Resistivity Complex Oxides on MgO using Pt as Buffer Layer," *J. Electronic Mater.* **25**, 51-55 (1996).
64. P. Tiwari, X. D. Wu, S. R. Foltyn, R. E. Muenchausen, and T. E. Mitchell, "Study of High Quality YBCO Thin Films Grown Directly on Y-cut $LiNbO_3$," *J. Electronic Mater.* **25**, 131-135 (1996).
65. S. G. Song, C. L. Chen, T. E. Mitchell, L. B. Hackenburger, and R. Messier, "Observation of Nano-scale Epitaxial Growth of Diamond on the Si (100) Surface," *J. Appl. Phys.* **79**, 1813 (1996).
66. C. L. Chen, T. T. Tsong, and T. E. Mitchell, "Surface Diffusion and Surface Atomic Roughness on Ir (001) Surface and Terraces," *Appl. Surf. Sci.* **94/95**, 224-230 (1996).
67. I. E. Reimanis, J. J. Petrovic, H. Suematsu, and T. E. Mitchell, "A Crystalline Si_3N_4 /Amorphous Si_3N_4 Composite," *J. Amer. Ceram. Soc.* **79**, 395-400 (1996).
68. H. Kung, T. R. Jervis, J.-P. Hirvonen, T. E. Mitchell, and M. Nastasi, "Synthesis, Structure and Mechanical Properties of Nanostructured $MoSi_2N_x$," *Nanostruct. Mater.* **7**, 81-88 (1996).

69. S. A. Maloy and T. E. Mitchell, "Dislocation Decomposition, Dissociation, and Deformation in MoSi_2 and $\alpha\text{-Al}_2\text{O}_3$ Single Crystals," in *Plastic Deformation of Ceramics*, R. C. Bradt, C. A. Brookes, and J. L. Routbort, eds., Plenum Press, New York, pp. 53-62 (1996).
70. F. Chu, Ming Lei, S. A. Maloy, J. J. Petrovic, and T. E. Mitchell, "Elastic Properties of C40 Transition Metal Disilicides," *Acta Metall. Mater.* **44**, 3035-3048 (1996).
71. H. Suematsu, J. J. Petrovic, and T. E. Mitchell, "Plastic Deformation of Silicon Nitride Single Crystals," *Mater. Sci. Eng. A* **209**, 97-102 (1996).
72. F. Chu, D. P. Pope, and T. E. Mitchell, "Phase Stability and Elastic Properties of C15 Compounds HfV_2+Nb ," in *Mechanical Properties and Phase Transformations of Multi-Phase Intermetallic Compounds*, A. F. Giamei, K. Inoue, and Y. Mishima, eds., TMS, Warrendale, PA, 17-24 (1996).
73. H. Kung, A. J. Griffin, Y. C. Lu, K. E. Sickafus, T. E. Mitchell, J. D. Embury, and M. A. Nastasi, "The Stabilization of B.C.C. Cu in Cu/Nb Nanolayered Composites," Proc. Microscopy and Microanalysis 1996, G. W. Bailey, J. M. Corbett, R. V. W. Dimlich, J. R. Michael, and N. J. Zaluzec, eds., San Francisco Press, 228-229 (1996).
74. P. G. Kotula, I. M. Anderson, F. Chu, T. E. Mitchell, and J. Bentley, "ALCHEMI of NbCr₂/V C15-structured Laves Phase," Proc. Microscopy and Microanalysis 1996, G. W. Bailey, J. M. Corbett, R. V. W. Dimlich, J. R. Michael, and N. J. Zaluzec, eds., San Francisco Press, 554-555 (1996).
75. I. E. Reimanis, H. Suematsu, J. J. Petrovic, and T. E. Mitchell, "The Properties of Single Crystal Si_3N_4 ," *J. Amer. Ceram. Soc.* **79**, 2065-2073 (1996).
76. C. L. Chen, D. Zhou, T. E. Mitchell, and H. Q. Ye, "Direct Observation of $\beta\text{-TaH}$ Precipitation in Tantalum-Hydrogen Solution," *J. Vac. Sci. Tech.* **14**, 2551-2553 (1996).
77. Q. X. Jia, F. Chu, C. D. Adams, X. D. Wu, M. Hawley, J. H. Cho, A. T. Findikoglu, S. R. Foltyn, J. L. Smith, and T. E. Mitchell, "Characteristics of Conductive SrRuO_3 Thin Films with Different Microstructures," *J. Mater. Res.* **11**, 2263-2268 (1996).
78. A. Ormeci, F. Chu, J. M. Wills, T. E. Mitchell, R. C. Albers, D. J. Thoma, and S. P. Chen, "A Total-Energy Study of Electronic Structure and Mechanical Behavior of C15 Laves Phase Compounds: NbCr_2 and HfV_2 ," *Phys. Rev. B* **54**, 12753-12762 (1996).
79. H.W. Sizek and G.T. Gray, III, "Deformation of Polycrystalline Ni_3Al at High Strain Rates and Elevated Temperatures," *Acta Metallurgica Materiala* **41**, 1855-1860 (1993).
80. S.I. Hong, G.T. Gray, III, and J.J. Lewandowski, "Dynamic Deformation Behavior of an Al-Zn-Mg-Cu Alloy Matrix Composite Reinforced with 20 vol. % SiC ," *Acta Metallurgica Materiala* **41**, 2337-2351 (1993).

81. J. C. Huang, Y.-S. Lo, and G. T. Gray, III, "The Response of Metal-matrix Composites Subjected to Quasi-static and Shock-wave Deformation," *Materials Chemistry and Physics* **35**, 71-85 (1993).
82. G. T. Gray, III, S. I. Hong, and B. J. Marquardt, "Influence of Strain Rate on the Structure/Property Behavior of the Alpha-2 Alloy Ti-24.5Al-10.5Nb-1.5Mo," *Titanium '92 - Science and Technology*, edited by F. H. Froes and I. L. Caplan, TMS, Warrendale, PA (1993), pp. 1163-1170.
83. S. I. Hong, G. T. Gray, III, and J. J. Lewandowski, "Microstructural Evolution in an Al-Zn-Mg-Cu Alloy-20 vol.% SiC Composite Shock-Loaded to 5 Gpa," *Scripta Metall.* **27**, 431-436 (1992).
84. S. I. Hong, G. T. Gray, III, and K. S. Vecchio, "Quenching and thermal cycling Effects in a 1060-Al Matrix-10 vol. % Al₂O₃ Particulate Reinforced Metal Matrix Composite," *Matls. Sci. and Eng. A* **171**, 181-189 (1993).
85. S. I. Hong and G. T. Gray, III, "Dynamic Mechanical Response of a 1060-Al / Al₂O₃ Composite," *J. Mat. Sci.* **29**, 2987-2992 (1994).
86. S. Song and G. T. Gray, III, "Omega Phase Formation in Shock-Loaded Zirconium," *High-Pressure Science and Technology-1993*, edited by S. C. Schmidt, J. W. Shaner, G. A. Samara, and M. Ross, American Institute of Physics, AIP Conf. Proceedings 309 (1994), pp. 251-254.
87. S. I. Wright, A. J. Beaudoin, and G. T. Gray, III, "Texture Gradient Effects in Tantalum," *Materials Science Forum*, **157-162**, 1695-1700 (1994).
88. S. G. Song and G. T. Gray, III, "TEM Examination and Analysis of a New Type of Stacking Fault in HCP Metals," *Philos. Mag. A* **71**, 263-274 (1995).
89. S. I. Wright, G. T. Gray, III, and A. D. Rollett, "Textural and Microstructural Gradient Effects on the Mechanical Behavior of a Tantalum Plate," *Metall. & Matls. Trans. A* **25A**, 1025-1031 (1994).
90. D. Albert and G. T. Gray, III, "A Determination of Deformation Twinning in Dynamically Deformed and Shock-Loaded Polycrystalline Ni₃Al," *Philos. Mag. A* **70**, 145-158 (1994).
91. S. Song and G. T. Gray, III, "Structural Interpretation of the Nucleation and Growth of Deformation Twins in Zr and Ti - I. Application of the Coincidence Site Lattice (CSL) Theory to Twinning Problems in hcp Structures," *Acta Metallurgica et Materialia*, Vol. 43, No.6, 2325-2337 (1995).
92. S. Song and G. T. Gray, III, "Structural Interpretation of the Nucleation and Growth of Deformation Twins in Zr and Ti - II. TEM Study of Twin Morphology and Defect Reactions during Twinning," *Acta Metallurgica et Materialia*, vol.43, No. 6, 2339-2350 (1995).
93. G. T. Gray, III, "Deformation Twinning: Influence of Strain Rate," *Twinning in Advanced Materials*, M. H. Yoo and M. Wuttig, eds., The Minerals, Metals, & Materials Society, 337-349 (1994).[INVITED Paper]

94. S. G. Song and G. T. Gray, III, "Microscopic and Crystallographic Aspects of the Retained Omega Phase in Shock-Loaded Zirconium and Its Formation Mechanism," *Philos. Mag. A* **71**, 275-290 (1995).
95. G. T. Gray, III, "Influence of Shock Loading on the Structure / Property Response of Ti-48Al-2Cr-2Nb and Ti-24Al-11Nb", *DYMAT 94*, Les Editions de Physique, France, pp. C8-373-C8-378 (1994).
96. S. G. Song and G. T. Gray, III, "Double Dislocation Pole Model for Deformation Twinning in FCC Lattices." *Philos. Mag. A*, Vol. 71, #3, 661-670 (1995).
97. D. E. Albert and G. T. Gray, III, "Dislocation Reactions Responsible for the Formation of a Twin in the Ordered Intermetallic Alloy Ni-20Al-30Fe," *Philos. Mag. A*, Vol. 71, #3, 473-487 (1995).
98. S. G. Song and G. T. Gray, III, "Influence of Temperature and Strain Rate on Slip and Twinning in Zr," *Metallurgical and Materials Transactions* **26A**, 2665-2675 (1995).
99. D. A. Hoke and G. T. Gray, III, "Arrangement of Dislocation Networks in Hot-Pressed Titanium Diboride," *Scripta Metall. et Materialia* **33**, 171-177 (1995).
100. S. G. Song, R. U. Vaidya, A. K. Zurek, and G. T. Gray, III, "Stacking Faults in SiC Particles and their Effect on the Fracture Behavior of a 15 vol.% SiC/6061-Al Matrix Composite," *Metallurgical and Materials Transactions* **27A**, 459-465 (1996).
101. D. E. Albert and G. T. Gray, III, "Dislocation Substructures in Shock-Loaded Ni₃Al," **High-Temperature Ordered Intermetallic Alloys-VI**, Materials Research Society, Horton, S. Hanada, I. Baker, R. D. Noebe, and D. Schwarz, eds., Mat Res. Soc. Symp. Proc., vol. 364, Materials Research Society, pp. 725-730 (1995).
102. D. E. Albert and G. T. Gray, III, "Mechanical and Microstructural Response of Ti-24Al-11Nb as a Function of Temperature and Strain Rate," *Acta Metallurgica et Materialia* **45**, 343-356 (1996).
103. Z. Jin and G. T. Gray, III, "Deformation and Strain Hardening of Ordered and Disordered Single Crystals of Cu₃Au at High Strain Rate," **Metallurgical and Materials Applications of Shock-Wave and High-Strain-Rate Phenomena**, L. E. Murr, K. P. Staudhammer, and M. A. Meyers, eds., Elsevier Science B.V., The Netherlands, pp. 901-908 (1995).
104. G. T. Gray, III, S. I. Hong, and B. J. Marquardt, "Influence of Strain Rate on the Mechanical Response of a Ti₃Al-Nb-Mo Alloy," *Metals and Materials* **2** 31-36 (1996).
105. F. Chu, Q. X. Jia, G. Landrum, X. D. Wu, M. Hawley, and T. E. Mitchell, "Microstructures and Electrical Properties of SrRuO₃ Thin Films on LaAlO₃ Substrates," *J. Electr. Mater.* **25**, 1754-1759 (1996).

106. D. Butt, D. Albert, and T. Taylor, "Kinetics of Thermal Oxidation of Silicon Nitride Powders Silicon Nitride Powders," *Journal of the American Ceramics Society* **79**, 2809-2814 (1996).
107. D. E. Albert and A.W. Thompson, "Effect of Stress-Temperature Regimes on Creep Mechanisms in Ti-24Al-11Nb," *Mater. Sci. Engin. A* **210**, 48-56 (1996).
108. S. P. Ablen, R. D. Field, and M. Mataya, "Elevated Temperature Stress-Strain Behavior of Beryllium Powder Product," Second IEA International Workshop on Beryllium Technology for Fusion, Jackson Hole, Wyo., September 6-8, 1995.
109. D. P. Butt, D. A. Korzekwa, S. A. Maloy, et al., "Impression Creep Behavior of SiC Particle-MoSi₂ Composites," *J. Mater. Res.* **11**, No. 6 (1996).
110. D.P. Butt, K. S. Lackner, C. H. Wendt, et al., "Kinetics of Thermal Dehydroxylation and Carbonation of Magnesium Hydroxide," *J. Am. Ceram. Soc.* **78**, 1892 (1996).
111. E. A. Cooper, H. Kung, and M. Nastasi, "Systematic Study of the Ion Beam Mixing of Oxide Markers into Alumina," *Nucl. Instrum. Methods B* **106**, 9-16 (1995).
112. R. Devanathan, N. Yu, et al., "Electron Diffraction Analysis of a Metastable State in Ion-Irradiated MgAl₂O₄ Spinel," *Proc. Microscopy and Microanalysis* **53**, 160 (1995).
113. R. Devanathan, N. Yu, et al., "Relationship between Structure and Mechanical Properties of Ion-Irradiated MgAl₂O₄ Spinel," *Proc. Microscopy and Microanalysis* **53**, 358 (1995).
114. R. Devanathan, N. Yu, et al., "Structure of the Metastable State in Ion-Irradiated Magnesium-Aluminate Spinel," *Phil. Mag. Lett.* **72**, 155-161 (1995).
115. C. J. Foster and A. K. Zurek, "Strain Rate and Temperature Dependence of Strength and Work Hardening in Molybdenum-Rhenium Alloys," Proc. of the International Conference of the Society of Engineering Science, New Orleans, La., 1995.
116. A. J. Griffin, M. F. Hundley, T. R. Jervis, et al., "Residual Stress, Mechanical Behavior and Electrical Properties of Cu/Nb Thin Film Multilayers," *Mater. Res. Soc. Symp. Proc.* **382**, 309-314 (1995).
117. J-P. Hirvonen, I. Suni, H. Kattelus, et al., "Crystallization and Oxidation Behavior of Mo-Si-N Coatings," *Surface Coatings Technol.* **74/75**, 981 (1995).
118. J-P. Hirvonen, P. Torri, R. Lappalainen, et al., "Tribological Characteristics of MoSi₂/SiC Nanocomposites," *Nanostruct. Mater.* **6**, 881 (1995).
119. T. R. Jervis, J-P. Hirvonen, et al., "Tribology and Mechanical Properties of Excimer Laser Processed Ti-Si₃N₄ Surfaces," *J. Mater. Res.* **10**, 1857 (1995).

120. H. Kung, R. G. Castro, et al., "The Structure of Plasma Sprayed $\text{MoSi}_2\text{-Al}_2\text{O}_3$ Microlaminate Tubes," *Scr. Metall. Mater.* **32**, 179 (1995).
121. H. Kung, T. R. Jervis, et al., "The Structure and Mechanical Properties of $\text{MoSi}_2\text{-SiC}$ Nanolayer Composites," *Philos. Mag. A* **71**, 759-779 (1995).
122. H. Safar, S. Foltyn, H. Kung, et al., "ab-Plane Anisotropy of the Critical Currents in Twinned $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$ Superconductors," *Appl. Phys. Lett.* **68**, 25 (1996).
123. K. E. Sickafus, N. Yu, and M. Nastasi, "Radiation Resistance of the Oxide Spinel: The Role of Stoichiometry on Damage Response," *Nucl. Instr. Meth. B* **116**, 85 (1996).
124. K. E. Sickafus, N. Yu, et al., "The Irradiation Damage Response of $\text{MgO}\cdot 3\text{Al}_2\text{O}_3$ Spinel Single Crystals Under High-Fluence Ion-Irradiation," *Nucl. Instr. Meth. B* **106**, 573-578 (1995).
125. D. J. Thoma, E. M. Schwartz, S. R. Bingert, et al., "Microsegregation During Melt-Spinning of Dilute Palladium Alloys," *Melt Spinning, Strip Casting and Slab Casting*, E.F. Matthys and W.G. Truckner, eds., The Metals, Materials, and Minerals Society, Warrendale, Penn. (1996).
126. R. U. Vaidya, D. P. Butt, et al., "Effect of Microbial Corrosion on the Tensile Stress-Strain Response of Aluminum and Al_2O_3 -Particle Reinforced Aluminum Composite" (to be published in *Corrosion Prevention and Control*).
127. R. U. Vaidya, L. E. Hersman, et al., "Microbiologically Influenced Corrosion of Aluminum 6061 and Al_2O_3 Particle Reinforced Aluminum 6061 Composite under Anaerobic Conditions and Elevated Temperatures: Effect on the UTS and Strain to Failure" (to be published in *Corrosion Prevention and Control*).
128. R. U. Vaidya, S. G. Song, et al., "The Effect of Structural Defects in SiC Particles on the Static and Dynamic Response of a 15 Percent SiC/6061-Al Matrix Composite," APS Topical Conference, Seattle, Wash., August 1995.
129. R. U. Vaidya and A.K. Zurek, "Effect of Aging Treatment on the Compression Behavior of a $\text{B}_4\text{C}/\text{Al}$ 6061 Composite," *J. Mater. Sci. Lett.* **15**, 385-387 (1996).
130. R. U. Vaidya, A. K. Zurek, and A. Wolfenden, "Effect of Plasma Sprayed Al_2O_3 Coating on the Strength, Elastic Modulus and Damping of Ti-25 Al-10Nb Intermetallic," *J. Mater. Eng. Perf.* **4**, 3 (1995).
131. K. C. Walter, H. Kung, J. T. Tesmer, et al., "Characterization and Performance of DLC Films Synthesized by Plasma and Ion Beam Techniques," *Surface and Coatings Technol.* **74/75**, 734-738 (1995).
132. K. C. Walter, M. Nastasi, H. Kung, et al., "Diamond-Like Carbon Deposition for Tribological Applications at Los Alamos National Laboratory," *Mater. Res. Soc. Symp. Proc.* **383**, 411 (1995).

133. N. Yu, P. C. McIntyre, et al., "High-Quality Epitaxial Growth of Gamma-Alumina Films on Sapphire Induced by Ion Beam Bombardment," *Phys. Rev. B* **52**, 17518–17522 (1995).
134. N. Yu, K. E. Sickafus, and M. Nastasi, "Temperature Effects on Ion Irradiation Damage in MgAl_2O_4 Spinel Single Crystals," *Mater. Res. Soc. Symp. Proc.* **373**, 401–406 (1995).
135. N. Yu, Q. Wen, D. R. Clarke, et al., "Formation of Fe or Cr Doped Epitaxial Sapphire Thin Films on Sapphire Substrates," *J. Appl. Phys.* **78**, 5412 (1995).
136. A. K. Zurek, W. R. Thissell, J. N. Johnson, et al., "Micromechanics of Spall and Damage in Tantalum," *J. Mater. Proc. Technol.* **60**, 261–267 (1996).
137. A. K. Zurek, W. R. Thissell, and D. L. Tonks, "Spall Behavior and Damage Evolution in Tantalum," Assoc. for the Advancement of High Pressure Science and Technology International. Conf., Warsaw, Poland, Sept. 10–15, 1995.